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Special Issue Reprint

Landscape, Water, Ground, and Society Sustainability under Global Change Scenarios

Edited by
Kevin Cianfaglione, Angela Curtean-Bănăduc and Doru Bănăduc

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Contents

Preface . . . . **vii**

Kevin Cianfaglione and Doru Bănăduc
Landscape, Water, Ground, and Society Sustainability under the Global Change Scenarios
Reprinted from: *Sustainability* **2024**, *16*, 1897, doi:10.3390/su16051897 . . . . **1**

Doru Bănăduc, Saša Marić, Kevin Cianfaglione, Sergey Afanasyev, Dóra Somogyi and Krisztián Nyeste et al.
Stepping Stone Wetlands, Last Sanctuaries for European Mudminnow: How Can the Human Impact, Climate Change, and Non-Native Species Drive a Fish to the Edge of Extinction?
Reprinted from: *Sustainability* **2022**, *14*, 13493, doi:10.3390/su142013493 . . . . **7**

O. U. Charlene Gaba, Yae Ulrich Gaba and Bernd Diekkrüger
A Flashforward to Today Made in the Past: Evaluating 25-Year-Old Projections of Precipitation and Temperature over West Africa
Reprinted from: *Sustainability* **2022**, *14*, 12093, doi:10.3390/su141912093 . . . . **46**

Adam Płachciak and Jakub Marcinkowski
Humanitarian Assistance in G5 Sahel: Social Sustainability Context of Macrologistics Potential
Reprinted from: *Sustainability* **2022**, *14*, 8862, doi:10.3390/su14148862 . . . . **74**

Horea Olosutean and Maria Cerciu
Water Sustainability in the Context of Global Warming: A Bibliometric Analysis
Reprinted from: *Sustainability* **2022**, *14*, 8349, doi:10.3390/su14148349 . . . . **99**

Yuntao Bai, Qiang Wang and Yueling Yang
From Pollution Control Cooperation of Lancang-Mekong River to "Two Mountains Theory"
Reprinted from: *Sustainability* **2022**, *14*, 2392, doi:10.3390/su14042392 . . . . **113**

Mohammed Achite, Gokmen Ceribasi, Ahmet Iyad Ceyhunlu, Andrzej Wałega and Tommaso Caloiero
The Innovative Polygon Trend Analysis (IPTA) as a Simple Qualitative Method to Detect Changes in Environment—Example Detecting Trends of the Total Monthly Precipitation in Semiarid Area
Reprinted from: *Sustainability* **2021**, *13*, 12674, doi:10.3390/su132212674 . . . . **137**

Sumit Singh, Bikarma Singh, Opender Surmal, Mudasir Nazir Bhat, Bishander Singh and Carmelo Maria Musarella
Fragmented Forest Patches in the Indian Himalayas Preserve Unique Components of Biodiversity: Investigation of the Floristic Composition and Phytoclimate of the Unexplored Bani Valley
Reprinted from: *Sustainability* **2021**, *13*, 6063, doi:10.3390/su13116063 . . . . **154**

Ajmal K. Manduzai, Arshad M. Abbasi, Shujaul M. Khan, Abdullah Abdullah, Julia Prakofjewa and Mohammad H. Amini et al.
The Importance of Keeping Alive Sustainable Foraging Practices: Wild Vegetables and Herbs Gathered by Afghan Refugees Living in Mansehra District, Pakistan †
Reprinted from: *Sustainability* **2021**, *13*, 1500, doi:10.3390/su13031500 . . . . **185**

Alexandru Burcea, Ioana Boeraş, Claudia-Maria Mihuţ, Doru Bănăduc, Claudiu Matei and Angela Curtean-Bănăduc
Adding the Mureş River Basin (Transylvania, Romania) to the List of Hotspots with High Contamination with Pharmaceuticals
Reprinted from: *Sustainability* **2020**, *12*, 10197, doi:10.3390/su122310197 . . . . **202**

G.-Fivos Sargentis, Theano Iliopoulou, Stavroula Sigourou, Panayiotis Dimitriadis and Demetris Koutsoyiannis
Evolution of Clustering Quantified by a Stochastic Method—Case Studies on Natural and Human Social Structures
Reprinted from: *Sustainability* **2020**, *12*, 7972, doi:10.3390/su12197972 . . . . **221**

Preface

The landscape is a visible feature of land that integrates natural and human-made features (cultural, social, and economic) and dynamics at different scales. Ground, water, and society primarily determine the characteristics of the landscape. When at least one of these features changes, the landscape changes. Anthropic dynamics on the landscape are intended as the human past, present, or mixed activities that influence the landforms, land elements, and biodiversity or the natural dynamics of biological communities and populations.

Water must be understood as an essential component of life; as a part of all living organisms, habitats, and ecosystems; and as an energy resource. Problems related to water may be direct (water resource assessment, monitoring, management, use, impact, etc.) or indirect (soil use and slope stability, hydro-geological issues, erosion, floods, etc.).

Ground issues are intended to include soil topics; land occupation; substrates for natural species, agriculture, food, and other product sources; and chemical and ecological changes. The problems related to soil degradation are desertification, saltation, erosion, soil sealing, pollution, and other noteworthy chemical changes.

Integrated, multi-, or interdisciplinary analyses or considerations should be encouraged to improve our knowledge and foster the scientific debate on these issues.

Following this idea, in this Special Issue, we collected study cases and more theoretical papers on these topics.

Kevin Cianfaglione, Angela Curtean-Bănăduc, and Doru Bănăduc
Editors

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Editorial

Landscape, Water, Ground, and Society Sustainability under the Global Change Scenarios

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1. Special Issue Topic, Aims, and Scope

The increasing human world population and its hunger for space, ecosystem services, energy, and other natural resources are widely indicated as the main causes of human negative impact, together with the dominant cultural model and the currently predominant economic type of development.

The issues causing environmental problems that we are currently facing are the dark side of our economic development model, with its culture, society rules, and technology advances linked with an improper, unpredictable, and aggressive use of land and natural resources. All this is the cause of unsustainable way of our living and of our development. All this represent major challenges for the future of our planet and of humanity.

The most negative consequence of these problems are climate change, habitat degradation, pollution, biodiversity loss, invasive species chronicity, chronic anthropization, social unrest, and conflicts. Also human large migrations and wars, macroeconomic crises, loss of cultural traditions, wrong (local, national, and global) policies and incorrect land management approaches, are some of the main issues that impact the landscape, water, ground, and human society sustainability on a spatiotemporal scale.

All of them are crucial driving forces for our society's development, for our quality of life, for the environmental quality and functioning of our ecosystems, and even to face the possible challenges of global change. They are a major reason for constant concern in relation to the impact of human activities on ecosystems and human societies [1–4]. These editorials focus on the research topic issues related to landscape, water, ground, and society sustainability under global changes scenarios.

2. Special Issue Contributions

The aim of this Special Issue is to focus mainly on landscape, water, ground, and societal characteristics under global change scenarios: happenings, and perspectives.

Water is a constituent of all creatures and environments; consequently, it is a crucial element of habitats, communities and biocoenosis. Water is also considerable as an important landscape element, and an increasing important energy resource for human activities.

Ground is a needed base and component for the life cycle, agriculture, ecosystems. Ground is another important landscape element and an important resource for human activities.

Ground, water, and society primarily determine the characteristics of the landscape. When at least one of these features is altered, the landscape changes consequently. Anthropic dynamics on the landscape are intended as the human past, present, or mixed activities that influence the landforms, land elements, biodiversity, or the natural dynamics of biological communities, populations and ecosystems. Important problems related to water and the ground may be directly or indirectly caused by human activities.

The first manuscript of our Special Issue highlights the fact that throughout their history, humans "tamed" the whole Danube watershed terrestrial and aquatic ecosystems,

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significantly determining their species, communities, associations, and habitat characteristics. One of the characteristic flagship endemic fish species, the European mudminnow (*Umbra krameri* Walbaum, 1792), was influenced by the watershed geography, history, politics, and ecology. This research about this European community concern fish umbrella species in the circumstance of long-term human negative impact on its particular habitats, with possible synergic harmful effects of climate change, was treated as extremely desirable by an international researcher's group initiative to support the efforts for this species and its ecosystems survival. All the specific mapped wetlands habitats expose the diminishing trend of this fish distribution area continuousness; fragmentation being the power that skewed it severely until the present and influencing quantitatively and qualitatively the characteristic habitats. The key categories of human activities that impacted this species' habitats are water regulation, pollution, dredging, draining, and the introduction of non-native species. Generally, various human impact activities, especially in a climate change context, induce severe concerns about negative influence on this species. All the studied wetlands where this fish survived can be considered refuge and stepping stone wetlands, particularly in the growing climate change trend circumstances [5].

The second study in this Special Issue was based on the idea that today is yesterday's future. A set of comparisons among past Intergovernmental Panel on Climate Change climate projections and gauge-based observations of the last three decades (1990–2016) were undertaken. Monthly and annual precipitation and temperatures were studied over West Africa, separated into three climatic sub-regions. The outcomes highlighted that the identified variances are higher at higher latitudes and are strongly scenario-dependent. The Business-as-Usual scenario (few or no steps are taken to limit greenhouse gas emissions) seemed to be nearby to the observations. The AR1 projections were shown to be detached from the observations, the AR2 projections were the most performant, and the AR3 projections presented higher uncertainties in the northern zones. The relative significance and possible implications of the differences between projections and observations on people's perception were appreciated with regard to certain climate and weather-related factors that could seriously influence sustainable development in the studied area, such as water capital management, agriculture practices and yields, health conditions, and fishery management [6].

The third manuscript focused on how the G5 works in partnership with different worldwide entities, which are in authority for managing logistics actions, financial flows, and technological solutions. Charitable support has a major role in the area, in spite of its various challenges and limits in macroeconomic progress. This study targeted the macro-logistics potential of humanitarian aid and protection on national and international scales from a social sustainability perspective. Most of the humanitarian crises in the studied area came from conflicts, food access uncertainty, underfeeding, and malnourishment. Sahel necessitates numerous creative enterprises to deal with the effects of environmental-related problems. The quantitative and qualitative aspects of logistics infrastructure, a varied array of natural and human directly or indirectly induced calamities, and the economic circumstances of the G5 Sahel usually cause numerous problems for charity in the area, problems that should be supported by continuous transnational tightening strategies and partnerships [7].

Then, the fourth study of this Special Issue focused on water sustainability in the context of global warming. Using water in a sustainable manner is a crucial issue today, especially since global warming is more than ever having an important negative impact on water capital. This study's bibliometric analysis focused on water resource sustainability in the context of global change, trying to find potential gaps in the research. The selection and investigation of the most significant papers debating this topic revealed a robust rise in research, led by US researchers and research entities, concentrating both on the present impact of global warming on water sustainability and its characteristic effects on water supply and ecosystem functioning, or on problem solving and creating a framework for water sustainability, or on future perspectives and potential solutions for achieving water sustainability. It was revealed that only 6% of the studied papers dealing with water sustainability contain data related to global warming, with a growing trend lately in terms of articles and citation numbers, but the field of such studies seems to be in an early stage, with a large number of journals including very few such articles. The main weaknesses are that the focus of a large majority of the studies is on present problems and not on future challenges and reliable solutions for them. Importantly, there is also an almost complete lack of research about the role of conserving natural habitats or of re-naturalization, as well as a relative low number of studies including cultural aspects in addressing water sustainability issues [8].

The fifth contribution, in the context in which it focused on its main role in the process of regulating environmental pollution, was based on an example of pollution control in the Lancang-Mekong River watershed: "Lucid waters and lush mountains are invaluable assets" (referred to as the "Two Mountains Theory"). The study stresses the fact that upstream and downstream countries can carry out water pollution control by implementing fines on enterprises that induce environmental problems and making them invest in pollution control activities. Firstly, the differential game model of pollution control by individual countries and international collaboration is established. Then, a differential game model of joint pollution control with a recompense mechanism is established under the collaboration framework. Lastly, the feedback Nash equilibrium of each state is acquired. The research reveals that in the process of industrial pollution control by countries, due to the one-way externality of water pollution control, the more downstream countries are, the more resources will be financed for pollution control, and the fewer fines will be imposed on enterprises that cause environmental damage. At the beginning phase of management, if more pollution control resources are input, fewer countries will join in cooperation, and the fines for polluting enterprises will be less. When the amount of fines for enterprises is relatively small, the formation of a river pollution compensation mechanism is not conducive to the input of pollution control resources. The coordinated development of economic development and ecological civilization construction is the core purpose of the "Two Mountains Theory". Therefore, this case demonstrates the viability of this theory based on cooperation [9].

The sixth contribution focused mainly on precipitation as a vital element of the water cycle; on its irregularity, which radically impacts agriculture, ecosystems, and water resources; and on water scarcity induced by climate variability. In this research, the Innovative Polygon Trend Analysis (IPTA) method was applied for precipitation trend discovery in the Wadi Sly basin, Algeria, from 1968 to 2018. For different stations, the first results revealed that there is no regular polygon in the IPTA graphics, thus indicating that precipitation data varies by year. The IPTA method revealed different trend behaviors, with a precipitation increase in some stations and a decrease in others. This variability is induced by climate change. The results point to a greater focus on flood risk management in severe seasons and drought risk management in transitional seasons across the studied basin. The method used is appropriate for preliminary analysis trends of monthly precipitation in other neighboring basins too [10].

The seventh contribution was dedicated to the unexplored Bani Valley (2651 km^2) plant diversity in the Himalaya. A total of 196 plant species belonging to 166 genera and 68 families (70.62% native and 29.38% non-native) were inventoried as voucher samples, identified, and placed in the Janaki Ammal Herbarium. In total, 46% of species were Indo-Malayan, followed by 22% of Palearctic species. In angiosperms, dicotyledon species (68.37%) dominated. *Poales* were the most dominant order, with 38 species (19.38%). The most abundant families were *Poaceae*, with 29 species (14.79%), *Fabaceae* (17, 8.67%), *Rosaceae*, *Cyperaceae*, and *Asteraceae* (9, 4.59% each). The life form analysis showed 50% of species as phanerophytes, followed by therophytes (25.77%). The leaf size spectra show mesophyllous species (34.69%) as the dominant group. The IUCN Red List of Threatened Plants categorized *Ailanthus altissima* as endangered (EN), *Aegle marmelos* and *Quercus oblongata* as near threatened (NT), *Ulmus wallichiana* and *Plantago lanceolate* as vulnerable

(VU), *Taxus baccata* and 75 other species as least concern (LC), and 2 species as data deficient (DD). The study helps to shape conservation and management plans for threatened species management and conservation [11].

The eighth study approaches the issue of foraging for wild food plants among migrants and relocated communities in order to understand how human communities readjust their habits in relation to nature and how they acclimatize to different socioecological systems. Here, the Traditional/Local Environmental Knowledge (LEK) changes linked to wild plants are addressed across four groups of Afghan expats living in Mansehra District, NW Pakistan. Forty-eight wild plants represented both the past and present wild plant gastronomic heritage. The prevalence of the quoted wild plant ingredients was only evoked and no longer used, thus revealing a significant loss of LEK. Furthermore, the total number of wild vegetables and herbs used at present by Afghan Pashtun farmers is much higher than those used by the other groups. The practiced LEK is constantly kept alive via continuous contact with nature, being important for the flexibility of the biocultural heritage, which is, however, also influenced by the readjustment of social life embraced by refugees after relocation [12].

The ninth contribution focused on the pharmaceutical pollution of aquatic ecosystems. High levels of four pharmaceutical compounds (carbamazepine, ibuprofen, furosemide, and enalapril) and some of their derived metabolites (enalaprilat, carboxyibuprofen, 1-hydroxyibuprofen, and 2-hydroxyibuprofen) were found in this research in the Mureș River Basin. Overall, pharmaceutical concentrations were identified to be highest in the wastewater treatment plant (WWTP) effluent, median downstream of the WWTP, and lowest upstream of the WWTP. Carbamazepine displayed the highest mean values upstream, downstream, and at the WWTP. The highest concentrations for all the studied pharmaceutical compounds were detected in the WWTP effluent. The relatively large and complex hydrographical system of the Mureș River Basin proved to be a hotspot in terms of contamination with emerging pollutants. Pharmaceutical compound concentrations were found to be the highest in WWTP effluents. The WWTP effluent concentrations were among the highest in Europe, showing that treatment plants are the primary source of water pollution with pharmaceutical compounds. The identified levels were higher than the safety limits for carbamazepine and ibuprofen. Based on the achieved results, human communities can assess, monitor, predict, and adapt to the present regional challenges and risks for sustainable use of natural resources, including water and associated products and services [13].

The tenth research paper in our Special Issue refers to clustering structures appearing on small to large scales that are omnipresent in the physical world. Clustering structures are ubiquitous in human history, oscillating from the mere organization of life in societies to the growth of large-scale infrastructure and policies for meeting structural needs. Mankind has continuously sought the advantages of unions. As the scale of the projects increases, the price of the provided products is cheaper while their quantities are maximized. Thus, large-scale infrastructures are considered beneficial and are always being pursued at greater scales. This paper develops a general method to quantify the temporal progress of clustering using a stochastic computational tool, namely 2D-C, which is appropriate for the research of both natural and human social spatial structures. The evolution of the structure of the universe, of ecosystems, and of human clustering structures was investigated using novel sources of spatial information. The outcomes highlight the existence of both episodes of clustering and de-clustering in nature and in human social structures; however, clustering is the general trend [14].

We are grateful to the authors and their institutions that have proposed their contributions to our Special Issue. We hope that this Special Issue can serve as a spark, illuminating the path we must take towards the future, perhaps contributing to scientific, societal, and environmental progress, and pursuing an increase in the quality of our environment and of our lives.

3. In Memoriam of Dr. Angela Curtean-Bănăduc

Tragically, the period between the conclusion of this Special Issue and the preparation of the second edition on the same topic SI (https://www.mdpi.com/journal/sustainability/special_issues/DFEHLSAIDN, accessed on 10 October 2023) was the final period of life for one of the editors, our beloved Angela Curtean-Bănăduc, who passed away in Clermont-Farrand, France, on 1 November 2023.

The other two editors, Dr. Doru Bănăduc and Dr. Kevin Cianfaglione, wish to pay an 'in memoriam' tribute to Angela, who was a valuable good friend, an esteemed colleague, and the beloved wife of Doru.

Angela was born in Orăștie (Transylvania, Romania) on 27 January 1971, into a caring family of intellectuals whose main educational moral rule, "everything you do, do it right!", profoundly influenced her contented golden childhood and teenage years.

This happy family and the location of their picturesque, multicultural native city, lying near the Carpathian Mountains where the legendary Sarmizegetusa Regia, capital of the ancient Dacians, over the last 2000 years beneficially influenced Romanian dreams and realities—if only to recall here a temple of the Romanian language, "Palia de la Orăștie", the monumental translation of the Old Testament into the Romanian language carried out in the 16th century—created the necessary milieu that inspired Angela to achieve something important with her life.

The vicinity of one of the largest Danube River tributaries, the scenic Mureș River, inspired her to fall in love with the color blue, as seen in her beautiful eyes, rivers, and streams. The chance to dream, imagine, organize, support, and directly shape the lives of people of goodwill involved in the continental waters scientific understanding and protection, and the forces that uphold them, came through the professional opportunities afforded by her studies in chemistry at the Nicolaus Olahus High School of Orăștie, in ecology at the "Lucian Blaga" University of Sibiu, for her PhD in aquatic ecology at the "Ovidius" University of Constanța, and her post-doctoral research in water resources management at the "Costin C. Kirițescu" Romanian Academy National Institute of Economic Research in Bucharest, etc.

The rivers and streams were indeed symbolic of her beautiful blue life on this blue planet. Nature was her temple, home, and source of support for numerous projects in ecology, biology, and nature protection and conservation. Benthic macro-invertebrates and fish populate her written output—scientific episodes that are on permanent record in over 200 publications. To give just some examples of what Angela founded and/or led over the years with fabulous positive and honest energy, efforts, and results: "Transylvanian Review of Systematical and Ecological Research" (https://magazines.ulbsibiu.ro/trser/index.html (accessed on 10 October 2023)) since 1999, including the Wetlands Diversity series; "Aquatic Biodiversity International Conference (ABIC)" since 2007 (https://magazines.ulbsibiu.ro/trser/events.html (accessed on 10 October 2023)); "Acta Oecologica Carpatica" since 2008; environmental "Ecotur Sibiu" Association since the end of the XX century; "Applied Ecology Research Center" in the last century (https://appliedecologysibiu.wordpress.com/ (accessed on 10 October 2023)); "Lucian Blaga" University of Sibiu Faculty of Sciences, where she has worked hard in teaching and research since 1996, finally for 10 years as a Dean; etc.

Many devoted friends accompanied her genuinely extraordinary and beautiful personal and professional life, the co-editors of this Special Issue being only two of them. A unique personal and professional match was achieved without a break since 2000 between the beloved Angela and her husband Doru, who, not by chance, pays his deep loving respect for an incredible shared lifetime experience.

A cruel illness took Angela too soon from this world, but up until her final days, she smiled with her characteristic kindness.

All of us who had the good fortune to meet Angela in this all-too-short life and to benefit from her angelic heart and mind will forever keep her in our warmest memories!

Family, friends, colleagues, and students wish her eternal blue waters on the other side, where sooner or later we shall all meet to again be happy together!

Conflicts of Interest: The authors have no conflicts of interest to declare.

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Article

Stepping Stone Wetlands, Last Sanctuaries for European Mudminnow: How Can the Human Impact, Climate Change, and Non-Native Species Drive a Fish to the Edge of Extinction?

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Abstract: Throughout their history humans "tamed" not only the Danube River basin land, but also the river and its associated wetlands, drastically influencing their characteristic habitats, associations, communities, and species. One of these flagship endemic fish species in this respect is the European mudminnow (*Umbra krameri* Walbaum, 1792), influenced by Danube Basin geography, history, politics, and ecology. A study about this European community concern species in the context of long term human impact on its specific habitats, with potential synergic negative effects of climate change, was treated as highly needed, in an international researchers group initiative to support the efforts to provide hope for preserving this fish species and its ecosystems, and brought it back from the brink of extinction. All the characteristic inventoried wetlands which were or some of them still are natural, semi-natural, or accidental anthropogenic habitats, reveal an accentuated diminishing trend of this species areal continuity; fragmentation being the force which skewed it drastically untill now, and inducing diminishing the specific habitats quantitative and qualitative characteristics in the Danube Basin where these fish fight for survival. The main categories of human activities which impacted the climate changes in the context of this species' habitats are: water regulation, pollution, dredging, draining, and introduction of non-native species. Overall, the diverse human impact in a climate changes in the context of this species' habitats, *Umbra krameri* wetlands, creates serious perspectives on negatively influencing this at a very high scale and level. All the inventoried wetlands where *Umbra krameri* still survive can be considered an ecologically managed as a refuge and stepping stone wetlands, especially in the increasing climate change trend situation. Supplementary inventory studies in the field should be done for the identification of some may be unknown *Umbra krameri* habitats and populations.

Keywords: drought; habitat degradation; refugees; endemic fish; isolation; risk management

1. Introduction and Background

Water is a key to understand the cosmos, controls the Earth environment [1,2], and drive among other elements the biodiversity [3–12]. In this context, the importance of wetlands for aquatic, semi-aquatic, and terrestrial biotopes is essential, mostly when are impacted by humans, such cases being in all the Danube Basin countries [13–30].

Climate change is one of the best known bad situations to face for wetlands, that Man has faced [31–36]. The planetary climate models reveals that the main element that caused this global event to happen are natural and induced by human activities; the conjunction of these factors can explain the last century and a half climate changes [36], influencing the water cycle and water supply [37] and the Earth ocean level rising [38].

The science agreed that among the determinants of the organisms' state, including the freshwater ones [39], the climate is on top because it influences everything [40]. Inland water is influenced by the weather and by the atmosphere temperature variations, consequently, the climate changes have effects on freshwater organisms [41].

The current IPCC Climate Report "Code Red for Humanity", reveals that warming has accelerated in the last decades; the planet is heating up, and supplementary warming is expected. Many changes inducing climate impact shocks will worsen [42]. Additionaly, the change of hydrologic cycles have repercussions on freshwater habitats organisms [42,43]. Increased climate modifications are predicted to impact the biodiversity of extensive regions [44]. The planetary heating up is putting at risk the Earth biodiversity, including fish [45–51], a main taxonomic group under high worldwide human-impact risks [52–63].

The air temperatures will increase in Europe too, due to anthropogenic effects on the atmosphere [64–66]. The forecasts reveal that the precipitation regime will be changed, with increasing drought events [67], and climatic crises anticipated [68]. Climate warming is due to a heating trend since the mid-20th century, tied to human activities [60–71].

Drought is an effect-dependent phenomenon [72], and human impact is partially responsible for the drought incidents [73] provoking a complex hydro-climatic risk influencing the ecosystems [74]. The heat waves' strength is forecasted to boost [75].

In the climate change context, the temperature raises all-around [76], even in surprising regions, like in a relative moderate climate of Danube Basin [77–90].

In the present heating up, freshwater ecosystems are strikingly sensitive, freshwater biodiversity has descended faster than marine or terrestrial [3–6].

The Danube Basin, due to the climate change effects together with other human activities' impact, present changes of temperature, precipitation, and hydrological regime [91–100] and of features of the associated aquatic communities. Overall, the climate change was identified as a new water management main issue in this basin [77–87].

Research in the Danube Basin reveal accentuated heat waves, droughts, evapotranspiration, and a runoff diminishing, disturbing the low flow seasons [43], and the associated organisms including fish are under humans' negative effects [101–107].

This study's main objective is to provide data related to the environmental relevance and risks of one of the imperiled fish of Europe [107] rather scarce and fragmented stepping stones and refuge habitats in the Danube Basin, in the context of human impact and climate change effects, the European mudminnow (*Umbra krameri*, Walbaum, 1792).

The Danube Basin extends up to 801,093 km^2, in 19 countries, from the Black Forest springs to the Black Sea, collecting nearly 827 km^3 of water every year [104].

Many historical records have voiced the importance of a high variety of fish species and fisheries in the Danube Basin [101–105], overlapping highly variable ecological and functional guilds [106], and covering a large variety of aquatic and semi-aquatic habitats.

There were and a high number of fish species of conservation importance, some of them having a high degree of specificity for the Danube Basin, one of them, is *Umbra krameri* which is one of the most endangered species of the original Danubian fish fauna and all the threats are directly and indirectly anthropogenic [107].

The European community's aim in the environment care is the protection, conservation, and improvement of the nature-related resources management characteristics and value, on the condition that these resources should be used wisely. Biodiversity protection and conservation is a more important aim of the European Union. The climate change background boosts the intricacy of this important issue [108].

The Umbridae family is present in some parts of the Northern Hemisphere in freshwater environments. It encompasses *Dallia*, *Novumbra*, and *Umbra* genera [109,110].

The genus *Umbra* is known since the Paleogene in the European continent [111]. The European representative of this genus *Umbra krameri* occur in south-eastern Europe, and has its terra typical in the Danube Basin, and have scattered small populations in the Danube and Nistru basins in Austria, Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Slovakia, Hungary, Ukraine, Bulgaria, Moldova, and Romania [112–116]. This species was introduced recently in Poland, Germany, England, and Holland [114–116].

The genus term *Umbra* (shade) possibly invokes its aquatic habitat with often almost impenetrable vegetation associations, this tiny, quite enigmatic fish, an inhabitant of rather isolated and not easy accessible wetlands, has no direct economic value and is used by the fishermen only as living bait or sometimes as aquarium fish [110].

A concern must be always present, about the risks for these vegetation associations, that are given by an excessive (intense or/and frequent) anthropic pressure that can overwhelm the natural resilience, adaptability, and resistance that characterize these wetlands plant communities, and so changing the habitat. The greatest risks are for the more meso and oligotrophic plant species [117]. But even the communities that generally appear much more resistant to the anthropic pressure in certain situations can instead show a regression or disappearance phenomena, as especially happened for example, in several European wetlands [118] and as possible to observe in Danube Basin [119,120].

Umbra krameri is a short life span species, reaching its sexual maturity at one/two years. The reproduction is in the March–June, at a water temperature of 12–18 °C. For reproduction the females dig nests in the mud/sand, defend and oxygenate the spawn, and also the roes are laid on aquatic plants [110,112,121].

Even though this fish species is under the Bern Convention, CITES, IUCN Red List, etc. care [110,122], there are many causes that have induced its downturn, its spotty range along with its decreasing distribution area, and potential extinction risk, every one of the existing hazards can push to a major decline of this species [110,114,122,123].

Are the late climate changes a new synergic major risk for this already threatened European wetlands key and flagship indicator fish species? This paper's main goal is to reveal the bio-geographical and ecological situation of the *Umbra krameri* specific habitats and populations and propose Danube Basin conservation strategy elements, measures, and actions, to conserve the still existing specific habitats and populations.

Climate studies go further than temperature tendency done in the past, and it was drawn up to the habitat and ecosystem approach when the first famous IPCC synthetic report was publicly released in 1990. Since that period, there was growing data about the effects of global warming overlapping depreciations by other human-induced impacts in scientific works, also in the whole area of the Danube Basin. Climate reaction for the Danube Basin is highlighted by four main elements: How to accurately determine the impact of climate change on freshwaters? What techniques are specific to revealing an ecosystem response to climate modifications? How to tackle which information suits an optimum way for climate study? What have we understood from climate research to better evaluate, monitor, and manage the ecosystems?

At the 21st century dawn, it was obvious that the human-nature interconnexions are unbalanced and had a serious complex negative impact on biodiversity, and the Danube Basin to which the studied area belongs is not an exception [13–30].

This study addressed some ecological aspects of frequent, extended, and intense drought periods of time and their long-term negative effects on the Danube Watershed *Umbra krameri* wetland habitats and populations, a fish species with a high indicative importance for the researched ecosystems' ecological status trends under the constant significant negative human impact and climate change/drought seasons' pressure.

The indirect and direct anthropogenic activities effects influence are the main elements of comprehension of the drought effects on the researched species habitats.

It is sure that the tendency of climate in this century in the Danube Basin will be very much like that of the end of the last past one, with rising values of extreme hotness and high-temperature waves and frequency [77–91]; this reaffirms the challenge for specific research based on field inventories of existent problems and update suggestions of proactively management plans including for key indicator species like *Umbra krameri*.

This study had the main aim to inventory and map the present wetland refuges and stepping stone habitats of *Umbra krameri*, and also to identify new potential areas where such wetlands should be rehabilitated or made, and repopulated with this species. Also, monitoring and management elements were suggested for these wetlands' natural processes recovery and improvement. It must be featured that no such specific study concerning the Danube Basin wetlands refugee and stepping stones habitats for *Umbra krameri* has formerly been done.

For the readers' navigation in the paper support, we highlight here the included chapters and subchapters: 1. Introduction and Background; 2. Materials and Methods; 3. Results and Discussion; 3.1.1. Wetlands in Austria; 3.1.2. Wetlands at the Austria-Slovakia-Hungary border; 3.2. Wetlands of the Danube River in Hungary; 3.3.–3.4. Lugomir and Kraljevac channel system in Danube drainage in Serbia; 3.5. Wetlands at the Serbia-Romania border; 3.6. Jiu River lower part in Romania; 3.7.–3.8. Olt-Vedea-Argeş rivers lower partin Romania; 3.9. Lower Danube River Basin-Danube River Delta in the Romania-Moldova-Ukraine border area; 3.10. Mura and Drava river system at the Slovenia-Croatia-Hungary border; 3.11. Zala River, Lake Balaton system in Hungary; 3.12. Upper Tisza system in Ukraine and Hungary; 3.13. Borsodi-mezőség plane, Tisza system in Hungary; 3.14. Bihar-plaine Tisza system in Hungary; 3.15. Wetlands at the Romania-Hungary border; 3.16. Lonja and Odra wetlands in Croatia; 3.17. Matura River system in Bosnia and Herzegovina; 3.18. Wetlands at the Serbia-Bosnia and Herzegovina border; 3.19. Timiș River system in Romania; 3.20. Prut River at the Moldova-Romania border; 3.21. Dniester River at Moldova-Ukraine border; 3.22. Danube Basin Umbra krameri populations state and potential trends under climate change impact; 3.23. Umbra krameri refuge and stepping stone habitats management elements proposals for the Danube Basin; 4. Conclusions.

2. Materials and Methods

This study was based on the synthesized available scientific studies results and on the biological samples obtained by the authors in the field from 2016 to 2021, in summer drought periods when this helpless fish were caught even by hand, simple fishing net-tools, electrofishing, or found in the fisherman captures in all the Danube Basin still proper areas (Figure 1). The major method limitation is field activities for checking the presence of this species were done over a six years period some of these populations can locally be extinct now.

The obtained data features the presence and refugee-stepping stone value of the analyzed sites.

The *Umbra krameri* fish species individuals were sampled with bare hands, simple fishing tools, electric fishery devices (Hans Grassl IG200b, Samus 725MP) or found in the fisherman captures alive, were released in the habitat of origin after a visual identification, specific research literature data was used too.

Different habitat characteristics data were registered and presented in the paper text.

This study suggests at the end in situ adapted management elements for the rehabilitation or reconstruction, at least in part, of the former ecologic status of these wetlands, and *Umbra krameri* populations.

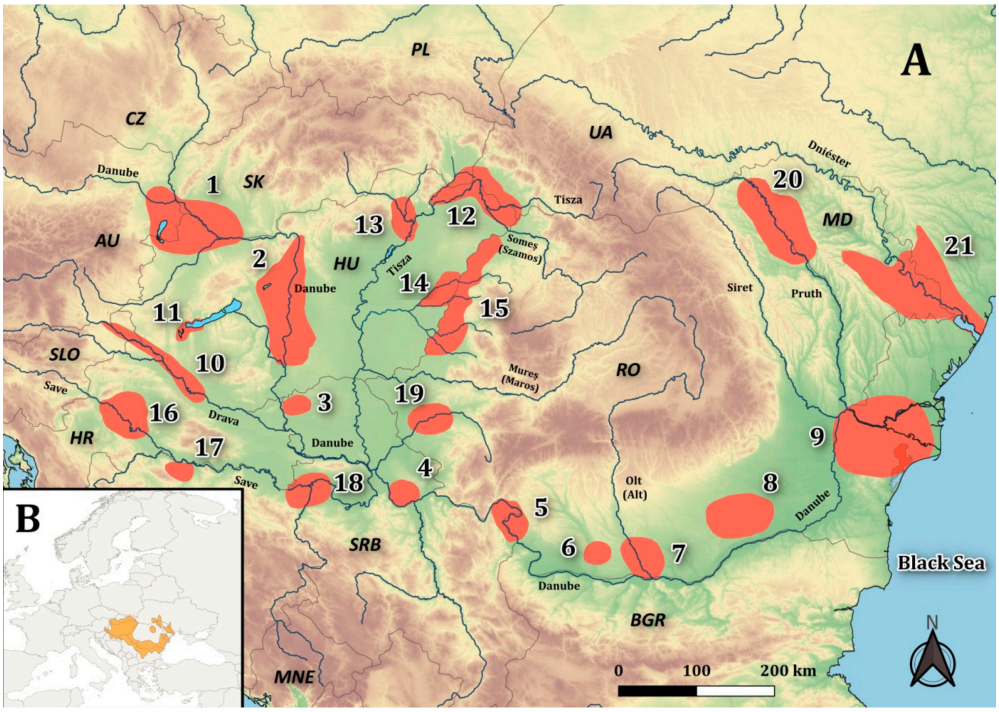

Figure 1. Recent (**A**) and historical (**B**) distribution of *Umbra krameri* in Europe. Biogeographical regions with numbers were designed by right of occurrence data adapted from this research's database and the following references: Kottelat & Freyhof, 2007 [124]; Sekulić et al. 1998 [125]; Takács et al., 2015 [126]; Marić et al., 2017; 2019 [126,127]; Covaciu-Markov et al., 2018 [128]. Recent regional distribution reports shown on the map include: (1) Wetlands in Austria and its borders with Slovakia and Hungary; (2) Wetlands of the Danube River in Hungary; (3) Lugomir channel system in Danube drainage in Serbia; (4) Kraljevac channel system in Danube drainage in Serbia; (5) Wetlands at the Serbia-Romania border; (6) Jiu River lower part in Romania; (7) Olt river lower part in Romania; (8) Vedea-Argeş rivers lower part in Romania; (9) Lower Danube River-Danube River Delta at the Romania-Moldova-Ukraine border; (10) Mura and Drava river system at the Slovenia-Croatia-Hungary border; (11) Zala River, Lake Balaton system in Hungary; (12) Upper Tisza system in Ukraine and Hungary; (13) Borsodi-mezőség plane, Tisza system in Hungary; (14) Bihar-plaine Tisza system in Hungary; (15) Wetlands at the Romania-Hungary border; (16) Lonja and Odra wetlands in Croatia; (17) Matura River system in Bosnia and Herzegovina; (18) Wetlands at the Serbia-Bosnia and Herzegovina border; (19) Timiș River system in Romania; (20) Prut River at the Moldova-Romania border; (21) Dniester River at Moldova-Ukraine border.

3. Results and Discussion

3.1. Wetlands in Austria and Its Borders with Slovakia and Hungary

- Wetlands in Austria

The *Umbra krameri* was described from the Danube floodplain by Marsili, the first record which comes from Austria was given by Kramer after whom the fish was named, later was considered extinct in Austria during the late 1970s and 1980s, however, has been rediscovered in 1992, exactly 30 years before present [129–132].

There were three historically known areas the fish could be found (before 1992): (1) The Danube floodplain between Vienna and Bratislava, (2) the lowlands southeast of Vienna along the rivers Leitha and Fischa, and (3) the Lake Neusiedl (Fertö).

After the rediscovery in 1992 in area 1, in the Danube old sidearm between the villages Orth and Eckartsau, the so called "Fadenbach" [129,130], the other areas were checked for remnant populations. In area 2 the result was positive and an extant population could be found near the Moosbrunn village. However, in area 3 the search was unsuccessful for Lake Neusiedl (Fertö). Two more areas were checked: The Austrian sides of the River

March (Morava) forming the border with Slovakia and of the River Mur (Mura) in the south of Austria, before it fully enters Slovenia. Potential occurrence in the latter area was hypothesized, because in Slovenia populations were found in the oxbows of the Mura river not far from the border with Austria. Nevertheless, no mudminnows could be found in those additional areas during the fishing campaigns in 1993–1996.

A metapopulation viability analysis was performed for the Fadenbach based on empirical demographic parameters obtained during the monitoring campaign of five years and additional experimental propagation [129]. A main finding was a probability of 50% of extinction of this metapopulation within 24 years, if trends in habitat reduction seen at that time persisted. This trend in the decline of habitat carrying capacity down to zero, i.e., complete disappearance or drying out of primarily groundwater-fed floodplain ponds, is based on the hydrological changes of the Danube river. Water regulation, which started in the 19th century, resulted in increased flow velocities causing the river to permanently cut a deeper main channel and concurrently sediment transport is blocked from upriver by a chain of hydropower plants. This lowers the groundwater level in the adjacent floodplain and transformed the former sidearm of the Danube into a chain of disconnected ponds unless high floods of the Danube reconnect the pools occasionally. All the ponds containing mudminnows are located outside of the main flood control dam, increasing the probability of desiccation, but also protecting mudminnows from occasional recolonization with other fish species.

Management actions to preserve the one and only remaining metapopulation of the Austrian Danube floodplain in the Fadenbach channel were conceptualized [133]. These authors suggested digging the channel of the Fadenbach deeper to slow down the trend of drying out of pools or becoming so shallow that drastic winter kills, caused by freezing of the water column, lead to population collapses. Furthermore, we suggested to locally deepening existing pools to sustain their role as refuge habitats during droughts. This was further developed by Spindler [134], in cooperation with the Austrian Danube National Park, established in 1996 (https://www.donauauen.at/en, accessed on 11 April 2022). Digging of the channel and of some pools carried out in winter 2000/2001 and a pronounced increase in metapopulation abundance was noted afterwards (Spindler 2006). Over one decade the mudminnow was found as the most abundant fish species in the Fadenbach channel [135]. There were confirmed habitat characteristics and associated fish community from the literature [116,136]. Then, the management of the mudminnow metapopulation in the Danube floodplain of Austria seemed to work since the management actions carried out in 2000/2001 in line with ecological goals defined for this channel [137]. The last survey, with good results, of that area was done in 2018 during a monitoring campaign fulfilling the Austrian obligations for the EU Habitats Directive [138].

For the second historic area of occurrence, in the Vienna basin southeast of the city, close to the Moosbrunn village, a viable population could be confirmed during 1993–1996. In the following few years a new monitoring campaign reconfirmed the recent existence of that population [139]. That population seems fairly stable and no specific management actions are imposed except the general protection of the area. The habitat is very different from the habitats in the Danube floodplain. It represents a groundwater fed spring followed by a rivulet running through a bog area. The cold-water stream is heavily overgrown and accompanying fish species consist of northern pike (*Esox lucius*) and bullhead (*Cottus gobio*) [133]. Similar habitat types are described from Hungary, for some streams entering Lake Balaton [139] and from Romania [128,140].

For the third historic area of occurrence, the Lake Neusiedl (Fertö) basin, no extant populations were found on the Austrian and the Hungarian side during early 1990s [130,141]. The reed belt of the lake was monitored in Austria, however, no mudminnows could be found [142]. In 2002–2005 a project for the re-introduction of this species was done [143,144], but not in the reed belt of the lake but in drainage ditches in the Hansag area east of the lake, very close to the Hungarian border. It was planned to get mudminnows from nearby Hungarian populations, however, as this proved difficult, reintroductions were performed with fish from the Danube floodplain (Fadenbach) metapopulation. A small remnant population was found in 2018 at the reintroduction site [139]. Close to the southern end of Lake Neusiedel (Fertö) mudminnows were detected in a drainage ditch on the Hungarian territory during a survey in 2017–2018 [145].

- Wetlands at the Austria-Slovakia-Hungary Border

In the past, *Umbra krameri* occurred in the Záhorie area only near Plavecký Štvrtok and Láb [146]. The historical area has been significantly reduced to only one locality near Plavecký Štvrtok [147], where the occurrence has now been confirmed. During the restitution of the species, the population coming from the Danubian Lowland was first stocked in the vicinity of Moravský Svätý Ján [148]. In 2007, the site was threatened with a complete drying out, so rescue catches and the transfer of European mudminnow to other sites were carried out. In 2008, we reaffirmed its occurrence in the channel system in the vicinity of Plavecký Štvrtok and Láb. Due to the occurrence of *Umbra krameri* in Záhorie, in the Morava's alluvium right-bank, it is highly probable that this species occurred in the territory of the Czech Republic in the left-bank alluvium of the Morava River in the past. In the seventies of the last century, old fishermen told us that they knew this species from the end of the First World War. Expanding occurrence within the original region would increase the stability of the population in Záhorie.

Within the Danube region, in the past, the richest localities of *Umbra krameri* were located on Žitný ostrov (Rye Island), especially in its SE part [149]. These were mainly drainage channels. To the east, the species extended beyond Komárno and to the north to Nové Zámky to the Nitra river basin, i.e., beyond the borders of Žitný ostrov (Rye Island). Valuable insights into the historical distribution and occurrence of the dark fern from the Danube region are summarized in the works of Kux [149], Mišík [150], Kopáčik [151], Balon [152], Brtek [153], and Hensel [154]. Recent data on the occurrence of mudminnow in the Danube region are in the works of Hajdú [155], Hajdú & Kováč [156], and Májsky & Hajdú [157]. Of the natural habitats, the occurrence of *Umbra krameri* on Žitný ostrov was confirmed practically only in the Čiližský stream. However, the occurrence of the species is mainly related to the system of drainage channels communicating with this former meandering arm of the Danube. Isolated populations on Žitný ostrov survive in the system of amelioration channels connected to the Jurová—Veľký Meder channel (Gabčíkovo, Vrakúň, Padáň) and in the lower section of the Čiližský brook. The most isolated and most vulnerable locality is the Ham Channel near Číčov.

The center of the *Umbra krameri* occurrence in the East Slovakian lowland was Medzibodrožie, in the southeast Slovakia bordered by the rivers Latorica and Bodrog. The only known locality north of this area was the old arm of Laborec, mentioned by Chyzer [158], Vladykov [159], and Záleský [160]. From Medzibodrožie there is more detailed research from the second half of the last century, mudminnow was found by Kux [149], Kirka et al. [161], Kokorák [162], and Weisz & Kux [163]. Evidence of its occurrence outside the river Bodrog basin—in the Slovakian part of river Tisza, was provided by Žitňan [164]. In the area of the Medzibodrožie, it is not currently a permanent occurrence, the population has symptoms of oscillation within the edge of the area. In recent years, we have confirmed *Umbra krameri* only at the channel near Streda/Bodrogom, connected through a network of other channels to the Tisza Old Arm—Krčava. Other sites are the old arm of Tisa-Tice near the village of Sv. Mária, the old arm of Bodrog and the channel near Somotor and also the Krčavský channel near the Dobrá village.

Umbra krameri lives in overgrown slow-flowing or stagnant waters in space beyond or outside active inundation, out of the direct reach of flood waves. It also occupied man-made drainage channels or material pits. The main center of gravity is in the banks zone. The habitats inhabited by *Umbra krameri* are characterized mainly by shallow, clear, slow-flowing, or stagnant water and dense stands of aquatic vegetation. The bottom of these habitats is made up mostly of the fine substrate (clay, sapropel) and remnants of dead vegetation. [165] Among the aquatic plants, the dominant ones are *Lemna trisulca*, *Lemna minor*, *Spirodela polyrhiza*, *Stratiotes aloides*, *Ceratophyllum demersum*, *Hottonia palustris*, and

Hydrocharis morsus-ranae. The riparian stands are dominated by *Carex* spp., only rarely by the islets of *Phragmites australis*, *Typha latifolia*, and *Salix cinerea* [166].

Characteristic for these localities is the organic mud from accumulating plant residues. These are alkaline, medium to hard waters, characterized by large fluctuations in oxygen content, associated with dense growths of aquatic plants. This factor may be one of the limiting factors influencing the composition of ichthyocenosis in individual localities. *Umbra krameri* is adapted to living in overgrown waters, where it tolerates short-term oxygen deficits well. It is found in the largest numbers in small channels (the depth of the water is in the range of 40–150 cm) with dense macrophyte growth, in the preferred community with a low number of predominantly limnophilic fish species [166].

In terms of vegetation cover, mudminnow inhabits very diverse localities [166]. Localities with a dominant occurrence of *Umbra krameri* represent habitats in which the substrate is formed by fine-grained sediments—sapropel and clay. The depth of the water is in the range of 40–150 cm. These habitats are characterized by stagnant or only very low flowing water, they are often richly supplied with nutrients, with richly developed submerged vegetation and a thin layer and a continuous riparian edge of helophytes. The riverbeds tend to be continuously overgrown with submerged macrophytes, some of which have a well-developed layer, and all of them also have a continuous helophyte ridge, which in some cases overgrows to the center of the riverbed. In general, it can be stated that although these are mostly artificial channels, these also have the character of older grounded depressions in the advanced stage of succession in terms of vegetation cover. In some localities, only the native layer of macrophytes and the continuous riparian hemisphere, sometimes penetrating to the center of the riverbed, are well developed. The more massive development of macrophytes is probably hindered by shading by woody plants, which in the case of these channels from a more continuous riparian growth, especially *Salix cinerea*. *Umbra krameri* was most often recorded in habitats that are at an advanced stage of grounding in terms of succession, with a well-developed submerged layer of vegetation. These are often channels with a predominance of pleustofytes of the Lemnetea class, the dominant species being *Lemna trisulca* in the submerged layer and *Lemna minor* and *Hydrocharis morsus-ranae* in the natant layer.

In waters with a dense growth of aquatic macroflora, differences in the concentration of dissolved oxygen occur between day and night, also during the season. The intensity of putrefaction processes is associated with the consumption of oxygen and the production of toxic substances (methanogenic and hydrogen sulfide processes). Methane and hydrogen sulfide are released from sediments and become toxic to fish. Oxygen deficits determine the dominance of species with accessory respiration—*Umbra krameri* and *Misgurnus fossilis* [154]. Oxygen deficiency also occurs in the winter due to freezing of the level—1.52–12 mg/L. Significant oxygen deficits were also recorded in localities with the occurrence of the species in the winter during the freezing of the surface [154].

One main reason for the *Umbra krameri* decline is the hydrological regime change due to river regulation, flood reduction, gradual extinction, and the impossibility of the creation of new alluvial habitats suitable for this species. As a result of extensive hydromelioration modifications on Žitný ostrov (Rye Island) carried out after 1960, changes in hydrological conditions occurred in the system of the inland Danubian delta [153]. These changes induced the disappearance of *Umbra krameri* from much of the territory, mainly from the Čiližský brook basin. The formation of new dead branches and side branches is impossible due to the river regulations, and the old branches slowly ground, dry out, and disappear. Although *Umbra krameri* quite often occurs in channels (it tends to migrate mainly to newly dredged ones or deeper ones), they are unable to provide it with conditions for permanent existence they are not suitable habitats throughout the year due to their hydrological conditions. The main reason is their unnatural hydrological regime, but also the need to maintain them in a successive stage, as they are artificial ecosystems with a tendency to extinction. This relict fish species had long-term adaptations (especially reproductive ones) to the natural flood regime. The absence of a natural flooding regime is the most serious cause of the decline of this fish. The natural floods allowed the *Umbra krameri* populations to pulsate, to communicate with each other (between inundation populations and river populations—in the east—Bodrog, Tisa, in the west—Danube, Little Danube, Čiližský stream), which is important in terms of intraspecific diversity in terms of settlement of new localities after the extinction (succession) of old ones. Due to the floods, *Umbra krameri* had the opportunity to escape on its own from sites where the site was in danger of extinction due to succession. Another factor that may have caused its decline in the past was the appearance of non-native species, of which the brown bullhead (*Ameiurus nebulosus*) probably played the most negative role. Of the recently identified non-native fish species, black bullhead (*Ameiurus melas*) as a predator and food competitor and Amur sleeper (*Perccottus glenii*) as a food and habitat competitor poses greatest danger to European mudminnow [167].

We consider it important for the *Umbra krameri* population in Slovakia preservation to ensure the successful reproduction in localities in which it occurr, by appropriate management, especially of old river branches, which considered as being its refuges. The adjustments should concern the follow-up channel network and should aim at creating suitable habitat conditions for reproduction, rearing young, and the possibility of migrating back to the old branches. When maintaining channels (sediments cleaning) it is necessary to respect the ecological needs of this species. Details concerning the conservation management of the species' sites were elaborated in the European Mudminnow Rescue Program [157]. At selected localities on Žitný ostrov (Rye Island), measures were implemented in 2007 to restore the depth conditions of grounded sites, and to clarify the surface to support the development of macrophytes. This program thus became the starting point for the design and implementation of practical care and revitalization measures in specific localities. In order to evaluate the success of revitalization measures, *Umbra krameri* population development is monitored. In order to improve the condition of localities with the occurrence of *Umbra krameri* in the Záhorská lowland, the shading riparian vegetation of the melioration channel in the locality near Moravský Svätý Ján was experimentally removed. The purpose was to support the development of macrophytes, which are a necessary part of the habitat suitable for this species. In addition, the channel was deepened in selected sections. The deeper parts can serve as refuges during extremely low water conditions and the purpose of this measure is to prevent the extinction or excessive reduction of the population due to the desiccation that affected this site in the summer of 2007. We recommend setting up *Umbra krameri* breeding in Medzibodrožie, eastern Slovakia, most threatened with extinction [167].

3.2. Wetlands of the Danube River in Hungary

The Carpathian Basin, chiefly the Hungarian area of the Danube Basin, has suffered from large anthropogenic modifications in the middle of the 19th century. Antecedently, more than 21,000 km^2 areas were flooded periodically, providing a special type of habitat for many organisms [125]. The flooded fields were the main occurring places of swamp-like species, such as *Umbra krameri*, which were used in feeding domesticated animals due to its high abundance [168]. After the river regulations and hydro-technical modifications, 97% of fen habitats have been lost, which implied the declining and vanishing of a notable part of the *Umbra krameri* populations [169,170]. Remained populations have to adapt to the altered habitats and invade the newly constructed meliorate channels and remained oxbow lakes. Nowadays, recent occurring data have shown that habitats preferred by this fish are rare and isolated from each other [126,169].

The Danube Plain in the Middle Hungarian Danube basin area was rich in wetlands before the river regulation. With its wide and continuous floodplain, Danube Valley was appropriate for *Umbra krameri* [168]. After the regulations, the wideness of the Danube floodplain, for this reason, the living habitat of *Umbra krameri* had highly decreased. Presently, natron lakes, channels and oxbow lakes, and backwaters remained in the place [165]. Records about *Umbra krameri* have been found from the beginning of the 19th century till nowadays [111,157]. In the northern part of the Danube Valley still extend some relics of the olden swamps with small *Umbra krameri* populations, like Rákos creek and its marshland [109,125], the Turjánvidék in the Ócsa Protected Landscape Area [126,171,172]. In the middle of the Turjánvidék, one of the most important wetland habitats of Danube Plain have found, named Lake Kolon, which makes part of many international conventions. One of the densest *Umbra krameri* populations has lived here [126,173–175]. Different types of channels and streams contribute to living habitats for some remaining populations like Karasica-main-channel, Szőlőaljai-channel, and Adacsi-chanel in the southern part of the Valley [126,173,176]. Sallai and Vajda [177] have recently reviewed the status of *Umbra krameri* in the middle and the south part of the Danube Valley. They highlighted that the species have stable populations there, however, the decreasing water levels (and drying out) of wetlands is a serious problem in the region [177].

Along the Danube Valley, relatively many fen habitats, marshlands, melioration channels, backwaters, and natron lakes preferred by the *Umbra krameri* have remained.

In the case of Turjánvidék, a complex of shallow fen habitats and moorland forest are present. Although after regulations, the water supply of the area has been damaged, a major part of the habitat is still untouched. Fields are inundated permanently, and quite rich in organic matters. Several species of plants form suitable habitats for many species (e.g., *Cladium mariscus*, *Caricion davallianae*, *Stratiotes aloides*, *Iris pseudacorus*, *Hottonia palustris*, *Nuphar lutea*, *Lemna minor*). Lake Kolon, as a unique freshwater marshland habitat of the southern part of the Danube Valley, has salinating on the shallow parts. In the foreshadowing progress of succession, this fen has been loading. Submerse macrophytes like *Ceratophyllum demersum* and *Potamogeton natans* is considerable, but *Nymphaea alba* and *Lemna trisulca* are characteristic elements too [173,175,177].

The melioration channels and lowland streams function like potential secondary living habitats. Their average width varies between 1–5 m and the average water depth between 0.5–4 m. Because of the surrounding agricultural lands, these habitats are rich in nutrition, which can result in eutrophication. Generally, the conductivity varies between 500–1100 μS/cm, which can be explained by a high level of nutrition. Water flow in these channels is slow in general and the deposited layer could be almost 1 m depth. The level of dissolved oxygen does not exceed the 1 mg/L. Due to the increasing water use, and the climate change, their water levels have relevant fluctuations, and they show a decreasing trend. If their beds and banks have macrophytes they are generally the following: *Typha latifolia, Phragmites communis*, *Lemna minor*, *Lemna trisulca*, *Hydrocharis morsus-ranae*, *Nymphaea alba*, *Nuphar lutea*, *Utricularia vulgaris*, *Ceratophyllum demersum* [168,169,173].

River regulations have caused a large-scale degradation in the swamp-like habitats since the 19th century [126]. Aquatic organisms have low ability for dispersion, and habitats degradation could lead to genetic erosion [178,179]. Hungarian wetland habitats have been isolated from each other conducting genetic isolation of these populations too, there were proved the differences among the *Umbra krameri* populations. Based on the population genetic patterns among and within the observed areas, they justified that *Umbra krameri* populations can be related into two evolutionarily significant units, which measure up with the Danube and Tisza rivers basins [126].

Another type of hydro-technical modification is the treatment of the melioration channels newly colonized by the *Umbra krameri*. These narrow and shallow habitats have been used just periodically and reinforcements of the water are not appropriated. They can drought more times a year, even in the middle of the reproductive period of this fish species. As a short lifespan fish, whole populations can extinct without offspring recruitment. Poorly designed dredging of the river or stream beds can result in the decline or disappearance of the remained *Umbra krameri* population. This process could be harmful during winter dormancy or the spawning period [173,179,180].

Invading of alien species has become lately one of the main global issues likewise in the Carpathian Basin too [180]. Amur sleeper (*Perccottus glenii*) has been recorded in the Tisza River system (in Lake Tisza) in 1997, and its spreading is still happening [181]. Its ecology shows overlap with those of *Umbra krameri* [168,182] and as a generalist species, *Perccottus glenii* has an aggressive behavior against *Umbra krameri*, being a successful competitor [181]. *Perccottus glenii* was found at the Middle Danube Region in 2008 too [183,184]. The main parts of the wetlands of the Danube River are not penetrated by *Perccottus glenii*, but its further expansion can threat the *Umbra krameri* populations [183].

Towards to protect the remained European mudminnow populations, we should to work out conservation management plans, and avoid the destruction and artificial modification of their habitats. To reinvade the European mudminnow into its natural occurrence place, we have the opportunity to make up the offspring recruitment with artificial breeding techniques [126,169,173].

Degradation and alteration of fen habitats leading to the decline and vanishing of *Umbra krameri*. Many melioration channels are semistatic or astatic, so they can desiccate at least one time a year. During the drought, there is no chance to survive in these shallow habitats [174,177]. We recommend the aware use of irrigator water in the case of surviving any aquatic animals living in these places. In our opinion, keeping a 60 cm level of water would serve as a solution, permanently [168,169,173].

As an important part of watercourse management, dredging is a radical way to manage the load of the waterbed. Poorly planned management work can result in the destruction and alteration of the watercourses. Especially, in the winter period, *Umbra krameri* hide in the near of waterbed, therefore winter dredging can cause the death of many specimens. Hyidrotechnical modifications under the spawning season can disrupt the spawning of the fish or destroy its nest, resulting in the vanishing of recruitment. Therefore, we consider dredging out of the dormancy and spawning season, as well as the half part dredging of the waterbed [169,173].

The spreading of non-native species, especially the *Perccottus glenii* is a major issue. As a generalist competitor, this species can pose a serious threat to the extant *Umbra krameri* populations [182]. However, *Perccottus glenii* is not widespread in the Middle Danubian Region, but its further expansion can be expected in the near future [185].

3.3. Lugomir Channel System in Danube Drainage in Serbia

The Lugomir is part of the channel system which draining excess water from riverine land. It is situated close to the Serbia-Croatia-Hungary border, in the upper part of Danube drainage in Serbia, near Special Nature Reserve Gornje Podunavlje. The first record of *Umbra krameri* in Lugomir was in 2008. This species were frequently confirmed in this location [186,187].

This area represent extorted, artificial habitats formed due to the conversion of wetlands into agricultural land. These lowland channel biotopes characterize cold, clean water, muddy bottom, and dense macrophyte vegetation. The channels' widths are between 4–6 m, and deep up to 2 m. Large agricultural complexes surround the location.

This area is sensitive to changes in the hydrological regime. Additional human impacts are present through: pollution of habitats with pesticides and fertilizers, which lead to eutrophication and an overall decrease in habitat quality; introduction of non-native species, and their impact through competition and predation.

Prevention and restoration measures of human impacts on *Umbra krameri* habitats of Lugomir are the following: decrease of water usage for irrigation; reduction of using artificial fertilizers and pesticides near the watercourses; prohibition of the introduction of non-native species and reduction of the biological contamination level; dredging the channel network, to prevent their overgrowth and turn into terrestrial biotopes; since these are small localities, establishing aquaculture in ex situ conditions would enable an increase in the size of populations; raising awareness and active public involvement in the protection of this species and its habitats [188].

3.4. Kraljevac Channel System in Danube Drainage in Serbia

The Kraljevac belong to the channel system which draining water in excess from riverine area. Special Nature Reserve Kraljevac is located in the southern part of Banat region and belongs to the middle part of Danube drainage in Serbia, with 264 ha of protected area. The first record of *Umbra krameri* in Kraljevac was in 2014. This fish were frequently reconfirmed here [187].

This area is an extorted, human made habitats formed due to the transformation of wetland areas into agricultural land. These lowland channel biotopes characterize cold, clean water, muddy bottom, and dense macrophyte vegetation. The channels' widths are between 4–6 m, and deep up to 2 m. Big agricultural farms encircle this area.

This area is sensitive to modifications in the local hydrological regime. Supplementary human impacts are present: pollution, eutrophication, diminish of habitat quality; non-native species introduction, etc.

Mitigation and rehabilitation measures of human impacts on *Umbra krameri* ecosystems of Kraljevac are: decrease of using fertilizers and pesticides near the water bodies; diminish of water usage in agriculture; baning non-native species introduction; dredging the local channels; raising public consciousness regarding this species conservation.

3.5. Wetlands at the Serbia-Romania Border

Here, the Danube makes a huge meander, in few small riverine wetlands, *Umbra krameri* was found in the 19–21th centuries [189]. This species was rarely found in this area also in the last years by the authors on the Romanian side Danube bank area small wetlands. In the Serbian Danube River side no recent findings were registered [188,190–192].

The preferred habitats for the *Umbra krameri* in this area are small wetlands, with a muddy bottom and rich aquatic vegetation. This area's small wetlands are characterized by a high human activities impact, especially due to water pollution and favorable habitat destruction, on its fish fauna. The impacts of climate change on this area's fish species have not yet been studied. On the Serbian side, this site/population no longer exists because it was totally flooded by the construction of the Iron Gates/Đerdap Reservoir.

Prevention, mitigation, and reconstruction work to compensate the human impacts on *Umbra krameri* habitats of this area are the followings: reductions in habitat fragmentation and loss; reductions of the current biocontamination level; stopping the impoverishment of aquatic habitats; restoration of floodplains and old-deserted irrigation channels; monitoring of water pollution and ichthyofauna habitats and populations; etc.

The following management elements for *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species habitat and populations; elaboration of management plans for specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; fighting pouchery, etc. [193].

3.6. Jiu River Lower Part in Romania

With a 339 km length and 10,080 km^2 of its basin, the Jiu River is formed in the Transylvanian Alps, it flows southward before flowing into the Danube [191,192]. In the 19th and 20th centuries *Umbra krameri* was not mentioned in the Lower Jiu River basin wetlands [112,193] but it was accidentally found in the present in some of these lower basin wetlands anthropogenic channels relatively close to the Danube [193]. This species was rarely found in this area also in the last years by the authors.

The preferred habitats for the Umbra krameri in this area are wetlands formed by old deserted small irrigation channels, with a muddy bottom and rich aquatic vegetation.

The Jiu River basin is characterized by a high human activities negative impact, especially due to water pollution and favorable habitat destruction on its fish fauna [193]. The impacts of climate change on this area's fish species have not yet been researched.

Prevention, mitigation, and restoration of this fish habitat affected by the human impacts in the study area are following: reductions in habitat fragmentation and loss;

stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; reductions of the current biocontamination level; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; etc.

The following management elements for these species populations are suggested: extension and creation of reserved areas for the conservation of this species habitat; dedicated management plans for the proper habitats; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands; etc. [193].

3.7. Olt River Lower Part in Romania

The 615 km long Olt River in central and southern Romania drains a catchment of 24,439 km^2 and enters the Danube. *Umbra krameri* was mentioned by Bănărescu [106] in some rather degraded wetlands. The preferred habitat for the *Umbra krameri* species in this area are wetlands with a muddy bottom and aquatic vegetation.

The Olt River basin is characterized by a high human activities and negative impact [100,191–195], especially due to water pollution and favorable habitat destruction. The impacts of climate change on this area's fish species have not been studied.

Degradation prevention, mitigation, and reconstruction of *Umbra krameri* habitats activities proposed for this area are: reductions of the current biocontamination level and habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution and ichthyocenosis; etc.

The following special management elements for these *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of management plans for specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; etc. [193].

3.8. Vedea and Argeş Rivers Lower Part in Romania

The 244 km long Vedea River confluence with the Danube River. The 327 km long Argeş River located also in southern Romania drains a catchment of 12,590 km^2 and enters the Danube [191,192]. *Umbra krameri* was mentioned by Bănărescu [106] in some degraded wetland areas. The favorite habitats there for this fish are wetlands with a muddy floor and thick aquatic vegetation.

These basins are influenced by accentuated human activities [100,195], in particular due to water pollution and habitat destruction. The influences of climate modification on this fish have not been studied in this area.

Habitats degradation avoidance and rehabilitation activities suggested for this area are: reductions of the existing biocontamination intensity and habitat breakup and loss; stopping the misery of aquatic ecosystems due to the extreme use of land for the agriculture; rehabilitation of floodplains and old channels; building and upgrading of wastewater treatment plants; water quality and biodiversity monitoring; etc.

The following management actions for these fish populations are recommended: creation of specific management plans for wetland areas of interest; ensuring sufficient water regime by omission the capture of springs and drainage of wetlands; expansion and establishment of reserved areas for the protection of this species and its ecosystems; etc. [193].

3.9. Lower Danube River Basin-Danube River Delta in the Romania-Moldova-Ukraine Border Area

The Danube Delta was created by a unique combination of integrated biotopes and biocoenosis related forces and counter-forces in time and space, is the second-largest (4152 km^2) and best-preserved river delta on Europe with its largest part in Romania, forms an extremely rich complex of ecosystems and "ichthyosystem" [91].

In the past *Umbra krameri* was mentioned as very common in all the Danube Delta. Since 1990, sporadic specimens have been reported in a small number of ponds and channels. Compared to the past, the number decreased due to the eutrophication phenomenon and consequently to the reduction of favorable habitats. [102,107,110,112,122,140,196–201] This fish was relatively rarely found in this area also in the last years.

Relatively numerous evidence of *Umbra krameri* presence in the Ukrainian section of the Danube Delta and adjacent water bodies were recorded by staff of the Danube Biosphere Reserve. The data of the collections catalog of the National Museum of Natural History at the National Academy of Sciences of Ukraine are the most reliable [202], the collection contains 158 specimens of mudminnow, collected nearby the town of Vilkovo over the years 1963–1974. Besides, the museum collection contains one specimen 57 mm long, taken on the Lung Lake, and four specimens, taken in the town of Vilkovo in 2007.

Indirect evidence regarding the occurrence of this species in many water bodies of the Danube Delta is contained in the paper [203] which states, that the *Triturus dobrogicus* and mudminnow inhabit the same water bodies outside the town of Vilkovo.

There is also evidence of the mudminnow occurrence in the Sasyk liman. After the liman desalinization by the Danube water, it was recorded in 1981 and by 2006 has become quite common [204]. The occurrence in the Danube lakes Yalpug, Kugurluy, and Katlabukh is confirmed [205]. The preferred habitat for the *Umbra krameri* in Danube Delta is formed by small ponds, with a muddy bottom and rich in vegetation [122,140].

The Danube Delta ecosystems exhibits, a significant level of flexibility, resilience, and adaptation over geological time, but have become much more sensitive to environmental perturbations due to the last century of human impact on the Danube Basin (e.g., geomorphological and hydrological changes, aquatic and semiaquatic riverine habitat fragmentation and/or loss, aquatic and semiaquatic vegetation diminishing/disparition, pollution and/or eutrophication, fish pouching and/or overexploitation, alien species introduction, and trophic resources diminishing/disparition, etc.) [91].

Prevention, mitigation, and restoration of human impacts on *Umbra krameri* habitats are the following: dam management in a way in which the hydrological, morphological, and hydraulic effects will be controlled in terms of sediment balance up and downstream at a basin-wide scale; reductions in riverbank covering and reinforcement; introduction of non-native species; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of hydropower; recreational and professional poaching control; restoration of floodplains to fulfill the targets of European Union Water Framework Directives; acceleration of construction and improvement of wastewater treatment plants; monitoring of organic pollutants, heavy metals, and any other hazardous substances in the fish meat; etc. [91].

The following special management elements for these *Umbra krameri* populations are suggested: rehabilitation of old destroyed wetland areas; extension of new reserved areas for the conservation of this species and its habitat; elaboration of management plans for wetland areas of specific interest; ensuring adequate water regime by prohibiting the drainage of wetland habitats to obtain new agricultural land; etc. [193].

3.10. Mura and Drava River System at the Slovenia-Croatia-Hungary Border

The Drava River is a right, fourth longest tributary of the Danube, with 725 km length it crosses five countries, and is of European Union fish fauna conservation interest. The largest tributary of the Drava is Mura River which flows through four countries and after more than 400 km near Legrad town inflows into the Drava [206–209].

The first data about the *Umbra krameri* presence in Drava-Mura river system comes from the end of the 19th century [210] with mentions in the reeds at the confluence of the Drava and the Danube (Kopački rit). Several later authors mention this species as part of the Yugoslavian ichthyofauna and write that it lives in this part of the Danube basin, but do not specify the exact range or specific localities [211–214]. This fish was recorded again in the Drava-Mura river system, in the early 1980s in oxbows along the Mura River near the settlement Petišovci in Slovenia [215–219]. This species was found also in oxbows south of the Mura River, in the area of Međimurje in Croatia [220]. These first findings were followed by more sites along the Mura River in Slovenia and Croatia [221–223]. It was recorded also in several localities in the middle part of the Drava in Slovenia [224] and Croatia [221,225]. In the lower reaches of the Drava River the species has been found at a large number of localities in the Virovitičko-podravska County in Croatia [226–228].

Umbra krameri along the Mura River in Slovenia and Croatia, mostly lives in small swamps and ponds (dead arms, backwaters, marshes, oxbows) [217,221,223]. These are smaller water bodies of very complex habitats, with muddy bottoms, large amounts of organic material, dense aquatic vegetation, and filled with fallen trees. In Međimurje in Croatia, inhabits also smaller flowing waters such as streams and channels with the constant or occasional flow and well-developed aquatic vegetation. Along the Drava River, the species is much more often recorded in streams and irrigation channels that form an amelioration network connected to the main river [221,226–228]. For most of the year, the water in streams and channels stagnates or flows slowly, they are overgrown with dense riparian and aquatic vegetation, and their surface is often covered with duckweeds Taler [211] and Pavletić [212] among the first mentions that the biggest threats for this fish in Yugoslavia are land management and stream regulations. Other negative impacts on *Umbra krameri* populations in the Mura-Drava River system are habitat degradation and destruction due to regulation and channelization of watercourses, drainage of wetlands, and embankment construction, river damming, and introduction of the alien (exotic) fish species [218,219,221,223,226–228]. Various forms of water pollution, such as agricultural, industrial, and municipal wastewater, also have an impact. Natural burying, overgrowing, and disappearing ponds and wetlands are also a problem in some places.

In order to protect and manage the populations of the *Umbra krameri* in the area of the Mura-Drava River system, it is necessary primarily to protect and preserve the habitats where the species was recorded. Mura and Drava with their wetland habitats are protected as a UNESCO 5-country Biosphere Reserve Mura-Drava-Danube. It is the largest protected river area in Europe, called the European Amazon. In addition, Croatia protected most of the river system as the Regional Park Mura-Drava which stretches from the Slovenian border to the confluence of the Drava and the Danube. Within the park, natural wetland habitats are protected (e.g., floodplain forests, dead backwaters, abandoned river beds) as well as the species that inhabit them. In Slovenia and Croatia, the *Umbra krameri* is one of the target species in 10 special areas of conservation of the EU ecological network NATURA 2000. Within the Interreg Danube Transnational Program, in Virovitičko-podravska County, an expert report for the implementation of the Management Action Plan for *Umbra krameri* was prepared [227]. Specific measures that would contribute to the protection of species in the Mura and Drava river system are protection, rehabilitation and revitalization of wetlands (i.e., dredging oxbows), preservation of small irrigation channels and improving water quality and ecological conditions.

3.11. Zala River, Lake Balaton System in Hungary

Before the 19th century hydro-technical works, drainage of the Lake Balaton had one of the biggest marshland and fen habitats in the Transdanubian area. Due to the human impact (e.g., construction of railway network, agricultural cultivation, etc.) which resulted in the large-scale degradation of fen habitats, several animal species, as well as the population of the European mudminnow, have started to decrease considerably. Nowadays, the Kis-Balaton reservoir system, as the result of the restoration of fen habitats, forms a prominent wetland of the Lake Balaton catchment [229,230]. Based on the regular ecological assessment by the fish fauna, the European mudminnow has a dense and stable stock in the Kis-Balaton reservoir system and its channels [173,176,231–235].

The first records about the European mudminnow originated from the middle of the 19th century, before the draining of the region [236]. After the hydro-technical modifications and habitat degradation, a decrease in the mudminnow population has been recorded. In our days, the constructed reservoir system and the connected channels are protected by nature conservation, therefore the mudminnow stocks are stable now, based on regular surveys of the fish fauna [173,237–239].

Within the reconstructed reservoir system, we can distinguish several types of natural habitats. The lakes of the reservoir (Lake Hídvégi and Lake Fenéki) with dense aquatic macrovegetation represent the standing water environment. Dense reeds (*Phragmites communis*, *Glyceria maxima*, *Schoenoplectus lacustris*, and *Typha angustifolia*) and other aquatic and hydrophilic plants (*Iris pseudacorus*, *Ceratophyllum* spp., *Utricularia* spp., *Lemna* spp., and *Stratiotes aloides*) serve not just like a perfect filtering system prevent the nutrition overload of Lake Balaton but provide a much appropriate living and spawning habitat for fish. As the connection between the lakes of the system, River Zala serves a heterogenous, riverine ecosystem for the fish species. Artificially created irrigation or melioration channels forms a transition between the lotic and lentic environment [173,240,241].

Since the middle of the 19th century, the Lake Balaton catchment and the Zala River had changed. Due to the construction of the railway along the southern part of the Balaton, drainage of the marshlands and fen habitats and regulation of the Zala River has been started. After this, agricultural cultivation and peat extraction led to further habitat degradation [241,242]. Nowadays, many reconstructions work has resulted in this unique natural habitat which is a prominent spot for plants and animals, being part of many international conveniences and being protected by nature conservation. Currently, insufficient treatment of wastewater and the spreading of nonnative species constitute a threat to the wildlife and the remained mudminnow stocks. In many cases, the Zala River is the recipient of mainly treated wastewater, antibiotics, endocrine disruptors, and pharmaceutical residues that can harm the environment [242–245]. The appearance of the Amur sleeper in the late 2000s is a serious concern, as well as the tropical aquarium fish, which originated from the field of aquaria [165,176,177,234,235,245,246].

In the light of faunistic surveys and human impacts, the Kis-Balaton reservoir and Zala River Basin still have stable mudminnow populations, although, we cannot ignore all of the obvious menace factors. Monitoring of the populations of the European mudminnow and nonnative species like Amur sleeper is necessary. In consideration of the impact of Amur sleeper on other mudminnow populations, we have to prepare a conservation management plan for saving mudminnow stocks and their specific genetical background too in the case of a strong population decrease [173].

3.12. Upper Tisza System in Ukraine and Hungary

In the Ukrainian part of the Tisza basin, *Umbra krameri* was distributed quite widely [247]. Particularly, it was found nearby the town of Beregovo in the leftovers of the drained wetland massif "The Black Mochar," in the flood-land water bodies of the Tisza, Latoritsa, and Borzhava rivers. The maximal number of the relatively recent records of the *Umbra krameri* is known from the flood-land over-wetted slow-flowing water bodies in the area of the modern location of the Beregovo polder system.

Reliable data on records of the *Umbra krameri* in the Ukrainian part of the Tisza Basin are absent. The collections' catalog of the National Museum of Natural History at the National Academy of Sciences of Ukraine contains information on specimens, taken in July 1986 in the Latoriza river side arms (35 specimens 24–87 mm long) [203].

Kurtiak et al. [248,249] mention this species in the species lists, however, without any specification of the sampling site or size of the taken specimens.

Over fish studies in Transcarpathia in 2008–2014 [165,250,251], this species was not found, though investigation covered the water bodies in the flood-lands, where habitat conditions to the maximal degree correspond to the *Umbra krameri* biological features.

Our only actual record of the species occurred in August 2015, two years after ichthyomeliorative activities, mechanical cleaning of a small area and stocking with herbivorous fish were carried out, in the dead arm Charonda/Csaronda, which previously was thoroughly surveyed and *Umbra krameri* was not found [252,253]. Two specimens 42 and 64 mm long were found in the forgotten poachers' fishing pot (48°26′13.74″ N, 22°15′59.24″ E). The net catches of the closest biotopes gave no results. Probably, it was brought along with the fish stocking, taken in the Transcarpathian fish farms.

The Upper Tisza Region in Hungary involves three typical biogeographical plains areas where *Umbra krameri* have existed: Bodrogköz, Szatmár, and Bereg [126,173,254].

Before the regulations of the Tisza River system in the 19th century, the Bodrogköz was characterized as a large floodplain of Tisza and Bodrog Rivers. This area was rich in wetlands, where limnophilic species such as *Umbra krameri* was widely distributed. After the regulations and draining of these wetlands, the stocks of this species have started to decline. The remained populations survived in the artificial channels e.g., Ricsei, Bélyi, Tiszakarádi, Szenna-lápi [126,173]. Due to the expansion of the Amur sleeper and the regular desiccation of these channels, the species is surely extinct from Bodrogköz, the last occurrence data is from 2012 in this rergion [126].

The Bereg plain was also rich in wetland habitats before the 19th century. The largest in the area was the Szernye marsh, where the *Umbra krameri* was extremely abundant, and it was used to feed domestic animals (e.g., pigs and ducks). After the regulation of the Tisza River, the populations of *Umbra krameri* also decreased significantly and were established sporadically in artificial channels (e.g., Csaronda/Charonda, Szipa main channel), and in the unique peat bog habitats of the Bereg plain (e.g., Bábtava) [173]. Tatár et al. [170] assumed the extinction of *Umbra krameri* from the Bereg plain in the early years of the 2010s. Due to the dynamic expansion of Amur sleeper in this area, and the regular drying out of habitats, the extinction was also confirmed in 2019. At the same time, Polyák et al. [253] described a new population of *Umbra krameri* from the peat bog called Lake Zsid in 2020, which is the last known population in the Bereg plain.

One of the most famous wetlands was the Ecsedi marsh in the Szatmár plain before the 19th century, where limnophilic species were abundant. After the water regulations, the *Umbra krameri* was known only in two watercourses: Gőgő-Szenke and Öreg-Túr. In the early years of the 2010s, due to the expansion of Amur sleeper and regular water pollution, the population of *Umbra krameri* critically decreased in the Gőgő-Szenke [170]. Tatár et al. [170] rescued fish from the polluted watercourse and reintroduced the captive-produced offspring to their original habitat. But despite all these factors, the habitats of *Umbra krameri* in Gőgő-Szenke dried out more than once in the second part of the 2010s, and the population extinct. Sevcsik and Tóth recorded a huge population from Öreg-Túr in 2010 [255], but thereafter, only five specimens were caught in the last 11 years, in 2021 and 2022 [256], which indicated the critically decrease of this population especially due to the Amur sleeper's appearance.

In the Ukrainean dead arm, "Charonda", is a sinuate lake system of the Charonda River, which once was a tributary of the Latoritsa River (Tisza's basin). Owing to the water flow redistribution after the construction of the channels "Charonda-Tisa" and "Charonda–Latoritsa", the river section from the Demychi village to the mouth was transformed into the dead arm of the same name. Its width somewhere reaches 57 m, depth from 1 m near the bank to 1.5–1.8 and even 3.4 m. The water flow is absent owing to the embankment. At the distance of 6.5 km from the dead arm upper, there is a pumping station N12.

The bottom substrate consists mainly of the silt deposition up to 1.5 m thick, plant residues, and filamentous algae. In summer the water area is overgrown by 70–90%, mainly by the Stratiotes aloides. Among the invertebrates, the Chironomidae larvae are the most diverse (25 species) and abundant, both on the bottom and in aquatic plants. Other groups comprised 1 to 5 species.

When *Umbra krameri* was widely distributed in the Hungarian Upper Tisza Region, the increasing agricultural cultivation, the not well-treated wastewater influents, and the decreasing water levels were the most threatening factors of the habitats. From the second part of the 2010s, the annual drying out by artificial flow regulation and climate change is the most serious problem. Due to these changes, the original habitats of *Umbra krameri* became astatic, and the rate of decrease of populations is higher than 95% [253].

In the Hungarian Upper Tisza Region generally, *Umbra krameri* exists only in Zsid lake and Öreg-Túr. In the northeastern part of the Great Hungarian Plain, peat bog lakes were formed from old oxbow lakes of Tisza River from the last glacial period, providing now a unique living habitat for the *Umbra krameri*. As the southernmost peat bogs of Europe, they have a special microclimate, flora, and fauna. The water chemistry of peat bog lakes is so specific, the only source of nutrition recruitment originates from precipitation, and therefore these habitats are oligotrophic. In terms of acidity, they have an acidic pH environment (<6 pH), however, Hungarian peat bog lakes need a special way of water reinforcements, therefore the acidity can change between a wider range. From a vegetation point of view, the following relatively rare plants occur: *Sphagnum magellanicum*, *Dryopteris cristata*, *Typha latifolia*, *Hammarbya paludosa*, *Eriophorum vaginatum*, and *Lemna minor* [257]. The most relevant peat bogs are the Bábtava and the Lake Zsid in the Bereg plain. To avoid the desiccation of these peat bogs, they have had an artificial groundwater supply since the 1980s [257].

The Öreg-Túr is the original lower part of the regulated Túr River. Nowadays it is the only habitat of *Umbra krameri* in the Upper Tisza Region which is not endangered by the drastically changing water level and drying out. The average width of the lower section of Öreg-Túr changes between 5–10 m and the average water depth changes between 1–2 m. *Sparganium erectum* are very specific for the Öreg-Túr, they make a floating vegetation cover on the surface of the sides of the river [258].

In the territory of the Ukrainian Transcarpathia, the lacustrine-wetland ecosystems experienced the most drastic modifications owing to amelioration and flood-protective measures. Only in the Transcarpathian lowland their area reduced almost by 90%. For instance, the wetland massif "The Black Mochar", which once was the biggest and covered about 15 ha, or about 1/5 of the Transcarpathian lowland area, was totally ameliorated as early as to the first half of the 19th century [259]. Further, the large-scale construction of the polder and ameliorative systems, like Beregovo and Tur-Botar, almost destroyed the natural water bodies—the Umbra krameri habitats. At the turn of the 20th century, agricultural activity decreased, vast areas of agrocenoses are not developed and ameliorative systems in many regions are out of operation. The biogeocenosis started renaturalization, and ameliorative channels were not cleared and became excessively overgrown by diverse submerged and emerged aquatic plants.

The priority tasks regarding the *Umbra krameri* protection and conservation in this Ukrainian area should include protection and rehabilitation of its habitats. This can be reached by creation of the botanical and hydrological reserves. The protection measures should cover all remaining wetlands, natural water bodies (dead and side arms, flood-land oxbow lakes), flood-land complexes and forests, independently of their origin. This work in Ukraine was started by the organization of the Regional Landscape Park "Prytysianskiy". For the groundwater level elevation and hydrological regime improvement, this park should include all forest massifs, which surround "The Black Mochar" wetland. The most depressing sites of the former bog should be considered as zones of the landscapes' renaturalization. The system of the ameliorative channels in the lower sections of the Tisa River and its tributaries, particularly Latoritsa, should be rearranged in order to partially rehabilitate the hydrological regime of the naturally over-wetted territories.

Due to the huge habitat loss and the rapid expansion of Amur sleeper, definitively there are no viable habitats for *Umbra krameri* in the Hungarian Upper Tisza Region. The Hungarian "European Mudminnow Conservation Pilot Programme" has solved the rescuing and artificial breeding process of *Umbra krameri*, and they captured 15 specimens from Gőgő-Szenke in 2010, and 30 specimens from the Lake Zsid peat bog in 2021 [169,170,260]. For the successful restocking of *Umbra krameri*, rehabilitation and creation of habitats without the presence of non-native species and stable water levels is essential.

3.13. Borsodi-Mezőség Plane, Tisza System in Hungary

Borsodi-Mezőség plane is a small biogeographical region of the Tisza River Basin. Before human alterations, the northern part of the plane was characterized by alluvial fens, streams, and channels from Bükk Mountains. The southern part was abounding in watercourses, fen habitats, and marshlands which were flooded by the Tisza River periodically. After hydro-technical activities the southern part of the plane has lost most of these habitats, drained fields had been used for agricultural cultivation. However, the northern region still has many streams, channels, oxbow lakes, and fen habitats [261].

Ichthyological records of the region have remained from the beginning of the last century [261]. The watercourses in the northern part of the region originate from the Bükk Mountain and are regulated (e.g., Hejő-main-channel, Álom-Zugi-channel, Matola-channel, Rigós, Takta). Due to the hydrogeological modifications, the lower sections of these channels are suitable for stagnofil fish species, as well as the European mudminnow [173]. Several oxbow lakes of Takta and Tisza River have remained from the river regulation and serve as a potential lentic ecosystem. Residual fens and oxbow lakes, as well as the lowland channels, are surrounded and covered by emerse and submerse macrophytes (*Phragmites communis*, *Typha latifolia*, *Stratoides aloides*, *Hydrocharis morses-range*, and *Ceratophyllum demersum*) and have a thick deposit layer [262].

After the great river regulation and canalization of the 19th century, the degradation and disappearance of fens and marshland have been started. Today, agriculture is the main economic sector of the region, which result in the nutrition overload and eutrophication of the remaining and created waterbodies [173,263]. Poorly planned hydro-technical modifications, like dredging of stream and river bed can be harmful in the winter dormancy and breeding season either. Furthermore, these waterbodies are quite shallow and usually desiccate [173]. At the beginning of this century, the non-native Amur sleeper appeared in the region. Due to its rapid spread, the Amur sleeper is one of the most dominant species in some of the region's waterbodies [173,181,244,264,265].

Because of the large-scale destruction of the biotope and rapid expansion of Amur sleeper, the development of a suitable conservation management plan is needed [169,170]. Due to these threats, artificial breeding is necessary to keep populations stable in the future [170]. To avoid desiccation and the accompanying extinction of mudminnow stocks, we suggest controlling the water level and supplementing water bodies [126].

3.14. Bihar-Plaine Tisza System in Hungary

As an alluvial fan of the Berettyó and Sebes-Körös River, the Bihar plain is a unique region of the Tisza Basin. Before the Bihar plane became part of the agricultural sector of Hungary, it was rich in marshlands and fens. Due to the draining of these wetlands and the creation of irrigation channels, nearly all wetlands disappeared, causing the alteration of wildlife [173,259,262,266–268]. Nowadays, the irrigation channels as a secondary habitat serve as a sanctuary for fish. Stable and dense mudminnow stocks have been recorded here in the last decades (e.g., Kutas-main-channel, Kis-Körös, Barát-ér, Ölyvös-ér) [126,173,266]. Only a few isolated natural salt marsh habitats have remained after the hydro-technical modifications. The most significant is the Pocsaj swamp, which has a stable European mudminnow population [126,173]. The irrigation channels are temporary watercourses, their water supplements are organized artificially, which is usually not synchronized with the life history (spawning period, diapause) of aquatic animals. Because of the poorly planned artificial recharge of water, these water bodies desiccate regularly, therefore, the aquatic macrovegetation cover is quite poor in the channel's bed, presence of reeds is sporadically. Beyond anthropogenic activity, pollution originates from agricultural cultivation and desiccation, and the spreading of alien species, especially the non-native Amur sleeper is threatening the remained European mudminnow population. The first occurrence of the species had been recorded from the Berettyó River and its northern tributaries in 2011 and appeared in southern watercourses too less than a decade [269]. In order to prevent further disappearance of the European mudminnow, we should moderate human impact like water pollution, nutrition overload, organizing the artificial recharge of the water bodies and develop a suitable management plan for alien species.

3.15. Wetlands at the Romania-Hungary Border

The Someş River has a 15,015 km^2 and a length of 435 km; Ier River has in Romania a 100 km length and a basin of 1392 km^2; Crişul Alb has a 235.7 km; Crişul Negru has a length of 168 km and Crişul Repede a length of 209 km [269].

In all of this west-northwest of the Romanian border with Hungary low courses associated wetlands *Umbra krameri* populations were constantly found in the 19–21th centuries. In the present these were still found in the Ier basin area [270].

In this area Hungarian side of the border most of the watercourses are originated from Romania and belong biogeographically to the Hungarian Bihar plain [260]. The species still have stable stocks in many streams e.g., Kis-Körös [266].

The preferred habitat for the *Umbra krameri* species in the Romanian side wetlands is formed in old river branches, with a muddy bottom and rich aquatic vegetation.

In the Hungarian side channels usually shallows, with the average width between 0.5–6 m, and the average depth changes between 0.3–3 m, with stream banks covered with aquatic and hydrophilic vegetation densely (e.g., *Typha latifolia*, *Phragmites communis*, *Lemna minor*, *Lemna trisulca*, *Hydrocharis morsus-ranae*, *Nymphaea alba*, *Nuphar lutea*, *Utricularia vulgaris*, and *Ceratophyllum demersum*). Conductivity is usually higher and the level of dissolved oxygen is lower, the water temperature is high in summer. Extant fen habitats are usually covered by macrovegetation (e.g., *Phragmites communis*, *Typha latifolia*, and *Stratiotes aloides*), and have quite high conductivity, and water temperature in summer too [169,269]. The studied Romanian area wetlands are characterized by a high human activities negative impact, especially due to water pollution, hydro technical works, water accumulations, settlement works and construction of dikes and banks defense, agricultural and industrial development, and urbanization, inducing finally favorable habitat destruction of its fish fauna [196]. The impacts of climate change on this area's fish species have not yet been studied.

On the Hungarian side, artificially constructed melioration channels are endangered by erosion, and desiccation, and their water supplement are not appropriate. The regulation of the water flow and water level is poorly planned, channels are usually desiccating by the end of summer causing the strong decline of the *Umbra krameri* population year by year. The region has been consisting of agricultural cultivation, therefore the extravasate of nutrition into the surface waters from the fields is considerable [266].

Basically, the same management elements should be enforced on both Romanian and Hungarian sides of the border.

Prevention, mitigation, and especially reconstruction and restoration of negative human impacts on *Umbra krameri* habitats of this area wetlands are the followings: reductions of the current biocontamination level; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; reconnection of the old river courses branches with the neighboring wetlands, channels, and river sectors, etc.

The following special management elements for these *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of specific management plans for the wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land and to redirect too much water in different basins; etc.

Desiccation of the habitats is not sustainable for the living organisms in the biotopes of the studied area, therefore, we suggest keeping a permanent water level in each season. As a competitor species, the spreading of Amur sleeper can result in the destruction of *Umbra* *krameri* populations in the near at hand. Because of its rapid proliferation, we have to keep the species under constant monitoring by fishery surveys.

The main problem is the artificial damming and water retention, due to this fact not enough or no water arrives from upper sectors in lower sectors. In order to avoid further habitat loss and a decrease of populations of *Umbra krameri*, a transborder agreement about the guarantee ecological water demand in the lower areas would be essential.

Overall, *Umbra krameri* stocks have been living in the studied area, however, some menace factors can result in the rapid decline of these populations like desiccation, habitat degradation, and the spreading of Amur sleeper.

3.16. Lonja and Odra Wetlands in Croatia

The Sava River is the largest Danube tributary in terms of discharge and the second largest (after the Tisza) in terms of length and catchment area, which is under human impact [271–275]. Lonja and Odra are rivers in Croatia that belong to the Sava River Basin. Their floodplains are part of the former wider floodplain of the middle part of the Sava River, which extends downstream from Zagreb after which the Sava begins to flow more slowly and becomes a typical lowland river with characteristic meanders. Furthermore, the Sava River downstream from Zagreb is affected by several larger tributaries such as Lonja, Ilova, and Orljava on the left, as well as Kupa and Una on the right, which influenced the formation of the biggest floodplain and wetland area of the Sava river basin—Lonjsko polje/field. Something smaller but equally interesting floodplain is the Odransko field, which is located somewhat more upstream along the river Odra between the Sava and the Kupa rivers [276].

The first data on the presence of the Umbra krameri in this area are from the end of the 19th century from wetland habitats in the Lonja river basin near settlement Lupoglav, about 20 km east of Zagreb [276]. Today, the species probably does not inhabit this area because the area is ameliorated, drained, and the Lonja River is channelized and enclosed with embankments. After that, there were no findings of *Umbra krameri* in Croatia, only the presence of species was mentioned, but without actual data on specific water bodies or localities [204,205,277]. The next *Umbra krameri* finding in this area was recorded a hundred years later, 20 km to the south in the Žutica forest near Ivanić Grad [278]. Žutica forest is located on the northwestern border of the Lonjsko polje/field and it is an old flooded (swamp) forest in which the remains of the old course of the river Lonja and its tributary Lonjica are partially preserved. The species was found at several sites in the oxbows and the old course of the river. In the rest of the Lonjsko polje/field, *Umbra krameri* was never found, despite many years of intensive research [274,278] A few years ago, Umbra krameri was surprisingly recorded at a new site in the very source part of the Odra River [274,278], which is the westernmost finding of the species in the Sava River Basin. Despite further research, it has not been recorded in the surrounding wetland habitats and tributaries of the Odra River.

Umbra krameri in the Lonja River basin uses mostly typical wetland habitats. Žutica is a floodplain forest that occupies an area of 60 km^2, and it is located at the Northwestern edge of the Lonjsko polje/field. *Umbra krameri* occurs in the marshes, oxbows, and dead arms of the Lonja and Lonjica rivers [278]. These are mostly smaller water bodies with very complex habitats, muddy bottoms, large amounts of organic material, and dense aquatic vegetation and they are full of old tree trunks [278].

In the Odra Basin, *Umbra krameri* is recorded in the source area of the river but only in the smaller section of the river, which in that part is about 5 m wide and 1 m deep. It is a small lowland river that flows slowly, but the water is clear and transparent. The bottom is composed of silt, sand, and gravel and it is well-developed underwater and floating aquatic vegetation along the banks as well as riparian vegetation.

The Žutica forest, located on the very edge of Lonjsko polje/field serves as a semi-natural retention area into which the high floodwaters of the Sava River are released in order to mitigate the flood wave and protect downstream areas, especially the city of Sisak [278].

As the surrounding watercourses are channelized and enclosed by embankments and the inflow of water depends on the floodgate on the Sava River, the hydrological regime is not natural, and lately it also depends on the water inflow from hydropower plants on the Sava River in Slovenia. Žutica has been serving as an oil field exploitation area for 60 years, i.e., the so-called satellite reservoir of the Sava Depression [279]. There are more than 150 different oil wells in the forest area, which changed the appearance of the forest and affected the whole area due to road, paths, and pipeline construction. In the waters of the floodplain of Žutica forest, an increase in the number of alien species has been recorded, where they are becoming dominant in the population and negatively affecting the number of *Umbra krameri* due to competition and predation pressure [280]. Most wetland habitats in the Žutica forest are smaller water bodies (oxbows and ponds) that makes an additional negative influence on the Umbra krameri populations because of sedimentation and disappearance of water bodies.

The *Umbra krameri* population in the upper reaches of the Odra River is isolated and it was recently discovered [280,281]. The whole area is not sufficiently investigated and there is lack of data on the size and status of the *Umbra krameri* population. The upper course of the Odra River flows between several settlements and is surrounded by agricultural land, which leads to different types of pollution. Thus, they were measured during the field research lower oxygen concentration, as well as quite high values of BOD5, nitrite, and nitrate [276]. Based on genetic research, low values of genetic diversity and a very small effective population size have been recorded [278].

Umbra krameri is protected by the Convention on the conservation of European wildlife and natural habitats (Bern convention) as a strictly protected fauna species (Annex II). It is protected by Council Directive 92/43/EEC 1992 on the conservation of natural habitats and of wild fauna and flora (EU Habitats Directive) as one of the animal species of community interest whose conservation requires the designation of special areas of conservation (Annex II). It is also listed on the Croatian red list of endangered species in the category of vulnerable species (VU) and protected by national legislation as a strictly protected species [278].

The Žutica forest is one of the areas of the NATURA 2000 ecological network (HR2000465), and the *Umbra krameri* is designated as one of the target species. In terms of conservation and management of the *Umbra krameri* population in the floodplain of the Žutica forest, the remaining microhabitats and water bodies in which the *Umbra krameri* has been recorded need to be protected and preserved. Specific conservation measures would include habitat restoration and revitalization in terms of dredging small water bodies like oxbows and pools. In case the *Umbra krameri* disappears from some previously known water bodies, translocation from the closest existing micropopulation should be considered. More detailed research is also needed in the whole forest with the aim of discovering new potential locations inhabited by the *Umbra krameri*.

3.17. Matura River System in Bosnia and Herzegovina

The Matura River belongs to the middle Sava River in Bosnia and Herzegovina (Republic of Srpska). In the Matura River system, *Umbra krameri* was discovered for the first time in 2016 [127]. The species was detected in the Matura River, including the tributaries Kraljica, Karavida, Glibača, and Adžaba, as well numerous springs in this area. Umbra krameri was frequently found in this area, which covers the surface of 35 km^2.

The preferred habitats of *Umbra krameri* in the Matura River system are lowland rivers and springs, with a muddy or gravel bottom and rich in submersed vegetation.

The Matura River system is very sensitive to environmental perturbations due to intensive human impacts that include: regulation of watercourses and changes in the hydrological regime; pollution and loading of habitats with communal waste, which lead to eutrophication, and the overall deterioration of habitat quality; intensive agricultural activities reflected in meliorations and the usage of artificial fertilizers and pesticides;

introduction of non-native species and their impact through competition and predation; the impacts of climate change on this area.

Proposals for the prevention, mitigation, and restoration of negative human impacts on *Umbra krameri* habitats of the Matura River system are following: preserving habitats by enabling optimal water regime especially during the summer season; construction of wastewater treatment plants; prohibition of the introduction of non-native species and reduction of the current biological contamination level; stopping the desiccation of aquatic habitats due to their excessive use for agricultural activities; reductions of using artificial fertilizers and pesticides in the immediate vicinity of watercourses; placing the area under state protection; raising awareness and active public participation in the protection of species and habitats.

3.18. Wetlands at the Serbia-Bosnia and Herzegovina Border

Transboundary wetlands include Special Nature Reserve Zasavica in Serbia and Special Nature Reserve Gromiželj marsh in Bosnia and Herzegovina (Republic of Srpska). Both areas belong to the lower Sava River system. The Special Nature Reserve Zasavica is situated east of the Drina River and south of the Sava River, with 1825 ha of the protected area. The Special Nature Reserve Gromiželj marsh is situated west of the Drina River and south of the Sava River, with an area of protected asset of 831 ha. The first record of *Umbra krameri* in Zasavica was in 1998, while in Gromiželj marsh, it was in 2008. After the first registrations, the presence of this species was frequently confirmed in microspecific locations in both areas [109,125,127,186,281,282].

The preferred habitat for the *Umbra krameri* in Zasavica is lowland reverie and creek biotopes with a muddy or gravel bottom and dense macrophyte vegetation. In Gromiželj marsh species dominantly inhabits a small, deep pond (0.14 ha) with a muddy bottom and dense macrophyte vegetation. This pond is the only water body in the Gromiželj area that never dries out. Thus, both areas are characterized by the mosaic of aquatic and wetland ecosystems with fragments of flooded forests [186,280].

These two close areas are very sensitive to environmental perturbations due to climate changes (dry year, formation of arid surfaces) and changes in the hydrological regime (reduction of groundwater levels, absence of floods, and human regulations of watercourses including habitat fragmentation). Also, additional human impacts are present through: pollution of habitats with communal wastewaters, leachate from landfills, pesticides, and fertilizers from arable land, which overall lead to eutrophication and deterioration of habitat quality; conversion of wetlands into the agricultural surfaces and forestry plantations of monocultures; introduction of non-native species and their impact through competition and predation [186,188].

Prevention, mitigation, and restoration measures of negative human impacts on *Umbra krameri* habitats of Zasavica and Gromiželj are the following: dam and water management, which will enable control and maintenance of optimal water regime; reductions of habitat fragmentation and using artificial fertilizers and pesticides in the immediate vicinity of watercourses; construction of wastewater treatment plants and remediation of illegal landfills; stopping desiccation of aquatic habitats due to intensive use for agricultural and forestry activities; prohibition of the introduction of non-native species and reduction of the current biological contamination level; raising awareness and active public participation in the protection of species and habitats [186,188].

3.19. Timiș River System in Romania

With a 359 km length and 10,280 km^2 of its basin, the Timiş River is formed in the Semenic Mountains, it flows into the Tisza River [193]. In the 19–20th centuries *Umbra krameri* was not mentioned in the Timiş River basin wetlands [102,111] but it was accidentally found in the present in some of these lower basin old river courses dead branches [193]. This fish was rarely found in this area also in the last years by the authors.

The preferred habitat for the *Umbra krameri* species in the Lower Timiş River basin wetlands consist of old river branches, with a muddy bottom and rich aquatic vegetation.

The Lower Timiş Basin wetlands are defined by a high human activities impact, mainly due to pollution, hydro-technical works, water accumulations, settlement works and construction of dikes and banks defense, agricultural and industrial development, and urbanization, inducing favorable habitat destruction of its fish fauna [283–285]. The impacts of climate change on this area's fish species have not yet been studied.

Prevention, mitigation and reconstruction and restoration of the human impacted habitats of *Umbra krameri* of the Lower Timiş Basin are the followings: reductions of the biocontamination level; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; reconnection of the old Timiş River branches with the neighboring wetlands, channels, and river sectors, etc.

The following management elements for *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of specific management plans for the wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land and to redirect too much water in different basins; etc.

3.20. Prut River at the Moldova-Romania Border

With a 953 km length and 28,396 km^2 of its basin, the Prut River flows southward for the big majority of its length between Romania and Moldavia into the Danube [286]. In the 20th century *Umbra krameri* was mentioned in this area by Bănărescu et al. [111]. This species was rarely found in this area also in the last years by the authors.

The preferred habitat for the *Umbra krameri* species in the Prut River basin is the wetland habitat, with a muddy bottom and rich aquatic vegetation.

The Prut River basin wetlands are characterized by a high human activities negative impact, especially due to water pollution and favorable habitat destruction on its fish fauna. The impacts of climate change on this area's fish species have not yet been studied.

Prevention, mitigation, and especially reconstruction and restoration of negative human impacts on *Umbra krameri* habitats of the Prut Basin are: reductions of the biocontamination level; habitat fragmentation and loss; impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; etc.

The following management elements for *Umbra krameri* are proposed and creation of reserved areas for the conservation of this species and its habitat; elaboration of management plans specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; etc.

3.21. Dniester River at Moldova-Ukraine Border

In the relative proximity of the Danube basin is also the Dniester basin, with together have a good potential refuge and stepping stone habitats role for *Umbra krameri*.

The Dniester River's source is located in the northern slopes of the Ukrainian Carpathians (the Chentiyivka Mountain, of 932 m altitude), runs through different geographical zones and falls into the Dniester liman. Total river length amounts to 1362 km, of them 662 km in the territory of Ukraine, 225 km—along the Ukrainian-Moldavian boundary, and 475—in the territory of Moldova. The total basin area is of 72.1 km^2, of which 52.7 km^2—in the territory of Ukraine. In the view of the peculiarities of the geographical location, hydrological and hydrochemical regime the Dniester basin is traditionally divided into three parts: Carpathian—upper section, Podillia—middle section, and southern—lower section. The average river discharge in the lower section amounts to 310 m^3/sec, the annual river discharge is estimated as equal to 10 km^3 [287].

The basin comprises both quite undisturbed and densely populated and urbanized territories. Significant elongation of the basin from the north-west to the south-east (about 700 km) induces notable difference of the climatic characteristics. It is also essential that the upper river part is located in the Carpathian region' mountainous and piedmont, which explains significant differences in conditions of the river flow forming in the upper and lower sections of the basin [287].

The Carpathian part amounts to 9% of the total basin area, however, it is covered by the well-developed and dense river net (1.0–1.5 km/km^2), and the main river discharge is formed just here, mainly owing to the floods. The upper, properly mountainous section, is located upstream of the Stryi River mouth and is the main for the discharge forming. The mountainous tributaries produce 50% of the river discharge. The rivers of the upper basin section run within the Carpathians, Pre-Carpathian upland, and Volyn-Podillia plateau. Thus, the riverbeds within these regions are different in terms of the discharge regime, including the geology, relief peculiarities, and climatic conditions [287].

The Dniester River, along with Danube, Dnieper, and South Bug rivers belong to the big rivers, which fall to the north-western section of the Black Sea. The Dniester River basin district is located in the territories of three states—Poland, Ukraine, and Moldova. Though the portion of Polish territory in the Dniester basin is only 0.6%, it belongs to the European Union transboundary river basins [287].

Actual data on *Umbra krameri* numbers in the Lower Dniester basin in the territory of Ukraine are practically absent. Relatively actual data (2006–2010) are given in a report [287]. The obtained data regarding distribution, abundance and size-weight characteristics of *Umbra krameri* in the water bodies of the Lower Dniester basin were analyzed. On the basis of analysis of the dependence of the ichthyofauna diversity on the annual water yield and pollution degree it was stated, that the flow regulation and pollution are the main reasons of the *Umbra krameri* and other fish species' abundance decrease.

The relatively good status of the species in the Ukrainian part of the Lower Dniester basin is confirmed by the Official application of the Lower-Dniester National natural park on 10.03.21 N 132/05 to the National Commission on the Red Data Book of Ukraine regarding issuing Permission to catch *Umbra krameri*, which indicated, that according to data of the research catches, carried out by the park staff in 2020, in the channel in the 51st km of the automobile road Odesa—Reni (the section between the villages of Mayaki and Palanka, Biliayivkka district of the Odesa oblast) the local population of *Umbra krameri* occurs, not less than 2000 specimens.

The Dniester River is the biggest river in Moldova and third biggest river in Ukraine, serving with its tributaries for water extraction for some big cities. In this basin, are also pollutant oil extraction and refinery enterprises, as well as other numerous industries.

3.22. Danube Basin Umbra krameri Populations State and Potential Trends under Climate Change Impact

Major geographical obstacles (e.g., the Carpathian and Alps mountains and the Black Sea), significant different geographical areas with significantly different climate and zoogeographical influences (i.e., Alpine, Pannonian, Continental, Mediterranean, and Steppic), major/significant river and lake water catchments with more or less dense and permanent or not hydrographical nets basins where the *Umbra krameri* populations were identified (i.e., Danube, Morava, Bodrog, Ipoly, Jiu, Olt, Vedea, Argeş, Mura, Drava, Kis-Balaton area, Tisza, Sava, Crişuri, Timiş, Lonja, Odra, Matura, Suceava, Prut, Dnister) and highly dynamic ichthyological zone like the Danube Basin is, are the main natural driving forces which clustered along with history the wetlands fish fauna. The relatively recent human impacts (dams, pollution, siltation, dredging, draining, desiccation, habitat imperiling, fragmentation and destruction, introduction of non-native fish, pouching, etc.) as well as unproper fish fauna management hazards including chaotic stockings created changed separate geographical clusters of wetlands as habitats for *Umbra krameri*.

The ichthyofauna had full geological extent of time over which had to evolve and acclimate together with their habitats characteristic changes, and this included wetlands which played the role of refuge habitats and stepping stones in the distribution Danube basin area. All these refuge and stepping stone wetlands were and still are of extremely high importance in the circumstances of the zoogeographical and ecological importance of a needed hydro-biological Danube trans-basin functional ecologic macro-continuum.

The present and estimated and expected climate warming and the becoming more intense and extensive of droughts, as well as the human impacts nevertheless will form a synergic significant complex of pressures that will endanger the optimum *Umbra krameri* characteristic wetlands and this fish species itself.

Climate change-induced impacts, were not studied on the whole Danube basin scale till now regarding *Umbra krameri*, in spite of the fact that is to be expected that them induced and will induce potential breaks-in the existing stepping stones Danubian hydrographical net qvasi-continuum of wetland habitats.

Moreover, climate change effects will also substantially disturb the *Umbra krameri* and other fish species which depend by wetland habitats. Therefore, there is a need for the Danube basin management plan of action relying on lasting and even improving suitable climate and microclimate typical features, wetlands connectivity, their quantitative and qualitative attributes safety, the fish genetic diversity backing, and survival potential for *Umbra krameri* populations and species.

3.23. Umbra krameri Refuge and Stepping Stone Habitats Management Elements Proposals for the Danube Basin

Climate modifications impact the biotopes and biocoenosis and activate hidden risks concerning the natural products and services; humans should forecast and adjust to such global challenges situations and conditions. The management actions which should be implemented to diminish/ward off the climate modifications' unfavorable effects on the researched wetland habitats should be made at the watershed level, for integrated rationality in actions and best outcomes. Among these actions we propose: the design and development of a long-lasting intricate integrated monitoring system for the wetland habitats, their water bodies connections, and fish, controlling poaching, water use rationalization, forestation/reforestation of the wetland ecosystems riverine basins to stimulate the local and regional water cycles water recirculation, imposing taxes for ecosystem services including for the natural water and riverine wood resources, discriminatory fishing of non-native and not economically or conservation important species, reducing/preventing fragmentation of the hydrographical nets which connect permanently or seasonally the wetland habitats, reducing/avoiding pollution, etc.

The Danube Basin was revealed as being one of the major hot spots in terms of fish fauna status major threats, pressures, and risks, this time in a potential climatic change (heating-drought-water depth decreasing) scenario.

As a result of climate change, it is likely the wetlands will suffer disturbance through the worsening water quality and quantity, some spawning habitats will be lost, there will be habitat and species loss, increased suspended sediment and nutrient levels in water and eutrophication, diminishing and/or loss of hydrological connectivity, alteration of fish communities structure, and an increase in eurytopic fish species occurrence.

The climate change impact on the studied wetlands can be: isolation of wetlands by the surrounding hydrographical networks, either for safety reasons or to reclaim land should to be forbidden in a future drought scenario; these wetlands should be considered as international importance and needed stepping stone for *Umbra krameri* fish species; avoiding the complex human impact effects on already unbalanced from the point of view of the fish communities and the most sensible to any other supplementary stress, including the climate changes type too.

The Danube Basin hot spot area identified potential ecological changes trends that can be used also as a pre-alert information area, for the potential arrival of similar changes for other surrounding major European and West Asian hydrographic systems like (i.e., Évros, Po, Rhine, Elbe, Oder, Vistula, Dnestr, Bug, Dnepr, etc.).

It is more than questionable that a species like *Umbra krameri* will be able to shift to more appropriate habitats/climate conditions, the relatively unnaturally fast likely changes will strongly affect the ecological equilibrium of wetlands locally and regionally, diminish their populations, and break down the natural continuity of the specific wetlands net as habitats for this species, along the entire Danube Basin.

Opportune and convenient water resource management actions for *Umbra krameri* wetland habitats can safeguard fish populations' climate modification-related effects and alike threats. The disaster-case scenario should be to guarantee an optimum frequency and density of potential refuge wetland habitats as abundant as possible, or it will not be possible then knots of convergence and divergence of an ecologic functional hydrographic Danubian Basin network, in which climate modifications alert conservation managers to can be capable of performing the optimization and conservation of economic objectives by recognition, focusing, and connecting all these wetlands as potential *Umbra krameri* refuge/areas of a functional convergence-divergence Danube basin net.

The climate changes trend in the Danube Basin will affect the studied wetland areas' ecological state and associated *Umbra krameri* populations, increasing the threats and risks upon this endemic protected fish species; mitigating measures are urgently needed. The future diminishing of these habitats areas, the quality of the habitat lowering and the fragmentation and isolation of these habitats increasing by the surrounding hydrographical nets, for so-called safety reasons of human communities or to convert inland areas should be fought against.

The conservation measures should target the characteristic wetlands preservation in their original state; the avoidance the changes which might affect the water regime and alter the vegetation. The partial rehabilitation and restoration of its native distribution area and its reintroduction should be also strongly recommended for this species quantitatively aspects and stability increase. Due to its relatively complex behavior of breeding and wintering, in its reproduction and winter periods, the human impact on its habitats should decrease to a minimum.

From the scientific point of view, population studies and monitoring are needed in respect of highlighting the trend of this species at all these as well as other sites.

On a yearly basis, the hydrologic regime and water temperature are conspicuous elements that stimulate or restrict the life cycles of this fish, so the climate changes unmanaged effects can be significant.

Exceptional parameters of genetic polymorphism of the species impose mandatory genetic characterization of individuals during the implementation plans for future protection, conservation, and sustainable management of this species.

4. Conclusions

Small-bodied freshwater fish species like *Umbra krameri* with a high conservation value but with no commercial value can be considered as excellent environmental indicators, being antropofuge species. These species possess special requirements (specialized habitat, ichthyocenosis, and/or diet), a small population size, a short lifespan, a reduced dispersal capability, and a low fecundity rate. Thereby *Umbra krameri* are often living in fragmented residual habitats that could be much distanced and geographically and hydrographicaly isolated. Fragmentation and habitat degradation and loss are causes of the formation of small isolated subpopulations with possible little to no gene flow, consequently further under risk of inbreeding and associated bottleneck negative effects. Population fragmentation, due to specific habitat requirements, has existed partially in the past too but at a much lower level, but gene flow among these fragmented habitats has been ensured by regular floods with subpopulation mixing. Today, the situation is negatively changed from this perspective, for those populations, random genetic drift leading to loss of genetic diversity and inbreeding may reduce the species' adaptative and evolutionary potential, pushing it toward local extinction risk.

Comparing recent occurrence data with old literature records we established a strong population decline in the *Umbra krameri* populations along the Danube and Dniester river basins. This short lifespan, metaphytic species is extremely sensitive to the disturbances in their natural habitat. Intensifying anthropogenic effects (e.g., hydro-technical modifications, dredging) and the change of our climate induces the large-scale degradation of fen habitats and the decline and dispersion of its stocks. Furthermore, the widely isolated populations are threatened by not just the loss of genetic diversity, but the dynamic spreading of adventives species is an additional major risk.

Hence, for the conservation of *Umbra krameri* species, protecting the specific habitats is of immense importance and may contribute largely to its preservation. Also, appropriate artificial breeding techniques and the outplacing of the offspring to its natural or restoration habitats are as important as the management of adventives elements to prevent the further population decline of the species.

For these reasons, *Umbra krameri* can be used as indicators of environmental quality and excessive human impact. As an endemic species of the Danube Basin with a high conservation value, the expansion of integrated conservation management plans is essential. In consequence, we should think about the human impact reduction/primary habitat restoration together with the conservation of natural spaces where vegetation is allowed to evolve according to natural processes and dynamics. The non-channeled water bodies with natural vegetation in natural dynamics/non-managed by man, it is very important to be protected and conserved.

Umbra krameri has become a rarity in its native endemic area, disappearing from many zones due mainly to the human-induced deterioration of favorable habitats to which the pressure of climate change was added. This fish is given increased concern for protection at the European level and only well-oriented efforts including obtaining genuine biological and ecological knowledge and management know-how and best practices will succeed to avoid not only postpone a final death blow strike and extinction. It is possible that these paper authors' generations may be one of the last ones to have direct memory of this species in perilous decline in the last remaining watersheds as habitats for European mudminnow before it will vanish? The authors of this study still hope that will not be the case, in spite of the fact that this species has been significantly winking out in the course of our life!

General permanent ichthyological monitoring is necessary for the characteristic wetland habitats and also emphasized for the adventive species, which can be the competitors and predators of native elements.

With the present-day obvious climate changes, the *Umbra krameri* situation needs to make the scientific community, wetlands stakeholders, and managers, keep monitoring this species population and stay on track with new extended innovative measures in all the Danube Basin.

Based on all of the above it would be recommended to develop specific in-situ tailored locally adapted action plans for the management of *Umbra krameri* in each identified stepping stone area, all of them being only finally put together in a general master plan for the whole area of the Danube basin.

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A Flashforward to Today Made in the Past: Evaluating 25-Year-Old Projections of Precipitation and Temperature over West Africa

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Abstract: While scientists generally generate new projections with the newest models, the paper suggested the use of past projections as a different approach which could be explored and then complement classical approaches. With the idea that today is yesterday's future, a set of past Intergovernmental Panel on Climate Change (IPCC) climate projections (first-AR1, second-AR2 and third-AR3 assessment reports) were compared to gauge-based observations of the last three decades (1990–2016). Why would someone need to check previous models and scenarios when the new ones are currently available? Some in-depth discussion points were raised to answer that question. Monthly and annual precipitation and temperatures were analyzed over West Africa, divided into 3 climatic sub-regions. The results revealed that observed differences are greater at higher latitudes and are strongly scenario dependent. The Business-as-Usual scenario (few or no steps are taken to limit greenhouse gas emissions) appeared to be closest to the observations. The AR1 projections were shown to be disconnected from the observations. AR2 exhibited the best performance, and AR3 presented higher uncertainties in the northern areas. The relative importance and potential implications of the differences between projections and observations on society were appreciated with regard to certain climate and weather-related factors that could greatly influence sustainable development in the region, such as water resources management, agriculture practices and yields, health conditions, and fishery management. Finally, some recommendations to policy and decision makers were given as well as further research topics for the scientific community.

Keywords: climate model verification; IPCC past projections; West Africa; precipitation; temperature

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1. Introduction

A good quality of life is a requirement for sustainable development and is hugely affected by a healthy environment [1]. Nevertheless, human activities in the recent past have altered the atmosphere of our planet in a way that has led to a change in the climate. In addition, this has been established as evidence over the last decades by observations and numerous studies. Climate change affects and may have negative consequences on many key development determinants including water resources, extreme climate events (e.g., floods and droughts), agricultural practices and yields, livestock, fisheries, health, the economy, energy, ecology, policy, transport, human mobility, and so on [2–9]).

Given these critical stakes, a lot of efforts is deployed. We can find in the literature that the scientific community addresses this challenge in many ways. Various types of investigations have been conducted so far. These studies aim at generating the scientific basis needed to develop the best responses in terms of adaptation and mitigation strategies. We may mention the category of descriptive studies which, on the one hand, aim at running historical simulations in order to characterize past and present climate. They also assess how skillful climate models are in reproducing past and present-day key features of various climate variables such as temperature or rainfall [10–18]. Descriptive studies, on the other hand, are concerned with assessing the current and recent potential impacts of climate change, as shown in [19–26]. Another category of climate change impact related studies addresses the question of how the future climate will develop under various scenarios (societal, land use/land cover, or carbon dioxide emission scenarios). These studies describe potential impacts on various determinants for development (mentioned above). In the last ten years, numerous studies of this type have been undertaken in West Africa (WA) (IPCC, National Communications, Universities, Research institutions, Projects, etc.): ([18,27–30]). If most of these studies are quite recent, we do also have previous studies, conducted during the 1990s, and which projected various trends for temperature and precipitation (see a sample of studies from the National Communications of WA countries to the United Nations Framework Convention on Climate Change (UNFCCC) in Table 1).

Table 1. A summary of some climate change impacts on temperature and precipitation projected by WA countries in the framework of their National Communications to the UNFCCC.

	Study	Models Used and Scenarios	Projected Change
1	Initial National Communication of Benin [31]	MAGICC SCENGEN (ensembles of models), 3 scenarios IS92a (reference scenario); IS92c (optimistic scenario) et IS92e (extreme scenario) from 1990	$\Delta T = +0.5\ °C$ by 2025 $+1\ °C < \Delta T < +2.5\ °C$ by 2100 $(-30\%) < \Delta P < +50\%$ (reference 1961–1990) by 2100
2	National Communication of Burkina Faso [32]	Japan Meteorological Agency; 2 scenarios (equilibrium and transient at 0.5% annual rate)	$\Delta T = +0.5\ °C$ by 2025 $\Delta P < +50\%$ (reference 1961–1995) by 2025
3	Initial National Communication of Côte d'Ivoire [33]	GFD3 and UK89 climate models, reference 1994	$+2\ °C < \Delta T < +4\ °C$ by 2100 UK89: increase of P GFD3: decrease of P
4	First National communication of the Republic of the Gambia [34]	Seven models were run but 4 were kept for analysis: 1-GFDL (Geophysical Fluid Dynamic Laboratory), 2-CCCM (Canadian Climate Change Model), 3-HCGG (Hadley Centre with Greenhouse Gases (GHGs)), 4-HCGS (Hadley Centre with GHGs and Sulphate aerosol) $1xCO_2$ and $2xCO_2$	$+3\ °C < \Delta T < +4.5\ °C$ by 2075 $(-59\%) < \Delta P < +29\%$ (reference 1951–1990) by 2100
5	Ghana's Second National Communication to the UNFCCC [35]	Hadley Centre Model 2 (HadCM2); UK Meteorological Office Transient Model (UKTR); UK Meteorological Office High Resolution Model (UKHI). Business as usual scenario	Reference: 1961–2000 $\Delta T = +0.6\ °C$ by 2020 $\Delta T = +2\ °C$ by 2050 $\Delta T = +3.9\ °C$ by 2080 Decrease in P 3% by 2020 and 21% by 2080
6	Initial Communication of Guinea [36]	Same models as Ghana IS92	Reference: 1961–1990 $+0.2\ °C < \Delta T < +4.8\ °C$ by 2100 over (2000–2100) Decrease in P that could reach (-40%) by 2100
7	Initial National Communication of Liberia [37]	ECHAM5, HadCM3 and 10 RCM A1B scenarios	Reference: 1961–1990 $\Delta T = +0.4\ °C$ (over 2010–2019) $\Delta T = +2.6\ °C$ (over 2020–2049) Decrease in P 2% by 2019 and 9.2% by 2049

Table 1. *Cont.*

	Study	Models Used and Scenarios	Projected Change
8	Initial Communication of Mali [38]	MAGICC SCENGEN: HadCM2 1xCO_2 and 2xCO_2	Reference 1961–1990. 2xCO_2: +2.7 °C < ΔT < +4.5 °C by 2025 Decrease in P 10% by 2025
9	Second National Communication of Niger [39]	HadCM3: scenarios A2 and B2. CGCM3 (Canadian Centre for Climate Modeling and Analysis): scenarios A2 and B1. MPI-ECHAM5, CSIRO-MK3, GFDL-CGCM2, MRI-CGM2. 1 RCM	Reference 1961–1990. Over 2020–2049: +1.5 °C < ΔT < +2.3 °C (–2%) < ΔP < +50%
10	Nigeria's Second National Communication [40]	No clear reference to models used. B1 and A2 scenarios	Reference: 1961–1990. 2050s (2046–2065): +1.8 °C < ΔT < +2.2 °C 2090s (2081–2100): +2.2 °C < ΔT < +4.5 °C
11	Initial National Communication of Togo [41]	HadCM2, Csiro-Tr (Australia's Commonwealth Scientific and Industrial Research Organization, Australia), and BMRC-EQ (Australian Bureau of Meteorological Research Center) Scenario IS92a	Reference: 1961–1990 -by 2025 + 0.47% < ΔT < +0.58% (−0.3%) < ΔP < (−0.1%) -by 2050 +1 °C < ΔT < +1.25 °C (−0.8%) < ΔP < (+0.6%) -by 2100 +2.3 °C < ΔT < +2.7 °C (−1.25%) < ΔP < (+1%)

Table 1 illustrates how past projected trends over WA considerably varied from one model to another. It also provides evidence that WA countries do rely a lot on IPCC models projections as inputs for their planning. Nevertheless, model predictions and scenarios suffer from high uncertainties due to the many unknowns in regard to the future behavior of society, climate feedbacks in the face of greenhouse gases (GHGs) concentrations, climate model structural errors, or the evolution of land use and land cover [42]. Due to the uncertainties, past projections should be assessed by comparing projections to observations. We agree with Rahmstorf et al. [43] and Singh et al. [44] who assert that it is important to keep track of how well past projections match the accumulating observational data. Some might consider that those past models and projections are outdated and therefore do not need to be assessed because we have a better understanding of society, and climate dynamics and also because we have better models (increased complexity; with higher temporal and spatial resolution). Although this may be true, the same will be true in 30 years from now. Since we are simulating the future, previous models will always be outdated compared to the target year or horizon of the projections. Furthermore, the performance of a climate model against observations does not guarantee its performance in simulating future climates. This is what Reinfen and Toumi [45] found after testing the principle of selecting climate models based on their agreement with observations for surface temperature using 17 of the IPCC AR4 models.

Few studies have currently assessed past projections. Some studies have evaluated the accuracy of past projections by addressing variables such as temperature, sea level rise, and/or atmospheric carbon dioxide concentration on a global scale. Hausfather [46], e.g., analyzed how well climate models have projected global warming from 1973 until the fifth IPCC assessment report (2014). Kahn [47] published climate projections made by the Exxon oil and gas company in 1982. The company had projected the growth of atmospheric CO_2 and the average global temperature increase from 1980 until 2100. Rahmstorf et al. [43] conducted an analysis of global temperature and sea-level data for the past decades up to

2011 and compared them to projections published in the third (2001) and fourth (2007) AR of the IPCC.

Exploring the performance of past projections might give us some insight into a better planning for the future. Many countries in WA have built their adaptation plans based on projections made by a number of these models. Almost 30 years later, it is time to check how right the projections were. What could be the consequences of relying on potentially incorrect projections? What then should be the best attitude for decision-makers in the face of projections so that we establish a "no-regret" situation? This exercise may provide us with insights into the best models to use for a specific application (agriculture, ecology, energy, etc.) in the near future.

The research presented here tends to look back at what was projected 20 to 30 years ago. The goal is to assess the performance of past projections in comparison with observations, considering the state of scientific knowledge at that time in the past, the computing capacity, the models available and the defined scenarios.

The approach proposed in this paper is based on the assumption that if a coupled "society scenario + CO_2 scenarios + climate model" has demonstrated some predictive capacity for the future (future here being the past 20–30 years), it may be able to provide some useful insight for the short (i.e., near-future) and long terms. We are not saying that other approaches should be abandoned; rather, they should be complemented by this different approach, which is worth some attention and testing. Our research is an attempt to define a complementary approach to classical ones. From our perspective, this type of study can be easily understood by non-scientists. Consequently, we believe the study has a non-negligible advantage in terms of supporting scientists in their communication to non-scientists about uncertainties concerning their research on climate change projections.

The objective of the study is to compare IPCC past projections on precipitation and temperature to observations over the WA sub-region. We are interested in the data produced in the context of the First, Second, and Third Assessment Reports (further referred to as AR1, AR2 and AR3). The study was conducted with the intention of learning from the past (period 1990–2016) in order to support short-term predictions for decision-makers in various key development sectors and to possibly improve future projections (i.e., for the period 2020–2050 or 2025–2055 or further). Our first research question addresses how good our climate models have been so far in WA. There are a number of climate and weather-related factors which directly influence sustainable development, such as water resources management and agricultural practices. The second research question investigates what the implications could be of the similarities and differences between projections and observations in regards to these factors for WA countries. Additionally, how could these similarities or differences be interpreted and what are the potential drivers for them? Thirdly, from analyses conducted ahead, what could we learn from the past for better projections?

Section 2 of the paper will describe the methodology applied both for the processing of data and structuring the results, and Section 3 will present the results and discuss them. Section 4 will summarize the research and share recommendations for further steps.

2. Materials and Methods

2.1. Data Description

Data for this study comprised two sets of observational data and six sets of past IPCC climate projections. Variables considered were precipitation and temperature. We chose observation data according to the quality of the product. Projected precipitation was compared to the Global Precipitation Climatology Centre Full Data Monthly Product (GPCC Version 2018 with a spatial resolution of 0.25°). Data is given as globally gridded monthly land-surface precipitation totals from rain-gauges built on GTS-based and historical Data. Precipitation anomalies at the stations were interpolated and then superimposed on the GPCC Climatology V2018 in the corresponding resolution [48]. Data is available for the period ranging from January 1891 until December 2016. Precipitation being more uncertain than temperature, we recognize and endorse the possible sensitivity of our results to this specific precipitation data product. Many studies such as those of Sylla et al. [10] or Poméon et al. [49] pointed this out.

Projected temperatures were compared to a. product which results from the combination of two large individual data sets of station observations collected from the Global Historical Climatology Network version 2 (GHCN) and the Climate Anomaly Monitoring System (CAMS) and the use of interpolation methods [50]. The resulting dataset is called GHCN-CAMS. It includes analyzed monthly mean global land surface temperatures at a spatial resolution of 0.5° from 1948 to near present. As we decided to look at datasets from the IPCC, we limited the selection of past projection datasets (model runs and scenarios) to those available at the IPCC Data Distribution Centre (DDC) [51]. We also made the decision to focus on models used by WA countries in the elaboration of their National Communications to the UNFCCC. Furthermore, transient runs were preferred over equilibrium ones because we were comparing data until the year 2016. Details about chosen models and scenarios are summarized in Table 2.

Table 2. Characteristics of the Ocean and Atmospheric General Circulation Models (OAGCMs) and scenarios used for the observations-projections comparison.

IPCC Assessment Reports (AR)	Climate Models. (Lat. × Long.). References	Available Runs	Selected Runs	Period	Sources of Data
AR1, 1990	Goddard Institute for Space Studies (GISS). USA. $(7.83^0 \times 10^0)$. [52]	Control Scenario A Scenario B Equilibrium	Scenario A:"Business-as-Usual (BaU)". It was run in the mid-1980s.	1958–2062	National Aeronautics and space Administration [53]
			Scenario B: the 2060 Low Emissions Scenario. It was run in the mid-1980s.	1958–2029	[54]
AR2, 1995	Geophysical Fluid Dynamics Laboratory (GFDL-R30). USA. $(2.25^0 \times 3.75^0)$. [55]	Control ghg ghg + s: (ghg and sulphate aerosol)	GHGs—"Business-as-Usual (BaU)". The value of CO_2 increases gradually at the rate of 1% per year from the initial value (approximately equal to the value observed in 1958).	1958–2058	[56]
AR2, 1995	Hadley Centre for Climate Prediction and Research (Hadley Centre Coupled Model version 2: HadCM2). UK. $(2.5^0 \times 3.75^0)$. [57]	Control 1 ensemble of 4 runs: (ghg 1%) 1 ensemble of 4 runs: (ghg 0.5 %) 1 ensemble of 4 runs: (ghg + s 1%) 1 ensemble of 4 runs: (ghg +s 0.5%)	First ensemble member of ghg 1%: (IPCC Scenarios) IS92a (approx. IPCC: "Business-as-Usual (BaU)" scenario). The GHGs forcing is increased gradually to represent the observed changes in forcing due to all the ghg from 1860 to 1990. From 1990 to 2100 it uses a 1% per year compounded increase in concentrations.	1860–2099	[58]
AR3, 2001	Hadley Centre for Climate Prediction and Research (Hadley Centre Coupled Model version 3: HadCM3). UK. $(2.5^0 \times 3.75^0)$. [59]	1 ensemble of 3 runs: (A2, A2b, A2c) Scenario B2	Special Report on Emission Scenarios (SRES) A2 storyline: continuous increasing population together with a slower economic growth and technological change	1950–2099	[60]
			Special Report on Emission Scenarios (SRES) B2 storyline: emphasis is put on local solutions to economic, social and environmental sustainability. The global population is increasing at a lower rate than storyline A2.	1950–2099	[61]

2.2. A Brief Description of Socio-Economic and GHGs Scenarios

As pointed out before, the choice and definition of scenarios plays a major role in the models results. We have to remember that the goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures [62]. Another important thing to mention is that scenarios have been updated from AR1 to AR6. Table 3 shows a brief summary of the evolution of IPCC scenarios from AR1 to today.

Table 3. Summary of IPCC scenarios used since AR1.

Year	Name	Used in	Scenarios
1990	1990 IPCC Scenario A: SA90	AR1	A (=Business as Usual—BaU) /B/C/D
1992	IPCC Scenarios (IS) IS92	AR2	IS92a, IS92b, IS92c, IS92d, IS92e, IS92f
2000	SRES—Special Report on Emissions and Scenario	AR3 and AR4	Storylines A1; A2; B1 and B2
2009	RCP—Representative Concentration Pathways	AR5	RCP 2.6/RCP 4.5/ RCP 6.0/RCP 8.5
2021–2022	SSP—Shared Socio-economic Pathways	AR6	SSP1-1.9/SSP1-2.6/SSP2-4.5/SSP3-7.0/SSP5-8.5

In 1990, for the AR1, the IPCC Working Group III generated four emission scenarios referred to as policy scenarios (A, B, C and D). Scenario A approximates a Business-as-Usual (BaU) case or "the 2030 High Emissions Scenario" and assumes that few or no steps are taken to limit GHGs emissions. Working Group I explicated that under this scenario, the equivalent of a doubling of pre-industrial CO_2 levels would occur by around 2025. The other three scenarios incorporate a progressive penetration of controls on GHGs emissions and each scenario includes emissions of the main GHGs, and other gases (such as NOx and CO_2) which influence then concentration [63]. Under Scenario B also called "the 2060 Low Emissions Scenario", it is assumed that CO_2 levels will double around 2060 [64]. In the futures envisioned by scenarios C and D, it is assumed that more steps (use of renewable energy sources among others) will be taken to reduce GHGs emissions so that their levels will go below scenario B's level.

In 1992, scenarios were updated to six alternative IPCC scenarios (IS92a to f) as described in the 1992 Supplementary Report to the IPCC Assessment. Leggett et al. [8] insisted that scenario outputs are not predictions of the future, and should not be used as such: they illustrate the effect of a wide range of economic, demographic and policy assumptions; and because they reflect different views of the future, they are inherently controversial. They further explained that the IS92e scenario (that combines among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and eventual phase out of nuclear power) generates the highest GHGs. As for the lowest level of GHGs emissions, it is given by IS92c which has a CO_2 emissions path that eventually falls below its 1990 starting level. In that scenario, it is estimated that population will first grow, then will decline by the middle of next century, that economic growth will be low, and that there will be severe constraints on fossil fuel supply. Scenarios IS92a and IS92b are the closest to SA90. Although IS92 proposed up to six various scenarios, IS92a has been adopted as a standard scenario for use in impact assessments [8].

In 2000, new scenarios were published and used for AR3. They comprised four so-called "storylines" A1, A2, B1 and B2. Each storyline represents different demographic, social, economic, technological, and environmental developments (driving forces of GHGs and sulfur emissions) that diverge in increasingly irreversible ways [51]. The storylines result from the combination of two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization. Under each storyline could be constructed a scenario or a scenario family.

In 2009, a new set of scenarios was proposed. van Vuuren et al. [65] explained that the need for new scenarios prompted the IPCC in 2007 to request the scientific communities to develop a new set of scenarios to facilitate future assessment of climate change. The new scenarios were built with a new "philosophy": There are RCPs (Representative Concentration Pathway) which are separated from SSPs (Shared Socioeconomic Pathways). RCPs fix the pathways for the radiative forcing and the concentrations of GHGs, and then climate modelers can run their simulations without necessarily connecting to a pre-defined storyline. According to a defined radiative forcing value in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, respectively), RCPs are designated RCP2.6, RCP4.5, RCP6, and RCP8.5. SSPs are developed in a parallel process and represent a set of consistent socio-economic scenarios with storylines to guide mitigation, adaptation, and mitigation analysis [66]. It appears then that with the new RCPs many different socio-economic futures are possible leading to the same level of radiative forcing [66].

For more details about the changes that occurred in the scenarios since the AR1 the readers are referred to the comprehensive analysis conducted by Girod et al. [67]. Regarding the latest scenarios in AR6, detailed information can be found in the Working Group I contribution to the Sixth Assessment Report [68].

2.3. Methodology for Data Processing

After retrieving data from their original source or database, they were processed in three main steps:

1. Change in the format of the data, conversion to netcdf format for the files which were not originally at that format.
2. Subsetting of the data to the same temporal resolution. For precipitation, data was converted to mm/month (monthly totals). For temperature we considered the monthly mean in degrees Celsius. As the temporal extent, we considered the period from 1990–2016.
3. Resampling of the data to the same spatial resolution. We remapped the original datasets according to the bilinear method to a $0.25° \times 0.25°$ grid. We also extracted the WA Region (as defined above) from the processed datasets.

For the present observation-past projections data comparison, we selected a 27-year period ranging from 1990 to 2016. In order to assess the performance of past projections with regard to observations, various types of analysis were conducted.

The methodology has been designed so that for each variable three main aspects are investigated which are (1) the mean climatology; (2) the mean annual cycles and (3) the trends.

First, the mean climatology was analyzed through the plotting of mean variable patterns and the percentage of the difference between observations and projections. The annual mean (for total precipitation) and monthly mean (for temperature) were computed at the grid points and then the percentage of difference for each projection dataset by comparison to observation were calculated. Here, data was averaged over time and the results were displayed as maps.

Second, the mean annual cycles were studied not only by averaging the monthly means over time and space, but also over time and longitude. Hovmöller diagrams were obtained from the latter analysis. A Hovmöller diagram, as highlighted by Di Liberto [69] is a cross between a map and a graph; it was created by a scientist named Ernest Hovmöller in order to show movement in static pictures. Time is generally put on one axis of the graph and either latitude or longitude on the other. For our analysis, we chose to use the horizontal dimension (X-axis) to represent time and the vertical dimension (Y-axis) to represent latitude as our purpose here was to put in evidence the seasonal migration of rainfall in WA along latitudes. After calculating the annual cycle at the grid points over our study domain, data was averaged by latitude, i.e., for a given latitude point and a given month, data along all longitude points were averaged.

Third, the trends are plots of observations (from approximately 1950 to present) and projections (over the whole period of the corresponding run).

In addition, two metrics were computed in support of the analysis: the Percent Bias (PBIAS) and the Root Mean Squared Error (RMSE). The methodology is summarized in Figure 1.

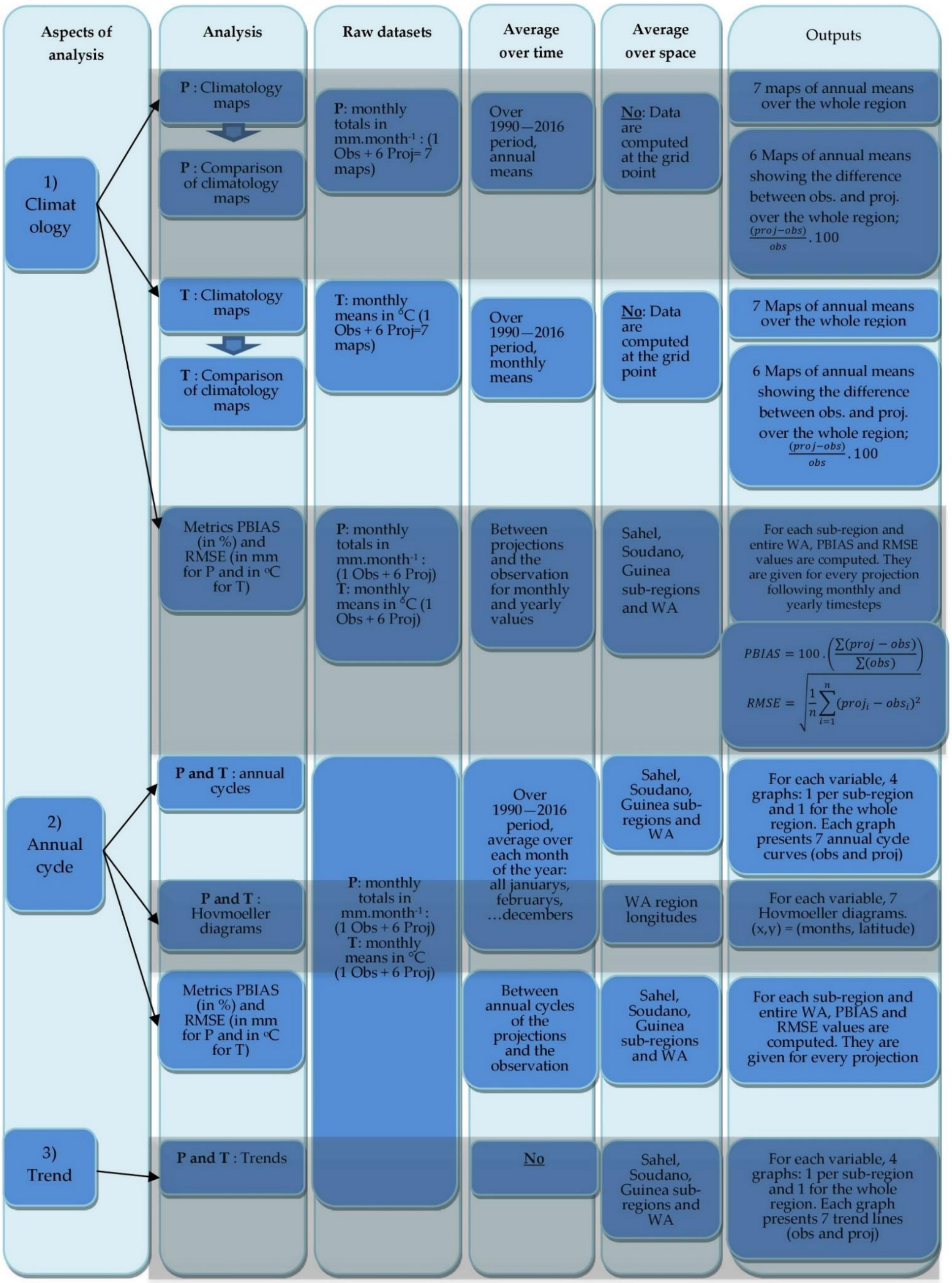

Figure 1. Summary of the methodology.

Novel computer codes were developed for the treatment and analysis of the data used in this study. The files are freely available on Bitbucket upon request (see Supplementary Materials).

2.4. Study Area

The evaluation of the past projections was undertaken over the West African region (Figure 2). The map shows that following a north–south gradient in increasing annual precipitation, WA can be subdivided into five broad east-west belts that characterize the climate and the vegetation [70]. These are the bioclimatic zones known as the Saharan, Sahelian, Sudanian, Guinean, and Guineo-Congolian regions. Considering these bioclimatic zones, we divided West Africa in 3 analysis sub-regions defined as follow: with the longitude 13° W–13° E, Sahel goes from 14° N to 19° N, Soudano from 9° N to 14° N and finally Guinea from 4° N to 9° N according to Heinzeller et al. [18]'s domain of study (Figure 3).

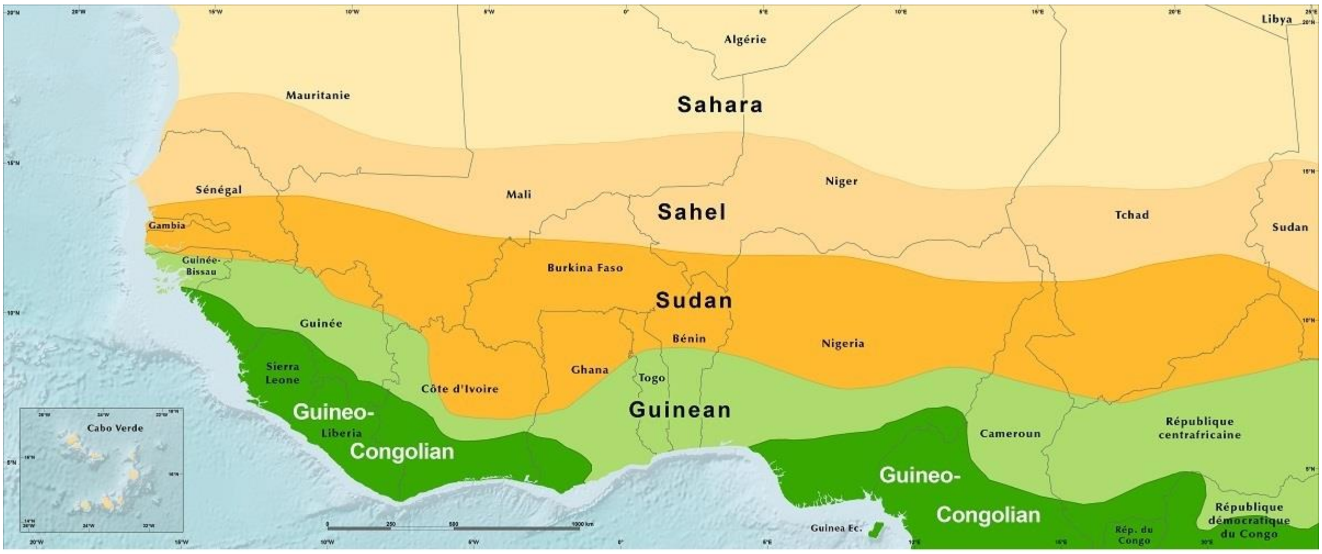

Figure 2. Bioclimatic Regions of WA. Source: [70].

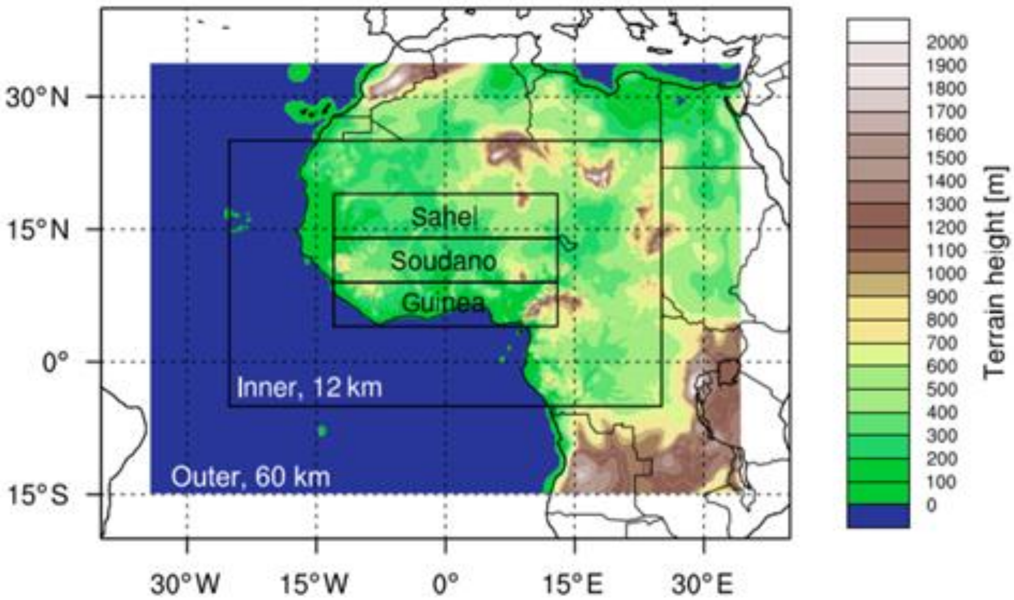

Figure 3. Definition of Sahel, Soudano and Guinea sub-regions for our study. Taken from Heinzeller et al. [18].

The climate over the Sahel is mainly dominated by two seasons; a dry season of nearly eight months from October to May and a wet season of approximately four months JJAS [71]. In the Soudano sub-region, the annual cycle is composed of two seasons with a longer rainy season which has a length of seven months from April to October [72,73]. Over the Guinea region, four seasons are observed: two rainy seasons with drier periods between the rains. The drier periods are NDJF and JA [70].

3. Results and Discussion

3.1. Precipitation

3.1.1. Precipitation Climatology

The spatial distribution of the mean annual precipitation for GPCC observations and past projections is shown in Figure 4. The maps display the spatial patterns and amounts of precipitation for each dataset. The observation depicted a south-north gradient of decreasing precipitation. All the projections were characterized by the same spatial pattern with some important differences in amounts, and shapes of the east-west belts. As explained by [11] and Sylla, Elguindi, et al. [16], precipitation maxima are associated with WA orography: they are found around the Guinean Highlands—GH (750 m), Jos Plateau—JP (1220 m to up to 1766 m) in Nigeria and the Cameroun Mountains—CM (4040 m) (Figure 4). We noticed that AR1 showed a general overestimation; which is consistent with the results of the model validation reported by Hansen et al. [52]. In the context of their experiments with the GISS model, the authors identified a chief problem which was the movement of monsoon rainfall into the Sahara and the excessive northward movement of precipitation. This was attributed to insufficiency in the physical parametrizations. The authors acknowledged that some important processes such as moist convection, clouds, boundary layer transports and ground hydrology each were treated in very crude ways and that there was a need for better numerical calculations.

We also noticed that isohyets were less smooth, which was not surprising given the fact that the spatial resolution is twice to three times coarser than the observations. Although AR2-GF reproduced the general patterns well, the precipitation amounts were largely underestimated. AR2-HC2 and AR3 seemed to have a better agreement with the observations. The percentage of difference of each projection by comparison to GPCC observation dataset is illustrated in Figure 5. Table 4 reports quantitative performance measures. PBIAS is identical for monthly and yearly data, as yearly data is the sum of the months. There was a systemic underestimation over orographic areas. For AR1, although topography was taken into account, the maximum altitude considered over WA on the digital map for topography was 650 m [52]. When moving from the Coast of Guinea towards the continent, there was an increasing wet bias. In other words, there was a greater percentage of difference in higher latitudes (drier areas).

AR1 exhibited the largest biases and a yearly bias of more than 600% in the Sahel. AR1-B (2060 low emissions) had a slightly lower bias than AR1-A (2030 high emissions); this can be attributed to the GHGs concentrations scenarios. AR3 tended to overestimate the precipitation, A2 (more economic scenario) at a lower rate than B2 (more environmental scenario). Along some coastal areas (Liberia/Sierra-Leone and Nigeria/Cameroon), there was a systematic underestimation. When analyzing the map of the West–African climatic zones, these coastal areas match with the Guineo-Congolian climate. We can notice then that there was an underestimation of maxima and an overestimation of minima. The analysis metrics allowed us to confirm that AR2-HC2 is the projection having the best agreement with observations. For a given report, when we compared the metrics of the entire domain to those of each sub-region, we remarked that the metrics were improved (at least for one of the sub-regions). This lead us to the same conclusion as Gbobaniyi et al. [11], who identified high heterogeneity of the sub-regions as a driving factor which makes it difficult to adequately capture fine-scale features. Furthermore, it clearly appeared that models' performance was better for newer reports. Additionally, the metrics revealed that the performance of the models was lower over the Sahel sub-region for all reports. Similar results over Sahel have been obtained by Hulme et al. [74] who examined the inter-decadal precipitation variability of the 20th century. HadCM2 model then revealed a discrepancy in the magnitude of simulated precipitation in comparison with observations.

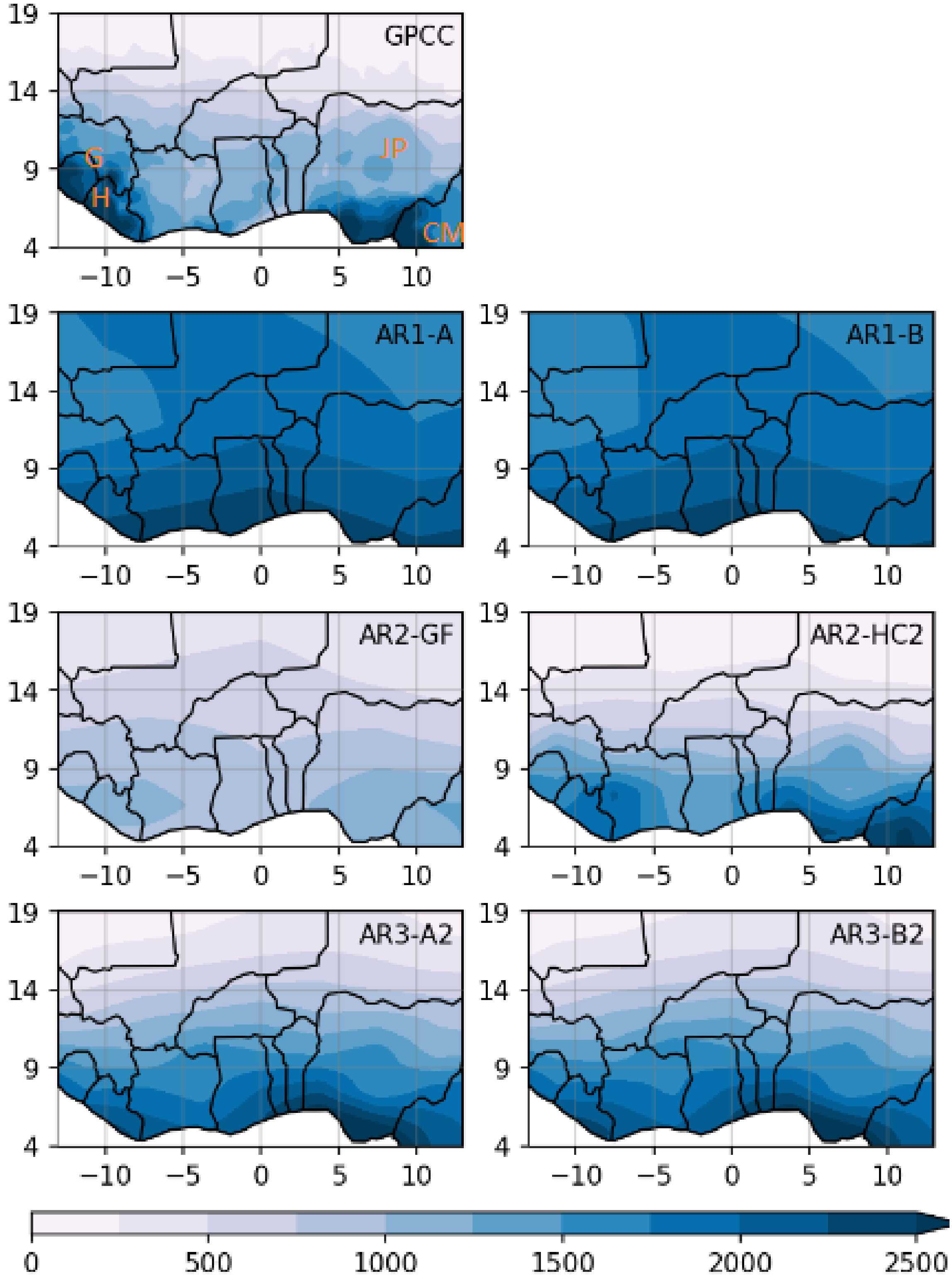

Figure 4. Mean annual rainfall climatology (mm month^{-1}) for the period 1990–2016 for GPCC observation and each of the past projections. Orographic zones: GH (Guinea Highlands), JP (Jos Plateau) and CM (Cameroun Mountains) are indicated.

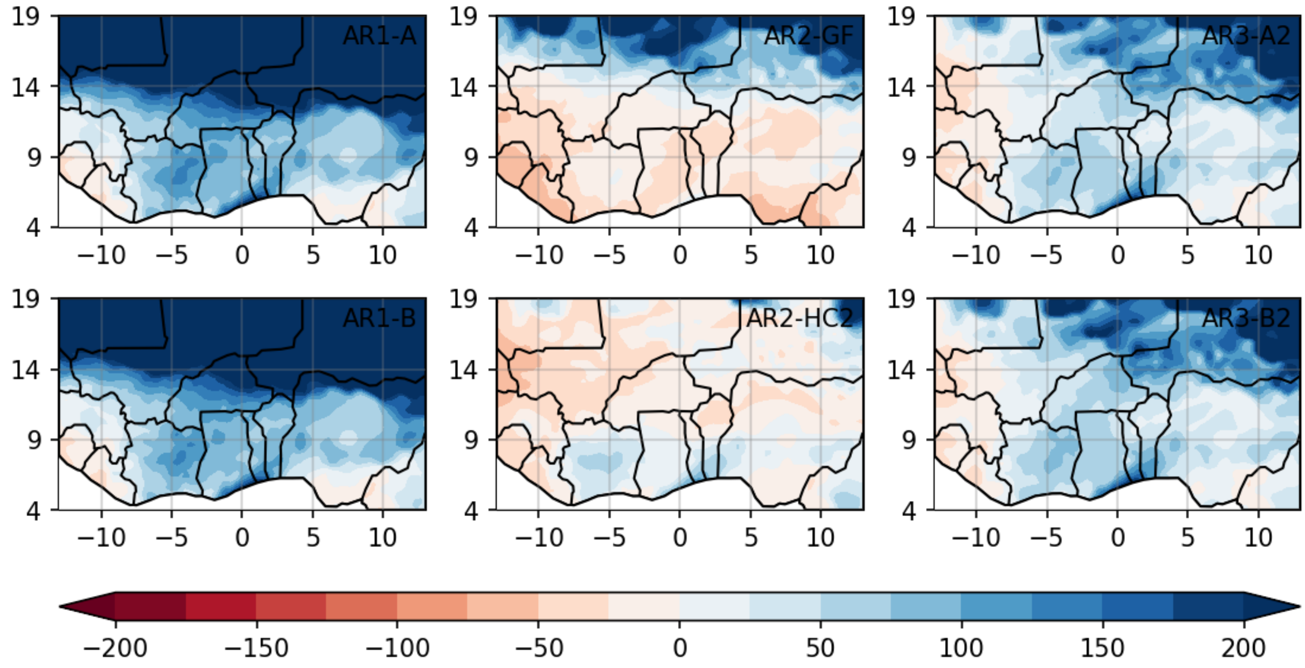

Figure 5. Percentage of difference in mean rainfall climatology for the period 1990–2016 between each of the past projections and GPCC observation dataset.

Table 4. PBIAS and RMSE between projected precipitation and the GPCC observation for monthly and yearly values. Monthly precipitation (M) and Yearly precipitation (Y) values.

		Sahel			**Soudano**			**Guinea**			**Entire WA**		
		PBIAS%	**RMSE mm**	**Obs mm**	**PBIAS%**	**RMSE mm**	**Obs mm**	**PBIAS%**	**RMSE mm**	**Obs mm**	**PBIAS%**	**RMSE mm**	**Obs mm**
AR1-A	M	643	136	20	92	135.9	78	36.5	108.7	133	118.2	118	78
AR1-A	Y	643	1513	240	92	890	940	36.5	607	1600	118.2	1032.43	930
AR1-B	M	640.5	135.8	20	91.4	136.5	78	33.7	107.3	133	116.3	117.92	78
AR1-B	Y	640.5	1507	240	91.4	888	940	33.7	563.2	1600	116.3	1017.63	930
AR2-GF	M	79.4	32.56	20	−23.3	66.05	78	−35.5	81.35	133	−19.3	46.55	78
AR2-GF	Y	79.4	203	240	−23.3	250.5	940	−35.5	585.7	1600	−19.3	187.22	930
AR2-HC2	M	−22	28.09	20	−22	59.55	78	5.8	49.76	133	−8	39.78	78
AR2-HC2	Y	−22	79.38	240	−22	254.2	940	5.8	180.7	1600	−8	126.31	930
AR3-A2	M	69.7	31.52	20	18.7	44.59	78	21.6	55.1	133	25.2	34.86	78
AR3-A2	Y	69.7	181.6	240	18.7	218.3	940	21.6	377.2	1600	25.2	238.02	930
AR3-B2	M	79.4	33.19	20	23.4	46.09	78	23.6	58.63	133	29	36.9	78
AR3-B2	Y	79.4	199.8	240	23.4	242.2	940	23.6	407.5	1600	29	266.48	930

If we examine the data from a decision-making perspective, one could determine threshold values that could be considered as the maximum acceptable bias. In the situation where the data would be tested for a resource planning purpose (agriculture for example), a set of sub-region dependent thresholds are proposed in Table 5 to serve as an illustration. This would allow for the easy location of (on the percentage of difference maps) areas where these thresholds were not reached. We selected values that depend on the sub-region because they do not have the same mean annual precipitation. For an example of application, the reader is referred to Gaba et al. [75]'s work on WA.

Table 5. Illustration of possible threshold values for the analysis of the maps related to the percentage of difference in precipitation for a resource planning purpose.

Sub-Region	Mean P mm/Year	Threshold in %	Threshold in Total Amount mm/Year
Sahel	240	10	24
Soudano	940	8	75.2
Guinea	1600	6	96

3.1.2. Precipitation Annual Cycles

The second part of our analysis focused on mean annual cycles of monthly precipitation for the observations and the past projections datasets (Figure 6). Metrics for the numerical assessment of the plots are given in Table 6.

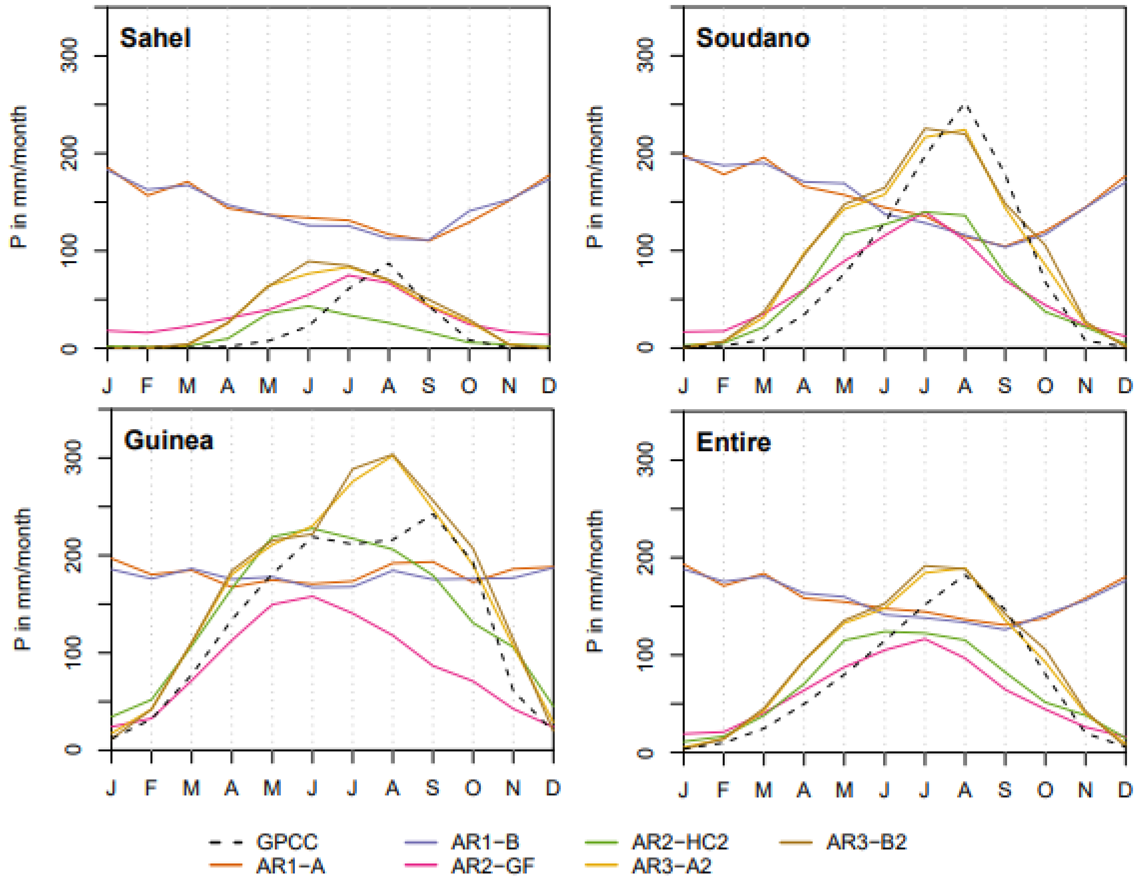

Figure 6. Annual cycle of monthly precipitation (mm month^{-1}) averaged over the Sahel, Soudano, Guinea sub-regions and the entire WA and for the period 1990–2016 for GPCC observation and each of the past projections.

Table 6. PBIAS and RMSE between projected precipitation and the GPCC observation for annual cycles.

	Sahel			Soudano			Guinea			Entire WA		
	PBIAS%	RMSE mm	Obs mm	PBIAS%	RMSE mm	Obs mm	PBIAS %	RMSE mm	Obs mm	PBIAS%	RMSE mm	Obs mm
AR1-A	643	134.18	20	92	132.05	78	36.5	100.13	133	118.2	115.8	78
AR1-B	640.5	134.11		91.4	132.37		33.7	98.62		116.3	115.49	
AR2-GF	79.4	20.81		−23.3	56.43		−35.5	70.44		−19.3	38.43	
AR2-HC2	−22	23.29		−22	50.78		5.8	35.32		−8	32.63	
AR3-A2	69.7	25.57		18.7	32.64		21.6	39.03		25.2	25.86	
AR3-B2	79.4	28.13		23.4	35.98		23.6	42.57		29	28.58	

In the Guinea sub-region, all projections were unable to capture the second peak of the cycle, but AR2 and AR3 captured the timing of the first peak in June well. AR2-GF underestimated the total precipitation by approximately 20% and AR3 roughly captured the seasonality with some important overestimations in July and August. AR1 did not simulate the seasonality correctly. The amount of precipitation was almost the same the whole year: around 200 mm/month which means that GISS model showed no variation of seasons for Guinea region. AR2-HC2 presented the best metrics.

In the Soudano sub-region, the seasonal pattern (unimodal rainy season) was well captured but not the timing: the peak of the season was projected to arrive one month earlier than observed. The precipitation amount was underestimated by AR2 and slightly overestimated by AR3. AR1projections patterns were the opposite of what we would expect; from January to September, there was a descending line and then from September to December, an ascending line. AR3-A2 presented the best metrics.

In the Sahel sub-region, the seasonal pattern was not well captured, although most projections agreed on a unimodal rainy season. For AR2 and AR3, there was a tendency to peak in June rather than in August (timing of peak in the observations). The patterns of AR1 were again opposite to the observed patterns with the lower point in September. AR2-HC2 presents the best metrics.

One major process influencing precipitation amounts and large-scale patterns over the study area is the West Africa Monsoon (WAM). The WAM modulates the moisture flux from the Atlantic Ocean to the WAn region [71]. The tropical rain belt (also known as the inter-tropical convergence zone, ITCZ) oscillates between the southern tropics and northern over the course of a year, and its movement commences rainfall in the southern region, progresses towards the north between June and October. It reaches a peak in August, and the amount diminishes rapidly with increasing latitude [76]. The way this process was simulated by models can be assessed through Hovmöller diagrams (Figure 7). The very characteristic pattern of the WAM on a Hovmöller diagram is clearly detailed by various authors among others [11,72,73,76,77]. It is composed of 3 main phases: the onset, the "monsoon jump" and the southward shift [11]. The onset occurs between April and June and consists of a gradual progression of the rain belt from the coast to about 5° N. The second phase is the "monsoon jump" which is characterized by an abrupt latitudinal shift of the ITCZ in late June from a quasi-stationary location at 5° N in May-June to another quasi-stationary location at 10° N in July–August. A [73,77]. This sharp discontinuity brings high amount of rainfall into the Sahel accompanied by a sudden cessation in appreciable precipitation intensities along the Guinean coast. The later phase is a southward shift towards the Guinean coast around September accompanied by a decrease in rainfall intensity over the Sahel [11,72]. We noticed that AR1 was not able to reproduce the pattern. For the four remaining projections, although the general pattern was followed (i.e., northward and then southward migration of the monsoon), timing, locations and rainfall amplitudes were not respected. In fact, there was no "monsoon jump" and the monsoon did not move far enough north. Such behavior resulted in a continuous rainy season in the Guinea region instead of two rainy seasons separated by a drier one. This may explain the large biases in precipitation estimations. Modelling the WAM remains one of the main challenges scientists are facing in climate change studies over WA [78,79].

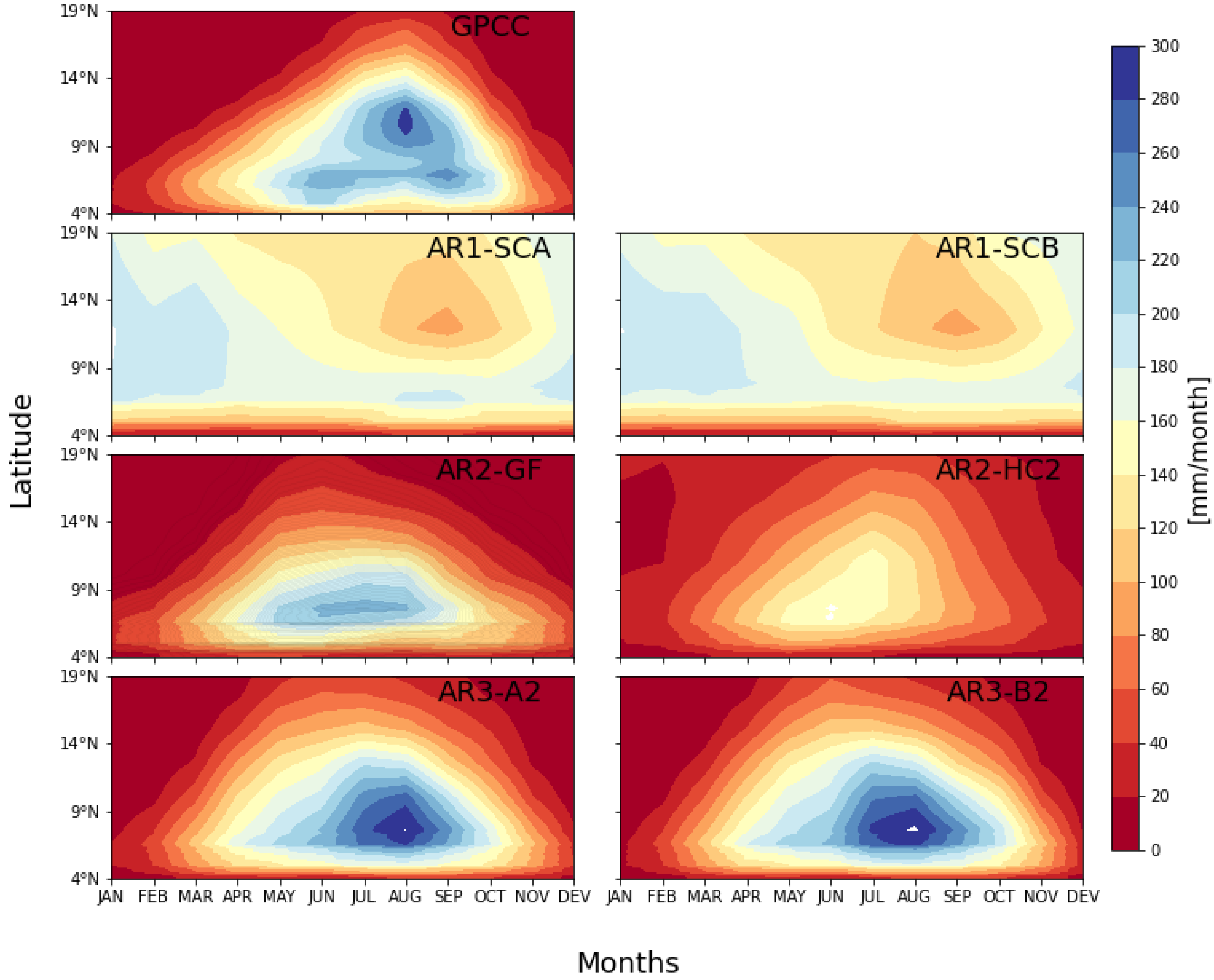

Figure 7. Hovmöller diagram of monthly precipitation (mm month^{-1}) averaged between 13° W and 13° E and for the period 1990–2016 for GPCC observations and each of the past projections.

3.1.3. Precipitation Trends

Finally, in Figure 8, we present the trends of annual precipitation from 1950 until 2100. Ranges vary according to each projection (see also Table 2). Many projections started a little far from the observations starting point in 1950. This suggests that the initialization in the model atmosphere and ocean and the initial forcing of GHGs scenarios have a certain influence on the results of models runs and the trends. For all sub-regions, AR1-A and AR2-HC2 had the highest trends while AR1-B and AR2-GF projected the lowest trends. The observed trend seemed to decrease but the majority of projections had an increasing trend.

Considering the results presented above, one would have expected AR2-HC2 trend to be the one closest to the observed trend. Projection AR2-GF seemed to be the one that is the closest to observations. This suggests that although AR2-GF is able to roughly capture the long-term trend, it is unable to reproduce short term temporal and spatial patterns. There is no clear evidence of what could explain such a result. Nevertheless, the Intergovernmental Panel on Climate Change (IPCC) [80] explains that as the area of interest moves from global to regional to local, or the time scale of interest shortens, the amplitude of variability linked to weather increases relative to the signal of long-term climate change. The authors further comment that this makes detection of the climate change signal more difficult at smaller scales and that conditions in the oceans are important as well, especially for interannual and decadal time scales (Intergovernmental Panel on Climate Change (IPCC) [3]. A more extensive analysis is certainly needed in order to deepen how long-term prediction could inform short term prediction and how today's decisions could positively impact the far future.

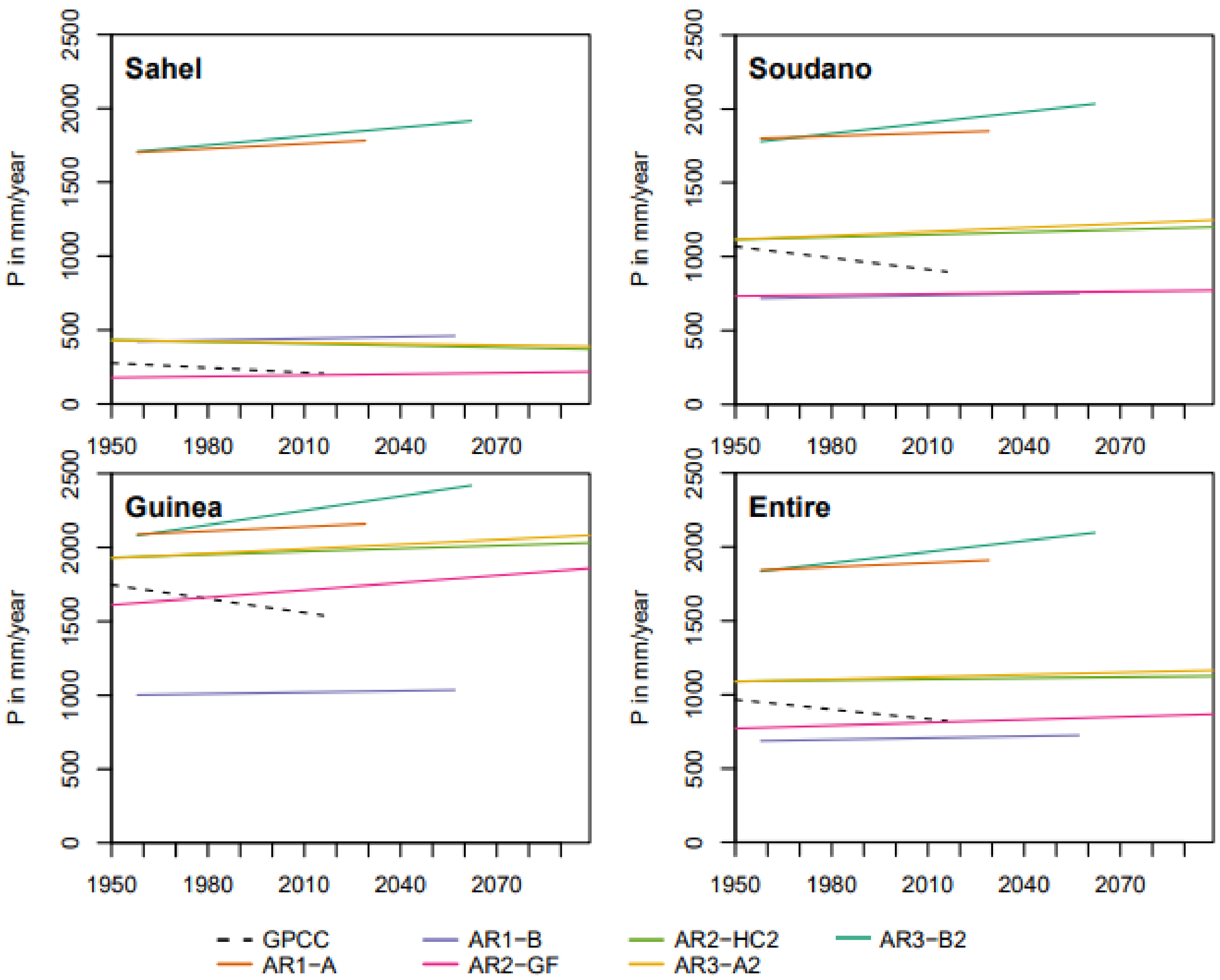

Figure 8. Trends of annual precipitation (mm year^{-1}) averaged over the Sahel, Soudano, Guinea sub-regions and the entire WA for the period 1950–2100 for GPCC observation and each of the past projections.

3.2. Temperature

3.2.1. Temperature Climatology

The mean observed temperatures over WA and the period of interest is displayed in Figure 9. The maps show the spatial patterns of temperatures and their values for each dataset.

Observations exhibited large-scale patterns which were characterized by cold temperatures along the Gulf of Guinea and warm temperatures in the Sahara Desert. It was also noticeable that the coldest observed temperatures were measured over the orographic peaks mentioned above [11] and the warmest temperatures along a west-east band passing through the north of Burkina Faso. Four (AR2-GF, AR2-HC2, AR3-A2 and AR3-B2) out of the 6 simulations reproduced these large-scale patterns well. In contrast, AR1 (A and B) showed an inverted trend, i.e., there was an increase of temperature from the Sahara to the Gulf of Guinea. AR2-GF had some additional patterns featured by a circular zone with the center located in the southern part of Mali and being the warmest point. From this point out, temperatures spread with a decreasing gradient. The percentage of difference of each projection by comparison to the GHCN-CAMS observation dataset is displayed in Figure 10.

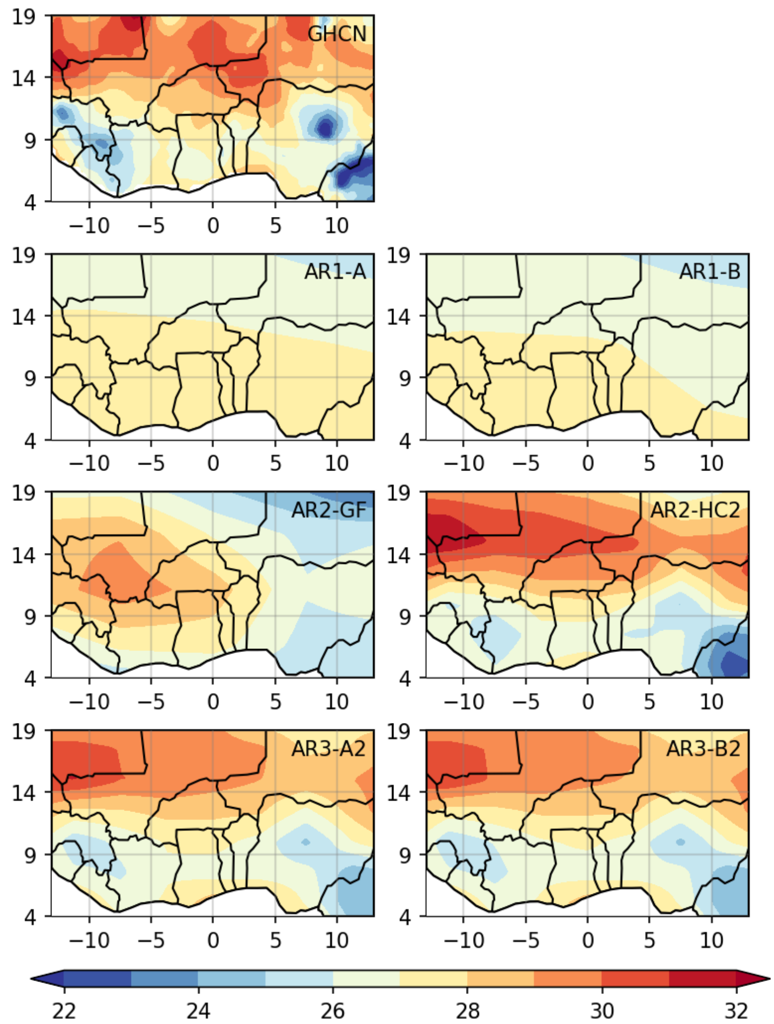

Figure 9. Mean temperature climatology (°C) for the period 1990–2016 for GHCN-CAMS observation and each of the past projections.

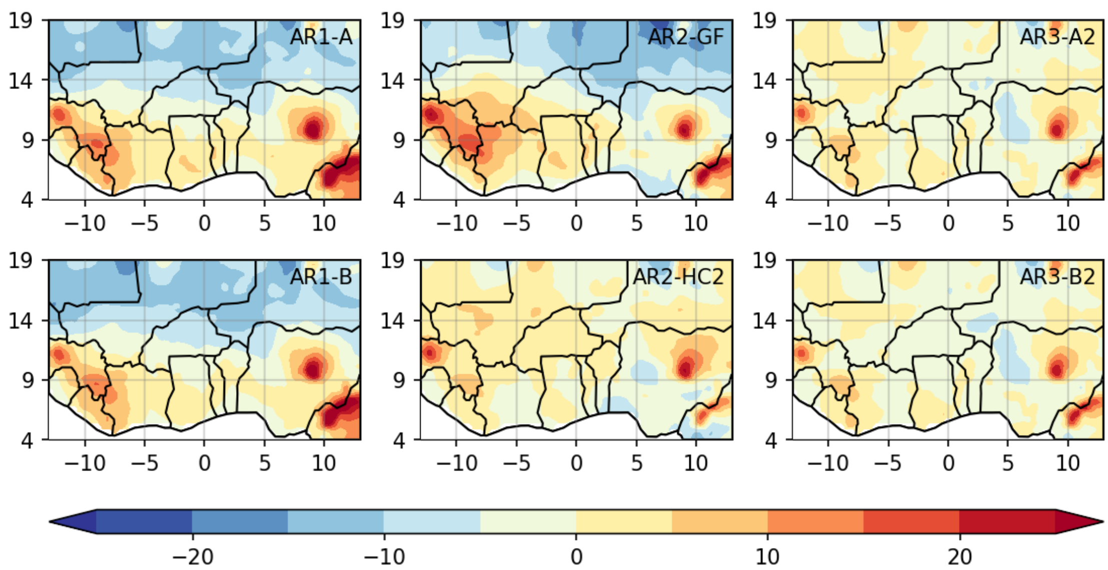

Figure 10. Percentage of difference in mean temperature climatology for the period 1990–2016 between each of the past projections and GHCN-CAMS observation dataset.

Quantitative performance measures are reported in Table 7. There appeared to be a systemic overestimation over orographic areas. AR1 and AR2-GF exhibited a greater percentage of difference in higher latitudes (drier areas). Other projections did not show a particular spatial pattern but rather a good agreement with observations. Although AR3 biases were relatively small, there were high warm biases over mountainous regions. This can be attributed to the HadCM3 problems of relating observations and model data in these regions and to the fact that all points above 1500 m were excluded from the analysis [81]. Metrics revealed that the percentage of difference was generally quite low meaning that projections were quite good in simulating the temperatures. We can mention that over the Sahel region, there was a general trend to high negative biases. This is not what is desirable for a region which is already warm. Slightly overestimated values are preferable (this is the case for AR2-HC2) for a better adaptation planning. For practical purposes, an option would be to choose threshold values for the plotting of maps showing the percentage of difference (See Table 8). In this case areas with values lower than the threshold could be directly identified. An example of such analysis is provided in the work of Gaba et al. [75] on WA.

Table 7. PBIAS and RMSE between projected temperature and the GHCN-CAMS observation for monthly and yearly values. Monthly temperature (M) and Yearly temperature (Y) values.

		Sahel			Soudano			Guinea			Entire WA		
		PBIAS%	**RMSE °C**	**Obs °C**	**PBIAS%**	**RMSE °C**	**Obs °C**	**PBIAS%**	**RMSE °C**	**Obs °C**	**PBIAS%**	**RMSE °C**	**Obs °C**
AR1-A	M	−10.1	4.67	30	−1.3	2.14	28	5.2	1.98	26	−3	2.15	28
AR1-A	Y	−10.1	2.98		−1.3	0.46		5.2	1.37		−3	0.89	
AR1-B	M	−10.6	4.79		−2	2.18		4.3	1.84		−3.7	2.23	
AR1-B	Y	−10.6	3.15		−2	0.63		4.3	1.16		−3.7	1.08	
AR2-GF	M	−9.9	3.54		0.6	1.89		2.1	1.33		−3.1	1.79	
AR2-GF	Y	−9.9	2.97		0.6	0.48		2.1	0.66		−3.1	0.96	
AR2-HC2	M	0.4	1.83		2.6	1.71		−1.1	0.92		0.7	1.29	
AR2-HC2	Y	0.4	0.53		2.6	0.95		−1.1	0.47		0.7	0.53	
AR3-A2	M	−0.6	1.77		−0.2	1.33		0.8	0.96		−0.1	1.22	
AR3-A2	Y	−0.6	0.57		−0.2	0.53		0.8	0.48		−0.1	0.48	
AR3-B2	M	−0.9	1.76		−0.6	1.37		0.5	1.04		−0.4	1.24	
AR3-B2	Y	−0.9	0.49		−0.6	0.51		0.5	0.39		−0.4	0.42	

Table 8. Illustration of possible threshold values for the analysis of the maps related to the percentage of difference in temperature for a resource planning purpose.

Sub-Region	Mean T (°C)	Threshold %	Value (°C)
Sahel	30	5	1.5
Soudano	28	5	1.4
Guinea	26	5	1.3

3.2.2. Temperature Annual Cycles

Figure 11 displays the mean annual cycles of monthly temperatures for the observation and the six past projections from the three ARs mentioned above. Metrics for the numerical assessment of the plots are presented in Table 9.

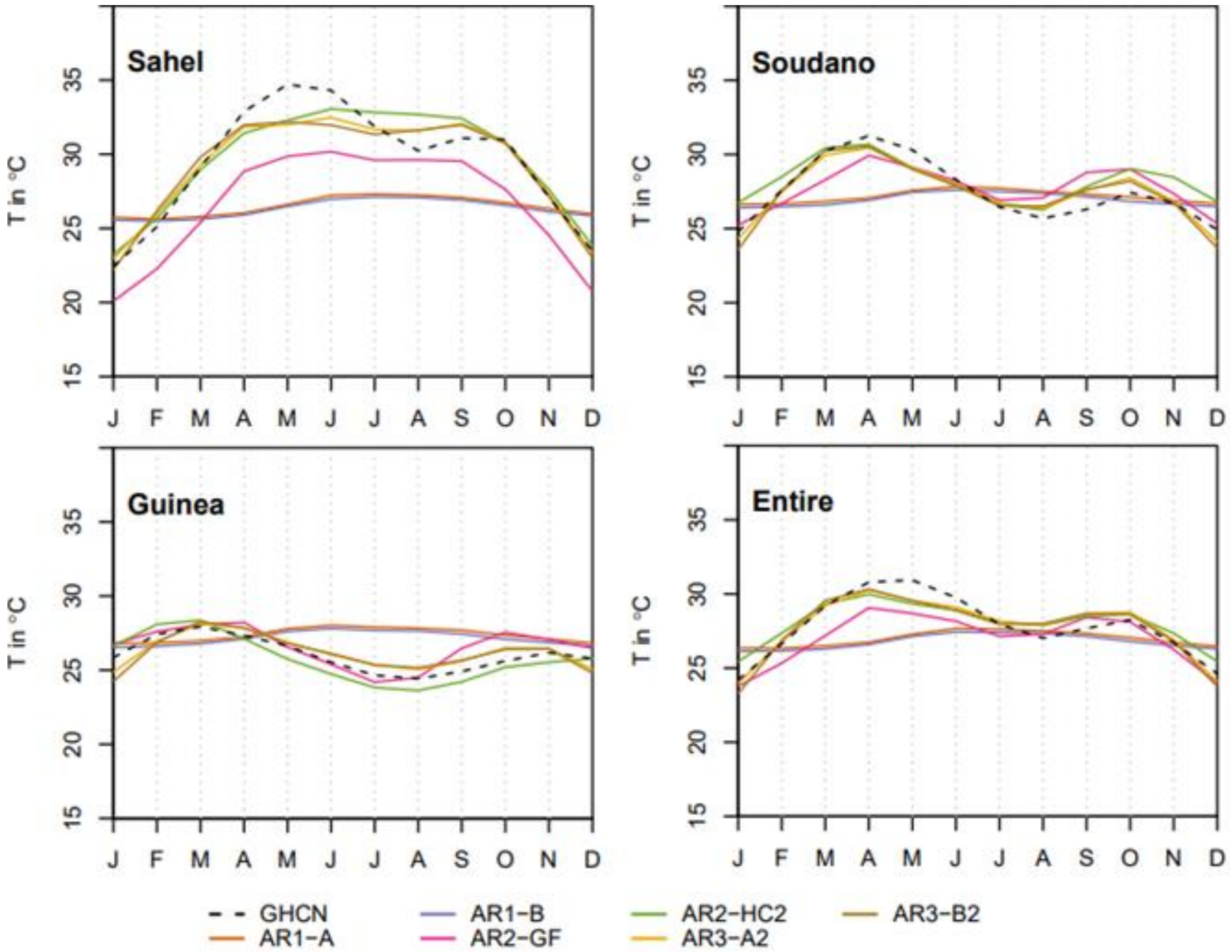

Figure 11. Annual cycle of monthly temperatures (°C) averaged over the Sahel, Soudano, Guinea sub-regions and the entire WA and for the period 1990–2016 for GHCN-CAMS observation and each of the past projections.

Table 9. PBIAS and RMSE between projected temperatures and the GHCN-CAMS observation for annual cycles.

	Sahel			Soudano			Guinea			Entire WA		
	PBIAS%	**RMSE °C**	**Obs °C**	**PBIAS%**	**RMSE °C**	**Obs °C**	**PBIAS %**	**RMSE °C**	**Obs °C**	**PBIAS%**	**RMSE °C**	**Obs °C**
AR1-A	−10.1	4.61		−1.3	2.05		5.2	1.93		−3	2.07	
AR1-B	−10.6	4.73		−2	2.09		4.3	1.78		−3.7	2.15	
AR2-GF	−9.9	3.13	30	0.6	1.27	28	2.1	0.88	26	−3.1	1.24	28
AR2-HC2	0.4	1.28		2.6	1.25		−1.1	0.65		0.7	0.85	
AR3-A2	−0.6	1.15		−0.2	0.73		0.8	0.62		−0.1	0.65	
AR3-B2	−0.9	1.21		−0.6	0.84		0.5	0.76		−0.4	0.75	

The temperature seasonal cycles were marked by the alternation of peaks (highest temperature values) and dips (lowest temperature values). Peaks were observed during the dry seasons while dips formed when precipitations reached their maximum. In the Guinea sub-region, the annual cycle was characterized by two peaks (in March and in November) and one dip in July–August. One observed that all projections were able to capture the seasonality except AR1. AR3 showed a very good performance at simulating the timing. During June-September, AR2 tended to underestimate the temperatures while AR3 overestimated them. AR3 presented the best metrics.

In the Soudano sub-region, the seasonal pattern (two peaks in April and October and one dip in August) was well captured except by AR1. During the rainy season JJAS, all projections overestimated the observations. This can be due to the poor reproduction of the "monsoon jump". AR3-A2 gives the best metrics. Within the Sahel sub-region, the seasonal pattern (two peaks in May and October; one dip in August) was not completely captured. AR2 were able to reproduce the peaks but there was no dip but rather a straight line, a plateau. AR2-GF underestimated the temperatures. AR3 caught the April-September seasonality but with some errors in the timing and values. AR1 did not catch any aspect of the seasonality nor the values; it simulated almost the same temperatures all year round. AR2-HC2 and AR3 present very similar and good metrics.

In addition to annual cycles, Hovmoeller diagrams were plotted (Figure 12). The plot of observations showed a peak in temperatures over the Sahel during April-May-June, just before the rainy season. This was not captured by the projections.

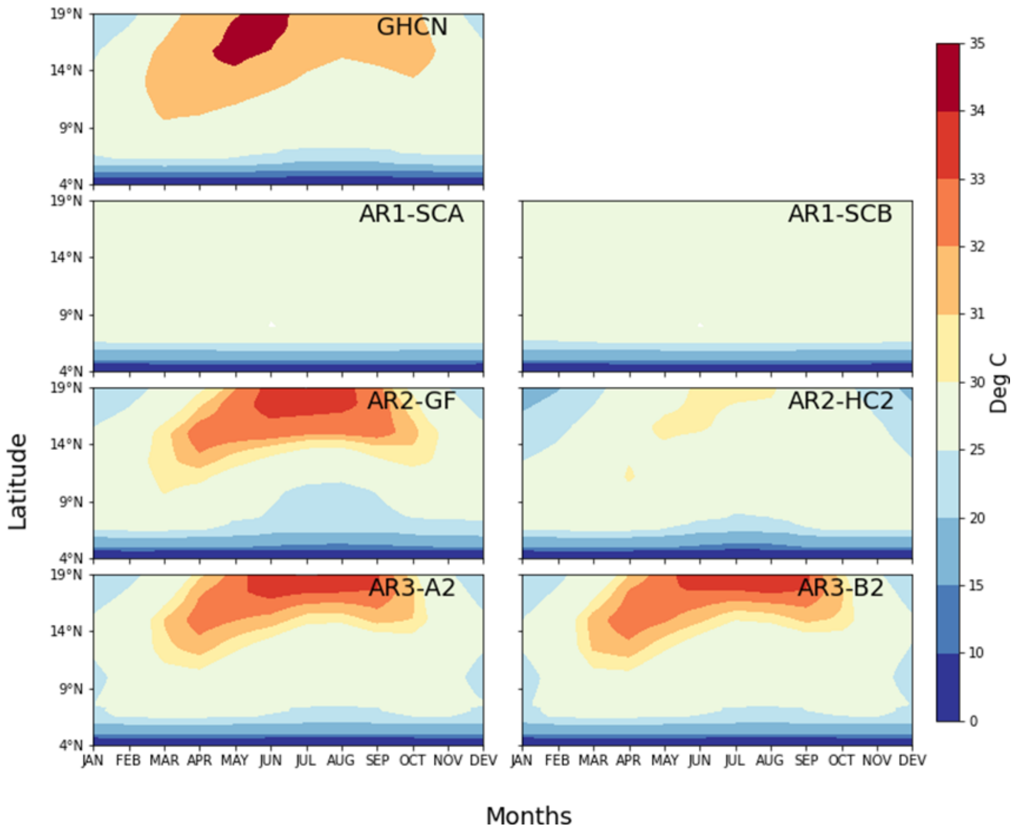

Figure 12. Hovmöller diagram of monthly temperatures (°C) averaged between 13° W and 13° E and for the period 1990–2016 for GHCN-CAMS observation and each of the past projections.

The pattern of AR1 was due to insufficiency in the physical parametrizations as explained earlier [52]. As noted by Dieng et al. [71], precise causes of the temperature biases are difficult to identify as they depend on a number of factors such as cloudiness, surface albedo, surface water, and energy fluxes.

3.2.3. Temperature Trends

Finally, in Figure 13, we present trends of monthly temperature (°C) averaged over the Guinea, Soudano, Sahel sub-regions and the entire WA for the period 1950–2100 for GHCN-CAMS observation and each of the past projections. Ranges vary according to each projection. Details for each run are available in Table 2.

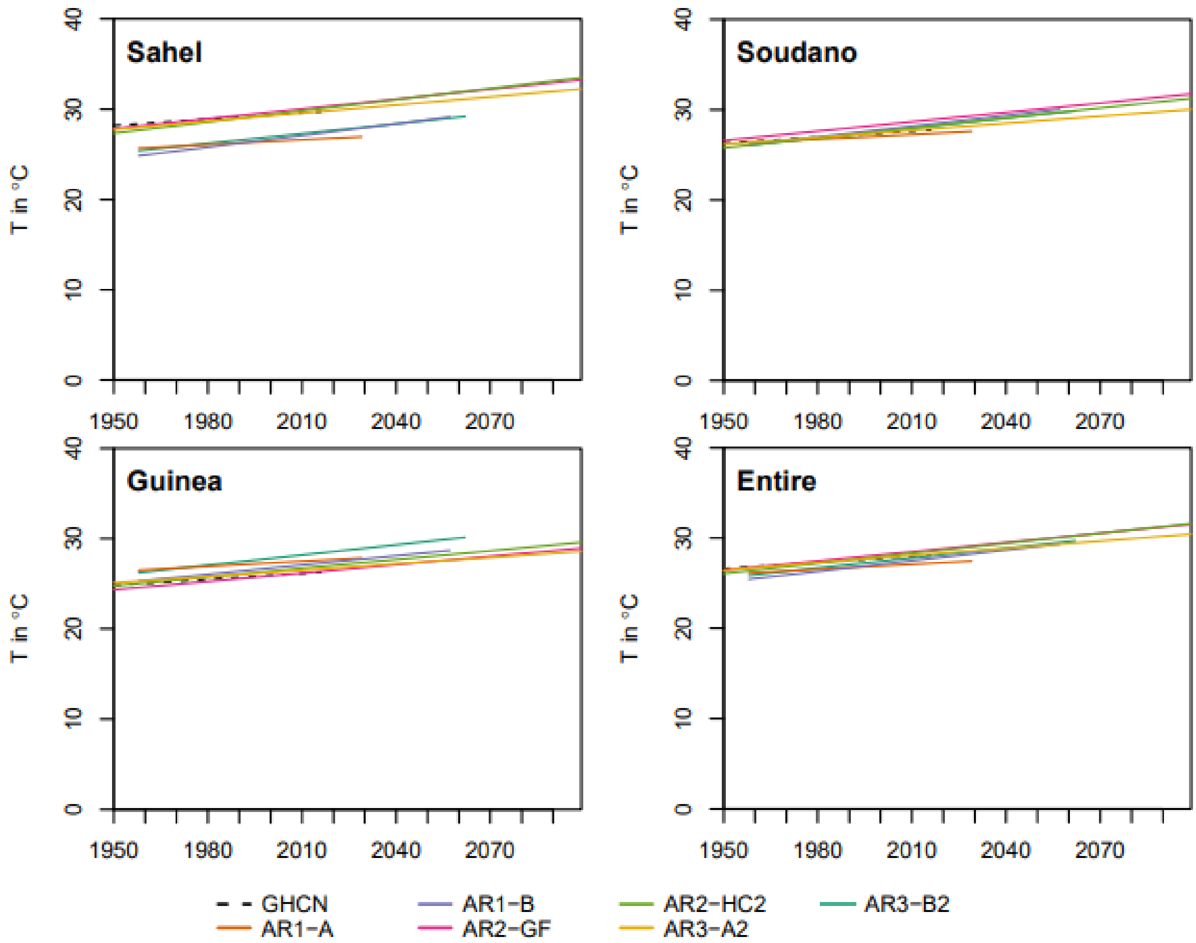

Figure 13. Trends of monthly temperature (°C) averaged over the Sahel, Soudano, Guinea sub-regions and the entire WA for the period 1950–2100 for GHCN-CAMS observation and each of the past projections.

In contrast with the precipitation, projected temperature trends followed reasonably well the trend of the observations. Nevertheless, AR1 and AR2-HC2 were slightly shifted from the observed trend. This result is consistent with earlier results which revealed that temperatures had small biases. The trends of temperatures in the models are probably linked to the climate sensitivities they have considered. It is known that climate sensitivity describes how sensitive the global climate is to a change in the amount of energy reaching the Earth's surface and lower atmosphere (radiative forcing) (Cook 2015). The equilibrium climate sensitivity is defined as the global average surface warming following a doubling of carbon dioxide concentrations from the pre-industrial level of 280 parts per million by volume (ppmv) to 560 ppmv. It is likely to be in the range 2 °C to 4.5 °C with a best estimate of about 3 °C, and is very unlikely to be less than 1.5 °C (Intergovernmental Panel on Climate Change (IPCC) [3].

3.3. Overall Analysis

In general, precipitation biases were higher than those of temperature. From AR1 to AR3 we noticed that there was a better spatial representation of parameters (precipitation, temperature) due to better physical parametrizations and model resolution. From AR2 to AR3, the version of the HC model had been improved. Nevertheless, HC version 2 showed a better performance than HC version 3; this might be linked to the choice of scenarios made in the framework of this research. In AR1, we had the same model but different scenarios. There was not much difference from one scenario to another. Values did not change—substantially. In AR2, two different models were tested. We noticed substantial differences from one model to another.

In AR3, HC3 was used with scenarios A2 and B2. No major differences were observed. Overall, we noticed that for a particular model, the good performance of spatially averaged variables might hide unacceptable performance for some locations. Contrary, the space-averaged low performance of a model might hide the fact that specific locations exhibit very good agreement with observations.

We argue that depending on the intended use of a projection and the target sub-region, country or area of application, there is a need for more criteria in order to facilitate the choice of appropriate models and scenarios. Table 10 illustrates the conclusions drawn from the results of the current work. Within the projections tested in the context of this study, AR2-HC2 seemed to be the best projection.

Table 10. Conclusion on the most appropriate set (model + scenario) depending on the use of projection and area within projections used in the present study.

	Climatology		Annual Cycle		Trends
	Value	Patterns	Season	Value	
Guinea	P: AR2-HC2/T: AR3-B2	P: AR2-HC2&AR3/T: AR2-HC2&AR3	P: AR3/T: AR2-HC2	P: AR2-HC2/T: AR3	P: AR2-GF/T: AR2-HC2
Soudano	P: AR3-A2/T: AR3-A2	P: AR2-HC2&AR3/T: AR2-HC2&AR3	P: AR3/T: AR3	P: AR3-A2/T: AR3-A2	P: AR2-GF/T: AR3-A2
Sahel	P: AR2-HC2/T: AR2-HC2	P: AR2-HC2&AR3/T: AR2-HC2&AR3	P: -/T: -	P: AR2-HC2/T: AR2-HC2	P: AR2-GF/T: AR2-HC2
WA	P: AR2-HC2/T: AR3-A2	P: AR2-HC2&AR3/T: AR2-HC2&AR3	P: AR3/T: AR3	P: AR2-HC2/T: AR3-A2	P: AR2-GF/T: AR3-A2

There are many factors influencing the quality of climate models outputs. When considering the current practice in climate modeling science, we have identified three factors we would want to focus on. They are featured in Figure 14, they are socio-economic scenarios, CO_2 and other GHGs concentration scenarios and climate model uncertainty.

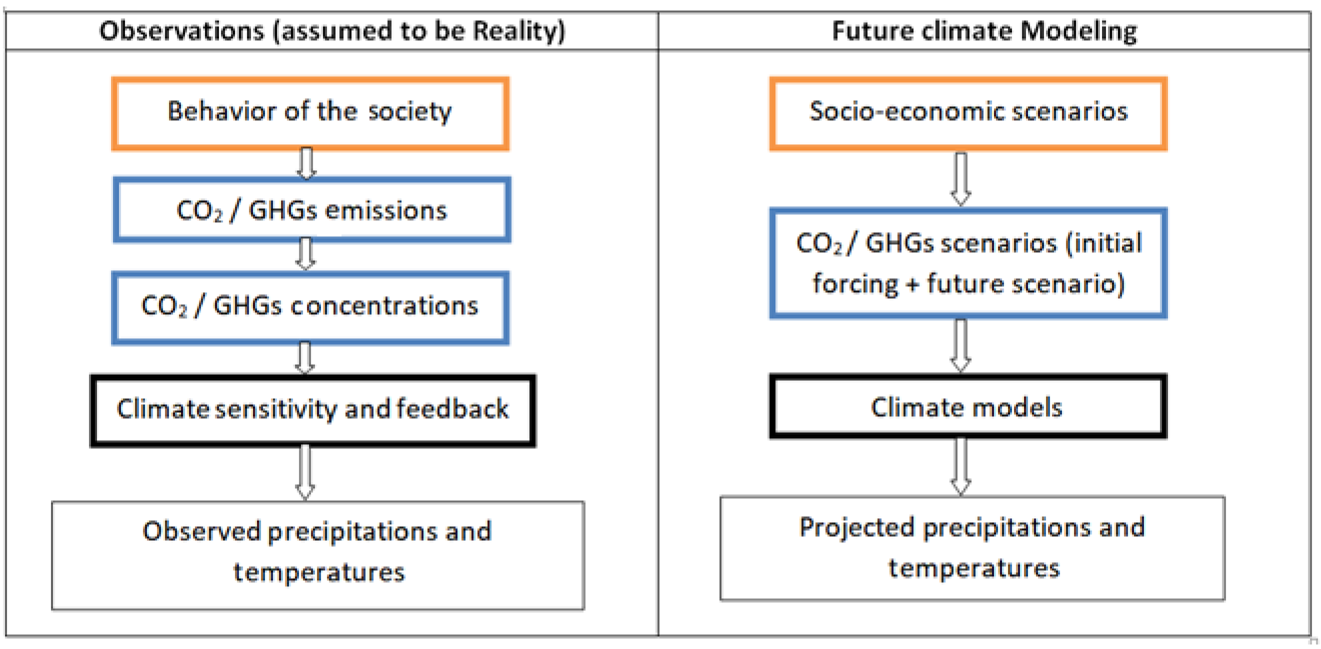

Figure 14. Identification of some important parameters influencing the quality of future climate change projections.

The results obtained from the models combine uncertainties originating from at least these three sources. Here we want to emphasize on the fact that because the task of predicting the impacts of climate change in the future does not depend solely on models or socio-economic/GHGs scenarios, projections carried out in the past should not just be left aside, at least from AR2. In fact, it is noticeable that past works related to the assessment of the impacts of climate change are generally quickly considered outdated in favor of new sets of socio-economic scenarios; GHGs scenarios; and climate models. These past projections might, however, bring some very useful insight for the future. They offer a unique possibility to verify 25 to 30 years (1990 to present) of past climate predictions. Indeed, Johns et al. [57] provided evidence that ability to reproduce the past record does not necessarily guarantee that predictions of future climate will also be accurate. Next, for the near future, past socio-economic scenarios; past GHGs scenarios; and past models could be evaluated over 1990–2016 and then combined with new socio-economic scenarios, GHGs concentrations and models; depending on the sub-region (See Table 11).

Table 11. Example of possible combination between past and new socio-economic scenarios; GHGs scenarios; and past models.

	Past Socio-Economic Scenarios (1)	Past GHGs Scenarios (2)	Past Climate Models (3)	Possibilities for Studies
New socio-economic scenarios (A)		X	X	(A) + (2) + (3)
New GHGs scenarios (B)	X		X	(B) + (1) + (3)
New climate models (C)	X	X		(C) + (1) + (2)
Possibilities for Studies	(1) + (B) + (C)	(2) + (A) + (C)	(3) + (A) + (B)	

4. Concluding Remarks

The research proposed an approach that intended to learn from the recent past in order to be better prepared for the near future and even for longer terms. Although AR1 projections were not good over WA mainly because of physical parametrizations and spatial resolution of the GISS model, AR2 and AR3 provided, to some extent, valuable results. The most recent models (AR2 and AR3) showed very appreciable performance regarding the climatology, the seasonality and trends. We now have a better insight into how past models and scenarios were able to predict various characteristics of today's climate. The results can be further analyzed in order to provide a valuable prediction of precipitation and temperature for the next 20–30 years. In fact, one could select, as explained before, a combination of past and new scenarios and models that suit the most specific locations and purposes. Then, results from these runs could be used as short-term projections. We think this approach can become complementary to current climate impact assessments studies.

The observational products used are derived from ground measurements. Knowing the sparse meteorological network and the lack of long-term measurements in WA, we acknowledge that the historical data might present some quality issues especially for precipitation. This WA context makes the evaluation of climate simulations much more difficult than for other geographical regions of the world [71]. Efforts are being made to improve data collection in WA in both quality and quantity, such as the WASCAL (West African Science Service Centre on Climate Change and Adapted Land Use) Hydrometeorological Observatory in the Sudan Savanna of Burkina Faso and Ghana [82]. Recently, in the year 2020, additional equipment has been acquired and added to this regional network.

Another limitation is the fact that our study made use of only 6 datasets, but more or all datasets available from the IPCC data center can be tested in the future, and further studies could consider ensemble- analysis and include analysis of extremes. Basically, new studies could consider comparison of ensembles while the present study just compared one projection to another. We did not consider bias correction of models' outputs. This is an interesting point to include in next studies. As new climate projections are constantly being developed, we believe an automation of our research methodology could allow us to integrating new observations as time goes by and more recent projections. In fact, we stopped at 2016, but new datasets would go beyond and allow us to work with datasets that span longer than 30 years.

Further studies could be conducted to analyze to what extent some projections might be used for short-term predictions for specific regions and/or applications and what range of uncertainty can be expected. With a larger number of input datasets, certain projections could be identified as more appropriate for a specific region and purpose and then proposed for an ensemble analysis. Such an investigation could be helpful in determining areas where developing models and scenarios will be most profitable.

We expect our study to be useful in complementing classical approaches. Classical approaches do not use previous projections to predict the future. Researchers generally generate new projections based on newer scenarios and models.

We can link the results to various key development sectors. For example, in terms of water resources availability (management purposes), an underestimation of precipitation is preferable to an overestimation, but it would be ideal if the result was as accurate as possible. In the case of preparation against extreme events (floods, droughts), an overestimation of precipitation is desirable for long-term flood risk; and an underestimation is desirable for drought prediction. For agricultural purposes, an analysis of the seasonal cycle, timing, and amplitude of precipitation may be relevant. When related to ecology, some aspects such as the seasonal cycle, timing of precipitation and temperature may be taken into consideration. The elaboration of safety measures in health may be supported by the analysis of seasonal cycles, timing, and values of temperatures; this may be relevant for predicting occurrences of certain vector-borne diseases such as malaria. Other sectors such as farming, fishing, and mobility may also be considered. Further steps could be to use more projection datasets in the analysis and determine to what extent the observed difference is acceptable depending on the sector and the country.

We expect to communicate our research with stakeholders and policy makers in WA via regional and national research and governmental institutions, non-novernmental organizations (NGOs), and possibly the private sector.

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Humanitarian Assistance in G5 Sahel: Social Sustainability Context of Macrologistics Potential

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Abstract: The G5 Sahel works in collaboration with various international organizations and countries, which are responsible for managing logistics activities, financial flows, and technological solutions. Humanitarian assistance holds a critically important role in the region, despite its multiple challenges and limitations in macroeconomic development. This research aimed to examine the macrologistics potential of humanitarian assistance and protection, on both national and transnational levels, in the social sustainability context. Most of the humanitarian emergencies in the region originate from conflicts, food insecurity, and malnutrition. Sahel countries require multiple initiatives to minimize the negative effects of climate change and natural disasters. The state of logistics infrastructure, a wide range of natural and man-made disasters, as well as the macroeconomic situation of the G5 Sahel, result in common problems with the organization of humanitarian logistics from the national and transboundary perspectives. Based on the selected indicators, identified problems of humanitarian assistance and protection in G5 Sahel suggest that the above-mentioned potential of logistics activities requires tightening of transnational collaboration.

Keywords: humanitarian assistance; macrologistics; humanitarian logistics; Sahel; social sustainability

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1. Introduction

Africa is a continent with rich history and unique natural resources, but endless civil conflicts and military uprisings, bad governance, and insecurity are basic obstacles to achieving sustainability and economic advancement [1–5]. The G5 Sahel (G5S) is an example that shows how the five-country members decided to defend their Sahelian space. This collective defense effort originated from the Malian civil war in 2012, which caused unpredictable instability across the Sahelian region. The conflict between the rebelling Tuareg people and the government's army progressively reached such border countries as Niger and Burkina Faso. The operation of different terrorist groups and drug smugglers became the most problematic at that time. The most active terrorist groups in the region remain Boko Haram, the Movement for Unity and Jihad in West Africa (MUJAWA), the Al-Qaeda in the Islamic Maghreb (AQIM), the Islamic State in Greater Sahara (ISGS), Jama'a Nusrat ul-Islam wa al-Muslimin (JNIM), Ansar-Dine, and Al-Mourabitoun [6,7].

Humanitarian assistance is of the highest importance in the G5S, yet, in the context of limitations in security and basic living conditions, humanitarian response must be treated as an operation before lifesaving, which can tackle the catastrophic existence of the most vulnerable inhabitants of Sahel. There are multiple aspects of logistics activities on the national and transnational level with room for improvement, from the perspective of macroeconomic potential in the social sustainability context. Research in the field suggests factors that could ensure the creation of successful, human-friendly, human-oriented, and sustainable places [8] that compose social sustainability, such as safety, justice, health, social inclusion, fair income distribution, active community organizations, cultural aspects, etc. [9]. This social dimension of sustainability fits the humanitarian assistance and protection concept [10]: "*Societies that do not meet basic human needs are expected to receive support through proper national policies and activities*" [10]. Thus, there is a justified need for wide cooperation and concentration of proper entities (such as governments or regional associations) on creating adequate institutions that could cover humanitarian challenges, combat or minimize natural disasters' effects, and include human dignity in economic development as well as ensure resilient infrastructure. This creates social sustainability context that could define and explore national and transnational challenges in humanitarian activities.

Countries and regions in need aim to receive humanitarian assistance and protection, which, in the long term, might transform into development aid [11]. All three types of humanitarian aid (in-kind, technical, and financial) require logistics support provided by different types of stakeholders. A wide range of connections among various HAs makes it challenging to synchronize and coordinate logistics activities on a macro scale. Such a perspective has not been widely discussed in the subject literature and reports from the field. The role of the state in humanitarian aid distribution in African countries has been discussed by Kessler [12], while Marcinkowski [13] discussed the place and role of the regional association in the case of ASEAN. Hence, it is required to explore the macrologistics perspective on the activities undertaken in humanitarian assistance and protection in the social sustainability context. Macrologistics can be understood as the highest-level field of logistics that requires its contribution to at least the level of the national economy [14]. In addition, the infrastructure and policy dimensions of macrologistics direct academic discussion on integration issues, as well as services standardization and the deployment of technologies for particular industries or trade in general [14,15]. A set of developed and proposed measurement tools for national and international logistics activities uphold the macrologistics field of research through supporting sustainable development [14], flows forecasting, analyses of timeliness and cost impact on selective attributes [16,17], as well as designing functional national policies (such as national transportation policy). Macrologistics itself is a key driver for strategic management of the national logistics industry, enabling infrastructural and investment shifts in the economy. In the freight logistics context, it might be also treated as a useful tool for trade-offs analysis and systemic measurement that foster sustainability (both in national policies and SDGs) [18]. Macrologistics can also contribute to reducing freight costs, the acceleration of digital transformation on the national level [19], or increasing environmental awareness, as suggested by Stojanović, Ivetić, and Veličković [20], who assessed Incoterms® rules from the perspective of CO_2 emissions from transport. Nevertheless, macrologistics factors might have an impact on logistics commitments for exporters and importers that can substantially improve the logistics competitiveness of a country [21]. The Logistics Performance Index (LPI) is seen as a useful indicator for assessing national logistics commitments in exports and imports, especially when correlated with Incoterms® rules [21]. A significant cognitive contribution has been made by Havenga, Witthöft, and Simpson [22], who proposed macrologistics instrumentation of national freight logistics costs which addresses the logistics challenges of a country. The authors proved that domestic investments in intermodal solutions can reduce logistics costs and improve domestic and international competitiveness [22]. The macrologistics perspective in the activities undertaken tends to increase economic growth, improve quality of life, protect resources, or shape spatial structures [15], thus fitting the concept of social sustainability.

Including the above-mentioned perspective on the humanitarian assistance and protection, it can be stated that humanitarian logistics can be approached as the coordination of processes involving the flow of aid-oriented goods, services, people, and financials, along with the accompanying information associated with the difficult situations experienced by the society in a particular area, as a result of the occurring temporary or long-term activities they do not influence, to provide them with assistance (and to eliminate or reduce the effects of the occurred events) effectively and efficiently [13]. Therefore, the macrologistics potential in humanitarian assistance and protection in the social sustainability context is defined as an opportunity for national and/or joint transnational humanitarian logistics activities cooperation. Tightening intranational and transnational activities synchronization and coordination is crucial for the effectiveness and efficiency of humanitarian assistance and protection ventures, as well as the successful fostering of social sustainability inclusion. Hence, the state of logistics infrastructure development, effects of disasters on the economy and society, the state of the economy, dependency on the humanitarian and development aid, transparency and quality of authority, expenditures on public health, the education system, and demographics [13,23] are the main determinants of macrologistics' potential measurement in the social sustainability context, both on the national and transnational level.

The adaptation of the macrologistics approach to the humanitarian aid sector with social sustainability agenda aims at:

1. In a theoretical manner through designing macrologistics management tools and instruments to synchronize and coordinate flows among various stakeholders (humanitarian actors—HAs) on a national, transnational, and global scale, as well as the identification of (humanitarian) macrologistics challenges to ensure social sustainability;
2. In a methodological manner through developing a quantitative and/or qualitative method or group of methods to measure macrologistics potential in the humanitarian aid sector in the social sustainability context;
3. In an empirical manner through the establishment of national, transnational, and global partnerships for humanitarian logistics activities' synchronization and coordination, aid distribution professionalization, increasing the effectiveness and efficiency of macrologistics management in the humanitarian aid sector.

The approach to humanitarian logistics presented above spots a research gap in the forms of:

1. Theoretical gap: the deficit of macro perspectives on logistics activities in humanitarian assistance in the social sustainability context, which forms a foundation for the identification of macrologistics' potential;
2. Methodological gap: the need to determine the triangulation of quantitative and qualitative methods to measure that potential;
3. Empirical gap: there is a small number of analyses of transnational cooperation in the field of humanitarian assistance from the common macrologistics and social sustainability perspectives.

The paper aims to examine the macrologistics potential of humanitarian assistance and protection in the social sustainability context on the national and transnational levels. Hence, the article aims to answer the following research question: what is the macrologistics potential of humanitarian assistance and protection in G5S that can ensure social sustainability?

The article is composed of six consecutive sections. Section 1 contains an introduction with general remarks on the analyzed fields, as well as gaps and goal identification. Section 2 refers to the G5 Sahel's landscapes in the social sustainability context of humanitarian assistance. Section 3 contains material and methods characteristics. Section 4 presents the results and discussion, while Section 5 contains conclusions and further research directions. There is also an additional sixth section with Appendix A with indicators used in the analysis.

2. Social Sustainability Context of Humanitarian Assistance—G5 Sahel's Landscapes

2.1. Institutional Landscape of G5 Sahel

The uprising tensions made the Group of G5S countries sign up for official collaboration on 16 February 2014, in Nouakchott (Mauritania), as an intergovernmental agreement of five Sub-Saharan African countries—Mauritania, Mali, Burkina Faso, Niger, and Chad [24,25]. The strategic goal of the initiative was to enhance development and security in the region, with the focus on the most basic challenges in three domains [26,27]:

1. Political, especially problems related to deficiencies in governmental management, law compliance, and human rights protection;
2. Security, related to the increase in terrorist activity in the region, extremist violence and organized crime, and unpredictable threats of climate change usually resulting from deforestation of rural areas or massive migrations of people, causing severe local conflicts;
3. Development, mainly associated with endemic poverty, unrestrained demographic growth, and weak socio-economic flexibility.

To accomplish its daily mission, the G5S works in collaboration with various international organizations and countries responsible for managing logistical, financial, and security assistance. The initiators of the G5S, in the preamble of its establishment convention, put a strong emphasis on achieving an efficient organizational setup that should play an indispensable role in the execution of the agreed tasks. Moreover, the intergovernmental cooperation framework for the G5S is permanently headquartered in Nouakchott (Mauritania).

Logistics activities for humanitarian assistance and protection in the G5S are characterized by dispersed competencies. From the macrologistics perspective, it generates organizational challenges, both strategically and operationally. There are five working organs in G5S responsible for planning and organizing work for the representative members, with a focus on improving peace and sustainability. These organs form a core of logistics coordination and synchronization for humanitarian assistance and protection, due to the low quality of the logistics infrastructure and the geographic dispersion of vulnerable people. The organs of the G5S are [28]:

1. The Conference of the Heads of the State—the supreme institution of G5S playing the role of a decision-making body with the responsibility of setting up its strategic objectives and directions. In the ordinary session, the Conference operates once a year, but in the case of an emergency, extraordinary meetings can be held.
2. The Council of Ministers—an organ that unites representative ministers in charge of economy and development in all five member countries.
3. The Executive Secretariat—this body operates under the umbrella of the Council of Ministers. It is directly responsible for managing strategic interfaces, administrating common fund financing, and providing operational guidance by monitoring and evaluating the agreed strategy.
4. The Defense and Security Committee—this Committee is generally in charge to control the border spaces of the region against all types of terrorist groups and criminal armies.
5. The National Coordination Committees of the G5S Actions—is an interdepartmental structure situated in all five-member states coordinating developed strategies and actions.

There is also one additional organ—The Meeting of Experts—which is not a part of the five organs numbered above. In practice, it regroups various experts in areas of defense and security, governance, and infrastructure from the five member countries of the G5S. On 2 July 2017, with strong international support from France, the Sahelian Group of Five established its military Joint Force (FC-G5) to fight terrorism and other transnational threats. The G5S Defense and Security Committee elaborated on the strategic concept (CONOPS) regarding operations for FC-G5S. It was mandated to [29,30]:

1. Combat terrorism, drug, and human trafficking; to create a secure environment by eradicating the actions of Terrorist Armed Groups and other organized criminal actions; and to restore security and peace by following international law;
2. Contribute to the restoration of state authority and the return of displaced persons and refugees;
3. Facilitate humanitarian operations and the delivery of aid to the affected populations;
4. Contribute to the implementation of development actions in the area of the G5S.

2.2. Humanitarian Landscape of G5 Sahel

In the last 10 years, the rapid deterioration of the Sahel crises created the need for humanitarian aid across the entire region at an unprecedented scale [31,32]. The most important drivers of humanitarian emergencies have been connected to conflicts, food insecurity, and malnutrition. The dramatic consequences of conflicts are related to the armed violence on the civilian population. The region of Burkina Faso and Niger, which borders Mali, has become a place of rising armed attacks that devastated communities and made hundreds of thousands of people flee their homes. Mali and the Lake of Chad Basin have been also recognized as regions with conflict hotspots. In Mali, conflicts are spreading from the north to the central parts of the state. More than 5.1 million people live in areas that are affected by insecurity [33]. Rising terrorist violence caused more people to leave their homes than ever before. At the beginning of 2020, almost 4.5 million people in the region were internally displaced as refugees—one million more than in 2018. At the same time, 2.5 million returnees were coping with restoring their lives [33].

According to the Economic Community of West African States (ECOWAS), the term security means both the traditional state-centric notion of the survival of the state and its protection from external and internal aggression by military means, as well as political, economic, social, and environmental imperatives, in addition to human rights [34]. Insecurity and terrorist attacks have been the main source of disruption in the functioning of the basic social services [35,36]. Due to the lack of security at the beginning of 2020 only in Mali, 1.129 schools, 338.700 children, and 6.774 teachers were affected [37]. It should be pointed out that children remaining out of school education and associated with the armed forces are usually the first victims of different terrorist recruitments and the violations of their rights [38]. UNICEF demands to respect children's rights and avoid their imprisonment or use as a measure of last resort, as it permits only actions within the framework accepted by internationally agreed standards for children [39]. Violence and extremism have caused the rise of an informal economy that functions based on illegal trade and exchange of goods such as trafficked drugs, illegitimate weapons, and black-market sales. Such a situation causes additional tensions and problems leading to the marginalization of new groups of the Sahelian population. An informal economy fuels criminal behavior and opens an easy recruitment path for young people to make ends meet for themselves and their families. It causes opportunities for terrorist organizations because the response of some central governments towards expectations of vulnerable populations is not often sufficient. Leaders of various groups of Islamic terrorism try to use strategies that appear very pervasive and trustworthy to local people [40]. The lack of basic needs and services such as protection, water, sanitation, healthcare, and unresolved conflicts among local communities help armed terrorist groups to spread their power and demands over the region [41]. In addition, the inability of some Sahelian states to maintain border security makes the area additionally completely out of control [26]. In the same sense as humanitarians struggle for bringing assistance and relief to Sahelian's vulnerable inhabitants, governments, especially those associated with the G5S, should recognize their strong sights in fighting terrorism and violence. There is a lot of expectation from the establishment of the G5S Joint Force to tackle the most neuralgic sources of regional instability. However, it seems that military strategies might additionally complicate humanitarian activity, which prefers dialog and coordination between humanitarian and military actors [42–44]. A reasonable form of dialog might be the only chance in persuading local communities and those conflicted ethnic groups that governments play an essential role in protecting their lives. Operating on solid foundations of political trustworthiness and border security in vulnerable areas should be regarded as particularly important, due to the provision of public goods, such as health centers, clean water supplies, education, communication, and information technology infrastructure or sanitation facilities.

Food insecurity and malnutrition are the additional reasons why the Sahel calls for international humanitarian assistance [34,45–48]. The African Sahel belongs to the most vulnerable places in the world at risk of crises and disasters. Eighty percent of its population depends on natural resources for their livelihoods, which rely on farming and herding livestock. The recent climate change proves that the region has been experiencing a rise in average temperature, bigger rainfalls, and more frequent droughts. All those natural phenomena created unprecedented land degradation/desertification, erosion, an increase in biodiversity loss, a decrease in water supply both for people and animals, and decreases in human health and quality of life [26]. The poor rains in the region made the lean seasons begin earlier and last longer. It caused many pastoralists to start migrating with their herds to search for new pastures earlier than usual. Farmers typically used to welcome herders since their cattle and gouts fertilized cultivated croplands. Yet, when they arrive too early and stay too long, intercommunal violence follows as a result. In consequence, not only does meat and milk production decline, but food prices also dramatically increase. Worsening food security and malnutrition seriously affect children. In 2020, over 5.4 million children living in Burkina Faso, Chad, Gambia, Mali, Mauretania, Niger, Nigeria, and Senegal suffered from malnutrition, including 2.4 million in its extreme form [44]. It is expected that malnutrition will remain or even become more serious if effective counteractions are not applied. In addition, the lack of proper healthcare, access to water, sanitation, and other basic social services have a direct impact on the nutritional state of the most vulnerable. The increase in recent epidemics in the region (cholera in Niger and Chad, yellow fever in Mali, measles in Burkina Faso and Chad, and COVID-19 in the entire G5S) also impact vulnerability among the most endangered populations.

It is beyond doubt that improved support by the international community is of unquestionable necessity in the region. Most of the Sahelian governments are overwhelmed. They lack the skills, structures, and technologies to cope with the issues of legitimacy. Almost all the countries are located on huge expanses of land. Chad is bigger than the space of France and Germany together. Large spaces and lack of capacity result in security deficiencies. According to the UN reports on humanitarian crises in the Sahel, the lack of international support would leave the region with the following problems [33,49,50]:

- Over 1.5 million children with severe acute malnutrition (SAM) will not receive the proper treatment they need;
- The absence of water, sanitation, and hygiene services (WASH) will affect the rise of epidemics;
- People living in insecure areas will face sexual and gender-based violence, especially in refugee camps;
- Thirty million people will risk being cut-off from life-saving assistance and experience deep vulnerabilities, half of them being women and girls, who are potential victims of gender-based violence;
- Millions of children staying out of school education, both due to COVID-19 as well as violence, will become easy targets of enslavement and forced recruitment;
- Communities struck by the consequences of climate change will not be able to handle shocks and loss of their livelihoods and increasing conflict risks;
- Inadequate shelter and congested living conditions will make families experience multiple unpredictable risks;
- The COVID-19 health emergency risks causing suffering, aggravating and creating new needs in zones already occupied by conflict and food insecurity.

2.3. Environmental Landscape of G5 Sahel

The G5 Sahel countries are located in semi-arid area. The region stretches between the arid Sahara (desert) to the north and the belt of humid savannas to the south. The semi-arid steps of the region have natural pasture, with low-growing grass and tall-growing herbaceous perennials. The thorny shrubs, acacia, and baobab trees also serve there as other forage for the region's livestock such as camel, pack ox, grazing cattle, and sheep. Primarily, the thorny shrub formed a woodland, but now, the area forms more open land. The terrain has a dangerous tendency to merge into the desert because of overstocking and overfarming. The dry season lasts at least eight months. The wet season occurs in June, July, and August with an average of 100–200 mm rainfall in the north and 500–600 mm in the south. There are also wide areas of pasturage which are watered by the flooding of the Niger and Senegal rivers [51].

The average temperature range is between 21.9 and 36.4 °C, with relatively cooler temperatures in the mountainous areas of northern Chad, Niger, and Mali and the coastal zone of Mauritania. The region has been experiencing the intensity of regular droughts and megadroughts, which always lead to the lack of food security and migrations of people to other parts of the continent. Located in the west-central Sahel, Lake Chad lost approximately 50% of its water over the last 50 years. The basin borders four African countries: Chad, Niger, Nigeria, and Cameroon. In this part of the region, the Lake has always been the main source of water not only for surrounding flora and fauna but also for over 30 million neighboring people. The shrinking of the Lake created several conflicts because those bordering countries argued over the rights to the remaining pieces of the water. In addition, there is an ongoing debate on the main causes of the lake's evaporation. It seems to be obvious that the main reason for this fact is climate change, which is treated as one of the basic challenges to environmental benefits from African agroforestry [52]. However, it should be emphasized that unsustainable usage of the lake both by governments and local communities over the years resulted in the lake to be over-used and not restored. Not only droughts but also irregular heavy rainfalls caused by climatic variations in some years cause severe land degradation. It usually erodes the surface of the fields and housing soils. Furthermore, the water supply and landscape irrigation are complex issues in the Western African Sahel, especially due to performance with surface water and reused wastewater [53]. Very sensitive vegetation of the semi-arid zone and lack of forests constitutes another challenging field for Sahelian space [54], especially when water governance is still being developed [55].

Soils in the region are nutrient-limited and at the risk of degradation. In recent decades activities such as overfarming, overgrazing and soil erosion have caused serious desertification in the region [56]. It is scientifically proven that desertification often occurs as a result of the combination of drought and the lack of proper land management. It usually takes place in hyper-arid, arid, semiarid, or sub-humid areas, dependent on precipitation. The lack of proper environmental governance and abandoning developmental measuring have turned a major part of Sahel into barren land. Ensuring food and agricultural security is far more justified in the region with constant humanitarian challenges. Interestingly, certain types of agricultural households are more exposed to conflicts; therefore, social inclusion is undoubtedly necessary [57]. It should result in livelihood improvement through the development of agroforestry in the context of its climate-smart context to face environmental challenges [58]. The application of the above-mentioned context in technologies led to increased food production, especially in places where food insecurity is one of the main categories of disasters [59]. Nonetheless, climate change has an impact on Sahelian agriculture. The research suggests that, up to 2050, agricultural production will be below 50 kg per capita, which would crop import and regional migration [60].

Increased temperatures, droughts, prolonged dry periods, and increased frequency of extreme climate events cause such risks as rapid land degradation and deforestation; declines in the density of trees/shrubs; loss of key ecosystems, ecosystem services, and biodiversity; reduced water levels, impacting biodiversity and the composition of flora and fauna in aquatic ecosystems; and loss of tourism potential. At present, approximately 50% of Chad, 65% of Mauritania and Mali, 80% of Niger, and most of the northern parts of Burkina Faso are within the Sahara Desert boundaries, which have been expanding into the Sahel at a rate of 1–10 km per a year. The migrating sand covers viable agricultural lands, which has resulted in migrations of people and, consequently, the intensification of resource requirements due to the settlements of more people on the remaining arable land. The intensification of drought events not only becomes a serious threat to drying out the land and water resources, but it is also vital for the survival of many species of flora and fauna, including migratory birds that use the Sahel as a stopover before crossing the Sahara Desert. It is beyond any doubt that the Sahel countries require a wide range of activities to minimize the negative effects of climate change and natural disasters: "*The rapid deterioration of the Sahel crisis has driven humanitarian needs across the region to unprecedented levels. Conflict, climate shocks, chronic vulnerabilities, and endemic poverty are putting millions at risk*" [33]. The International Disaster Database prepared by the Center for Research on the Epidemiology of Disasters—CRED [61] (it is the most accurate and widespread disaster database that relies on official reports) informs that, for the period 1900–2021, there were 336 natural disasters in the G5S. Among them, there were 68 droughts, 13 flash floods, 62 riverine floods, 3 convective storms (hail, severe storm, and tornado), and 116 diseases (such as cholera, meningitis, meningococcal disease, hepatitis E, dengue, Ebola, measles, Rift Valley fever, yellow fever, COVID-19), 9 grasshopper infestations, 13 locust infestations, 1 landslide (in Chad 2019), and 51 other natural disasters (such as acute watery diarrheal syndrome, rats). All of them resulted in over 225 thousand deaths and over 88 million people affected.

The key natural disasters that require humanitarian aid in the G5S in the last 10 years are [33] (some of the data refer to the entire Sahel region, including far North Cameroon, Northeast Nigeria, and Senegal):

- (2012) Drought and food crisis affecting 18 m people, when Mali government was overthrown, that caused the displacement of thousands of people;
- (2017) Famine alert with around 2 m people facing hunger;
- (2019) Flood in Chad affecting 200,000 people;
- (2020) 24 m people in need of humanitarian assistance and protection, 4.3 m people uprooted from homes, food insecurity among 12.3 m people in the lean season; COVID-19 pandemic began, first cases confirmed in all G5S nations;
- (2021) Spread of the COVID-19 pandemic, insufficient or lack of vaccination.

2.4. Macroeconomic Landscape of G5 Sahel

Analysis of the G5S situation requires a broader view of its place, role, and importance in sub-Saharan Africa. The region is not highly developed, so understanding the essence of economic development is conditioned by several indicators and measures. They help to position the region in the structure of the continent and global economy. Figure 1 presents the variability in the gross domestic product (GDP) growth in the period from 2009 to 2025 (the last four years of the analysis are forecasts). Significant annual fluctuations are visible, including a slowdown in GDP growth from 2010 to 2016. The situation related to the COVID-19 pandemic caused a 1.7% decline in GDP in 2020, while the positive rebound in the following years (between 3.8–4.5% increase) is quite optimistic. GDP based on the purchasing–power–parity (PPP) share of the world in the analyzed period is 3.0% [62].

Sub-Saharan Africa is affected by several risks to international supply chains. These risks are of fundamental importance for the economic development of states and indicate areas for improvement in public, private, and non-governmental sectors. The most significant risks include poor infrastructure (almost 36%), corruption (23%), government instability (over 18%), and terrorism (9%) [63].

At the same time, based on the responses of supply chain professionals, the key growth factors of the logistics industry in Africa can be identified. The authors of the "Agility Emerging Markets Logistics Index" asked the study participants the question: "*What do you perceive to be the most significant driver of growth in the emergence of Africa's logistics market?*" [64]. The results show several key factors that are crucial for the logistics sector over the years 2016 to 2018. The respondents chose the following drivers of growth in the African logistics industry [64]:

- Growing middle class and consumer spending (23.9% in 2016, 31.9% in 2018);
- Mineral and resource demand (23.8% for both years);
- Rapid structure development (13.6% and 21.4%, respectively);
- New oil and gas discoveries (22.6%, 8.1%);
- Stronger agricultural demand (11.5%, 9.5%);

- Increased FDI (4.6% and 5.2%, respectively).

Figure 1. GDP growth rate in Sub-Saharan Africa. Source: own elaboration based on [62].

Focusing on the region of sub-Saharan Africa makes it possible to distinguish key sectors of the economy that can facilitate the growth of the logistics industry. The authors of the same report asked the question: "*Which of the following vertical sectors do you believe have the greatest potential for future growth in emerging markets?*" The analysis shows that the most important is [65]:

- Mining (almost 27%);
- Humanitarian aid (almost 18%);
- Agriculture (over 17%).

Thus, the above-presented drivers of growth in the logistics industry across the African continent indirectly correspond to one of the macrologistics factors, namely, the improvement in domestic and international competitiveness. An increased demand, potentially higher supply of fossil fuels, growing income, and consumer spending, as well as investment potential constitute a set of drivers that gives a chance for a strategic improvement in the domestic and transnational logistics industry. However, such improvement could be hampered by the high proportion of humanitarian aid in sub-Saharan Africa. The Inter-Agency Coordinated Appeals suggest that 235 million people worldwide need humanitarian assistance and protection within 2021. The United Nations agencies in cooperation with humanitarian organizations aim to help 160 million people worldwide, which constitutes two-thirds of the global needs. It requires USD 35 billion of funds [66]. In terms of the G5S, four of them require increased humanitarian aid and protection [33]:

- Burkina Faso (3.5 m people in need, 83% targeted, USD 607.4 m requirements);
- Mali (7.1 m people in need, 82% targeted, USD 498 m requirements);
- Niger (3.8 m people in need, 58% targeted, USD 500 m requirements) [66] (Figures for Niger are provisional);
- Chad (5.3 m people in need, 57% targeted).

The COVID-19 pandemic strengthened the need for humanitarian aid and protection in the G5S, increasing the total number of people in need by two-thirds within a year [66].

2.5. Infrastructural Landscape of G5 Sahel

The poor infrastructure tends to impede any kind of logistics operations supporting humanitarian aid and protection [67]. The scale of infrastructure development in G5S nations has been presented in Table 1, which contains country profiles in terms of the logistics infrastructure and humanitarian logistics background that creates a framework for a potential macrologistics assessment.

Table 1. G5S infrastructure from the perspective of humanitarian assistance and protection. Own elaboration based on: [33,61,67].

Country	Infrastructure	Dominant Disaster Types	Seasonal Effects on Transportation
Burkina Faso	- Road transport: 15,000 km of roads (17% paved roads) - 80% of imports and exports are carried by road - Rail transport: decisive for the economy, one main rail line Abidjan–Ouagadougou - Air transport: 12 airports (2 international), but facilities are in disarray - Water transport: no access to the Ocean	- Natural disasters: drought, epidemics, flooding, insect infestation. - Man-made disasters: civil strife, refugees, industrial accident, transport accident.	- Secondary road transport and air transport: not every place is accessible during the rainy season
Chad	- Road transport: 40,000 km of roads - 4800 km of rivers (over 40% accessible all year) - Rail transport: no railway facilities. - Air transport: 53 airports (one international) - Water transport: Chari and Logone rivers.	- Natural disasters: drought, epidemics, extreme temperatures, flooding, storm, insect infestation, high waves, wildfires, high winds, deforestation. - Man-made disasters: civil strife, international conflict, internally displaced people, refugees, landmines, transport accidents.	- Primary and secondary road transport: impassable during the rainy season, some roads are unpaved - Air transport: many secondary airports are inaccessible during the rainy season - River transport: navigable only during the rainy season
Mali	- Road transport: 138,000 km of roads - Rail transport: one main rail line: Dakar–Bamako - Air transport: 22 airports (two international) - Water transport: no access to the Ocean.	- Natural disasters: drought, epidemics, extreme temperatures, flooding, insect infestation. - Man-made disasters: international conflict, internally displaced people, refugees, landmines, industrial accidents, transport accidents.	- Primary road transport: corridors are used all year; however, the rainy season in neighboring countries may cause impassability of roads. Some of the roads are not accessible during the rainy season. - Secondary roads are impassable during the rainy season - Rail transport: railway distortion due to high temperatures - During the dry season: sandstorms, limited visibility - River transport: Niger is navigable during the rainy season
Mauritania	- Road transport: 8900 km of roads (30% paved roads) - Rail transport: one long railway line - Air transport: 10 airports (three international) - Water transport: two Ocean ports and one river port	- Natural disasters: drought, flood, storm, epidemics, insect infestation. - Man-made disasters: transport accidents.	- No available information
Niger	- Road transport: 19,000 km of roads (21% paved roads) - Rail transport. no operational railway - Air transport: 24 airports (3 international) - Water transport: navigable Niger river	- Natural disasters: drought, epidemics, extreme temperatures, flooding, storm, insect infestation, wildfires, and high winds. - Man-made disasters: civil strife, international conflict, internally displaced people, refugees, landmines, transport accidents, industrial accidents.	- Primary road transport is vulnerable during the rainy season (poor drainage and insufficient maintenance) - Secondary roads are impassable during the rainy season - During the rainy season, there may be perturbations (lack of drainage) - Air transport: During the dry season sandstorms, limited visibility - River transport is not suitable for humanitarian cargo

3. Materials and Methods

3.1. Research Procedure

The research follows an idiographic paradigm and inductive reasoning, applying a blend of qualitative and quantitative methods. It starts from specific observation and identification of research needs, searching through tentative observation of patterns that lead to the identification of theoretical contributions [68]. It conducts a case study including all five-member countries of the G5S.

First, the literature review explores insights into transnational humanitarian logistics problems in the analyzed region. To measure the macrologistics potential of humanitarian assistance and protection in the G5S in the social sustainability context, two quantitative methods were applied (see Figure 2). The first one is an indicator analysis, which helped to form a macrologistics perspective (see Appendix A). The second one is the application of multidimensional scaling. This method was adopted based on a two-step procedure to visualize ordering results proposed by Walesiak [69] and on the identification of the impact of individual variables:

- The visualization of objects in two-dimensional space has been performed, and linear ordering has been conducted [69]. It identified distance from the pattern object of G5S member countries in terms of the macrologistics potential in the social sustainability context;
- Multidimensional scaling has been implemented, which allowed for the assessment of the individual variables on the macrologistics potential.

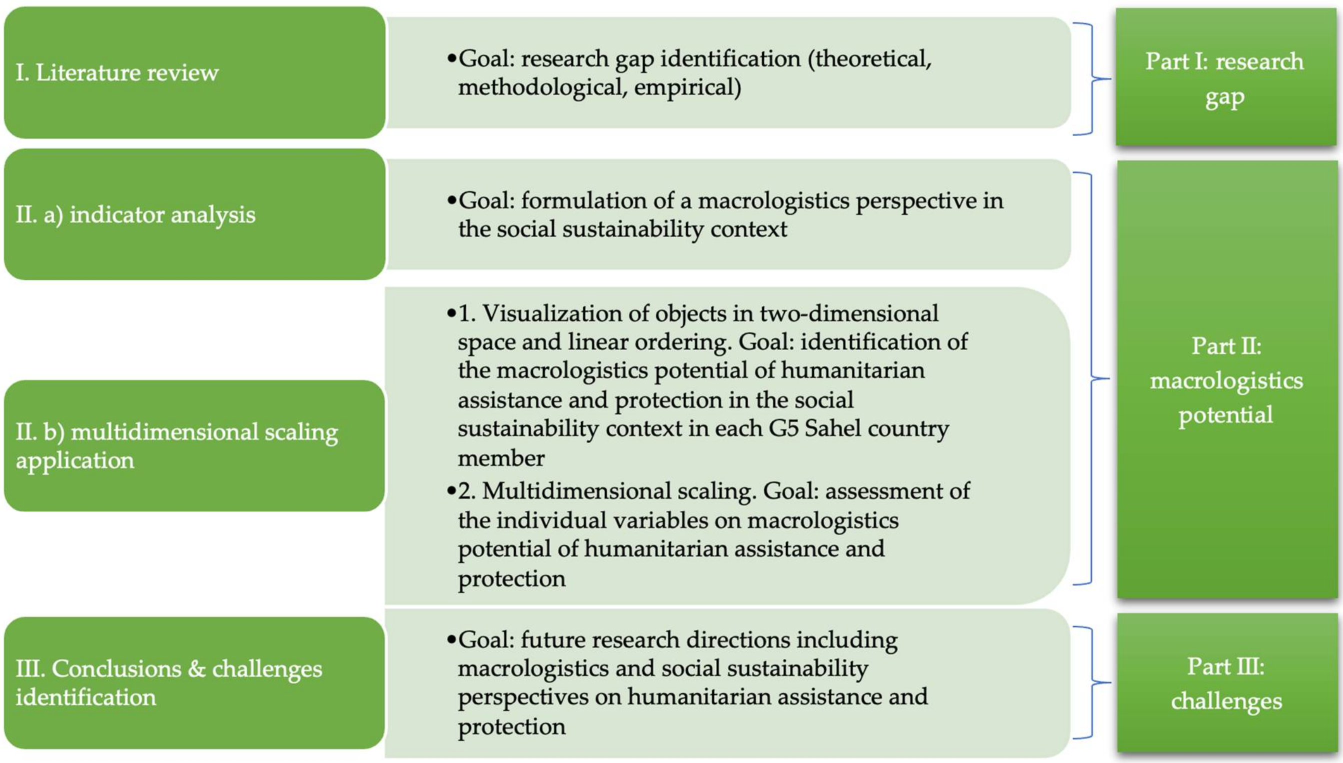

Figure 2. Methodology flowchart. Source: own elaboration.

In general, the visualization of objects and linear ordering depends on a proper choice of the research area to be analyzed, the selection of objects, the list of variables (in this research, it is the first part of the quantitative analysis—indicator analysis), stimulants and destimulants identification (see Appendix A), implementation of pattern object and anti-pattern object, strengthening the measurement scale with GDM2 distance, distance calculation, and multidimensional scaling [69]. The GDM2 distance (as a distance from the pattern) is calculated for ordinal data based on the following equation [69,70]:

$$1 - GDM2_i^+ = \frac{1}{2} + \frac{\sum_{j=1}^{m} \alpha_j a_{iwj} b_{wij} + \sum_{j=1}^{m} \sum_{\substack{l=1 \\ l \neq i,w}}^{n} \alpha_j a_{ilj} b_{wlj}}{2\left[\sum_{j=1}^{m} \sum_{l=1}^{n} \alpha_j a_{ilj}^2 \times \sum_{j=1}^{m} \sum_{l=1}^{n} \alpha_j b_{wlj}^2\right]^{\frac{1}{2}}}$$
$$a_{ipj}(b_{wrj}) = \begin{cases} 1 \; if \; x_{ij} > x_{pj}(x_{wj} > x_{rj}) \\ 0 \; if \; x_{ij} = x_{pj}(x_{wj} = x_{rj}) \\ -1 \; if \; x_{ij} < x_{pj}(x_{wj} < x_{rj}) \end{cases}$$
$$\text{for } p = w, l; \;\; r = i, l \tag{1}$$

where:

- $GDM2_i^+$ is a GDM2 distance from a pattern (anti-pattern) for i;
- $x_{wj} = x_{+j}(x_{wj} = x_{-j})$ for $GDM2_i^+ \left(GDM2_i^-\right)$;
- $x_{+j}(x_{-j})$ coordinate j of a pattern (anti-pattern);
- $i, l = 1, \ldots, n$—object number;
- $j = 1, \ldots, m$—variable number;
- α_j—the weight of the variable ($\alpha_j \in [0;1]$ and $\sum_{j=1}^{m} \alpha_j = 1$ or $\alpha_j \in [0;m]$ and $\sum_{j=1}^{m} \alpha_j = m$).

Nonetheless, the visualization of objects in two-dimensional space with the identified distance from the pattern is normalized based on the distance of d_i^+ from the pattern for i [69]:

$$d_i^+ = \frac{\sqrt{\sum_{j=1}^{2} \left(v_{ij} - v_{+j}\right)^2}}{\sqrt{\sum_{j=1}^{2} \left(v_{+j} - v_{-j}\right)^2}} \tag{2}$$

where:

- $d_i^+ \in [0;1]$
- $\sqrt{\sum_{j=1}^{2} \left(v_{ij} - v_{+j}\right)^2}$—Euclidean distance from the pattern for i;
- $\sqrt{\sum_{j=1}^{2} \left(v_{ij} - v_{+j}\right)^2}$—Euclidean distance of the pattern from the anti-pattern.

The objects of research are ordered according to increasing values of the distance measure (2) and visualized [69]. Then, the final part of the analysis is conducted, which refers to the assessment of the variables chosen for the linear ordering. To conduct a multidimensional scaling, the 'smacof' package for R software was used [71]. In the beginning, all variables were firstly normalized in the range [0, 1] (the normalization occurred in the form: ((x-mean)/max(abs(x-mean))) in 'clusterSim' package designed for R software (R version 4.1.0, The R Foundation for Statistical Computing, Vienna, Austria)). Then, the Generalized Distance Measure was calculated. As with the linear ordering, the ordinal scale (GDM2) has been chosen with equal weights [71]. The visualization of objects, linear ordering, and assessment of individual variables have been performed through the adoption of 'clusterSim' and 'smacof' packages designed for R software.

3.2. The Social Sustainability Context of Macrologistics Potential—The Structure of Indicators

The approach to measuring sustainable development through Sustainable Development Indicators [72,73], World Development Indicators [74], and ratios with measures referring to the humanitarian assistance and protection obtained by ReliefWeb [75] were included in the research. The list of the selected indicators and their importance for macrologistics potential is presented in Appendix A, while in the next paragraphs, the authors have discussed the general justification for group identification. The combination of the idiographic approach with indicator analysis used in the paper creates methodological triangulation, which is "*the combination of methodologies in the study of the same phenomenon*" [76].

The macrologistics perspective on humanitarian assistance and protection in the social sustainability context requires a wide, national (macro) look at the studied issue. Hence, the conducted analysis is a matched modification of the humanitarian logistics composite indicator [13]. Such an update and clarification were required, due to the specific conditions of the G5S: low level of economic development, poor infrastructure (especially in transportation), the number and intensity of chronic disasters and humanitarian crises, as well as early stage of joint, transnational activities. Having in mind those limitations, the following groups of indicators to measure the macrologistics potential of humanitarian assistance, reflected in the level of social sustainability, were identified: transportation, economic development, humanitarian and development aid, transparency and quality of authorities, public health, education, and demographics (see Appendix A). The authors of the paper would like to remark on the substantial challenge and perspective included in the analysis. The focus on the humanitarian assistance context with the social sustainability inclusion results in the specified approach of macrologistics understanding. As stated in Section 1, we have focused on the analysis of its potential, which is defined as an opportunity for national and/or joint transnational humanitarian logistics activities cooperation. The logistics costs analysis has been excluded from the macrologistics potential identification, as it should include in-depth freight flows analysis that, in the humanitarian context, can be analyzed in the further steps of G5S integration. Another challenging issue refers to the domestic and international competitiveness that, in humanitarian assistance activities, is not recognized as a crucial factor.

The transportation group of indicators constitutes a prerequisite for logistics cooperation in counteracting, minimizing, and eliminating disasters and crises' consequences. The humanitarian point of view is focused on the critical infrastructure, which affects the success of execution [77]. Therefore, it proves the predisposition of states in humanitarian assistance and protection activities, with a focus on difficulties in providing aid, such as seasonal effects on the type of transport or mortality in road traffic. The Logistics Performance Index [74] used in that group is a classical type of macrologistics indicator which assesses a country's logistics. The next group of indicators, economic development, is focused on macroeconomic determinants for which logistics is a balancing tool [78]. In a humanitarian context, the cooperation of entities involved in logistics operations results in wide economic cooperation [12]. The lack of financial resources inhibits the country's development and, therefore, the creation of crisis management plans [79]. Hence, official development assistance (ODA) plays an important role in the development of humanitarian logistics [12]. Countries with strong public administrations are better prepared to implement effective solutions [80], though transparency and quality of authority groups of indicators are included in the analysis. Nonetheless, the public sector is fundamental in aid provision, especially in the field of public health [81], which constitutes another group of indicators. The share of physicians, nurses, and midwives informs about the possibilities for efficiently dealing with the negative effects of disasters and humanitarian crises. Additionally, the shares of people using at least basic drinking water and sanitation services, adolescent fertility rate and share of mortalities from various diseases, unsafe water, sanitation, lack of hygiene, or ambient air pollution indicate the challenges for HAs and social sustainability on the national level. A similar situation is with an education system that is crucial for the long-term stability of the country's security and development [82]. Finally, the demographics group represents one of the key determinants of human development. Researchers suggest that the urbanization level impacts the number of disaster reports [80] which may be crucial in low-income countries, such as in the G5S. In addition, internal migrations in lower classes tend to propel lower-standard constructions, which increase the vulnerability to hazards [79].

4. Results and Discussion

4.1. Linear Ordering of Macrologistics Potential in Humanitarian Assistance and Protection

Based on the selected indicators, the authors focused on ordering G5S states in terms of macrologistics potential in the field of humanitarian assistance and protection in the social sustainability context. The number of indicators obtained encouraged the authors to analyze the distance from the pattern object (two-step procedure proposed by Walesiak [69]). Therefore, the 'clusterSim' package designed for R software has been adopted [83]. The data_patternGDM2 has been used to group G5S nations from the best to worst as a distance from the pattern. Its wide range of ordinal and nominal variables included in the analysis (see Appendix A) allowed for defining optimal values. The results are presented in Figure 3.

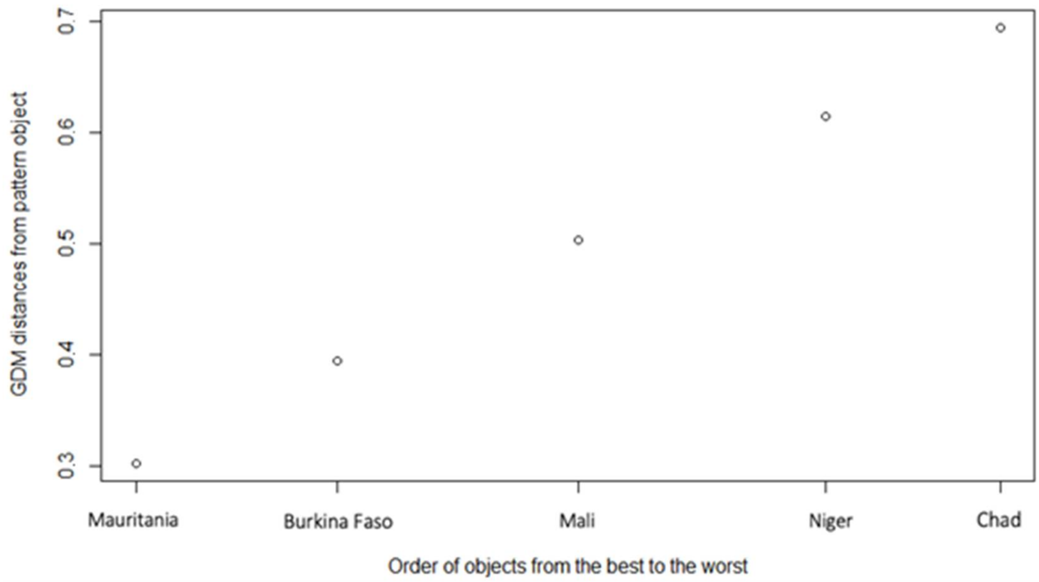

Figure 3. Linear ordering: G5S nations' distances from pattern object. Source: own elaboration with RStudio software.

Based on the analysis presented above, we can observe that three clusters define the level of macrologistics potential (The authors are fully aware that clusters should consist of a wider number of observations. However, even a small number of them may constitute a set of similar objects which can be grouped together and then analyzed. This was the idea behind the analysis). Cluster 1, which is closest to the reference site, includes Mauritania. It is the only country in this regional association not affected by cyclical humanitarian crises. Statistical data and reports do not indicate the occurrence of people in need, and also, in terms of infrastructure, the country is better prepared to cope with the negative effects of disasters, e.g., through wide access to logistics infrastructure (including maritime infrastructure). Cluster 2 (Burkina Faso, Mali) shows an average level of macrologistics potential from the perspective of the entire regional association. Nevertheless, it highlights certain issues that affect the effectiveness of humanitarian logistics operations in the tactical and operational dimensions. At the same time, the situation is hampered by the impact of dry and rainy seasons on the possibility of fully using the logistic infrastructure of each country. Cluster 3 provides direct information on the very low level of macrologistics potential of both member states: Niger and Chad. The number of people in need, the low level of logistics infrastructure, the susceptibility to the negative impact of the dry and rainy season on its quality, and issues related to the economy, society, public health, and the quality of public institutions directly complicate the implementation of humanitarian logistics operations and impede social sustainability. Identified clusters constitute a set of different potentials for ensuring macrologistics development. Each cluster requires specific macrologistics instruments that might enable reducing logistics costs and improving domestic and international competitiveness. Nonetheless, such instruments cannot be detached from the humanitarian challenges affecting G5S.

4.2. Multidimensional Scaling of Macrologistics Potential in Humanitarian Assistance and Protection

The analysis carried out above was supplemented with multidimensional scaling, which allowed for the identification of the impact of individual variables on the position of a given country in terms of its macrologistics potential in the area of humanitarian assistance and protection in the social sustainability context. The authors wanted to emphasize the negative role of particular variables on the above-mentioned macrologistics potential, related to technological limitations (The focus on the negative role of the variables is a result of the negative impact of disasters on communities and the economy. This impact is the modus operandi for humanitarian assistance and protection activities. Nonetheless, the positive role of variables may be also identified and is presented in the summary of multidimensional scaling for each G5S nation). The results are presented in Figure 4, while correlation coefficients are presented in Table 2. The number of iterations is 19.

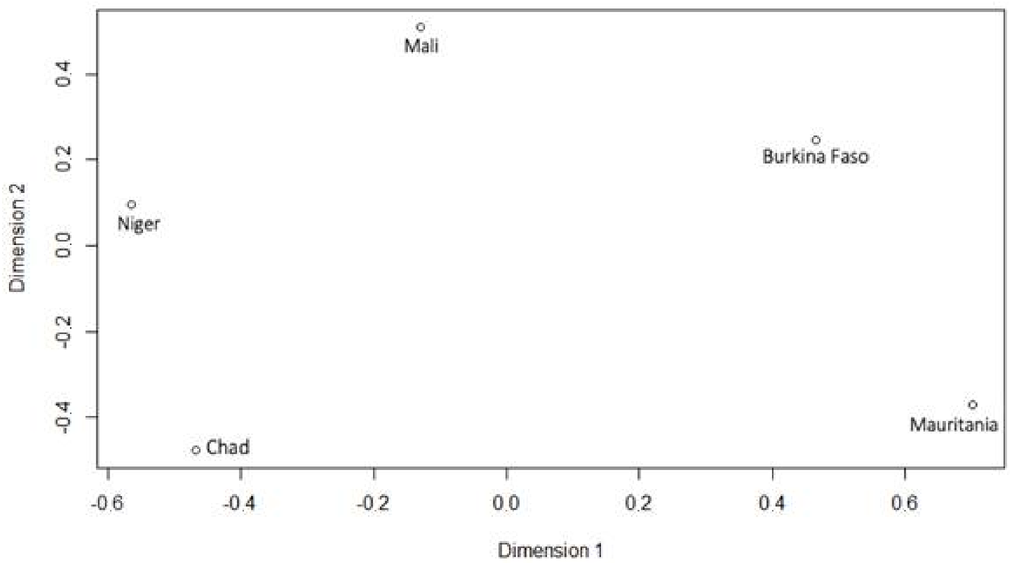

Figure 4. Multidimensional scaling of G5S nations. Source: own elaboration with RStudio software.

Table 2. Correlation coefficients. Source: own elaboration with RStudio software.

Variable Identifier *	Dimension 1	Dimension 2	Variable Identifier *	Dimension 1	Dimension 2
TRANSP1	−0.95287	0.265976	AUTHORIT4	0.442082	0.806737
TRANSP2	−0.12912	0.683301	AUTHORIT5	0.528504	0.436117
TRANSP3	−0.86975	−0.25072	AUTHORIT6	0.388185	0.837952
TRANSP4	−0.94644	0.139479	PUBHEAL1	−0.95637	0.326654
TRANSP5	0.110341	−0.13455	PUBHEAL2	0.788549	0.002244
TRANSP6	0.411617	0.365841	PUBHEAL3	0.977298	−0.05399
ECODEV1	0.775331	−0.49521	PUBHEAL4	−0.48927	0.3574
ECODEV2	0.854162	−0.45683	PUBHEAL5	−0.86616	−0.1921
ECODEV3	−0.82718	0.359972	PUBHEAL6	−0.89353	−0.21968
ECODEV4	0.768194	0.094206	PUBHEAL7	0.401033	0.418724
HUMAID1	−0.51303	0.862059	PUBHEAL8	0.675396	0.141341
HUMAID2	−0.75408	0.277483	EDUCAT1	−0.95426	0.170469
HUMAID3	−0.56917	0.503547	EDUCAT2	−0.66903	0.565477

Table 2. *Cont.*

Variable Identifier *	Dimension 1	Dimension 2	Variable Identifier *	Dimension 1	Dimension 2
HUMAID4	0.153398	0.462217	EDUCAT3	0.854729	0.049722
HUMAID5	−0.76851	−0.52889	DEMOGRA1	−0.07014	−0.96964
AUTHORIT1	0.375631	0.722487	DEMOGRA2	0.880992	0.127152
AUTHORIT2	0.68733	0.197955	DEMOGRA3	0.760165	−0.02007
AUTHORIT3	0.59479	−0.70934	DEMOGRA4	0.886318	0.208495

* See Appendix A for variables identification.

The following variables are associated with the first dimension: TRANSP1, TRANSP3 TRANSP4, ECODEV1, ECODEV2, ECODEV3, ECODEV4, HUMAID2, HUMAID3, HUMAID5, AUTHORIT2, AUTHORIT3, AUTHORIT5, PUBHEAL1, PUBHEAL2, PUBHEAL3, PUBHEAL5, PUBHEAL6, PUBHEAL8, EDUCAT1, EDUCAT2, EDUCAT3, DEMOGRA2, DEMOGRA3, and DEMOGRA4 (see Appendix A for variable identification). Those variables represent all the variables indicated in the indicators' groups of macrologistics potential for humanitarian assistance and protection in the social sustainability context. The higher the value of a given variable, the higher the impact on the macrologistics potential. Thus, the seasonal effects on road, air, and water transport have a huge negative impact on humanitarian aid distribution in the G5S. The same situation occurs with a low level of foreign direct investments (FDIs), increasing the number of people in need, as well as refugees and asylum-seekers. The negative impact on macrologistics potential also include those variables referring to the public health group, such as adolescent fertility rate, mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene, household, and ambient air pollution. In addition, the negative role is also visible in the field of high levels of adolescents out of school. The second dimension refers to the variables: TRANSP2, HUMAID1, HUMAID3, HUMAID5, AUTHORIT1, AUTHORIT3, AUTHORIT4, AUTHORIT6, EDUCAT2, and DEMOGRA1 (see Appendix A for variable identification). The low levels of these variables suggest the high negative impact on macrologistics potential of humanitarian assistance and protection in a social sustainability context. Among such variables, the following may be distinguished: people living in slums, as well as political instability and the existence of violence and terrorism.

The above-presented positive and negative impacts of particular variables on macrologistics potential in the humanitarian assistance context create interesting cognitive and applicative fields for in-depth analyses contributing to improving domestic and international competitiveness. It constitutes a quantitative framework explaining ontologically the dependencies of the humanitarian context in the logistics industry. However, as in the linear ordering part of the research, the general conclusions for each G5S nation may be identified:

- Mauritania received the highest positive impact of variables qualified in Dimension 1 while a negative impact on those qualified in Dimension 2.
- Burkina Faso received a positive impact of variables qualified in both Dimensions.
- Mali received a negative impact on variables qualified in Dimension 1 but a positive impact on those qualified in Dimension 2.
- Niger received the highest negative impact of variables qualified in Dimension 1 but a positive impact on those qualified in Dimension 2.
- Chad received a negative impact of variables qualified in both Dimensions.

5. Conclusions

All aid interventions should be based on the coherence between emergency and development, stopping the state of insecurity and fostering social sustainability. The G5S includes five Sub-Saharan African countries, which have been recognized among the world's most vulnerable countries and those most exposed to crises and disasters. The effects of unpredictable weather patterns, land degradation, food insecurity, and malnutrition are over any comprehensible norms. Additionally, the unstable political situation and uprising terrorist activity have put the region in a hopeless situation. The decline in governance increases distrust among people towards the authorities. The needs spread across all the segments of the Sahelian existence and cannot be reduced only to people's access to basic social services and security; they should also consider humanitarians' decreased access to affected communities. Maintaining restrictive security regulations makes humanitarian assistance suspicious in many cases. However, the government of Mali tries to be more flexible toward transnational humanitarian organizations, unlike Niger or Burkina Faso, where all humanitarian regulations are more restricted. However, France, whose willingness to engage in Mali is beyond any doubt, keeps an evident refusal in contact with non-state army groups (NSAGs), which confines humanitarian negotiation proposals.

The infrastructural underdevelopment of the G5S is visible in the low shares of paved roads, the small number of rail lines, air transport facilities in disarray, two ocean ports, and a few big river ports. It is insufficient for effective and efficient distribution of humanitarian aid, as well as ensuring social sustainability. The seasonal effects on transportation in each country intensify the difficulties in providing humanitarian assistance and protection. Regional cooperation is undoubtedly one of the key factors of effective humanitarian logistics operations on a transnational level. The political nature of such collective co-existence tends to improve security and is related to development constituting a social sustainable perspective. A widespread humanitarian need in the G5S that results from conflicts, food insecurity, and malnutrition determined the regional cooperation of nations. The idea of the "survival of the state and its protection" ceased to be the only function of a given state. Climate change, desertification, rising armed attacks, and food and water insecurity created a need for unprecedented humanitarian assistance to reduce and/or eliminate malnutrition, illegal trade and exchanges of goods, internal/external migration, and secure people's right to dignity and safety. Access to services such as protection, water, sanitation, or healthcare is of utmost importance for G5S citizens. For these reasons, humanitarian aid is one of the main vertical sectors with the greatest potential for future market growth and social sustainability development in sub-Saharan Africa.

Thus, from the perspective of the research question, it can be stated that the G5S is in the first stage of joint transnational humanitarian logistics activities that could enable social sustainability. The quantitative analysis underlined the three different levels of macrologistics potential of the G5S nations in the field of humanitarian assistance and protection in the social sustainability context. The highest level of readiness for joint tasks and leadership in the regional association is presented by Mauritania. This country should be a shepherd and transnational coordinator of humanitarian logistics activities that could manage domestic and transnational logistics activities. However, additional in-depth logistics costs analysis should be conducted to assess Mauritania's ability to reduce entire the G5S's logistics costs. Although domestic or international competitiveness is not a key issue in humanitarian assistance, such identification in the humanitarian context might lead to greater preparation for activities in the regional association. In addition, attention should be paid to Niger and Chad, who require wider international assistance in providing humanitarian and development aid. Burkina Faso and Mali, which are better assessed in macrologistics potential, cannot be left alone in dealing with chronic natural disasters and military conflicts or in dealing with domestic logistics costs, especially while having underdeveloped infrastructure resulting in low competitiveness level of each country. When it comes to the readiness of the humanitarian assistance to enhance its logistic capabilities with social sustainability, there is still room for improvement and further pilot implementations. Identified problems of humanitarian assistance and protection in the G5S from the perspective of macrologistics suggest that the above-mentioned potential of logistics activities require tightening transnational collaboration.

In conclusion, the research gaps in the macrologistics approach to humanitarian logistics in the social sustainability context identified in Section 1 have been addressed as:

- A theoretical gap in defining the macrologistics potential in humanitarian assistance and protection in the social sustainability context, as well as identifying humanitarian macrologistics challenges;
- A methodological gap in the combined use of quantitative and qualitative methods to measure that potential;
- An empirical gap in an analysis of transnational cooperation in the G5S in the field of humanitarian assistance and protection from the macrologistics perspective.

The research conducted by the authors therefore gives valuable input into existing research of macrologistics potential in the humanitarian context enabling for assessment of national and joint transnational humanitarian logistics activities cooperation. Such a perspective lacks logistics cost analysis, and in consequence, the assessment of domestic and international competitiveness. It requires additional research to be performed in the field of humanitarian freight flow analysis. Assessing externality costs [18] and providing a systemic view of the G5S freight logistics landscape, as proposed by Havenga, Witthöft, and Simpson [22], is a desirable direction for the further in-depth analysis of G5S international logistics competitiveness in the humanitarian context. Consequently, a few other limitations of the paper can be identified. The analogous research of macrologistics potential should be conducted in other transnational groups (regions or regional associations) to determine and delimitate the stages of joint transnational humanitarian logistics activities to ensure social sustainability. Such research could help to identify a broad set of utilitarian indicators that are independent of the local conditions (e.g., in the G5S, the seasonal effects on the type of transport) but could foster social sustainability. In addition, it should be added that the geopolitical situation related to the war in Ukraine will have a meaningful influence on humanitarian logistics among others in the African Sahel. At the beginning of 2022, the Malian authorities, remaining in an uneasy and ongoing conflict with France, and more broadly with the EU, decided to leave the G5 Sahel and its anti-jihadist force, accusing the organization of being too regulated by "the outside world". After the announced departure of Mali from the G5 Sahel, Russia took advantage of offering private security from Wagner's group. Russia's military partnership with Mali's army causes very difficult conditions for European cooperation, not only in the area of military defense but also in humanitarian missions. This additionally opens a new area of research.

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Appendix A

Table A1. The indicators in the field of macrologistics potential of humanitarian assistance and protection in the social sustainability context chosen for analysis. Source: own elaboration based on: [74,75].

Name of the Group	Indicator [Unit]	Importance of Macrologistics Potential in the Social Sustainability Context	Variable Identifier	Type *	Variable Scale *
Transportation	Seasonal effects on road transport [0–3]	Inaccessibility of main roads may affect the effective distribution of humanitarian aid. Therefore, the variable informs about the potential possibility of effective humanitarian logistics operations. Zero means that there are no problems with this type of transport or such transport does not exist. One means that there are some minor problems with infrastructure during the rainy season or the dry season. Two means that secondary roads and airports are inaccessible, while river transport is navigable only during the rainy season. Three means that main roads, airports, and river and rail transport are not accessible during the rainy season.	TRANSP1	n	n
	Seasonal effects on rail transport [0–3]		TRANSP2	n	n
	Seasonal effects on air transport [0–3]		TRANSP3	n	n
	Seasonal effects on water transport [0–3]		TRANSP4	n	n
	Mortality caused by road traffic injury [per 100,000 people]	Mortality caused by road traffic injury is estimated at road traffic fatal injury deaths per 100,000 population.	TRANSP5	d	m
	Logistics performance index [1–5]	Logistics Performance Index overall score reflects perceptions of a country's logistics based on the efficiency of the customs clearance process, quality of trade- and transport-related infrastructure, ease of arranging competitively priced shipments, quality of logistics services, ability to track and trace consignments, and frequency with which shipments reach the consignee within the scheduled time. The index ranges from 1 to 5, with a higher score representing better performance.	TRANSP6	s	n
Economic development	GDP per capita [constant 2010 USD]	GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. Data are in constant 2010 U.S. dollars.	ECODEV1	s	m
	GNI per capita [constant 2010 USD]	GNI per capita is the gross national income divided by the midyear population. GNI (formerly GNP) is the sum of value added by all resident producers plus any product taxes (fewer subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad. Data are in constant 2010 U.S. dollars.	ECODEV2	s	m
	Foreign direct investment, net inflows [% of GDP]	Foreign direct investments are the net inflows of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor. It is the sum of equity capital, reinvestment of earnings, other long-term capital, and short-term capital, as shown in the balance of payments. This series shows net inflows (new investment inflows less disinvestment) in the reporting economy from foreign investors and is divided by GDP.	ECODEV3	s	m
	Military expenditure [% of GDP]	Military expenditure data from SIPRI are derived from the NATO definition, which includes all current and capital expenditures on the armed forces, including peacekeeping forces; defense ministries and other government agencies engaged in defense projects; paramilitary forces, if these are judged to be trained and equipped for military operations; and military space activities.	ECODEV4	s	m

Table A1. *Cont.*

Name of the Group	Indicator [Unit]	Importance of Macrologistics Potential in the Social Sustainability Context	Variable Identifier	Type *	Variable Scale *
Humanitarian and development aid	Net official development assistance and official aid received [current US$]	Net official development assistance (ODA) consists of disbursements of loans made on concessional terms (net of repayments of principal) and grants by official agencies of the members of the Development Assistance Committee (DAC), by multilateral institutions, and by non-DAC countries to promote economic development and welfare in countries and territories in the DAC list of ODA recipients.	HUMAID1	d	m
	People in need [number]	The total number of people who need humanitarian assistance and protection informs about the scale of logistics operations that have to be conducted to achieve society's expectations. The most appropriate understanding fits the internally displaced persons. They are defined according to the 1998 Guiding Principles as people or groups of people who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of armed conflict, or to avoid the effects of armed conflict, situations of generalized violence, violations of human rights, or natural or human-made disasters and who have not crossed an international border.	HUMAID2	d	n
	People targeted for assistance [number]		HUMAID3	d	n
	Internally displaced persons [number]		HUMAID4	d	n
	Refugees and asylum-seekers [number]		HUMAID5	d	n
Transparency and quality of authorities	Control of corruption [−2.5–2.5]	Control of Corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT1	s	m
	Government effectiveness [−2.5–2.5]	Government Effectiveness captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT2	d	m
	Political stability and absence of violence/terrorism [−2.5–2.5]	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT3	s	m
	Regulatory quality [−2.5–2.5]	Regulatory Quality captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT4	s	n
	Rule of law [−2.5–2.5]	Rule of Law captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular, the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT5	s	m
	Voice and accountability [−2.5–2.5]	Voice and Accountability capture perceptions of the extent to which a country's citizens can participate in selecting their government, as well as freedom of expression, freedom of association, and free media. An estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	AUTHORIT6	s	m

Table A1. *Cont.*

Name of the Group	Indicator [Unit]	Importance of Macrologistics Potential in the Social Sustainability Context	Variable Identifier	Type *	Variable Scale *
Public health	Adolescent fertility rate [births per 1000 women ages 15–19]	The adolescent fertility rate is the number of births per 1000 women ages 15–19.	PUBHEAL1	d	m
	Physicians [per 1000 people]	Physicians include generalists and specialist medical practitioners.	PUBHEAL2	s	m
	Nurses and midwives [per 1000 people]	Nurses and midwives include professional nurses, professional midwives, auxiliary nurses, auxiliary midwives, enrolled nurses, enrolled midwives, and other associated personnel, such as dental nurses and primary care nurses.	PUBHEAL3	s	m
	Mortality from CVD, cancer, diabetes, or CRD between exact ages 30 and 70 [%]	Mortality from CVD, cancer, diabetes, or CRD is the percent of 30-year-old people who would die before their 70th birthday from any cardiovascular disease, cancer, diabetes, or chronic respiratory disease, assuming that s/he would experience current mortality rates at every age and s/he would not die from any other cause of death (e.g., injuries or HIV/AIDS).	PUBHEAL4	d	m
	Mortality rate attributed to unsafe water, unsafe sanitation, and lack of hygiene [per 100,000 population]	The mortality rate attributed to unsafe water, unsafe sanitation, and lack of hygiene is deaths attributable to unsafe water, sanitation, and hygiene focusing on inadequate WASH services per 100,000 population. Death rates are calculated by dividing the number of deaths by the total population. In this estimate, only the impact of diarrheal diseases, intestinal nematode infections, and protein-energy malnutrition are taken into account.	PUBHEAL5	d	m
	Mortality rate attributed to household and ambient air pollution, age-standardized [per 100,000 population]	The mortality rate attributed to household and ambient air pollution is the number of deaths attributable to the joint effects of household and ambient air pollution in a year per 100,000 population. The rates are age-standardized. The following diseases are taken into account: acute respiratory infections (estimated for all ages); cerebrovascular diseases in adults (estimated above 25 years); ischemic heart diseases in adults (estimated above 25 years); chronic obstructive pulmonary disease in adults (estimated above 25 years); and lung cancer in adults (estimated above 25 years).	PUBHEAL6	d	m
	People using at least basic drinking water services [% of the population]	The percentage of people using at least basic water services. This indicator encompasses both people using basic water services, as well as those using safely managed water services. Basic drinking water services are defined as drinking water from an improved source, provided collection time is not more than 30 min for a round trip. Improved water sources include piped water, boreholes or tubewells, protected dug wells, protected springs, and packaged or delivered water.	PUBHEAL7	s	m
	People using at least basic sanitation services [% of the population]	The percentage of people using at least basic sanitation services, that is, improved sanitation facilities that are not shared with other households. This indicator encompasses both people using basic sanitation services as well as those using safely managed sanitation services. Improved sanitation facilities include flush/pour flush to piped sewer systems, septic tanks, or pit latrines; ventilated improved pit latrines, compositing toilets, or pit latrines with slabs.	PUBHEAL8	s	m

Table A1. *Cont.*

Name of the Group	Indicator [Unit]	Importance of Macrologistics Potential in the Social Sustainability Context	Variable Identifier	Type *	Variable Scale *
Education	Adolescents out of school [% of lower secondary school age]	Adolescents out of school are the percentage of lower secondary school age adolescents who are not enrolled in school.	EDUCAT1	d	m
	Children out of school [% of primary school age]	Children out of school are the percentage of primary-school-age children who are not enrolled in primary or secondary school. Children in the official primary age group that are in preprimary education should be considered out of school.	EDUCAT2	s	m
	Literacy rate, adult total [% of people ages 15 and above]	The adult literacy rate is the percentage of people ages 15 and above who can both read and write with an understanding a short simple statement about their everyday life.	EDUCAT3	s	m
Demographics	Population living in slums [% of the urban population]	Population living in slums is the proportion of the urban population living in slum households. A slum household is defined as a group of individuals living under the same roof lacking one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area, housing durability, and security of tenure, as adopted in the Millennium Development Goal Target 7.D. The successor, the Sustainable Development Goal 11.1.1, considers inadequate housing (housing affordability) to complement the above definition of slums/informal settlements.	DEMOGRA1	d	m
	Unemployment, total [% of the total labor force: modeled ILO estimate]	Unemployment refers to the share of the labor force that is without work but available for and seeking employment.	DEMOGRA2	d	m
	Urban population [% of the total population]	Urban population refers to people living in urban areas as defined by national statistical offices. The data are collected and smoothed by United Nations Population Division.	DEMOGRA3	s	m
	Human capital index (HCI) [0,1]	The HCI calculates the contributions of health and education to worker productivity. The final index score ranges from zero to one and measures the productivity as a future worker of a child born today relative to the benchmark of full health and complete education.	DEMOGRA4	s	m

* Legend: m—interval scale. n—ordinal and nominal scale. nm—nominant. s—stimulant. d—dis-stimulant.

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sustainability

Article

Water Sustainability in the Context of Global Warming: A Bibliometric Analysis

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Abstract: Sustainable water use is becoming a key problem in the present time, since global warming is having a strong impact on usable water resources. This study aims to provide a systematic bibliometric analysis on water sustainability in the context of global warming, in order to provide a clearer view on the existing research trends and to find eventual gaps in research that can be exploited in the future. The selection and analysis of the most relevant papers discussing the chosen topic pointed out a strong increase in research in the last period, dominated by US scientists and research entities, with researchers focusing on either the present impact of global warning on water sustainability and its effects on water supply and ecosystem functioning, or on problem solving and creating a framework for water sustainability in the context of global warming, or on the future perspectives and potential solutions for achieving water sustainability in the future period. The study pointed out that only 6% of the article regarding water sustainability include information about global warming, with an increasing trend in the latter period in both the number of articles and citations, but the field of study seems to be incipient, with a large number of journals publishing a very low number of articles. The main drawbacks identified were the orientation of a large majority of the studies on present day problems and not on future approaches, the complete lack of studies regarding the role of preserving natural habitats or of spontaneous renaturalization, as well as the relative absence of including cultural aspects in addressing water-sustainability issues.

Keywords: water management; sustainability; global warming

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1. Introduction

Since the Brundtland Commission published its seminal report "Our Common Future" [1], "sustainable development" and "sustainability" have become basic ideas in policy generation, state and regional administration and scientific research; development and the environment are considered a single issue, and our new common goal became "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", leading Mays [2] to define "water sustainability" as the ability to use water resources in quantity and quality suitable for both the present and future needs of human populations and ecosystems, in such a way that we can protect human populations from the effects of natural or man-made hazards. Mays also pointed out that, among other factors to be considered, the change in climatic conditions, at both regional and global levels, plays a crucial role in achieving the goal of sustainable water use [2] as well as the role of the regional management of water resources versus a more decentralized approach [3]. In this context, an analysis of the water-sustainability aspects in relation to global warming presented in the scientific literature might point out the existing research trends in the field, as well as conceptual gaps, leading to the identification of potential future analysis that could improve the scientific knowledge and provide useful tools for addressing water-sustainability cases, at both regional and local levels.

Although the present–future binomial concept was clearly defined and its mechanisms were theoretically viable, practical water policies and uses are far from ideal, especially in areas affected by water scarcity and with developing socio-political regimes, as point out by Wada and Bierkens [4], who presented consistent information about the worldwide overuse of aquatic resources, with notable examples from the Aral Sea [5], Colorado and the Yellow river [6], Northwest India and Northeast Pakistan [7,8], and the Tigris–Euphrates system [9], etc. Some of these examples are strictly man-made hazards, such as the case of the Aral Sea, but in most situations, we can identify the influence of global climatic changes as a consistent factor in the degradation of aquatic ecosystems worldwide.

The complex problematics of sustainable water-resource management in the context of global climatic changes also encompasses aspects regarding the dependence of agricultural production on unsustainable groundwater [7,10,11], non-sustainable industrial use [12,13] or the operation of mining facilities [14].

At the current point, two main ideas have emerged from the scientific community. On one hand, water consumption will increase accompanied by an increase in the number of areas and hydrographic basins affected by water-scarcity problems [15–18], leading to the necessity of a more complex approach in managing water resources at both local and regional scales. Therefore, MacDonald [19] argued that "21st-century sustainability challenges in the Southwest will also require planning, cooperation, and integration that surpass 20th-century efforts in terms of geographic scope, jurisdictional breadth, multi-sectoral engagement, and the length of planning timelines", an opinion supported and supplemented by Gleick [17], who included, as a key factor in water-resource-management planning, the human factor in all its aspects: cultural, demographic and educational.

On the other hand, a socio-anthropological current is currently investigating aspects regarding sustainable water management, starting from the concept developed by Mauss [19], of treating water as a "total social fact". The ideas resulting from this approach are centered on the role of human perception of water [20,21], defined as "not only as a resource, but also as a substance that connects many realms of social life" [22]. Sivapalan et al. coined the term socio-hydrology [23], a scientific field focusing on "understanding, interpretation, and scenario development of the flows and stocks in the human-modified water cycle at multiple scales, with explicit inclusion of the two-way feedbacks between human and water systems", a concept that poses human society and water in interdependence and provides tools for a future cultural basis of water-resource conservation. However, this anthropological approach has the drawback of excluding global warming from the equation and mostly relying on small-scale models.

Starting from these premises, our objectives are (1) to provide a comprehensive analysis of the literature referring to the relations between water sustainability and global warming, (2) to identify the main research trends and their temporal evolutions, and (3) to point out the directions and the intensity of the collaborations between individual researchers and research entities. Our analysis consisted of three successive phases: a literature selection phase, in which we used a set of criteria to create a list of relevant documents related to the research field; a descriptive analysis of the selected papers, where we provided relevant information regarding the temporal evolution of the scientific interest and pointed out the main providers of scientific literature in the selected field; and a bibliometric analysis, which explained the main research trends and the relations between researchers and research entities. The article is composed of six sections: introduction; a section detailing the review methodology; a section containing the descriptive statistics of the articles selected after the data-collection phase; a section presenting and explaining the results of the bibliometric analysis; and, finally, a discussion section, where we presented our findings, we identified potential gaps in the research and proposed future research directions.

2. Materials and Methods

The literature analysis was conducted in the framework of the PRISMA-S system, consisting of six successive phases:

- Identification of scientific manuscripts.

- Screening of the identified manuscript for compliance with the general scope of the review.
- Filtering of the manuscripts referring to the specific goal of the review, by including only manuscripts referring to water sustainability in relation to global warming.

The selected papers were included in a two-phase analysis:

- A descriptive analysis, pointing out (a) the temporal trends in research in the analyzed field and (b) the main contributions of authors, countries, scientific journals, and research centers.
- A bibliometric analysis, pointing out (a) the main research directions and trends in the analyzed field and (b) the collaborations between authors and countries involved in research in the analyzed field.

2.1. Data Collection

The search was conducted using the Web of Science database, considered as containing the most significant scientific results at the present moment. The search included the entire time frame of the database, from 1975 to 2022. We focused on papers containing the terms "*water*" and "*sustainability*", and "*global warming*", mainly in the title and keywords. The search resulted in 3995 scientific manuscripts. Two duplicate records were found and eliminated from the list, resulting in a preliminary list of 3993 manuscripts.

2.2. Screening Process

The first phase of screening was the exclusion of the papers referring only to water sustainability and not considering aspects of global warming. Out of the 3993 papers, only 206 were found to refer to water-sustainability aspects strictly in the context of global warming; the rest of the papers referred to aspects regarding water sustainability without considering climate change. The exclusion of the non-suitable papers was carried out by reading their abstracts and keywords by both the researchers and the elimination of the papers was consensual. One paper was written in German and was also excluded, leaving a list of 205 papers.

Only peer-reviewed papers were included in the analysis, as a second phase of screening, book chapters, editorial materials, and conference papers were excluded. In addition, we excluded reviews from the selection, including only manuscripts classified as "article" in our analysis. The second phase of screening identified 35 manuscripts belonging to the excluded categories; therefore, the post-screening list consisted of 170 articles.

2.3. Eligibility Assessment

We used two criteria for the selection of relevant papers: (a) by re-reading their abstracts and eliminating the articles beyond the study's scope, and (b) examination of the articles by reading the full texts. For both phases, the two researchers independently read the abstracts and the full text of the papers, respectively, and consensually eliminated the papers not suitable for inclusion in the review. Six articles were eliminated after reading the abstracts, which clearly showed the aspects presented did not fall into the objective of our study, while another 27 were eliminated after reading their full text.

We eliminated papers referring to educational aspects (frameworks for training specialists or the general public regarding water-sustainability aspects), papers referring to state policy aspects regarding water sustainability and papers referring to the sustainable use of natural resources that have implications for the water cycle. Figure 1 presents the flowchart of the literature search and the successive aspects of the screening process.

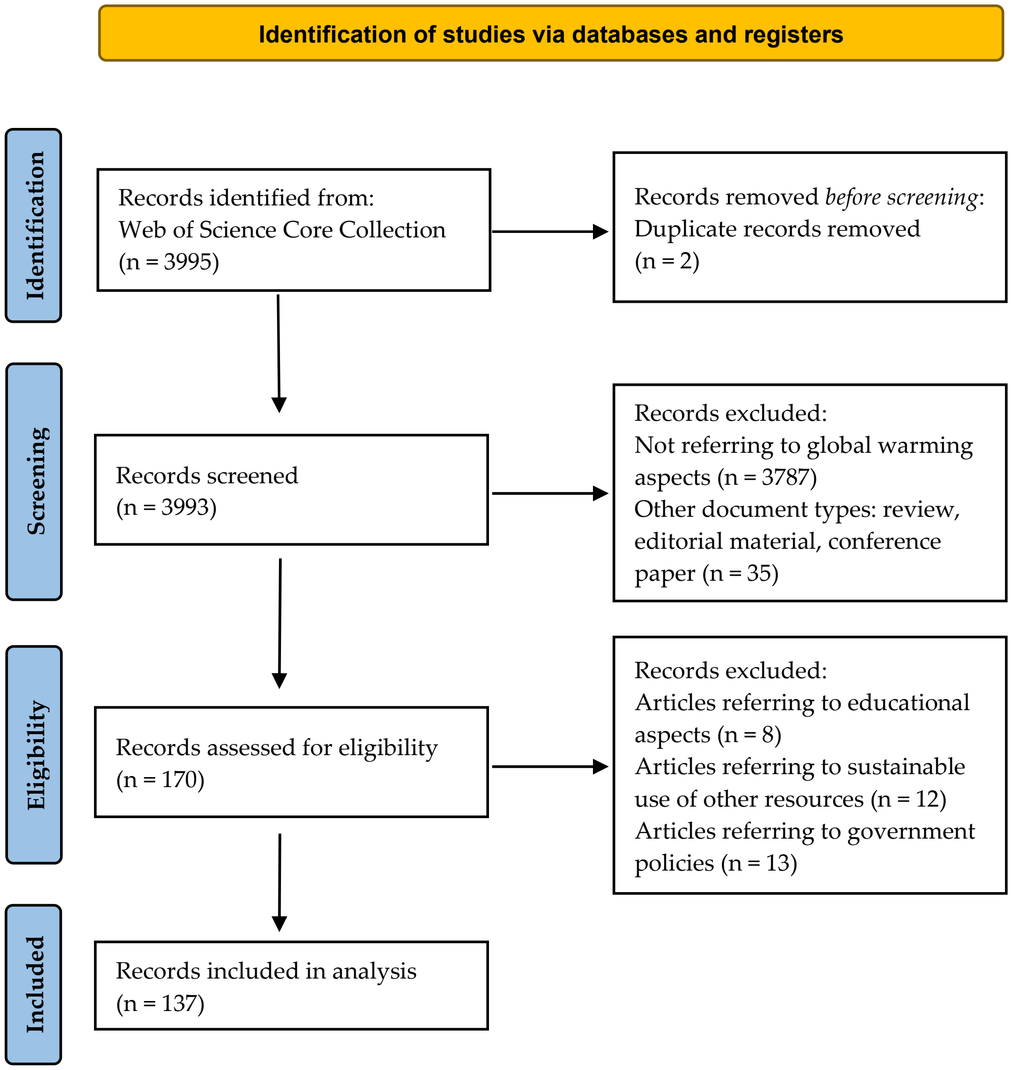


Figure 1. Literature selection process.

2.4. Bibliometric Analysis

For the bibliometric analysis, we used the VOS viewer software which analyzes numerous types of interrelations between manuscripts (bibliographic coupling, co-authorship, co-citation, and co-occurrence of keywords) by linking relevant and similar items, and produces network visualizations of the analysis. The software can use data from several bibliographical databases (e.g., WoS, Scopus, PubMed, RIS, Crossref JSON files), and is freely accessible at: http://www.vosviewer.com (accessed on 2 February 2022).

In our analysis, we looked for two separate aspects:

- Identification of the main research trends in the field of water sustainability in relation to global warming: for this purpose, we applied a text data analysis in which we included the full text of the selected manuscripts, at full counting (the total number of occurrences) in order to identify the most used terms and their connection inside the analyzed documents; the selected terms had at least 15 occurrences, and the list was cleared of terms usually appearing in scientific literature (e.g., person, year, paper, term, study etc.); we also excluded the term "Arizona", whose occurrence was in relation with the high number of articles published by researchers from Arizona State University.
- Identification of the relations between the implied researchers and research centers (expressed as countries): for this purpose, we applied two separate analyses: (a) a citation network analysis to point out the most cited researchers and the intensity of

the relations between them, and (b) a bibliographical coupling analysis (the situation when two documents cite one or more documents in common [24], identifying the most cited countries in the field of water sustainability in relation to global warming and the intensity of the citation process.

3. Descriptive Analysis

This section provides an overview of the articles studying the relation between water-sustainability and global-warming problematics. We considered three different perspectives for this purpose.

3.1. Temporal Trends of Publication and Citation

The assessed 137 articles produced a total number of 3014 citations, of which there were 2975 without self-citations (98.71%), representing an average of 22 citations per article and corresponding to an H-index of 27. The five top-cited papers (responsible for generating 1053 citations, 34.94% of the total number of citations) and their findings are presented in Table 1.

Table 1. Top cited papers.

Authors	Publication Year/Journal Name/No. of Citations	Results
Cayan et al. [16]	2010/*Proceedings of the National Academy of Sciences of the United States of America*/450	Prediction of the future models of water depletion in the context of increased water consumption.
MacDonald [17]	2010/*Proceedings of the National Academy of Sciences of the United States of America*/247	A model of increased dryness and a framework for reducing unsustainable water consumption.
Davies and Simonovic [25]	2010/*Advances in Water Resources*/136	A global water resources model including aspects of the social–economic–environmental system.
Barnett and Pierce [18]	2009/*Proceedings of the National Academy of Sciences of the United States of America*/111	A model of resource depletion in the Colorado River Basin.
Gleick [15]	2010/*Proceedings of the National Academy of Sciences of the United States of America*/109	A framework for future water-management practices in the context of new socio-economic challenges.

The earliest paper published in the investigated field dates from 2005, and a gradual and stable increase in both publications and citations can be observed from 2009 onward (Figure 2).

The temporal trends of publication and citation were tested, with both parameters showing a significant increase in the last period, indicating a growth in interest in the relations between water sustainability and global warming (Figure 3). Both models show a second-order polynomial ascendent curve, following the equation:

$$p = 224186.472 - 223.779 \times Y + 0.0558 \times Y^2 \quad (1)$$

for the relation between number of articles and time (R = 0.941, *p*-values of the parameters below 0.05; Y = year, *p* = number of publications), and

$$C = 10242497.675 - 10209.799 \times Y + 2.544 \times Y^2 \quad (2)$$

for the relation between number of citations and time (R = 0.991, *p*-values of the parameters below 0.05; Y = year, C = number of citations).

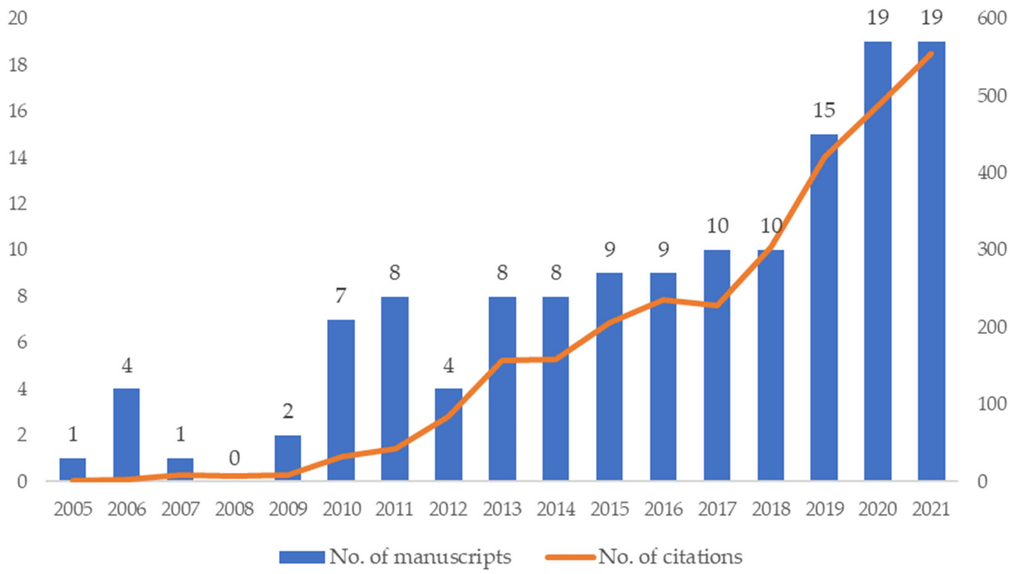
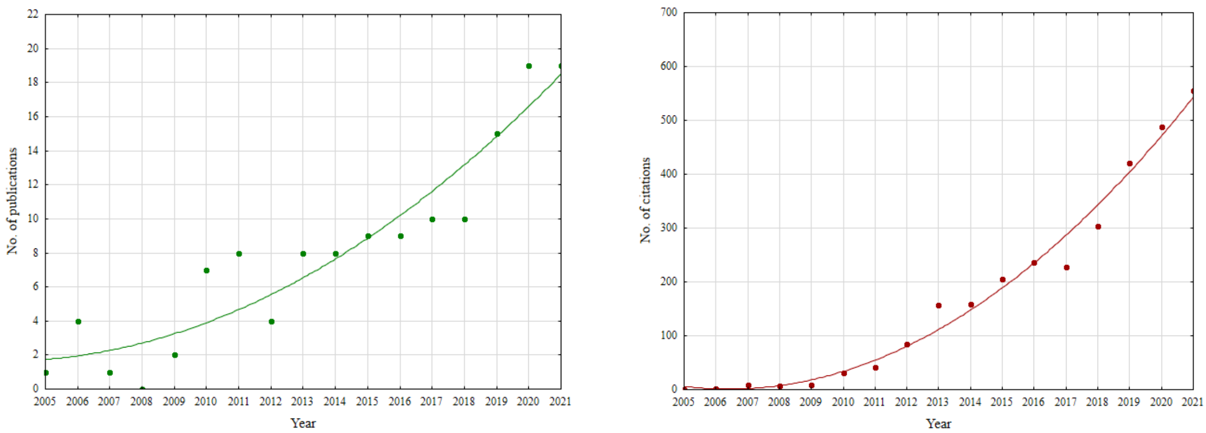


Figure 2. Distribution of articles and citations based on the year of publication.



(**a**) (**b**)

Figure 3. Temporal trends of the relations between time and (**a**) number of published articles; (**b**) number of citations.

3.2. Distribution of Papers among Research Entities

US authors produced by far the largest number of articles referring to the relation between water sustainability and global change (53 articles producing 1898 citations, of which there were 1881 without self-citation—99.1%), followed, by a long distance, by authors from China (12 articles with 154 citations), England (12 articles with 210 citations), Canada (11 articles with 110 citations), and Australia (10 articles with 273 citations) (Figure 4). The situation is even better reflected at an institutional level, where the top five research institutions and six out of the first eight are based in the USA (Figure 5), with the largest number of articles coming from relatively dry regions of the US: Arizona (18 articles with

263 citations) [26–28], California (9 articles with 930 citations) [29,30], or Texas (8 articles with 63 citations) [31,32]).

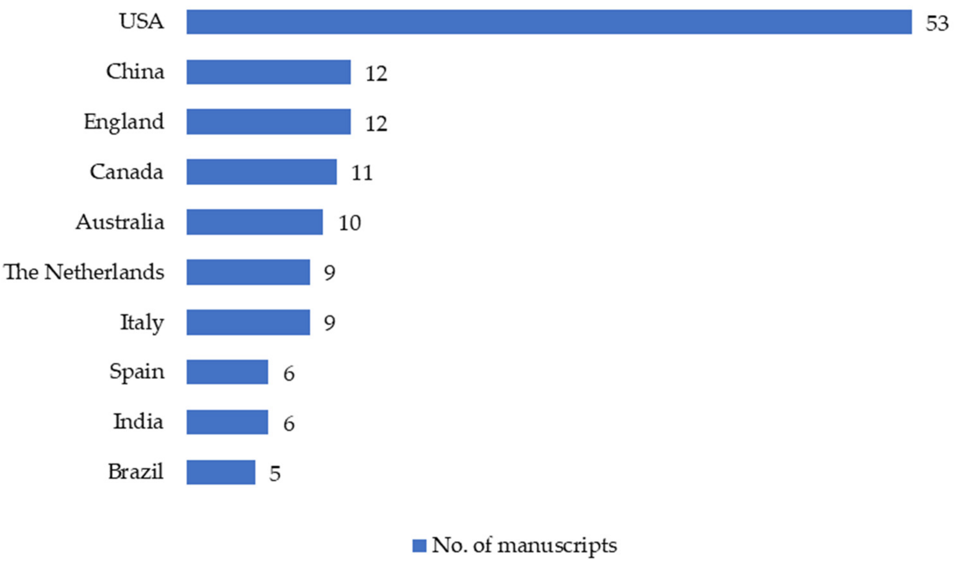


Figure 4. Distribution of articles based on country of provenience.

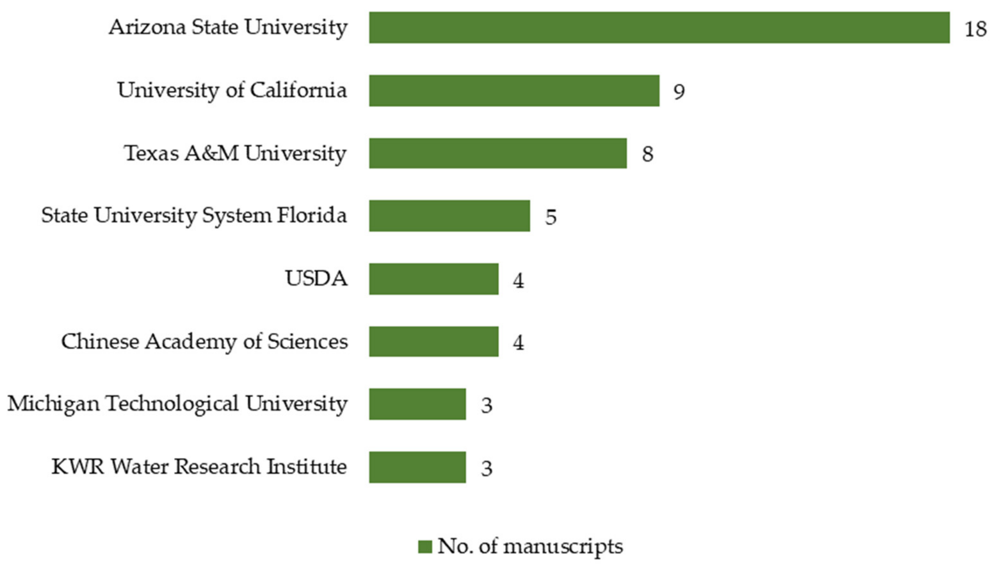


Figure 5. Distribution of articles based on the research entities involved.

3.3. Distribution of Papers among Journals

The selected articles were published in a very large number of scientific journal (76 journals for 137 articles), with a consistent number (56 journals) publishing a single article relevant for our study. The top ten scientific journals as far as number of articles are presented in Figure 6, led, in a logical way, by the two journals aiming to publish articles referring to sustainability and water (*WATER* and *Sustainability* journals, both with 9 articles published, producing 81 and, respectively, 59 citations). The top ten journals from our list are included by SCImago in the first two quartiles (Q1 and Q2).

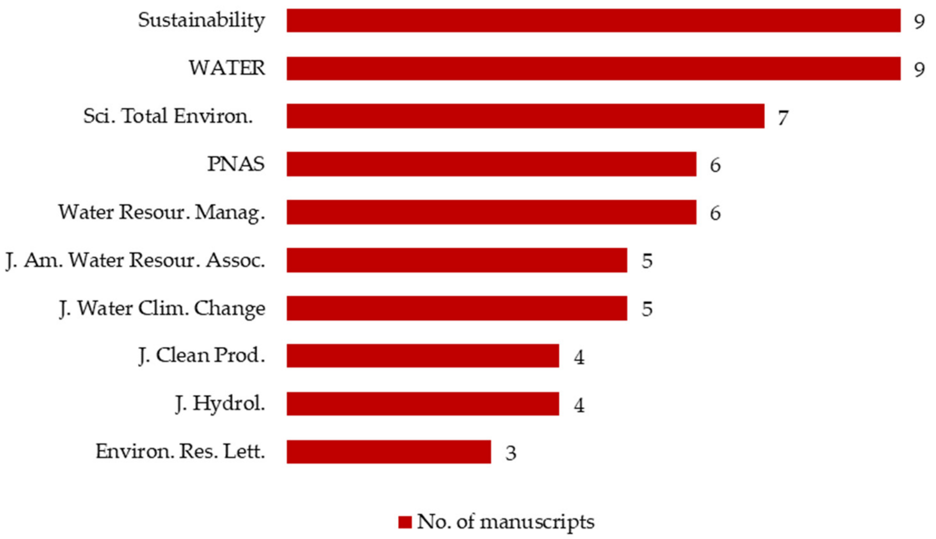


Figure 6. Top journals as number of articles published.

A special remark regarding Proceedings of the National Academy of Sciences, whose six published articles constitute for more than one third of the total citations in the investigated field (1025 out of 3014, 34.01%), and provide four of the top five most cited articles [15–18], as well as five of the top ten most cited articles.

4. Bibliometric Analysis

4.1. Analysis of Individual and State-Wise Collaborations

The citation network of the most cited authors studying the relation between water sustainability and global warming shows two clusters of authors with different characteristics (Figure 7). We included in this analysis authors who had published at least two articles in the selected field, reducing the number to 12 authors out of the total 314 authors identified in our study.

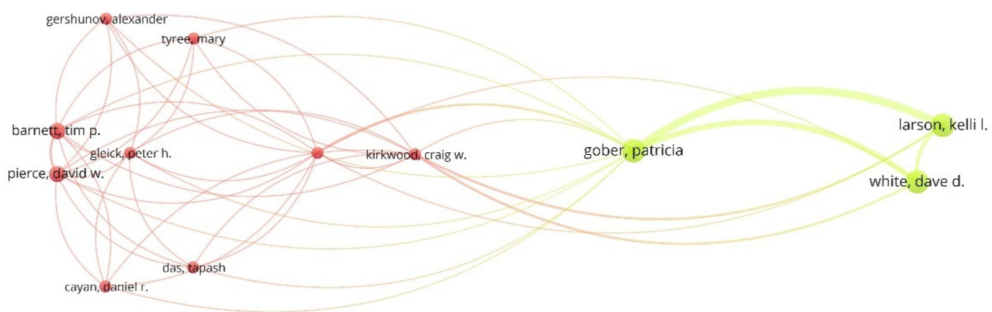


Figure 7. Citation network of the involved researchers.

The yellow cluster consists of the most prolific authors in the investigated field, Patricia Gober, Kelli Larson and Dave White, researchers from Arizona State University, who each contributed four articles from our list, including a collaboration between two of them or all three [28,33–35]. These authors present a strong link to each other and generate a total number of 194 citation.

The red cluster contains authors with only two contributions, but with a larger number of citations, including authors from the top ten cited papers from our list (for the same number of articles as the authors from the yellow cluster, seven, the authors from the red cluster generated 958 citation).

The bibliographic coupling network (Figure 8) shows three clusters of countries with close collaborations, namely, a blue cluster dominated by US researchers, seconded by collaborators from Italy, South Korea and Turkey (with a total of 67 articles generating 2066 citations); a blue cluster centered around researchers from The Netherlands and Canada, seconded by Iranian, Brazilian and Mexican researchers (with 28 articles generating 730 citations); and a red cluster formed by researchers from eight countries (China, Australia, India, Switzerland, South Africa, Chile, Spain and England), with a fewer individual contributions but with more intense relations between them (with 47 articles generating 521 citations).

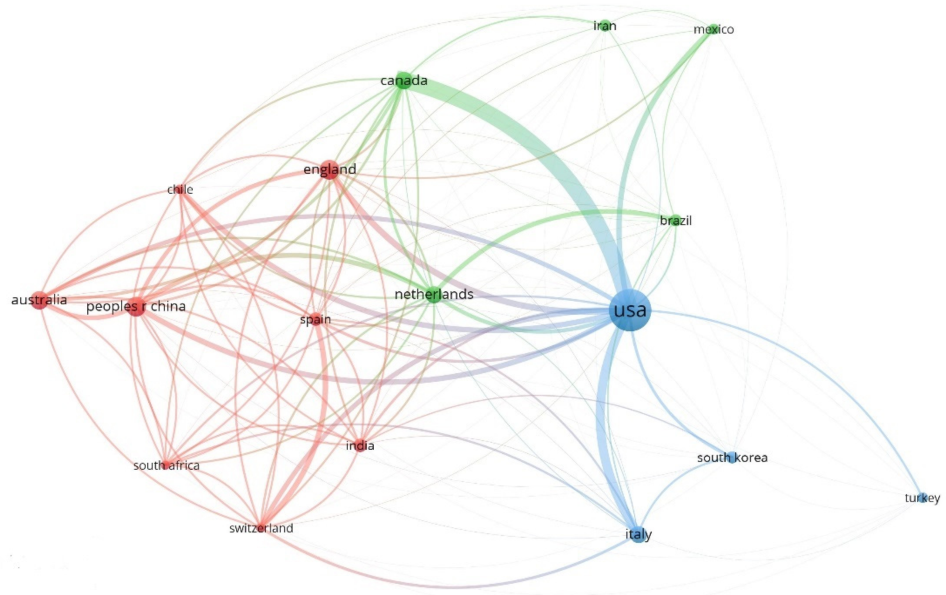


Figure 8. Bibliographical coupling of the countries involved in the analyzed research field.

4.2. Research Trends in Water Sustainability under a Global-Warming Scenario

The analysis of the most used terms identified a total of 4607 terms appearing in the selected articles, of which only 51 passed the threshold of 15 occurrences established for our analysis, before excluding the terms usually appearing in scientific literature, which resulted in 42 terms remaining. The results revealed three main clusters, indicating the three main research directions in the study of the relations between water sustainability and global warming (Figure 9).

The red cluster is the largest from the representation, comprising 19 terms (almost half of the terms analyzed), of which those with the highest importance are climate change (183 occurrences), water (170 occurrences), impact (136 occurrences), and system (124 occurrences), with lower importance terms such as agriculture (29 occurrences), irrigation (24 occurrences), energy (37 occurrences), drought (39 occurrences), food (17 occurrences) or forest (21 occurrences), indicating that a main research direction is oriented towards the present impact of global warning on water sustainability and its effects on water-supply and ecosystem functioning. We can include here Khan et al.'s analysis of South Korea and India [36], Emami and Koch's study on Iran's Boukan Dam [37], de Sa et al.'s study on the Rio Verde Grande basin [38], Fang et al.'s analysis on Chinese lakes [39], Ahmadaali et al.'s assessment of Iran's Urmia Lake [40] or Yehia et al.'s study on Upper Egipt [41].

The blue cluster (comprising of nine terms) contains the terms sustainability (128 occurrences), management (71 occurrences), approach (55 occurrences), and challenge (51 occurrences), indicating a research trend focused on problem solving and creating a framework for water sustainability in the context of global warming. In this category, we can include Chelleri et al.'s solution for the decentralization of water management in New Mexico [42], Van Leeuwen et al.'s framework for assessing the sustainability of the urban water cycle [43], or Gober and Kirkwood's dynamic simulation model, WaterSim, applicable to short-term water shortages in urban areas [44].

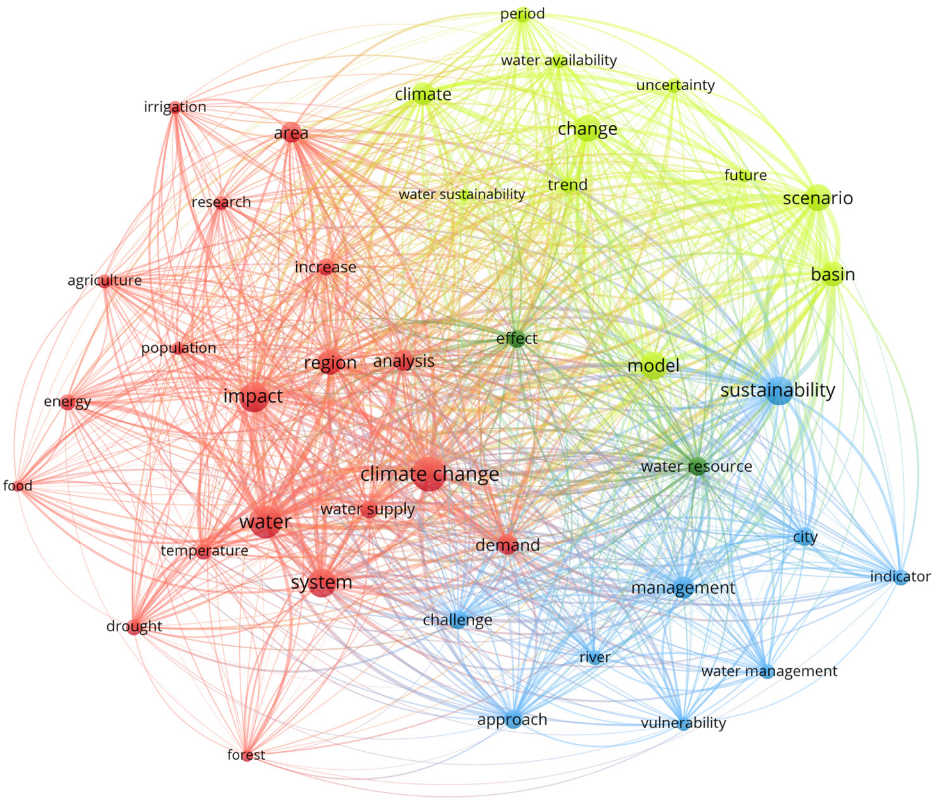


Figure 9. Co-occurrence of key terms—network visualization.

Finally, the yellow cluster (comprising of 13 terms), containing the terms scenario (115 occurrences), model (117 occurrences), change (108 occurrences), uncertainty (32 occurrences), and, most importantly, future (24 occurrences), seems to define a research trend focused on future perspectives and potential solutions for achieving water sustainability in the future period. For example, Jenerette and Larsen proposed a model of understanding the interactions between urban consumption and the regional availability of renewable water to be used in a future scenario in the event of increased water consumption [45]; Van Leeuwen introduced the concept of City Blueprints, a set of indicators to be used in the sustainable water management of urban areas [44,46]; Parkinson et al. created a system of trade-offs inside water-energy system configurations for the sustainable management of water flows [47]; while Jacobs et al. proposed a long-term monitoring system for the factors generating drought conditions in Arizona, in order to permit a long-term intervention from state authorities in preventing the effects of water shortage [48].

The temporal overlay (Figure 10) shows a shift in interest from the early studies, from relatively immediate problems (population, drought, city or challenge) to a future-oriented perception, dominated by terms such as future, model, analysis, scenario, management, as well as on the most important effects of a non-sustainable approach to water, represented by the terms food and forest.

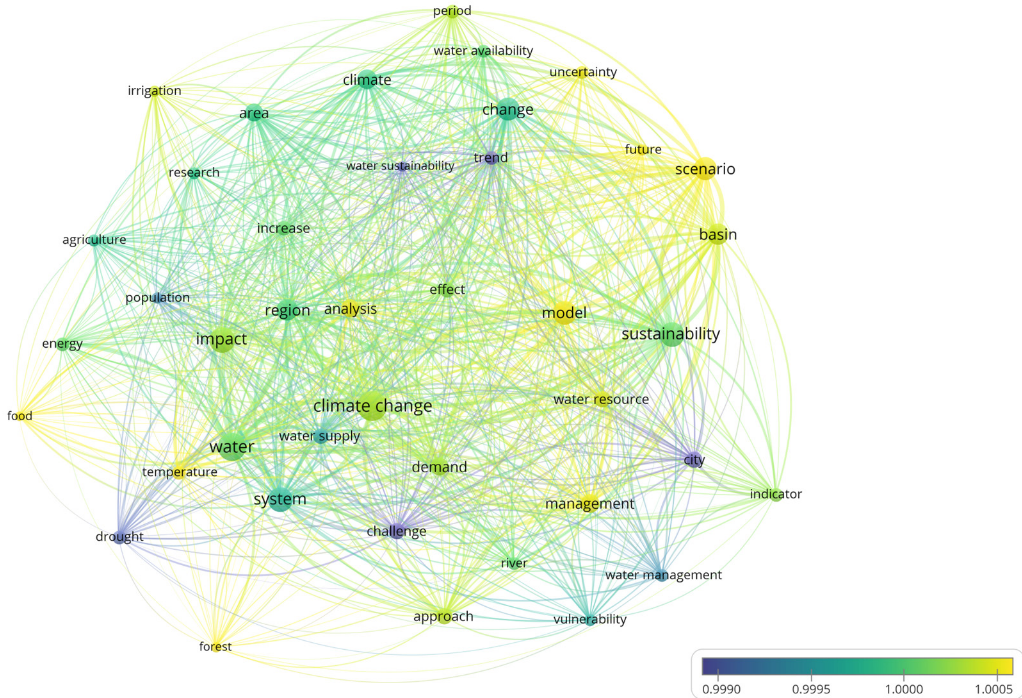


Figure 10. Co-occurrence of key terms—temporal overlay visualization.

5. Discussion and Conclusions

Our study analyzes the problematics of water sustainability in the context of global warming through the use of bibliometrics. Moreover, we tried to identify the eventual gaps in research and proposed a framework for future directions in the field. In this section, we summarize our findings and discus the challenges in the selected field of research.

For our analysis, we screened a total of 3995 scientific papers and conducted a four-step selection process to identify only research articles specifically examining water sustainability problems in the context of global warming. We observed a significant and constant increase in the number of publications in the last few years, indicating a clear trend and forecasting a larger number of studies to be published, therefore making the field of research more attractive in the years to come.

A first aspect reflected by our analysis is the relatively low number of studies including aspects regarding global warming from the scientific literature studying water sustainability. Only 6% of the scientific articles studying water sustainability considered global warming as an important factor, indicating that this field of research seems to be incipient and there is a lot more to be found regarding the relations between the two scientific concepts.

The 137 scientific articles included at the end of the selection process are the work of 541 authors, of which only three authored at least three papers and only 26 authored at least two, indicating that the investigated research field is more or less a marginal interest of the large majority of the researchers involved. In addition, we identified that there is a strong dispersal inside the academic community implied in the selected field of research, consistent with the previously presented impression of incipience. A very large number of scientific journals are publishing relatively disparate information and a coherent framework of research and publishing seems to be absent. Given the fact that the temporal trends in publishing and citation indicate a strong growth in the recent period, most likely we will be able to see more coherence in the near future, both in research and in publishing, where the two most dominant publications are *WATER* and *Sustainability*, suitable hosts for scientific papers in the field.

US authors are the most influential, leading by far the total number of articles (4.5 times more than the next country involved in the field), citations (seven times more than the next country involved in the field) and in articles published by individual researchers (the only authors with four articles are from the USA). In addition, four of the five most cited papers are published in *Proceedings of the National Academy of Sciences of the United States of America*, further indicating the US dominance in the analyzed field of research.

The journals with the highest number of articles are *Sustainability* and *WATER*, both with nine articles published, a somehow logical approach given the aims and scopes of the two journals. However, a very large number of journals are hosts to our article selection, further indicating the dispersal of scientific information and contributing to the incipience idea discussed before in relation to the very low percentage of article relating water sustainability to global-change problematics and to the very low number of authors with more than two studies published in the field.

The most influential papers present either models of water depletion and increased dryness (a prediction of water depletion in the context of increased water consumption [17]; a model of increased dryness [18]; a global water-resources model influenced by the socio–economic system [25]; and a model of resource depletion in the Colorado River Basin [19]) or frameworks for future water-management practices (a framework for reducing unsustainable water consumption [16]; and a framework for future water-management practices in the context of new challenges [18]), indicating the main interests in relating water sustainability and global warming.

The keywork co-occurrence analysis pointed out an imbalanced distribution, with almost half the studies investigating the present impact of global warning on water sustainability and its effects on water supply and ecosystem functioning, a large proportion of the evaluated studies being focused on "now" and "here", identifying local or regional problems regarding water sustainability and proposing a post-hoc solution to an already existing problem. The most important trend must be the prevention of water-supply problems and the creation of sustainable solutions for the near-to-medium future, addressing the problems before they can act. The temporal overlay showed that the scientific group involved in studying the field we analyzed is gradually shifting to such an approach.

The most important gap we identified in the selected field of research is the almost total absence of studies investigating the importance of preserving natural habitats as key factors is achieving water-sustainability goals, an aspect of high importance in areas with extensive anthropic impact and a strong presence of urbanized areas, both in intensity and extension. Similarly, we can observe a lack of articles studying the role of supporting natural dynamics as a factor for increasing the quality of aquatic habitats, the main aspects to take into account being spontaneous renaturalization, secondary successions, or the lack of anthropic interventions in already affected areas, and the relations between the presented aspects and future improvements in water sustainability at low spatial scales.

Finally, we observed a relatively low interest in addressing the cultural problems attached to water-sustainability issues, and a more economically oriented approach. Especially in developing countries, a consistent part of the problem is the improper education of the general population regarding sustainable water use and this factor must be taken into consideration in future studies, alongside agricultural, industrial and climatic factors.

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Article

From Pollution Control Cooperation of Lancang-Mekong River to "Two Mountains Theory"

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Abstract: "Lucid waters and lush mountains are invaluable assets " (referred to as the "Two Mountains Theory") plays an important role in the process of controlling environmental pollution. This article introduces this practice with an example of pollution control in the Lancang-Mekong River Basin (LMRB). The research considers that the upstream and downstream countries can carry out water pollution control by imposing fines on enterprises that cause ecological damage and investing in pollution control resources. Firstly, the differential game model of pollution control by individual countries and international cooperation is established. Then, a differential game model of joint pollution control with compensation mechanism is established under the cooperation framework. Finally, the feedback Nash equilibrium of each state is obtained. The study shows that in the process of industrial pollution control by countries in the LMRB alone, due to the one-way externality of water pollution control, the more downstream countries are, the more resources will be invested in pollution control and the fewer fines will be imposed on enterprises that cause ecological damage. At the beginning stage of management, if more pollution control resources are input, fewer countries will participate in cooperation, and the fines for polluting enterprise would be less. When the amount of fines for enterprises is relatively small, the establishment of a river pollution compensation mechanism is not conducive to the input of pollution control resources. On the contrary, it is beneficial for the state to invest in pollution control resources. The coordinated development of economic development and ecological civilization construction is the core purpose of the "Two Mountains Theory". Therefore, the case of the LMRB fully illustrates the feasibility of the "Two Mountains Theory" based on cooperation.

Keywords: upstream and downstream countries; ecological environment; differential game; transnational rivers

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1. Introduction

Nowadays, many countries in the world are implementing the strictest ecological and environmental protection system. All of these are practices of green and sustainable development concept under the top-level design of "Lucid waters and lush mountains are invaluable assets" (referred to as the "Two Mountains Theory"). This theory interprets the dialectical and unified relationship between economic development and environmental protection. The "Two Mountains Theory" has played an important role in the naturalization of various habitats. Under the guidance of the "Two Mountains Theory", habitats of various species in many countries have been revitalized [1,2]. In recent years, internationalized water resources pollution has become more and more serious [3–5]. The pollution of transnational rivers affects several countries upstream and downstream.

The Lancang-Mekong River is the ninth largest river in the world and the fifth largest in Asia. It originates in the Tanggula mountains in the south of Qinghai province of China. The LMRB is an ecosystem with many unique functions. It provides a lot of water, raw materials and food for human beings. In addition, it plays an important role in maintaining ecological balance and biodiversity as well as water conservation, flood storage and drought prevention, degradation of pollution, climate regulation, groundwater replenishment and soil erosion control. Industrial pollution and other human impacts in the LMRB are becoming more and more serious with the continuous accumulation of pollutants and the weakening of the basin's purification capacity, as well as the increasingly serious destruction of forest, grassland and other vegetation caused by human activities [6–8]. The ecology of the LMRB is no longer able to repair itself. It must rely on countries to recreate, guide or accelerate the natural evolution of the basin. In the basin outside China, although the Lancang-Mekong River continues are constantly polluted by organics and heavy metals [8], it still cannot attract enough attention from downstream countries [9]. It not only pollutes people's drinking water [10], but also leads to low efficiency of aquaculture in the basin [11]. Countries should take early measures to reduce ecological destruction on the Lancang-Mekong River. In the LMRB, special spatial location factors exist, and ecological destruction generated by upstream countries is shared by themselves and downstream countries. As a result, industrial enterprises in upstream countries have increased their emission in order to obtain greater benefits, which is obviously not conducive to the implementation of the responsibility system for pollution control. It does not accord with the basic principle of environmental protection of "who pollutes, who controls". Therefore, it is particularly important to implement the compensation mechanism for environmental governance so that the pollution responsible parties can effectively take charge of pollution control [12]. Enhanced cooperation between regions provides an important reference for effective control of river pollution [13]. It is not easy to reach cooperation in pollution control because of differences in justice, internal affairs and cognition [14]. The Lancang-Mekong cooperation is conducive to upstream and downstream countries enjoying rights and responsibilities towards each other in the face of ecological destruction and realizing the ecological resilience [15].

The ecological restoration of LMRB should focus on the self-organization and self-regulation ability of the ecosystem itself. In addition, the external artificial regulation ability should be supplemented [16]. If the ecological restoration can only be achieved by artificial control, the ecological environmental control of the Lancang-Mekong River will consume a large number of human, material and financial resources. In this case, the pollution control work on the Lancang-Mekong River is a failure. The Lancang-Mekong River has strong dynamic resilience. Its own dynamic recovery ability can gradually restore and realize the various functions of the ecosystem [17]. However, human production and living activities have increased in the past few years. This has resulted in significant damage to the dynamic resilience of the Lancang-Mekong River. The pollution control mode selected by countries in the LMRB can correctly create favorable conditions and promote the ecological restoration of countries in the LMRB. Once the ecological environment of the Lancang-Mekong River is restored to a large extent, all countries need to reduce the disturbance to the ecosystem.

With deepening research on river pollution by domestic and foreign scholars, a large number of achievements have emerged in the study of pollution control by using inductive method, multi-parameter analysis method, data analysis method, statistical method, decision-making systems and engineering technologies. For example, Surasinghe et al. sum up the problem of water pollution in the Kelani River basin [18]. Cooray et al. use a multi-parameter analysis to study water pollution in Sri Lanka [19]. Li et al. use data analysis to study water pollution in Shanghai [20]. Einax et al. use the multivariate analysis method for evaluation and interpretation of the river pollution data [21]. Nasiri et al. build expert system to calculate the water pollution index [22]. Zheng et al. use chemistry to study the causes of eutrophication in Hongfeng Lake [23]. Among them, game theory, which is used to analyze human social conflicts and cooperation, provides a good analytical tool for river pollution. Conventional games include bargaining games, static games and evolutionary game. Yuan built the bankruptcy and bargaining games to solve the problem of water resource allocation [24], the static game model between enterprise pollution emission control and government regulation [25]. Evolutionary game, including the evolutionary game model of government and sewage management in the process of Huai River water pollution control [26], the use of evolutionary game to control complex and changeable water pollution problems [27] and the use of evolutionary game to deal with the time consistency of downstream water pollution control [28]. The above literature analysis basically covers traditional game methods, evolutionary game and other emerging game theories. However, based on the above game theory literature on water pollution control, the assumption about time is simultaneous or time is discrete. The problem of time continuity in the decision-making interaction between upstream and downstream countries in the process of pollution control has not been considered.

Differential game refers to a time continuous game played by multiple players in a time continuous system. It has the goal of optimizing the independence and conflict of each player, and can finally obtain the strategy of each player evolving over time and reach the Nash equilibrium. The theory of differential game originated from research on the pursuit of flight by both sides in the military confrontation carried out by the US Air Force in the 1950s. It is a combination of optimal control and game theory. At present, it is mainly applied in the fields of pricing strategy [29], traffic network equilibrium problem [30], advertising decision [31,32] and information security [33,34]. In the field of environmental governance, Huang established a differential game model to deal with the dynamic governance of cross-border pollution in two regions [35]. Yeung used the cooperative differential game model to analyze cross-border ecological destruction [36]. Kossioris used the differential game model to study pollution control of lakes [37]. The above study on ecological destruction by using differential game has no spatial and geographical constraints and considers the compensation mechanism of pollution control.

Due to the upstream and downstream relationship between countries in the LMRB, this paper referred to the "Two Mountains Theory" and was based on Huang's differential game model of trans-boundary pollution [35]. How to construct international cooperative pollution control mechanisms under different governance modes on the basis of considering the spatial position relationship between the upper and lower reaches of the LMRB?

2. Methodology

In order to effectively protect the ecological environment, habitat and natural landscape of transnational river basins, the following three ecological environment governance modes are mainly adopted by countries in river basins:

(1) Individual management model. In the absence of effective international management mechanisms, each watershed country protects its own ecological environment, habitat and natural landscape. At this point, the ecological governance of upstream countries will produce positive externalities to downstream countries. However, the destruction of ecological environment, habitat and natural landscape by the upstream countries will have negative externalities to the downstream countries. That is, emissions by upstream countries can harm the interests of downstream countries. In addition, the upstream countries can protect the interests of the downstream countries by controlling pollution. On the contrary, the destruction of the ecological environment, habitat and natural landscape by the downstream countries will only have an impact on the domestic countries, not the upstream countries [38].

(2) Joint management model. If the damage to the ecological environment, habitat and natural landscape in the upstream countries is not effectively addressed, it will seriously affect the international reputation of the upstream countries. Therefore, it is necessary for upstream and downstream countries to carry out information and intelligence exchange on river pollution, and establish cooperation mechanism to deal

with river pollution emergencies. Therefore, cooperation among countries along the LMRB to protect the ecological environment, habitat and natural landscape will help reduce conflicts among countries [11].

(3) Joint management model based on compensation. As for the national responsibility caused by the damage to the ecological environment, habitat and natural landscape of transnational rivers, especially the compensation problem, there are great differences among the basin countries. Different from the second cooperation mechanism, in this compensation-based cooperation mechanism, compensation needs to be made according to the amount of pollution discharged, and the compensation can be used to control pollution.

The economic development of the LMRB requires the production and processing of products, but needs to discharge waste water, waste gas and waste residue. Thus, it causes certain damage to the ecological environment, habitat and natural landscape. The investment of pollution control resources (such as sewage pipes, push flow aerators and other pollution control equipment, hiring personnel for pollution control, ammonia nitrogen remover, limestone and other raw materials for water purification) can play a role in the ecological environment of the LMRB. How to make decisions on the amount of sewage discharge (or product production) and pollution control of each country has become an important issue studied in this paper. Therefore, this paper first sets up the relevant assumptions and parameters and then establishes the relevant model.

2.1. Assumptions

A river has a certain bearing capacity [11]. The upper and lower reaches of sewage beyond its bearing capacity will cause losses [39]. Due to the upstream and downstream relationship between countries along LMRB, pollutants from upstream countries can flow into downstream countries, thus adversely affecting downstream countries, while ecological destruction from downstream countries can hardly affect upstream countries. This paper makes the following assumptions about the analysis objects.

A1: This paper assumes that six countries in the LMRB (China, Myanmar, Laos, Thailand, Cambodia and Vietnam) make pollution control decisions in a continuous time and unlimited planning cycle [6]. The first upstream country is country 1, and the second upstream country is country 2, . . . , and the most downstream country is country 6.

A2: The ecological protection decision-making of each country is in a state of continuous and dynamic change.

Both upstream and downstream countries of transnational rivers can control the amount of pollution discharge and treatment to achieve the purpose of protecting the ecological environment, habitat and natural landscape. Under the separate treatment mode, the upstream countries of transnational rivers make use of their own geographical and spatial advantages, and their ecological destruction and restoration can affect the downstream countries; the downstream countries cannot influence the downstream countries. In order to restrict the upstream countries and achieve the purpose of jointly protecting the ecological environment of the upstream and downstream countries of transnational rivers, the countries in the LMRB can establish a common ecological protection model and a compensation-based common ecological protection model. Taking the common pollution control model as an example, under which the downstream countries can obtain certain economic compensation based on the net emission of the upstream countries, so that the upstream countries have to determine their emission according to the ecological compensation, and the net emission determined by the upstream countries further affects the ecological destruction level suffered by the downstream countries. Therefore, the ecological protection decisions of various countries are in continuous dynamic changes.

A3: Each country has only one major pollutant for the LMRB.

All countries in the LMRB are developing countries. In addition to China, which has a complete industry, other countries mainly focus on low-end industries. For example, although Vietnam has many companies in the LMRB, its main damage in the LMRB comes from its own sand mining industry. Perennial sand mining in Vietnam has caused serious soil erosion in the LMRB [40]. In addition, Cambodia's fishing industry has destroyed the food chain and ecological balance in the LMRB [41]. For convenience, this article assumes that each country has only one major pollutant for the LMRB.

A4: Every unit of product produced will result in a unit of river pollution in the LMRB.

The destruction of ecological environment in the LMRB is affected by many aspects. On the one hand, the production of the same product can produce a variety of pollutants, and the damage of different pollutants to the ecological environment, habitat and natural landscape is different. On the other hand, the self-regulation capacity of the LMRB at different times also affects the degree of damage. The LMRB is divided into dry season and rainy season. Compared with the dry season, rivers can effectively dilute pollutants in the rainy season, thus accelerating the decay of acid, alkali, oxidant, copper, cadmium, mercury and other heavy metal pollutants. In addition, rainwater, groundwater, snow and ice melt water supply in upstream and downstream basins are different, which will also affect the restoration rate of ecological environment, habitat and natural landscape. Some scholars have also made the same assumption. For example, although the production of many products can cause carbon dioxide emissions, Bertinelli et al. also assumed that only one product was produced when conducting carbon emission research [42]. For convenience, this paper assumes that unit product produces unit pollutant.

2.2. Parameter Setting

In the face of river pollution, habitat destruction and natural landscape damage in several countries along the LMRB [8], cooperation between governments is necessary for governance. Chen et al. studied the necessity of government cooperation [43], and Qi et al. studied the impact of China-South Korea cooperation on pollution emission [44]. Although these scholars studied the impact of pollution control cooperation on the effect of pollution control, they did not study the specific form of cooperation.

The profits from the production of goods in a region shall be enjoyed by that region alone. However, the pollution to the ecological environment has a certain spread. That is, the ecological destruction of one area will affect other areas. As a result, the ecological environment, natural habitat and landscape of other areas are also damaged. This results in inequality of ecological destruction and benefits in different areas. Therefore, some scholars have studied the form of cooperation based on compensation. For example, Rosemary's study concluded that compensation for victims can make the ecological destruction mechanism fairer [45], and Cui et al. studied the impact of air ecological destruction compensation on pollution emission [46]. Although these scholars studied the specific form of cooperation (ecological destruction compensation), they did not compare and analyze the abstract ecological cooperation with the cooperation based on ecological compensation. In order to make up for the shortcomings of the above research, this paper constructed three differential game models of pollution control by the upstream and downstream countries of the Lancang-Mekong River alone, cooperative pollution control and compensation-based cooperative pollution control, and then compared the balanced production and control quantity of the upstream and downstream countries under each pollution control mode.

In this paper, three pollution control modes are considered: individual ecological control, cooperative ecological control and compensation-based cooperative ecological control. The main variables and parameter definitions set in this paper are shown in Table 1.

Table 1. Definition of major variables and parameters.

Variables and Parameters	Specific Meaning
$A_i(t)$	The ecological governance resources invested by country i at time t, namely, the amount of pollution control, $A_i(t) \geq 0$
$q_i(t)$	The amount of damage to the ecological environment caused by products produced by country i at time t, $q_i(t) \geq 0$
$G_i(t)$	The penalty imposed on enterprises in country i at time t per unit of ecological damage, $G_i(t) \geq 0$
$x_i(t)$	Long-term impact of pollution, habitat destruction and other human activities on country i at time t, $x_i(t) \geq 0$
ρ	The discount rate that occurs over time. That is the discount factor, $0 < \rho < 1$
δ	Decay rate of ecological damage. That is, the restoration rate of ecological environment, habitat and natural landscape, $0 < \delta < 1$
π	The positive impact of unit pollution control, $\pi \geq 0$
b	Parameters in a requirement function. It is the vertical intercept of the price demand curve, and it is the price when demand exceeds supply, $b \geq 0$
$V_i(t)$	The benefit function of state i's pollution control at time t

Next, this article explains the parameters and variables in Table 1. Every country in the LMRB has some industrial enterprises. In the process of production and management, enterprises are prone to unreasonable use of water resources, excessive deforestation, overload mining of mineral resources and other behaviors. The resulting destruction of the ecological environment, habitat and natural landscape. The damage to ecological environment, habitat and natural landscape caused by products produced by country i at time t is $q_i(t)$. Of course, countries in the LMRB will take measures to protect the environment after discovering that their ecological environment, habitat and natural landscape are damaged. Specific measures include: (1) Water pollution control. For example: put sewage pipes, push flow aerator and other pollution treatment equipment, hire personnel to carry out pollution treatment, put ammonia nitrogen remover, limestone and other raw materials to purify water; (2) Reduce biodiversity loss and expand the connectivity of natural habitats in the LMRB; and (3) Invest manpower and material resources to restore the natural landscape of the LMRB. At this point, the ecological governance resource invested by country i at time t is $A_i(t)$. Different measures are adopted to regulate the ecological environment, habitat and natural landscape. For convenience, this paper sets the positive impact of unit pollution control as π. Although the countries in the LMRB invest pollution control resources to control the environment, it can play a certain role in the restoration of the ecological environment, habitat and natural landscape, but it cannot prevent the behavior of destroying the ecological environment from the source. Each country may also impose penalties on its own enterprises that damage the ecological environment, habitat and natural landscape if the expected results cannot be achieved by using pollution control resources. The penalty imposed on enterprises in country i by unit ecological damage at time t is $G_i(t)$. Human production and operation activities will have a long-term impact on the ecosystem of transnational rivers. Take migratory fish as an example, which require different environments for the main phases of their life cycle, which are reproduction, production of juveniles, growth and sexual maturation. The life cycle of diadromous species takes place partly in fresh water and partly in sea water. The reproduction of anadromous species takes place in fresh water, whereas catadromous species migrate to the sea for breeding purposes and back to fresh water for trophic purposes. Once the cross-border rivers are polluted, it will have an important impact on the reproduction, larval production, growth and sexual maturity of migratory fish, resulting in long-term damage to the migratory specie. The migration of dolphins will also change with their own environment. If cross-border rivers are damaged, the migration route of dolphins will be changed, and they will become an alien species, resulting in damage to the ecological environment and natural habitat. In this paper, $x_i(t)$ is defined as long-term impact of pollution, habitat destruction and other human activities on country i at time t.

The value range of the decay rate of ecological damage δ is (0,1). Nature has a special property that it can self-balance and self-repair. Like the immune system of all living things, nature is a self-repairing, circular, endless environmental system. The resilience is δ. The discounted factor ρ is different from the decay rate δ of ecological damage. The discount factor means that earnings have a time value. That is, because of factors such as inflation, even if the absolute amount of the return is the same, the return now will be different from the return some time later. Among them, the governance capacity of a country is the state variable, and the pollution control input and fines of a country are the control variables.

Enterprises tend to pursue the maximization of economic benefits. Therefore, enterprises that cause ecological damage do not consider the damage and loss of ecological environment, natural habitat and landscape into their own costs. Therefore, the cost of enterprises that cause ecological damage includes the production cost of products and fines imposed on enterprises that cause ecological damage, but it does not include the cost of the pollution, habitat destruction and other human impacts. For convenience of analysis, referring to the simple form of the convex return function proposed by Breton et al. [47]. The net income generated by all enterprises that cause ecological damage in country i is:

$$\varphi_i(t) = bq_i(t) - \frac{1}{2}q_i^2(t) - G_i(t)q_i(t) \tag{1}$$

In Equation (1), $bq_i(t)$ represents the operating income generated by all industrial enterprises in country i selling products of $q_i(t)$ units (product backlog is not considered in this paper). $\frac{1}{2}q_i^2(t)$ represents the cost of production for all industrial enterprises in country i. $G_i(t)q_i(t)$ represents the fines paid by all industrial enterprises in country i for damaging the ecological environment of the Lancang-Mekong River.

The total profits of all enterprises that cause ecological damage in country i within a production cycle T are as follows:

$$\max_{q_i}\int_0^T \left[bq_i(t) - \frac{1}{2}q_i^2(t) - G_i(t)q_i(t)\right]e^{-\rho t}dt \tag{2}$$

In Equation (2), $e^{-\rho t}$ represents the discount rate, which is the ratio of future returns to present values.

By solving Equation (2), the optimal output of enterprises in country i can be obtained as follows:

$$q_i^*(t) = b - G_i(t) \tag{3}$$

It can also be seen from Equation (3) that the output of commodities of country i is not directly related to the degree of damage to the ecological environment, natural habitat and ecological landscape, but is related to fines.

It is very difficult for country i to fully restore the ecological environment, habitat and natural landscape of the LMRB. Therefore, the degree of damage to the ecological environment is greater than the degree of repair. It can be expressed as: $q_i^*(t) \geq A_i^*(t)$, $b - G_i(t) \geq A_i(t)$.

Since the goodwill of an enterprise is affected by the advertisements made by itself and other enterprises [48], this paper considers that the effect of national pollution control is related to national pollution control capacity and that of other countries. In addition, according to the formula of demand price in economics, this paper obtains the income of country i for producing goods. With the continuous increase in pollution control, the input of pollution-related production factors is increasing, which is easy to cause the shortage of production factors, and eventually lead to the increase in the price of production factors. Therefore, the pollution control effect obtained by the state is as follows:

$$e_i(t) = \begin{cases} \left[\sum_{h=1}^{i} q_h(t) - \sum_{h=1}^{i-1} A_h(t)\right] A_i(t) & 2 \le i \le 6 \\ q_1(t)A_1(t) & i = 1 \end{cases} \quad (4)$$

In Equation (4), when i = 1, there is no upstream country in country 1. $q_1A_1(t)$ represents the effect achieved by country 1 in pollutant control of the Lancang-Mekong River. When $2 \le i \le 6$, $\sum_{h=1}^{i} q_h(t)$ represents the industrial pollutants generated by country i and upstream country to the Lancang-Mekong River. $\left[\sum_{h=1}^{i} q_h(t) - \sum_{h=1}^{i-1} A_h(t)\right]$ indicates the pollution, habitat destruction and other human impacts status of the Lancang-Mekong River in country i.

The long-term impact of the pollution, habitat destruction and other human activities of LMRB on country i is $x_i(t)$ ($1 \le i \le 6$). Its change at time t can be expressed as:

$$x_i^{\&}(t) = \alpha\left(\sum_{h=1}^{i} q_h(t) - \sum_{h=1}^{i} A_h(t)\right) - \delta x_i(t) \quad (5)$$

In Equation (5), α represents the influence coefficient of net damage to the ecosystem, and it is a negative number. $\sum_{h=1}^{i} q_h(t) - \sum_{h=1}^{i} A_h(t)$ represents the extent of net ecological damage in the Lancang-Mekong River in country i over the long term. $\delta x_i(t)$ refers to the degree to which an ecosystem recovers itself over time in the Lancang-Mekong River in country i.

2.3. Different Pollution Control Modes

2.3.1. Individual Management

In the process of industrial pollution control by each country alone, each country can not only invest in pollution control resources to restore ecosystems, habitats and natural landscapes, but also impose fines for domestic enterprises that cause ecological damage to affect their pollutant discharge, in order to maximize the benefits of pollution control.

In the separate process of ecological environment management of transnational rivers, ecological governance of upstream countries will have positive externalities to downstream countries. The destruction and management of ecological environment, natural habitat and natural landscape in the upstream countries will not only affect the country, but also affect the downstream countries. On the contrary, the destruction and management of ecological environment, natural habitat and natural landscape in upstream countries will only affect the country, not the upstream countries.

The social welfare function of the upstream and downstream countries consists of income from production, ecological restoration costs, fines imposed on enterprises that cause ecological damage, and losses caused by ecological environment damage. Based on the previous statement, the total net benefit V_i (i = 1 and $2 \le i \le$ N, respectively) of country i through pollution control in one cycle can be expressed as:

$$V_i = \begin{cases} \max\limits_{A_i,G_i} \int_0^T e^{-\rho t}\left(\pi\left[\sum_{h=1}^{i} q_h - \sum_{h=1}^{i-1} A_h(t)\right] A_i(t) + G_i(t)q_i(t) - \frac{1}{2}A_i^2(t) - x_i(t)\right)dt & 2 \le i \le 6 \\ \max\limits_{A_i,G_i} \int_0^T e^{-\rho t}\left(\pi q_1 A_1(t) + G_1(t)q_1(t) - \frac{1}{2}A_1^2(t) - x_1(t)\right)dt & i = 1 \end{cases} \quad (6)$$

In Equation (6), $\pi\left[\sum_{h=1}^{i} q_h - \sum_{h=1}^{i-1} A_h(t)\right] A_i(t)$ represent the gains made by China and the countries on the lower reaches of the Lancang-Mekong River in the process of pollution control at time t. $G_i(t)q_i(t)$ represents the revenue from fines for enterprises that cause ecological damage. $\frac{1}{2}A_i^2(t)$ represents the cost of water pollution control. Since the inequality $\sum_{h=1}^{i} q_h - \sum_{h=1}^{i-1} A_h > 0$ is also true, it can be seen that with the increase in pollution control capacity of country i, the benefit of pollution control of country i also increases at a certain point.

According to the solution of feedback Nash equilibrium, in order to maximize the benefit of Equation (6), it must satisfy (refer to Definition 1 and 2 in the Appendix A for the specific solving process):

$$G_i^*(t) = -\frac{\pi}{2}A_i(t) - \frac{\alpha}{2}e^{\rho t}V_x(t,x) + \frac{b}{2}1 \le i \le 6 \tag{7}$$

$$A_i^*(t) = \begin{cases} \pi \sum_{h=1}^{i} [b - G_i(t)] - \pi \sum_{h=1}^{i-1} A_h(t) - \alpha e^{\rho t} V_x(t,x) & 2 \le i \le 6 \\ \pi(b - G_i(t)) - \alpha e^{\rho t} V_x(t,x) & i = 1 \end{cases} \tag{8}$$

In Equations (7) and (8), $V_x(t,x)$ is the partial derivative of V with respect to x. $Vx(t,x)$ is less than zero because the more ecological damage there is, the less utility a country gets. In Equation (8), the equation $A_1^*(t) \le A_2^*(t) \le \cdots \le A_6^*(t)$ is satisfied because $b - G_i(t) \ge A_i(t)$. According to the relation between $G_i^*(t)$ and $A_i(t)$ in Equation (7), it can be obtained that $G_1^*(t) \ge G_2^*(t) \ge \cdots \ge G_N^*(t)$.

After analysis, it can be concluded that in the process of pollution control by countries in the LMRB alone, the optimal fine $G_i(t)$ imposed by country i on domestic enterprises that cause ecological damage is inversely proportional to the resource input $A_i(t)$ of country i on pollution control. Compared with upstream countries, downstream countries invest more in pollution control resources and impose fewer penalties on enterprises.

In the process of controlling the ecological environment independently, countries in the LMRB must constantly impose fines and invest ecological resources to achieve certain effects. In addition, under this model, the downstream countries are in a very disadvantageous position. This model is not conducive to the restoration of ecological environment, habitat and natural landscape in the LMRB, nor to the promotion of the "Two Mountains Theory". Therefore, this paper discusses the cooperative ecological governance model.

2.3.2. Joint Management

Although the water resources of transnational rivers are shared by upstream and downstream countries, the upstream countries are often the first to take advantage of transnational rivers by virtue of their favorable topography, thus causing losses to the interests of the downstream countries. The LMRB is an organic whole, and the restoration of ecological environment, natural habitat and ecological landscape is not dependent on a single country to achieve the overall goal of upstream and downstream countries. For example, the reproduction and growth of migratory species and the successful migration of dolphins need the cooperation of upstream and downstream countries. Upstream and downstream countries should establish a strong organization to coordinate their relations. They are working together to improve the ecological environment, natural habitat and ecological landscape along the LMRB. This can realize the coordination of multiple interests and make the links between upstream and downstream countries closer.

It is very important for many regions to cooperate in ecological environment management. For example, since many places (especially rural areas) have a large water supply burden, it is necessary to develop and utilize water resources rationally [49]. Under the condition of pollution control by each country alone, the more upstream the country is, the smaller the pollution control input will be. Therefore, the downstream country must cooperate with the upstream country to manage the ecological environment, habitat and natural landscape in its own basin. In the process of jointly controlling the ecological environment, a community of interests will be formed. When countries 1 and 2 jointly control the ecological environment, their fines for industrial enterprises are set as $G_2(t)$. The invested pollution control resources are set as $A_2(t)$. When country 1, country 2 and country 3 jointly control the ecological environment, the fines for industrial enterprises are set as $G_3(t)$, and the pollution control resources invested are set as $A_3(t)$. Similarly, when country 1, country 2... country i jointly control the ecological environment, the fines imposed on industrial enterprises are set as $G_i(t)$, and the pollution control resources invested are set as $A_i(t)$.

As the problem of the pollution, habitat destruction and other human impacts in LMRB becomes more and more serious, cooperation between countries to control the ecological environment has become an irresistible trend. When country i ($2 \le i \le 6$) is cooperating with upstream countries for pollution control, the sum of its revenue function with upstream countries can be expressed as:

$$W_i = \max_{A_2 \cdots A_i, G_2 \cdots G_i} \int_0^T \sum_{k=2}^{i} \left(\pi \left[\sum_{h=1}^{k} q_h(t) - \sum_{h=1}^{k-1} A_h(t) \right] A_k(t) + G_k(t) q_k(t) - \frac{1}{2} A_k^2(t) - x_k(t) \right) e^{-\rho t} dt \quad (9)$$

According to the solution of feedback Nash equilibrium, in order to maximize the benefit of Equation (9), it must satisfy (refer to Definition 3 in the Appendix A for the specific solving process):

$$G_i^*(t) = \frac{b}{2} - \frac{\sum_{k=2}^{i} k}{2(i-1)} \pi A_i(t) - \frac{\sum_{k=2}^{i} k}{2(i-1)} \alpha e^{\rho t} W_x(t,x) \quad (10)$$

$$A_i^*(t) = \frac{\pi \sum_{k=2}^{i} k \left(b - G_i(t) \right) - \sum_{k=2}^{i} k \alpha e^{\rho t} W_x(t,x)}{\left[\pi \sum_{k=2}^{i} 2(k-1) \right] + i - 1} \quad (11)$$

In Equations (10) and (11), $W_x(t,x)$ is the partial derivative of W with respect to x. $W_x(t,x)$ is less than zero because the more damaged the ecological environment is, the less utility the country gains. The resources invested in pollution control of LMRB $A_i > 0$. It can be concluded from this paper that if the input pollution control resources are fixed, when $-\alpha e^{\rho t} W_x(t,x)/\pi$ is greater than a certain value, $G_2^*(t) < G_3^*(t) < G_4^*(t) < \cdots\cdots < G_N^*(t)$ will set up. In addition, when $-\alpha e^{\rho t} W_x(t,x)/\pi$ is less than that, $G_2^*(t) > G_3^*(t) > G_4^*(t) > \cdots\cdots > G_N^*(t)$ will set up. If the fine to domestic enterprises that cause ecological damage is fixed, when the profit that every unit pollution control brings is small, $A_2^*(t) < A_3^*(t) < A_4^*(t) < \cdots\cdots < A_N^*(t)$ will set up. When the profit that every unit pollution control brings is small, $A_2^*(t) > A_3^*(t) > A_4^*(t) > \cdots\cdots > A_N^*(t)$ will set up.

In the process of joint pollution control of LMRB, when the impact of the pollution, habitat destruction and other human activities is greater than the benefit of pollution control, the more countries involved in industrial pollution control, the more fines will be imposed on enterprises that cause ecological damage. On the other hand, the more countries involved in industrial pollution control, the fewer fines will be imposed on enterprises that cause ecological damage. When the benefits from pollution control are relatively large, the more countries involved in industrial pollution control, the less pollution control resources each country will invest. On the contrary, the more countries involved in industrial pollution control, the more pollution control resources each country will invest.

Countries must intervene if the ecological environment, habitat and natural landscape of the LMRB are damaged to a large extent and the lives of local residents are greatly affected. However, with the gradual progress of ecological governance, the ecological environment, habitat and natural landscape in the LMRB have been greatly restored. At this time, countries should gradually withdraw from the intervention of the basin, and focus on the self-repair of the basin.

2.3.3. Joint Management with Compensation Mechanism

According to the conclusion drawn in Section 3, under certain circumstances, the state may impose more fines for enterprises that cause ecological damage and invest fewer resources in the treatment. While this provides financially challenged countries with a viable means of controlling the pollution, habitat destruction and other human impacts in LMRB, it is clearly detrimental to the sustainable development of LMRB. If we implement the responsibility system for pollution control, we must establish a compensation mechanism for pollution control and implement the basic principle of "who pollutes, who controls". All fines imposed by country i on domestic industrial enterprises are used to invest resources in pollution control. The function expression is $A_i(t) = G_i(t)$. In this paper, pollution control resources invested by country i, output of enterprises and the long-term effects of the pollution, habitat destruction and other human impacts on country i are respectively set as $\widehat{A}_i(t)$, $\widehat{q}_i(t)$ and $\widehat{x}_i(t)$.

$$\widehat{W}_i = \max_{A_2 \cdots A_i} \int_0^T \sum_{k=2}^{i} \left(\pi \left[\sum_{h=1}^{k} \widehat{q}_h - \sum_{h=1}^{k-1} \widehat{A}_h(t) \right] \widehat{A}_k(t) + \widehat{A}_k(t) \widehat{q}_k(t) - \frac{1}{2} \widehat{A}_k^2(t) - \widehat{x}_k(t) \right) e^{-\rho t} dt \tag{12}$$

According to the solution of feedback Nash equilibrium, in order to maximize the benefit of Equation (13), it must satisfy (refer to Definition 4 in the Appendix A for the specific solving process):

$$\widehat{A}_i^*(t) = \frac{\left(\frac{i^2}{2} + \frac{i}{2} - 1\right)\pi b + (i-1)b}{(2i^2-2)\pi + 3(i-1)} - \frac{(i^2+i-2)\alpha e^{\rho t} W_x(t,x)}{(2i^2-2)\pi + 3(i-1)} \tag{13}$$

When $-\alpha e^{\rho t} W_x(t,x) b\pi$ is greater than a certain value, $\widehat{A}_2^*(t) > \widehat{A}_3^*(t) > \widehat{A}_4^*(t) > \cdots\cdots > \widehat{A}_N^*(t)$ will set up. In addition, when $-\alpha e^{\rho t} W_x(t,x) b\pi$ is less than that, $\widehat{A}_2^*(t) < \widehat{A}_3^*(t) < \widehat{A}_4^*(t) < \cdots\cdots < \widehat{A}_N^*(t)$ will set up.

In the process of joint pollution control of the Lancang-Mekong River, the establishment of compensation mechanism for pollution control of the Lancang-Mekong River is not conducive to the increase in investment in pollution control resources when the pollution, habitat destruction and other human activities have a great impact. The establishment of compensation mechanism for industrial pollution control of the Lancang-Mekong River is conducive to the increase in investment in pollution control resources when the pollution, habitat destruction and other human impacts have a small impact.

The compensation mechanism of ecological damage has a very positive effect on the restoration of ecological environment. If the ecological environment, habitat and landscape are restored to a certain extent, this mechanism is not conducive to the self-repair of the ecological environment. At this point, countries in the LMRB should gradually withdraw from the compensation mechanism for ecological damage.

2.4. International Cooperation Control Concept

2.4.1. From Pollution Control to "Two Mountains Theory"

The main purpose of "Two Mountains Theory" is to solve the problems of ecological sustainable development and ecological restoration. Countries in the LMRB can restore their ecology through fines and pollution control. This paper presents a framework of how countries in the LMRB choose pollution control models to achieve ecological restoration.

Although these three pollution control modes play a certain role in restoring the ecological environment and realizing more sustainable development, they have different effects. In other words, every pollution control model is aimed at ecological restoration. However, a certain governance model may not achieve the desired results. Choosing the right pollution control mode can realize the recovery of ecological environment faster and better, and then achieve sustainable development. The path selection of the three pollution control modes is shown in Figure 1.

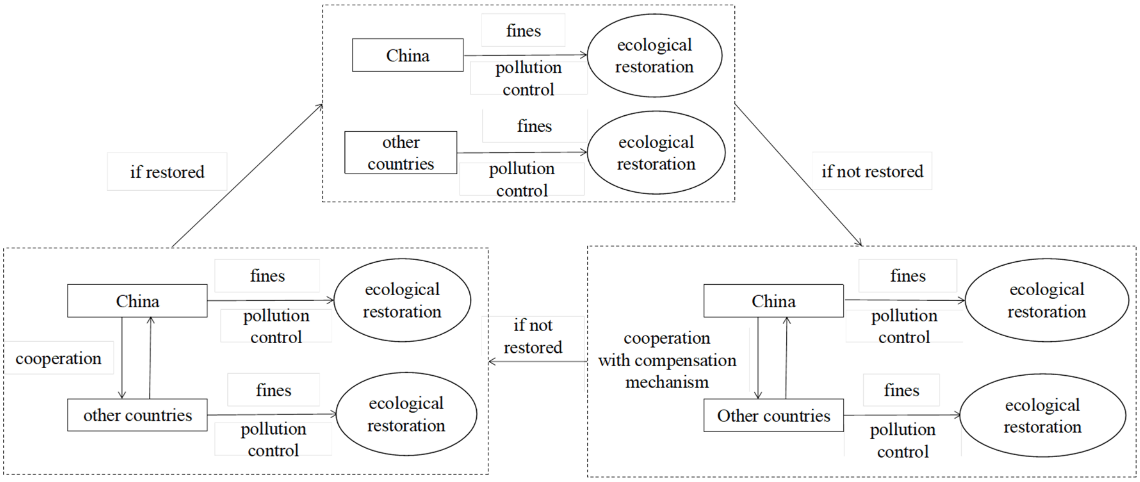

Figure 1. The path selection of the three management modes.

Pollution control is only the first step. Let habitats be re-naturalized/restored/re-wild through automatic natural dynamics, and maintain/protect/respect natural dynamics, forming a normalized mechanism for cooperation between countries. The ultimate goal of the "Two Mountain Theory" is to construct this normalization mechanism. The "Two Mountains Theory" can change the mode of economic development, and strengthen the comprehensive control of environmental. This theory can further accelerate ecological protection and restoration. The theory puts forward a solution to the seemingly irreconcilable contradiction between environmental protection and economic development in an easy-to-understand way.

2.4.2. "Two Mountains Theory" Based on Cooperation

Through the comparative analysis of the different pollution control modes mentioned, the applicable scope of different pollution control modes can be obtained. Then, this paper can find out how to choose pollution control mode to quickly carry out ecological restoration and sustainable development. However, in the process of protecting the ecological environment and economic development, the cooperation of all countries is necessary. The specific mode of the "Two Mountains Theory" based on cooperation is shown in the Figure 2.

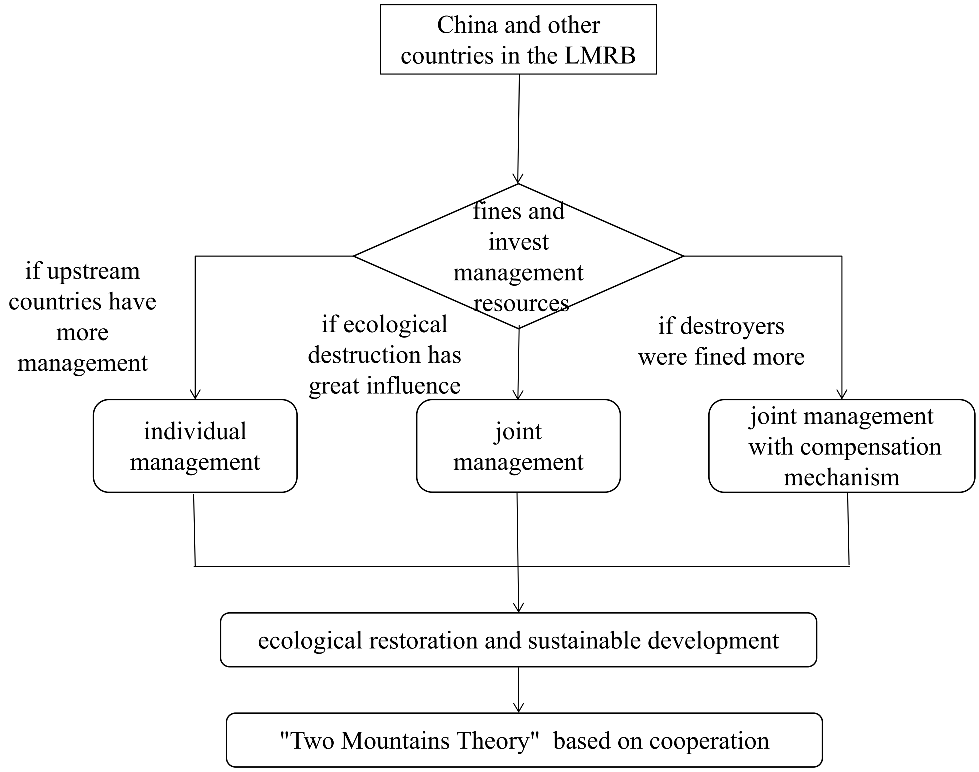

Figure 2. Specific path of "Two Mountains Theory" based on cooperation.

3. Equilibrium Results

The LMRB has a special spatial position relationship. The upstream and downstream countries can deal with the ecological destruction problem through three ways: individual pollution control, cooperative pollution control and joint pollution control under the compensation mechanism. In the first few sections of this article, the paper only discusses the optimal fines for enterprises that cause ecological damage and the optimal resource input amount under each pollution control method, but does not make a comparative analysis. This section will compare and analyze the optimal amount of fines and the optimal amount of resource input under the three pollution control methods, and then draw relevant conclusions.

3.1. Separate Management and Joint Management

As can be seen from the above, the optimal fines for enterprises that cause ecological damage and the optimal resource input for pollution control under the condition of pollution control alone are as follows:

$$G_i^*(t) = -\frac{\pi}{2}A_i(t) - \frac{\alpha}{2}e^{\rho t}V_x(t,x) + \frac{b}{2} \tag{14}$$

$$A_i^*(t) = \begin{cases} \pi\sum\limits_{h=1}^{i}[b - G_i(t)] - \pi\sum\limits_{h=1}^{i-1}A_h(t) - \alpha e^{\rho t}V_x(t,x) & 2 \le i \le N \\ \pi(b - G_i(t)) - \alpha e^{\rho t}V_x(t,x) & i = 1 \end{cases} \tag{15}$$

Under the condition of joint pollution control, the optimal amount of fine and the optimal resource input for pollution control are as follows:

$$G_i^*(t) = \frac{b}{2} - \frac{\sum\limits_{k=2}^{i}k}{2(i-1)}\pi A_i(t) - \frac{\sum\limits_{k=2}^{i}k}{2(i-1)}\alpha e^{\rho t}W_x(t,x) \tag{16}$$

$$A_i^*(t) = \frac{\pi \sum_{k=2}^{i} k\Big(b - G_i(t)\Big) - \sum_{k=2}^{i} k\alpha e^{\rho t} W_x(t,x)}{\left[\pi \sum_{k=2}^{i} 2(k-1)\right] + i - 1} \quad (17)$$

If the effect of pollution control resources and long-term ecological destruction on the utility function is certain, when $-\alpha e^{\rho t} W_x(t,x) - \pi A_i(\mathrm{t}) > 0$, it can be obtained that $G_i^*(t) < \overset{*}{G_i}(t)$. When $-\alpha e^{\rho t} W_x(t,x) - \pi A_i(\mathrm{t}) < 0$, it can be obtained that $G_i^*(t) > \overset{*}{G_i}(t)$. When $-\alpha e^{\rho t} W_x(t,x) - \pi A_i(\mathrm{t}) = 0$, it can be obtained that $G_i^*(t) = \overset{*}{G_i}(t)$. When $\sum_{h=1}^{i-1} A_h(t)$ is small, we can get $A_i^*(t) > \overset{*}{A_i}(t)$. When $\sum_{h=1}^{i-1} A_h(t)$ is large, we can get $A_i^*(t) \le \overset{*}{A_i}(t)$.

When the impact of the pollution, habitat destruction and other human impacts are greater than the benefit of pollution control, the fines for enterprises that cause ecological damage under joint control is more. When the impact of the pollution, habitat destruction and other human impacts are relatively small compared to the benefits generated by pollution control, the fines for enterprises under separate control are more. When more resources are invested in upstream pollution control, compared with joint pollution control, fewer pollution control resources are needed for separate pollution control.

The LMRB's countries need to cooperate to set up a penalty agency if the net discharge has a significant impact on the ecological environment. By fining countries that discharge large amounts of the pollution, habitat destruction and other human impacts, the basin's ecosystem can be protected. When the upstream countries have a large amount of pollution control, the downstream countries will have less human disturbance to the Lancang-Mekong River ecosystem. In this case, good results can be achieved by relying on the self-regulation ability of the ecosystem, and there will be less need for downstream countries to cooperate in pollution control [50]. On the contrary, if the upstream countries invest less in pollution control, the Lancang-Mekong River ecosystem will be damaged. It is not enough to rely on the self-recovery ability of the ecosystem, and the downstream countries must strengthen cooperation and human intervention to make the LMRB ecosystem develop towards a virtuous cycle [51].

3.2. Comparative Analysis of Two Kinds of Cooperative Governance

As can be seen from the above, the optimal resource input for pollution control under the compensation mechanism is as follows:

$$\overset{\frown *}{A_i}(t) = \frac{\left(\frac{i^2}{2} + \frac{i}{2} - 1\right)\pi b + (i-1)b}{(2i^2-2)\pi + 3(i-1)} - \frac{(i^2+i-2)\alpha e^{\rho t} W_x(t,x)}{(2i^2-2)\pi + 3(i-1)} \quad (18)$$

When $G_i(t)$ is small, we can get $\overset{*}{A_i}(t) > \hat{A}_i^*(t)$. When $G_i(t)$ is large, we can get $\overset{*}{A_i}(t) \le \hat{A}_i^*(t)$. As i gets bigger, $\hat{A}_i^*(t)$ gets smaller, and vice versa, as i gets smaller, $\hat{A}_i^*(t)$ gets bigger.

When the fines for enterprises are small, the establishment of compensation mechanism for the pollution, habitat destruction and other human impacts can reduce the input of pollution control resources. When the fines for enterprises are large, the establishment of compensation mechanism for the pollution, habitat destruction and other human impacts can increase the input of pollution control resources. The more countries that participate in cooperative governance, the less they need to invest in pollution control.

According to the above, under the compensation model, all fines imposed on enterprises that cause ecological damage are used for pollution control. When fines are higher, more pollution control is invested. In this case, it is easier to restore the ecological environment. The more countries in the LMRB participate in cooperation to control the pollution, habitat destruction and other human impacts, the better the ecological environment will recover [52].

3.3. Numerical Analysis

In the previous sections of this paper, the author constructed models to obtain the optimal fines for enterprises that cause ecological damage and the optimal pollution control resources under the three pollution control modes of Lancang-Mekong River countries: individual pollution control, cooperative pollution control and joint pollution control under the compensation mechanism. The stereogram of the change of pollution control input amount and fines for enterprises that cause ecological damage with time in the cooperation link can be characterized by numerical analysis. This section will analyze its construction model. The basic values of relevant parameters are assumed as follows, and sensitivity analysis of parameters will be conducted in order not to lose generality.

The discount factor is 0.9. Taking Vietnam in the Lancang-Mekong River Basin as an example, this paper analyzes the relationship between pollution parameters. In 2011, 50 million tons of river sand were mined [53], and the market price per ton of river sand was RMB 200. According to the results released by the National Bank of Vietnam, the refinancing interest rate in Vietnam was 5%. The bank's interest rate is also a kind of profit from the perspective of economics. If the profit of mining sand and stone is equal to the interest rate, the profit obtained by mining sand and stone every year is 200 × 5000 × 5% = RMB 500 million. If each ton of river sand is mined to pollute 2 tons of water, the treatment cost per ton of water is RMB 2, and the damage to other ecological environment is RMB 0.5 [40]. Then, the annual sewage treatment cost is 5000 × 2 × 2.5 = RMB 250 million. According to the data obtained, the ratio of industrial production to pollution control effect is 2. The gain per unit of pollution control effect is 1. The state earns 2 per unit of industrial production.

The decay rate of the pollution, habitat destruction and other human impacts is 0.8. The long-term impact of unit industrial pollutants on the LMRB was 1.

The optimal fines for enterprises that cause ecological damage and the optimal input amount of pollution control resources under the cooperation conditions are shown in Figures 3 and 4 (refer to Definition 4 in the Appendix A for the specific solving process):

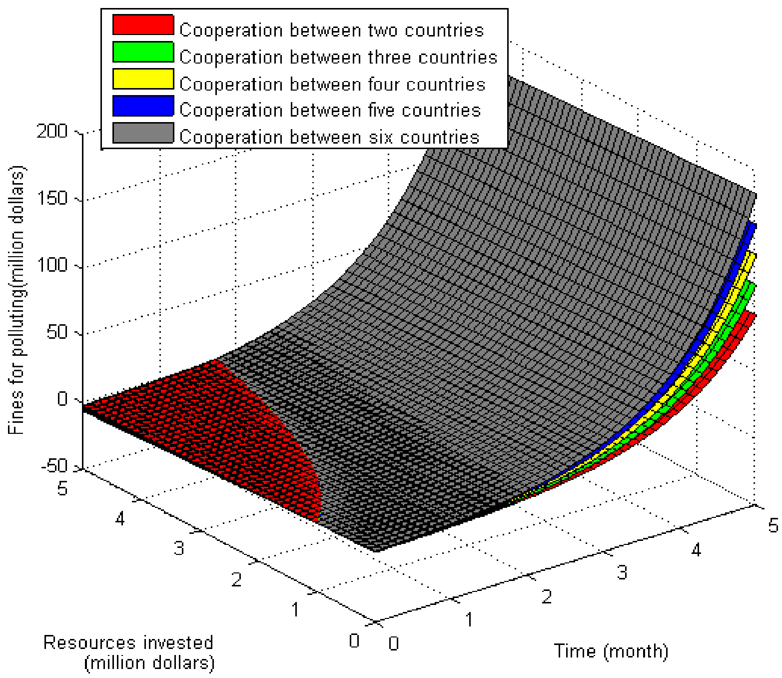

Figure 3. Optimal fines amount under cooperative condition.

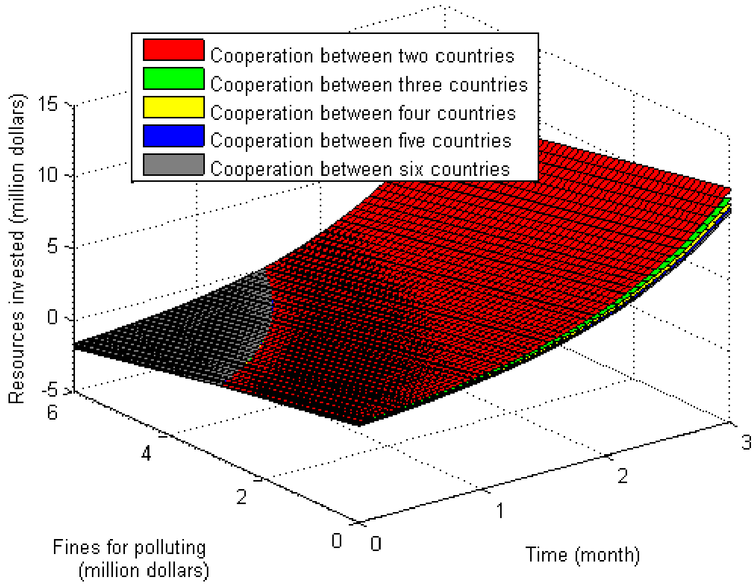

Figure 4. Optimal resource input for pollution control under cooperative condition.

The visibility of Figures 3 and 4 is not strong. In order to better show the changes of three-dimensional graphics, this paper made vertical sections of Figures 3 and 4, respectively. Figure 3 is cut along "Resource invested = 2" and "Resource invested = 4" respectively, and Figure 4 is cut along "Fines for polluting = 3" and "Fines for polluting = 6" respectively, yielding the following four figures.

Figures 3, 5 and 6 show the trend of fines imposed on polluters over time. Figures 4, 7 and 8 show the change trend of optimal pollution resource input over time. The difference between the two graphs is that the penalty imposed on polluting enterprises is taken as the dependent variable in Figures 3, 5 and 6, while the optimal input of polluting resources is taken as the dependent variable in Figures 4, 7 and 8.

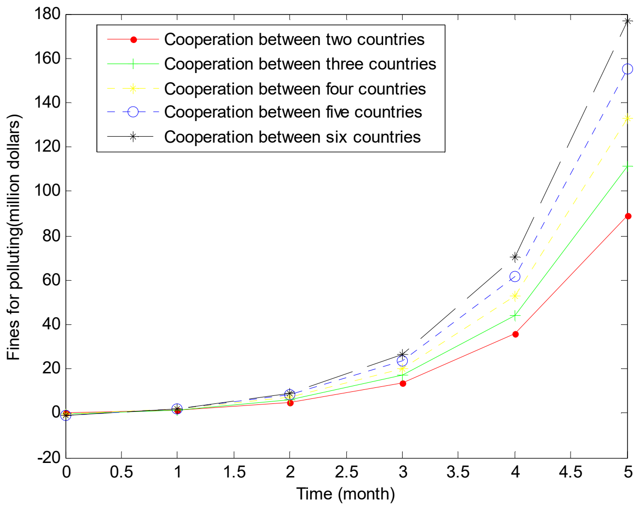

Figure 5. When the input pollution control resources are USD 2 million.

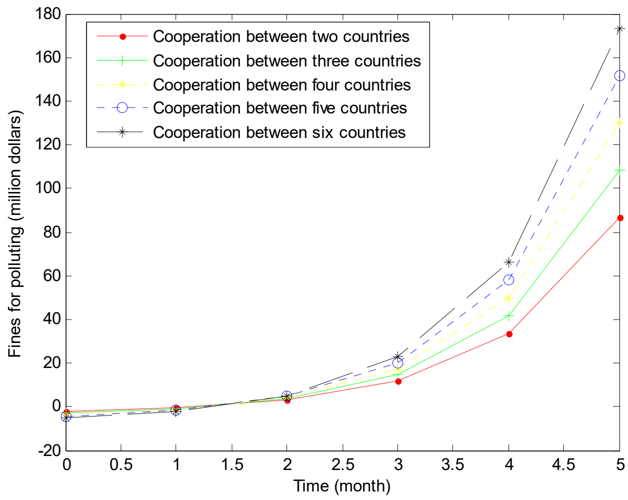

Figure 6. When the input pollution control resources are USD 4 million.

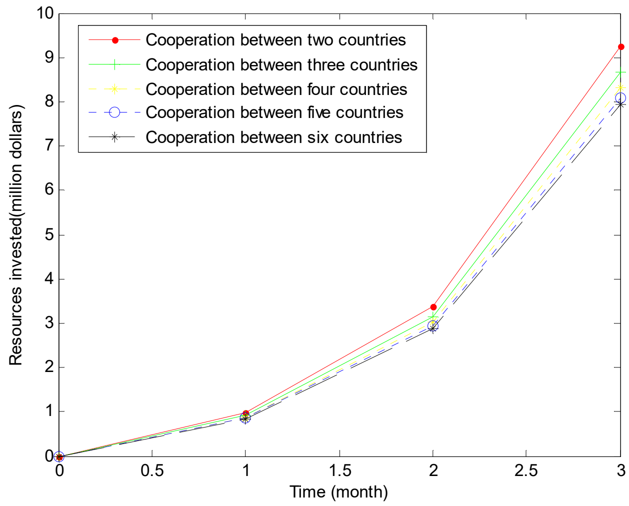

Figure 7. When the fine for polluting enterprises is USD 3 million.

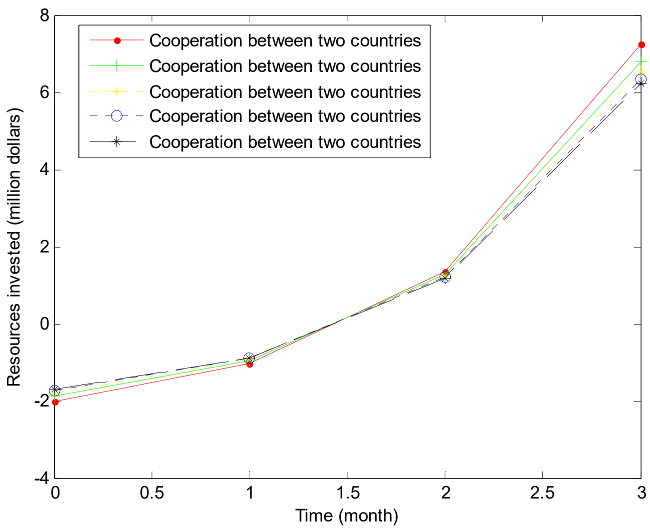

Figure 8. When the fine for polluting enterprises is USD 6 million.

The above six charts can show the relevant conclusions of cooperation in pollution control among countries in the LMRB. If more resources are invested in pollution control at the beginning of the pollution control, fewer countries will participate in the cooperation, and fewer fines will be imposed on enterprises that cause ecological damage. If the more fines are imposed on polluting companies, the more countries will cooperate and the more resources will be invested in pollution control.

Rather than imposing fines on polluters, the country's investment in pollution control resources can better help restore habitats in the LMRB. As the ecological environment of the LMRB recovers, countries will gradually reduce the disturbance to the ecosystem [54]. When transnational rivers are seriously polluted, countries should strengthen pollution control. Once the ecological environment, habitat and natural landscape of the basin have been restored, they should reduce intervention and focus on its self-regulation. At this time, if there are polluting enterprises, the punishment should be strengthened.

4. Discussion

As a freshwater resource shared by many countries, the Lancang-Mekong River can find a common divisor in line with the interests of all countries in order to achieve pollution control. Untreated sewage from upstream countries will affect urban life, industrial and agricultural irrigation water in downstream countries and even damage the ecosystem of the entire basin. No country in the LMRB can be immune from the pollution, habitat destruction and other human impacts, and strengthening cooperation on pollution control between countries has become a historical necessity [55]. As for the pollution control problem, the existing research mostly uses the traditional game methods such as static game, dynamic game and cooperative game [56], and few scholars consider the one-way externality of the transnational river water pollution control problem. In this paper, differential game is used to find the answer to this difficult problem. Differential game is a time continuous game. In addition, the restoration of ecological habitats is a long-term process. Differential game can analyze the ecological restoration and sustainable development of habitat more effectively.

If the upstream countries do more to control the pollution, habitat destruction and other human impacts in its own river basin, downstream countries will need fewer resources to control the pollution, habitat destruction and other human impacts. Strengthening economic cooperation among Lancang-Mekong countries is not only conducive to the economic growth and stability of the countries in the basin, but also to the new development of the countries in the basin in regional economic cooperation. It is also conducive to the building of the ASEAN Economic Community, narrowing the economic development gap among ASEAN countries, and facilitating the coordinated development of China, Southeast Asia and South Asia. The Lancang-Mekong Cooperation (LMC) promoted by China is a new sub-regional cooperation mechanism tailored to the common needs of the six countries and an important part of the overall cooperation between China and ASEAN [57]. Therefore, the Second Lancang-Mekong Cooperation (LMC) Leaders' Meeting held in Cambodia in January 2018 issued the Five-year Plan of Action for Lancang-Mekong Cooperation (2018–2022) [58] and the Phnom Penh Declaration of the Second Lancang-Mekong Cooperation (LMC) Leaders' Meeting [59]. Thanks to the continuous cooperation of countries in the upper and lower reaches of the LMRB to control pollution, the wildlife in the basin has become more abundant, while the water has become clearer, and the natural landscape such as grass and mountains has become more beautiful [60].

The restoration of ecological environment, habitat and natural landscape in the LMRB cannot always depend on ecological governance activities. Countries in the basin should withdraw from pollution control activities at an appropriate time. The ecological environment has a certain self-regulation ability. The ecosystem of the Lancang-Mekong River has negative feedback regulation ability, resistance stability and resilience stability. In addition, it has the ability to resist external disturbance and restore the original state. However, the countries in the LMRB should not increase the intensity of the pollution, habitat destruction and other human impacts. Once the ecological environment is damaged, it needs to consume a lot of material and financial resources to repair it. This will require continuous pollution control until the Lancang-Mekong ecosystem recovers to a certain extent. The purpose of ecological restoration is to improve, restore or rebuild the natural ecosystem, which has been degraded, damaged or destroyed, so as to enhance its self-regulation and self-repair function and maintain ecological balance [55]. For the damaged or destroyed ecosystem, because the original ecological balance has been broken, natural restoration alone is likely to be unable to reverse the damaged ecosystem, or the reversal cycle is long, and appropriate artificial restoration measures must be used. The damage of ecological environment, habitat and natural landscape can be stopped quickly and reversed by the aid of artificial restoration. Finally, it can create conditions and environment for natural restoration, accelerate restoration process and improve restoration efficiency.

Different from some papers that focus on ecosystem health assessment in the LMRB [61], this paper mainly studied how to protect and restore the ecosystem in this basin. Due to the self-regulation capacity of the LMRB, the ecological environment of the Lancang-Mekong River has always been able to restore its own balance. However, countries in the LMRB should not increase the destruction of the ecological environment and reduce the governance of the ecological environment just because the ecological environment has self-regulation ability. Countries in the basin should choose appropriate pollution control models. Every country should strike a balance between ecological protection and economic development. When the ecological environment, habitat and natural landscape of the LMRB are restored to a certain stage, countries should reduce their intervention in the basin. In addition, the Lancang-Mekong River can gradually restore its ecological environment, habitat and natural landscape to a better state by virtue of its self-recovery ability.

Different from some scholars studying how to protect the ecological environment by micro means [62], this paper provides macro theories and ideas. The “Two Mountains Theory” based on cooperation can have a significant positive impact on the sustainable development of the world’s ecological environment, habitats and natural landscapes. For example, Kenya and five east African countries fully carried out ecological protection cooperation in the construction of the Nairobia-Mombasa Railway. In this process, Kenya is sticking to both economic and environmental benefits. The project successfully protected the Mombasa mangrove forest and ensured the free passage of all types of wildlife [63]. In building coal-fired power plants, Bali uses advanced technology and cooperates fully with other countries to control the pollution, habitat destruction and other human impacts while keeping the nearby cove natural [64]. This not only promotes the economic development, but also effectively protects the ecological environment.

5. Conclusions

This article introduces this practice of “Two Mountains Theory” with an example of pollution control in the LMRB. This paper assumes that countries along the Lancang-Mekong River can deal with the pollution, habitat destruction and other human impacts by fining enterprises that cause pollution, habitat destruction, biodiversity loss and investing pollution control resources. Considering the spatial and positional relationship between the upper and lower reaches of the Lancang-Mekong River, this paper constructs a differential game model of pollution control between the upper and lower reaches of the Lancang-Mekong River under separate pollution control, joint pollution control and compensation mechanism. The research considers that the upstream and downstream countries can carry out water pollution control by imposing fines on enterprises that cause ecological damage and investing in pollution control facilities. Firstly, the differential game model of pollution control by individual countries and international cooperation is established. Then, a differential game model of joint pollution control with compensation mechanism is established under the cooperation framework. Finally, the feedback Nash equilibrium of each state is obtained. The study shows that at the beginning stage of management, if more pollution control resources are input, fewer countries will participate in cooperation. When the amount of fines for enterprises is relatively small, the establishment of ecological destruction compensation mechanism is not conducive to the input of pollution control resources. That is, after ecological governance reaches a certain stage, it is necessary to protect the ecological environment, habitat and natural landscape through the self-regulation ability of natural ecology. The coordinated development of economic development and ecological civilization construction is the core purpose of the "Two Mountains Theory". Therefore, the case of the Lancang-Mekong River fully illustrates the feasibility of the "Two Mountains Theory" based on cooperation.

The research in this paper can also be expanded. For example, this paper only assumes that the source of ecological destruction in the Lancang-Mekong River comes from industrial enterprises, without considering ecological damage caused by agriculture and other reasons. In future studies, ecological damage caused by agriculture and other reasons can be taken into account to study related issues. In addition, the research in this paper is not only applicable to pollution control issues, but also has certain reference significance for related issues such as the distribution of cross-border water resources and the anti-terrorism.

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Appendix A

Definition A1. *The strategy set* $\left\{\left[G_i^*(t), A_i^*(t)\right] = \left[\varphi_i^G(t), \varphi_i^A(t)\right], 2 \le i \le 6\right\}$ *provides a feedback solution to a Nash equilibrium for differential game (6). When there are functions* $V(t,x) : [0,T] \times R \to R$ *that can be continuously differentiated, the following partial differential equations are satisfied*:

$$\begin{aligned}-V_t(t,x) = \max_{G_i,A_i}\Bigg\{ &\left[\pi\left(\sum_{h=1}^{i} q_h^*(t) - \sum_{h=1}^{i-1} A_h(t)\right)A_i(t) + G_i(t)q_i^*(t) - \tfrac{1}{2}A_i^2(t) - x_i(t)\right]e^{-pt} \\ &+V_x(t,x)\left[\alpha\left(\sum_{h=1}^{i} q_h^*(t) - \sum_{h=1}^{i} A_h(t)\right) - \delta x_i(t)\right]\Bigg\}\end{aligned} \tag{A1}$$

Among them, $V(t,x)$ represents the return function of country i ($2 \le i \le 6$) in time $[t,T]$. It can be expressed as:

$$V_i = \int_t^T e^{-\rho(\tau - t)}\left(\pi\left[\sum_{h=1}^{i} q_h(\tau) - \sum_{h=1}^{i-1} A_h(\tau)\right]A_i(\tau) + G_i(\tau)q_i(\tau) - \frac{1}{2}A_i^2(\tau) - x_i(\tau)\right)d\tau \tag{A2}$$

Definition A2. *The strategy set* $\left\{\left[G_i^*(t), A_i^*(t)\right] = \left[\varphi_i^G(t), \varphi_i^A(t)\right], i = 1\right\}$ *provides a feedback solution to a Nash equilibrium for differential game (6). When there are functions* $V(t,x) : [0,T] \times R \to R$ *that can be continuously differentiated, the following partial differential equations are satisfied*:

$$\begin{aligned}-V_t(t,x) = \max_{G_1,A_1}\Big\{ &\left[\pi q_1^* A_1(t) + G_1(t)q_1^*(t) - \tfrac{1}{2}A_1^2(t) - x_1(t)\right]e^{-pt} \\ &+V_x(t,x)\left[\alpha\left(q_1^*(t) - A_1(t)\right) - \delta x_1(t)\right]\Big\}\end{aligned} \tag{A3}$$

Definition A3. *The strategy set*

$$\left\{\left[G_1^*(t),\cdots,G_i^*(t),A_1^*(t),\cdots,A_i^*(t)\right]=\left[\varphi_1^G(t,x),\cdots,\varphi_i^G(t,x),\varphi_1^A(t,x),\cdots,\varphi_i^A(t,x)\right],2\le i\le 6\right\}$$

provides a feedback solution to a Nash equilibrium for differential game (9). When there are functions $V(t,x):[0,T]\times R\to R$ *that can be continuously differentiated, the following partial differential equations are satisfied:*

$$\begin{aligned}-W_t(t,x)=\max_{G_2\cdots G_i,A_2\cdots A_i}&\left\{\sum_{k=2}^{i}\left[\left(k\pi q_i^*(t)-(k-1)\pi A_i(t)\right)A_i(t)+G_i(t)q_i^*(t)\right.\right.\\&\left.-\tfrac{1}{2}A_i^2(t)-x_k(t)\right]e^{-\rho t}+\sum_{k=2}^{i}\left[\left(kq_i^*(t)-kA_i(t)\right)\alpha-\delta x_k(t)\right]W_x(t,x)\}\end{aligned} \tag{A4}$$

Among them, $W_i(t,x)$ represents the return function of country i (i = 1) in time $[t,T]$. It can be expressed as:

$$W_i=\sum_{k=2}^{i}\int_t^T e^{-\rho(\tau-t)}\left(\pi\left[\sum_{h=1}^{k}q_h(\tau)-\sum_{h=1}^{k-1}A_h(\tau)\right]A_k(\tau)+G_k(\tau)q_k(\tau)-\frac{1}{2}A_k^2(\tau)-x_k(\tau)\right)d\tau \tag{A5}$$

In this paper, partial derivatives are obtained for $G_2(t)$, $G_3(t)$, $G_4(t)$, $G_5(t)$, $G_6(t)$:

$$G_2^*(t)=\frac{b}{2}-\pi A_2(t)-\alpha e^{\rho t}W_x(t,x)$$

$$G_3^*(t)=\frac{b}{2}-\frac{5\pi}{4}A_3(t)-\frac{5}{4}\alpha e^{\rho t}W_x(t,x)$$

$$G_5^*(t)=\frac{b}{2}-\frac{7\pi}{4}A_5(t)-\frac{7}{4}\alpha e^{\rho t}W_x(t,x)$$

$$G_6^*(t)=\frac{b}{2}-2\pi A_6(t)-2\alpha e^{\rho t}W_x(t,x)$$

By mathematical induction, we can obtain:

$$G_i^*(t)=\frac{b}{2}-\frac{\sum\limits_{k=2}^{i}k}{2(i-1)}\pi A_i(t)-\frac{\sum\limits_{k=2}^{i}k}{2(i-1)}\alpha e^{\rho t}W_x(t,x)$$

In this paper, partial derivatives are obtained for $A_2(t)$, $A_3(t)$, $A_4(t)$, $A_5(t)$, $A_6(t)$:

$$A_2^*(t)=\frac{2\pi}{2\pi+1}\left(b-G_2(t)\right)-\frac{2}{2\pi+1}\alpha e^{\rho t}W_x(t,x)$$

$$A_3^*(t)=\frac{5\pi}{6\pi+2}\left(b-G_3(t)\right)-\frac{5}{6\pi+2}\alpha e^{\rho t}W_x(t,x)$$

$$A_4^*(t)=\frac{9\pi}{12\pi+3}\left(b-G_4(t)\right)-\frac{9}{12\pi+3}\alpha e^{\rho t}W_x(t,x)$$

$$A_5^*(t)=\frac{14\pi}{20\pi+4}\left(b-G_5(t)\right)-\frac{14}{20\pi+4}\alpha e^{\rho t}W_x(t,x)$$

$$A_6^*(t)=\frac{20\pi}{30\pi+5}\left(b-G_6(t)\right)-\frac{20}{30\pi+5}\alpha e^{\rho t}W_x(t,x)$$

Similarly, by mathematical induction, we can obtain:

$$A_i^*(t) = \frac{\pi \sum_{k=2}^{i} k\Big(b - G_i(t)\Big) - \sum_{k=2}^{i} k\alpha e^{\rho t} W_x(t,x)}{\left[\pi \sum_{k=2}^{i} 2(k-1)\right] + i - 1}$$

Definition A4. *The strategy set* $\left\{\left[\widehat{A}_1^*(t), \cdots, \widehat{A}_i^*(t)\right] = \left[\widehat{\varphi}_1^A(t,x), \cdots, \widehat{\varphi}_i^A(t,x)\right], 2 \le i \le 6\right\}$ *provides a feedback solution to a Nash equilibrium for differential game (13). When there are functions* $V(t,x) : [0,T] \times R \to R$ *that can be continuously differentiated, the following partial differential equations are satisfied*:

$$\begin{aligned} -W_t(t,x) = \max_{A_2 \cdots A_i} \Bigg\{ \sum_{k=2}^{i} \Bigg[\pi \Bigg(\sum_{h=1}^{k} \widehat{q}_h^*(t) - \sum_{h=1}^{k-1} \widehat{A}_h(t) \Bigg) \widehat{A}_k(t) + \widehat{A}_k(t) \widehat{q}_k^*(t) - \tfrac{1}{2} \widehat{A}_k^2(t) - \widehat{x}_k(t) \Bigg] \\ \cdot e^{-pt} + W_x(t,x) \sum_{k=2}^{i} \Bigg[\alpha \Bigg(\sum_{h=1}^{k} \widehat{q}_h^*(t) - \sum_{h=1}^{k} \widehat{A}_h(t) \Bigg) - \delta \widehat{x}_k(t) \Bigg] \Bigg\} \end{aligned} \tag{A6}$$

In this paper, partial derivatives are obtained for $\widehat{A}_2(t)$, $\widehat{A}_3(t)$, $\widehat{A}_4(t)$, $\widehat{A}_5(t)$, $\widehat{A}_6(t)$:

$$\widehat{A}_2^*(t) = \frac{2\pi b + b}{6\pi + 3} - \frac{4\alpha}{6\pi + 3} e^{\rho t} W_x(t,x)$$

$$\widehat{A}_3^*(t) = \frac{5\pi b + 2b}{16\pi + 6} - \frac{10\alpha}{16\pi + 6} e^{\rho t} W_x(t,x)$$

$$\widehat{A}_4^*(t) = \frac{9\pi b + 3b}{30\pi + 9} - \frac{18\alpha}{30\pi + 9} e^{\rho t} W_x(t,x)$$

$$\widehat{A}_5^*(t) = \frac{14\pi b + 4b}{48\pi + 12} - \frac{28\alpha}{48\pi + 12} e^{\rho t} W_x(t,x)$$

$$\widehat{A}_6^*(t) = \frac{20\pi b + 5b}{70\pi + 15} - \frac{40\alpha}{70\pi + 15} e^{\rho t} W_x(t,x)$$

Similarly, by mathematical induction, we can obtain: [6]

$$\widehat{A}_i^*(t) = \frac{\left(\frac{i^2}{2} + \frac{i}{2} - 1\right)\pi b + (i-1)b}{(2i^2 - 2)\pi + 3(i-1)} - \frac{(i^2 + i - 2)\alpha e^{\rho t} W_x(t,x)}{(2i^2 - 2)\pi + 3(i-1)}$$

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The Innovative Polygon Trend Analysis (IPTA) as a Simple Qualitative Method to Detect Changes in Environment—Example Detecting Trends of the Total Monthly Precipitation in Semiarid Area

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Abstract: Precipitation is a crucial component of the water cycle, and its unpredictability may dramatically influence agriculture, ecosystems, and water resource management. On the other hand, climate variability has caused water scarcity in many countries in recent years. Therefore, it is extremely important to analyze future changes of precipitation data in countries facing climate change. In this study, the Innovative Polygon Trend Analysis (IPTA) method was applied for precipitation trend detection at seven stations located in the Wadi Sly basin, in Algeria, during a 50-year period (1968–2018). In particular, the IPTA method was applied separately for both arithmetic mean and standard deviation. Additionally, results from the IPTA method were compared to the results of trend analysis based on the Mann–Kendall test and the Sen's slope estimator. For the different stations, the first results showed that there is no regular polygon in the IPTA graphics, thus indicating that precipitation data varies by years. As an example, IPTA result plots of both the arithmetic mean and standard deviation data for the Saadia station consist of many polygons. This result means that the monthly total precipitation data is not constant and the data is unstable. In any case, the application of the IPTA method showed different trend behaviors, with a precipitation increase in some stations and decrease in others. This increasing and decreasing variability emerges from climate change. IPTA results point to a greater focus on flood risk management in severe seasons and drought risk management in transitional seasons across the Wadi Sly basin. When comparing the results of trend analysis from the IPTA method and the rest of the analyzed tests, good agreement was shown between all methods. This shows that the IPTA method can be used for preliminary analysis trends of monthly precipitation.

Keywords: precipitation; innovative polygon trend analysis; arithmetic mean; standard deviation; Wadi Sly; Algeria

1. Introduction

Precipitation can be considered among the major variables that are frequently used to trace the extent and magnitude of climate variability [1]. In fact, Gautam et al. [2] and Chen et al. [3] showed that hanging patterns of precipitation are among the chief consequences attributed to climate variability.

In particular, precipitation seasonality and variability are important factors to understand in hydrological processes in a catchment; they are paramount for many sectors of the economy, like agricultural [4], and they have serious environmental implications that can greatly influence the food security and ecological sustainability of the different regions on the world [5]. The influence of precipitation on the environment can be altered by land cover, especially by forest. Juez et al. [6] showed that forest can influence hydrological dynamics and delay catchments response on high precipitation. Moreover, overland flow can occur rarely because of the strong infiltration rate [7]; a strong influence reduces evapotranspiration, and thus, increases low flow [8] as well as reduces nutrient and sediment load [9]. An increase of forest area in catchments can also protect against the effect of climate change on water resources.

Within this context, long-term data with different time resolutions are used to evaluate precipitation variability [10–13] that is linked with synoptic conditions and large-scale circulation [14,15], e.g., phase pace of NAO (North Atlantic Oscillation) teleconnection patterns [16,17] and sea surface temperature (SST) anomalies [18,19]. In particular, the Mediterranean region is affected by high precipitation variability, at both a temporal and spatial scale, due to its geographical position between two strongly contrasting masses of water: the Atlantic Ocean and the Mediterranean Sea [20]. An Additional feature determining high variability of precipitation in this region is the presence of various mountain ranges distributed along the coastal areas from east to west [21]. For example, in the Macta basin (Algeria), Elouissi et al. [22] observed decreasing trends of monthly precipitations in the northern part, close to the Mediterranean Sea coastal area, and increasing ones in the southern part. Based on the Coupled Model Intercomparison Project phase 6 (CMIP6), Bogcaci et al. [23] identified increasing precipitation projection in winter and spring over the east of the Black Sea Region and north-east of Anatolia, with a consequent increase in flood risk. El-Geizry [24] detected high seasonal variations of precipitation in the southern Levantine Basin, Egypt.

To detect temporal changes of hydroclimatological phenomena, trend analyses are the most common methods used. These analyses can help monitor global changes in different environmental components. Moreover, they are very important especially in semiarid regions where high risk of water scarcity occurrs; thus, the knowledge about the hydro-meteorology phenomena behavior can be used in water resources management and planning. Generally, trend analysis is based on non-parametric tests, such as the Mann–Kendall test or Sen's slope methods, which are more appropriate than parametric ones to deal with non-normally distributed data [25,26]. These tests have some limitations, linked with the null hypothesis (H_0) [27], which assumes serial correlation of data [28,29]. Serinaldi et al. [30] showed that even if the empirical estimation of trends based on commonly statistical tests is always feasible from a numerical point of view, it has poor information sources of non-stationarity without assuming a priori additional information on the underlying stochastic process.

With the aim to overcome such a problem, the Innovative Trend Analysis (ITA) was proposed [31] and applied in several studies on precipitation variability worldwide. For example, Caloiero et al. [32], Caloiero [33], Gedefaw et al. [34], Haktanir and Citakoglu [35], and Malik et al. [36] applied this methodology on monthly, seasonal, and annual precipitation series of India, Ethiopia, Italy, New Zealand, and Turkey, respectively. Due to the large use of the ITA, recently, some updates of this method have been proposed, such as the Innovative Triangular Trend Analysis (ITTA) and the Innovative Polygon Trend Analysis (IPTA) [37–39]. In particular, the IPTA [40] is an approach that helps to identify the trend in a given series and also trend transitions between successive sections of two equal segments from the original hydro-meteorological time series leading to trend polygon. Therefore, it constitutes a productive basis for finer interpretations with linguistic and numerical interpretations and inferences from a given time series.

The purpose of this study is to investigate trends of monthly total precipitation data of seven selected precipitation monitoring stations in the Wadi Sly basin in north Algeria for the period 1968–2018. With this aim, the Innovative Polygon Trend Analysis (IPTA) technique was applied [40]. Moreover, results from the IPTA method were compared with results of trend analysis based on commonly known methods like the Mann–Kendall test (MK) and the Sen's estimator (SS).

2. Materials and Methods

2.1. Study Area

The Wadi Sly basin is located in the northwest of Algeria and has an area of 1225 km^2. It is a basin characterized by a typically semi-arid Mediterranean climate, with warm summers and cold winters. The database used in this study consists of seven high-quality and complete monthly precipitation series ranging from 1968–2018, with an average density of one station per 175 km^2 (Figure 1).

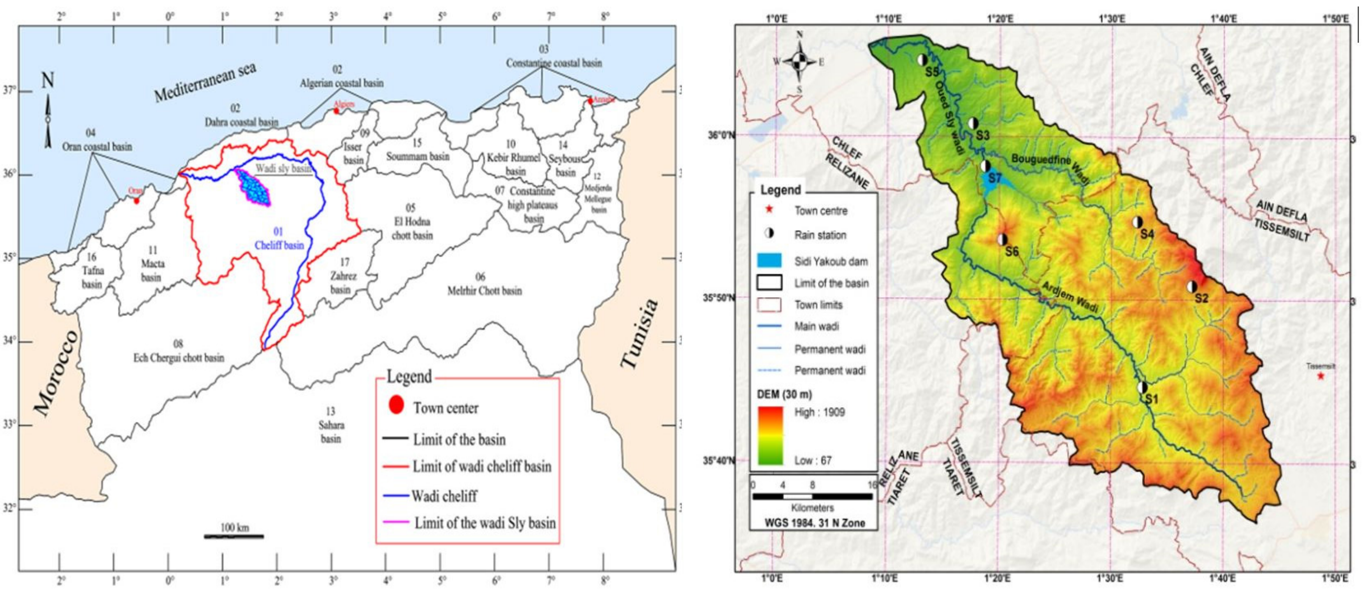

Figure 1. Localization of the selected rain gauges on DEM.

2.2. Data Analysis

The National Agency of Water Resources (ANRH) contributed data for this study from seven precipitation stations across Wadi Sly basin (Figure 1 and Table 1), each having long-term monthly precipitation records from 1968 to 2018.

Table 1. Precipitation Stations Characteristics.

Stations	ID	Name	Longitude (°)	Latitude (°)	Elevation (m)	Period of Observation
S1	012304	Souk El Had	1.55	35.75	550	1968/69–2017/18
S2	012306	Bordj Bounaama	1.62	35.85	1050	1968/69–2017/18
S3	012307	Ain Lellou	1.54	35.93	900	1968/69–2017/18
S4	012308	Ouled Ben A.E.K.	1.27	36.03	160	1968/69–2017/18
S5	012309	Oued Sly	1.20	36.09	95	1968/69–2017/18
S6	012316	SAADIA	1.34	35.90	1000	1968/69–2017/18
S7	012318	Sidi Yagoub Bge	1.32	35.97	202	1968/69–2017/18

However, the duration of these stations' records varies, and some have missing records; as a result, only observation stations with data series covering 70% or more of the whole period were chosen for our study in order to improve data quality. The data was subject to quality control and data gap filling using linear regression.

The descriptive statistics of monthly and annual precipitation in the Wadi Sly basin are shown in Table 2. According to these statistics, winter can be identified as the rainiest season for all the stations, with more than 40% of the total annual precipitation falling in this season.

Table 2. Descriptive statistics of monthly and annual precipitation (mm) in the Wadi Sly basin (1968–2018).

		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Year
S1	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	153.00
	Max	78.60	221.70	184.70	258.00	253.60	175.90	209.30	102.40	71.10	33.00	28.50	31.30	819.50
	Mean	15.57	32.48	45.22	56.27	66.44	53.94	46.50	34.60	20.39	3.80	1.34	2.40	378.95
	SD	16.90	37.58	39.18	50.95	53.13	45.26	39.66	26.12	22.84	8.00	4.75	6.48	155.73
	C (%)	4.11	8.57	11.93	14.85	17.53	14.23	12.27	9.13	5.38	1.00	0.35	0.63	100.00
S2	Min	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	172.07
	Max	75.00	170.90	153.70	189.80	247.60	251.70	216.00	176.59	155.74	81.20	16.10	48.00	763.40
	Mean	16.80	38.82	55.34	60.97	65.67	60.50	59.98	56.37	25.80	7.68	0.83	2.43	451.21
	SD	17.54	42.33	40.77	41.72	52.91	59.25	47.01	53.45	37.86	17.14	2.59	7.88	148.17
	C (%)	3.72	8.60	12.26	13.51	14.55	13.41	13.29	12.49	5.72	1.70	0.18	0.54	100.00
S3	Min	0.00	0.00	0.00	0.00	0.59	4.00	6.10	0.00	0.00	0.00	0.00	0.00	212.31
	Max	62.40	150.58	193.60	138.70	191.30	133.90	158.60	154.00	197.30	58.60	17.40	31.80	687.49
	Mean	17.23	35.83	55.77	53.83	77.64	57.52	62.44	42.43	25.58	4.89	0.84	2.46	436.47
	SD	16.61	32.87	46.92	28.36	53.02	36.59	35.16	35.40	41.87	10.20	2.74	6.82	122.71
	C (%)	3.95	8.21	12.78	12.33	17.79	13.18	14.31	9.72	5.86	1.12	0.19	0.56	100.00
S4	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	177.60
	Max	68.40	219.35	116.10	102.00	166.30	140.60	122.59	165.40	105.05	39.54	13.20	52.80	612.40
	Mean	15.37	31.10	44.96	43.73	45.89	48.16	47.60	39.91	25.52	6.37	1.00	3.24	352.87
	SD	16.02	40.67	28.17	26.93	32.17	36.43	32.68	36.71	25.82	9.48	2.57	10.11	100.74
	C (%)	4.35	8.81	12.74	12.39	13.00	13.65	13.49	11.31	7.23	1.81	0.28	0.92	100.00
S5	Min	0.00	0.00	0.00	1.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	129.60
	Max	37.90	123.00	94.70	112.00	151.30	118.00	110.40	125.90	146.80	24.55	16.55	23.00	466.01
	Mean	9.33	24.73	39.84	39.55	42.86	43.94	39.91	26.65	20.51	4.90	1.39	1.84	295.46
	SD	9.81	23.96	23.30	27.83	30.35	34.28	30.32	26.10	28.68	7.38	3.50	4.31	81.08
	C (%)	3.16	8.37	13.48	13.39	14.51	14.87	13.51	9.02	6.94	1.66	0.47	0.62	100.00
S6	Min	0.00	0.00	0.65	0.00	0.00	7.65	0.00	0.00	0.00	0.00	0.00	0.00	173.74
	Max	117.00	308.45	211.53	231.30	181.40	170.70	214.30	197.90	96.00	43.10	34.24	27.90	881.27
	Mean	23.33	44.60	66.47	75.18	68.44	72.81	69.59	42.07	21.64	7.03	2.56	2.29	496.03
	SD	26.54	54.42	55.58	51.13	51.83	46.77	48.95	49.04	27.95	11.46	6.38	5.87	157.77
	C (%)	0.05	0.09	0.13	0.15	0.14	0.15	0.14	0.08	0.04	0.01	0.01	0.00	1.00
S7	Min	0.00	0.10	0.00	0.00	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	136.05
	Max	68.70	165.20	127.60	105.50	167.70	95.38	107.40	134.80	75.30	31.70	14.70	19.10	543.13
	Mean	12.98	24.17	40.48	35.60	43.19	40.45	39.62	39.01	21.88	5.58	1.19	2.40	306.56
	SD	14.53	29.16	29.20	26.13	29.19	28.74	27.41	36.73	18.96	8.65	2.81	4.18	91.85
	C (%)	4.23	7.88	13.21	11.61	14.09	13.19	12.92	12.72	7.14	1.82	0.39	0.78	100.00

SD = Standard deviation; C (%) = Contribution, in percentage, to the total annual precipitation.

2.3. Innovative Polygon Trend Analysis Method

The IPTA was first proposed by Sen et al. [40]. For monthly precipitation records, given a series $x_1, \ldots, x_n$ of n years, the following monthly matrix was constructed:

$$\begin{bmatrix} x_{1,1}, & x_{1,2}, & . & . & . & x_{1,12} \\ x_{2,1}, & x_{1,2}, & . & . & . & x_{1,12} \\ . & . & . & . & . & . \\ x_{i,1}, & x_{i,2}, & . & . & . & x_{i,12} \\ . & . & . & . & . & . \\ x_{n,1}, & x_{n,2}, & . & . & . & x_{n,12} \end{bmatrix} \quad (1)$$

Then, the matrix was divided in two halves, the upper part (the first) for $i = 1, \ldots, n/2$ and the lower part (the second) for $i = n/2 + 1, \ldots, n$, respectively, and the next 12 sets of parameters (e.g., arithmetic mean, standard deviation, skewness coefficient, maximum, minimum, etc.) providing detailed information about the monthly precipitation variations, were calculated for each subseries. Results of this analysis are represented in a Cartesian system in which the first series is placed on the X-axis and the second series is placed on the Y-axis (Figure 2).

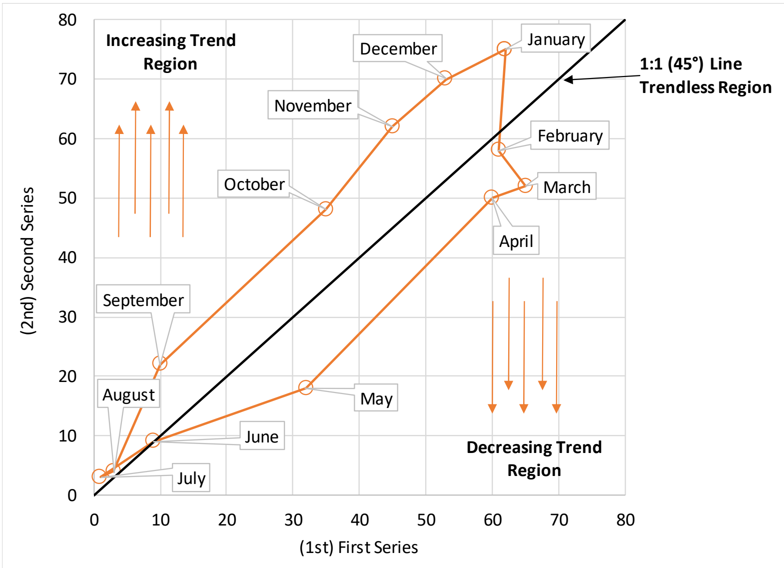

Figure 2. Hypothetical Innovative Polygon Trend Analysis template for monthly records.

As a consequence, the transition from 1 month's precipitation to the next is visible. Given the monthly precipitation distribution in the Cartesian system, homogeneity precipitation (single polygon) or non-homogeneity structure (multiple polygons) can be identified. Detailed information about the IPTA method can be found in Sen et al. [40].

2.4. The Mann-Kendal Test

The Mann–Kendall method is a non-parametric test for detecting trends in climatological and hydrological time series.

The Mann–Kendall test statistic S is calculated with the following equation [41,42]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(P_j - P_k) \tag{2}$$

where n is the number of data. P is the precipitation values at times i and j ($j > i$), and sgn is the sign function given as:

$$sgn(P_j - P_k) = \begin{cases} +1 \; if(P_j - P_k) > 0 \\ 0 \; if(P_j - P_k) = 0 \\ -1 \; if(P_j - P_k) < 0 \end{cases} \tag{3}$$

The variance of S is computed by

$$Var(S) = \frac{[n(n-1)(2n+5)] - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{4}$$

where t_i is the number of ties of extent i, and m is the number of tied rank groups. For n larger than 10, the standard normal Z test statistic is computed as the Mann–Kendall test statistic as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \, if \; S > 0 \\ 0 \, if \; S = 0 \\ \frac{S-1}{\sqrt{Var(S)}} \, if \; S < 0 \end{cases} \tag{5}$$

2.5. The Sen's Estimator

If a linear trend is observed in a time series, then the Sen's slope estimator can be used [43]. The slope estimates of N pairs of precipitation pairs are computed based on equation:

$$Qi = \frac{Pj - Pi}{j - i} \text{ for } i = 1.2, \ldots, N \tag{6}$$

where P_j and P_i are the precipitation values at time *j* and *i* (*j* > *i*), respectively. The median of these N values of Q_i is the Sen's estimator of slope. The Sen's estimator is calculated by:

$$Q_{med} = \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) \text{ if } N \text{ is even} \tag{7}$$

$$Q_{med} = \left(Q_{\frac{N+1}{2}}\right) \text{ if } N \text{ is odd} \tag{8}$$

3. Results and Discussion

3.1. IPTA Method

In this study, precipitation data from seven rain gauges in the Wadi Sly basin are analyzed using IPTA method. Figure 3 shows, for each station, the results of the IPTA method applied to the arithmetic mean data. Except for Bordj Bou Naama station, the IPTA charts of the other stations do not show a regular polygon. This is due to the fact that the arithmetic average of the monthly total precipitation data is not constant and the data does not change systematically. However, the fact that there is only one polygon at Bordj Bou Naama station, although not a regular one, indicates that the arithmetic mean of the monthly total precipitation data is generally stable. When the IPTA graph of this station is examined in detail on a monthly basis, it is seen that the months without a trend are October, December, June, July, and August. While an increasing trend is observed in September, November, and January, decreasing trends are observed in the remaining 4 months. This complex precipitation pattern can be explained considering the orographic factor and the geographic position of the basin in the Mediterranean, which is exposed to mid-latitude weather in winter and chronically challenged by subtropical dryness in summer. The seasonal trend behavior in precipitation at the Wadi Sly basin confirms the one detected by Achite and Caloiero [44] that evidenced a marked negative trend in spring and a less clear negative trend in winter. As described by Dettinger and Cayan [45] and by Polade et al. [46], precipitation in this region is characterized by typically infrequent frontal storms confined to the cold season. Precipitation changes over the Wadi Sly basin are similar to the ones in the Mediterranean region that can be explained by dynamical factors associated with changes in storm tracks and weather regimes, along with thermodynamic factors associated with increased water vapor content in a warmer atmosphere [47]. Meddi et al. [48] showed that in Algeria the temporal variability of the annual precipitation in the west of the country is influenced by ENSO, while Tramblay et al. [49] evidenced that precipitation in North Africa is mainly affected by the NAO.

General evaluation of arithmetic mean analysis results for each station in Figure 3 are given in Table 3.

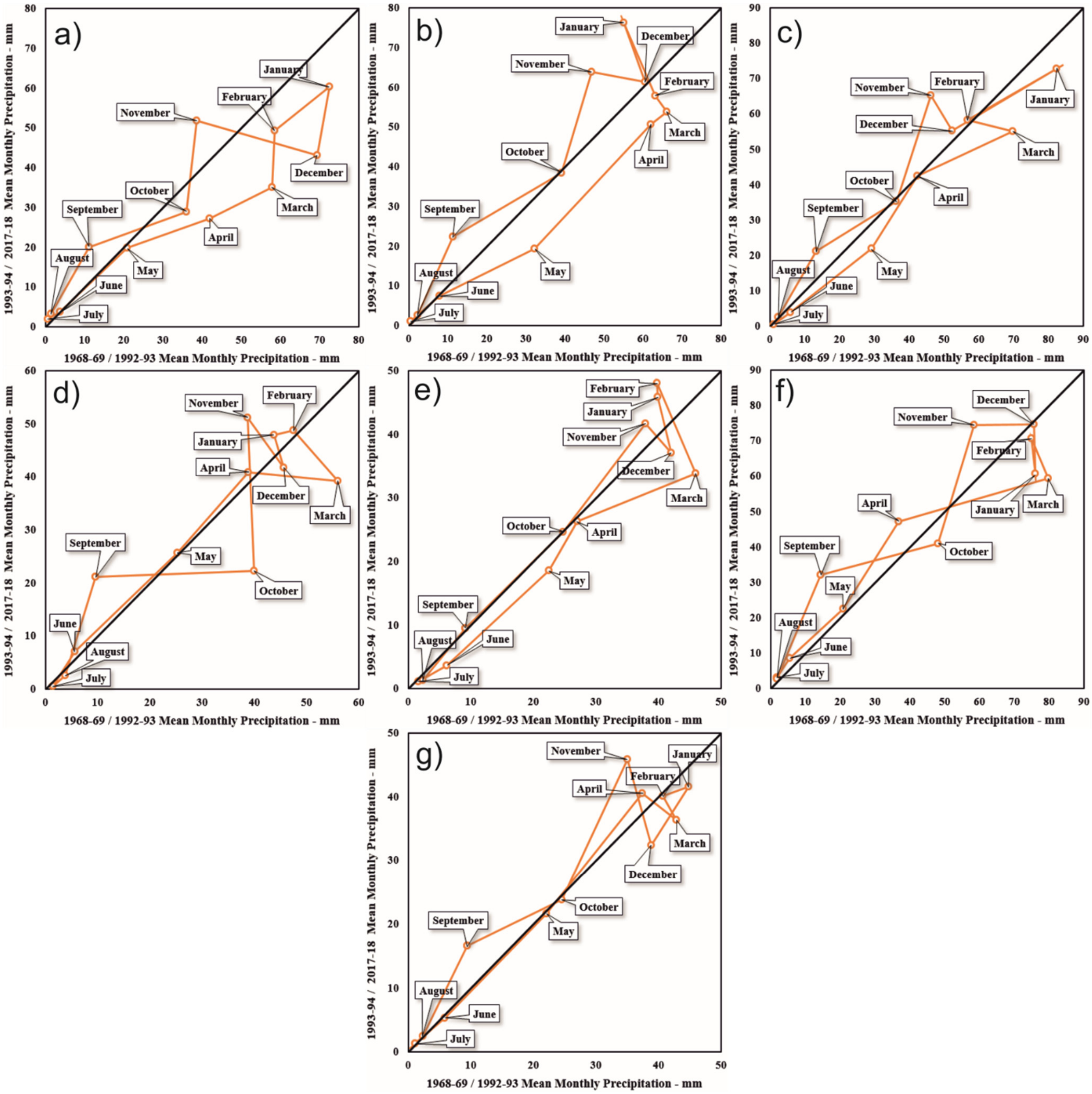

Figure 3. Innovative Polygon Trend Analysis Method graphics of arithmetic mean analysis results for each station: (**a**) Souk El Had, (**b**) Bordj Bou Naama, (**c**) Ain Lellou, (**d**) Ouled Ben A.E.K., (**e**) Oued Sly, (**f**) Saadia, and (**g**) Sidi Yakoub Bge.

Results generally evidenced four different behaviors of arithmetic mean of monthly precipitation in the Wady Sly basin: increasing precipitation trend in September and November; decreasing trend in March; mixed trend in October, December, January, February, April, May, and June; and no trend in July and August. The presented results are supported by Driouech et al. [50] who focused on observed evolutions and climate projections in Tunisia and Morocco. These Authors showed a trend towards drier conditions in the north-western part (Morocco) with a decrease in annual mean precipitation due to winter and spring negative trends similar to the ones detected in the Wady Sly basin (decreasing precipitation trend in winter and spring months). Figure 4 shows the results of the IPTA method applied to the standard deviation data of each station.

Table 3. General evaluation of arithmetic mean analysis results for each station.

Stations	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Souk El Had	↗	↘	↗	↘	↘	↘	↘	↘	→	→	→	→
Bordj Bou Naama	↗	→	↗	→	↗	↘	↘	↘	↘	→	→	→
Ain Lellou	↗	→	↗	↗	↘	→	↘	→	↘	↘	→	→
Ouled Ben A.E.K.	↗	↘	↗	↘	↗	↗	↘	↗	→	↗	→	→
Oued Sly	→	→	↗	↘	↗	↗	↘	→	↘	↘	→	→
Saadia	↗	↘	↗	→	↘	↘	↘	↗	→	↗	→	→
Sidi Yakoub Bge	↗	→	↗	↘	↘	→	↘	↗	→	→	→	→

↘: Decreasing Trend. ↗: Increasing Trend. →: No Trend.

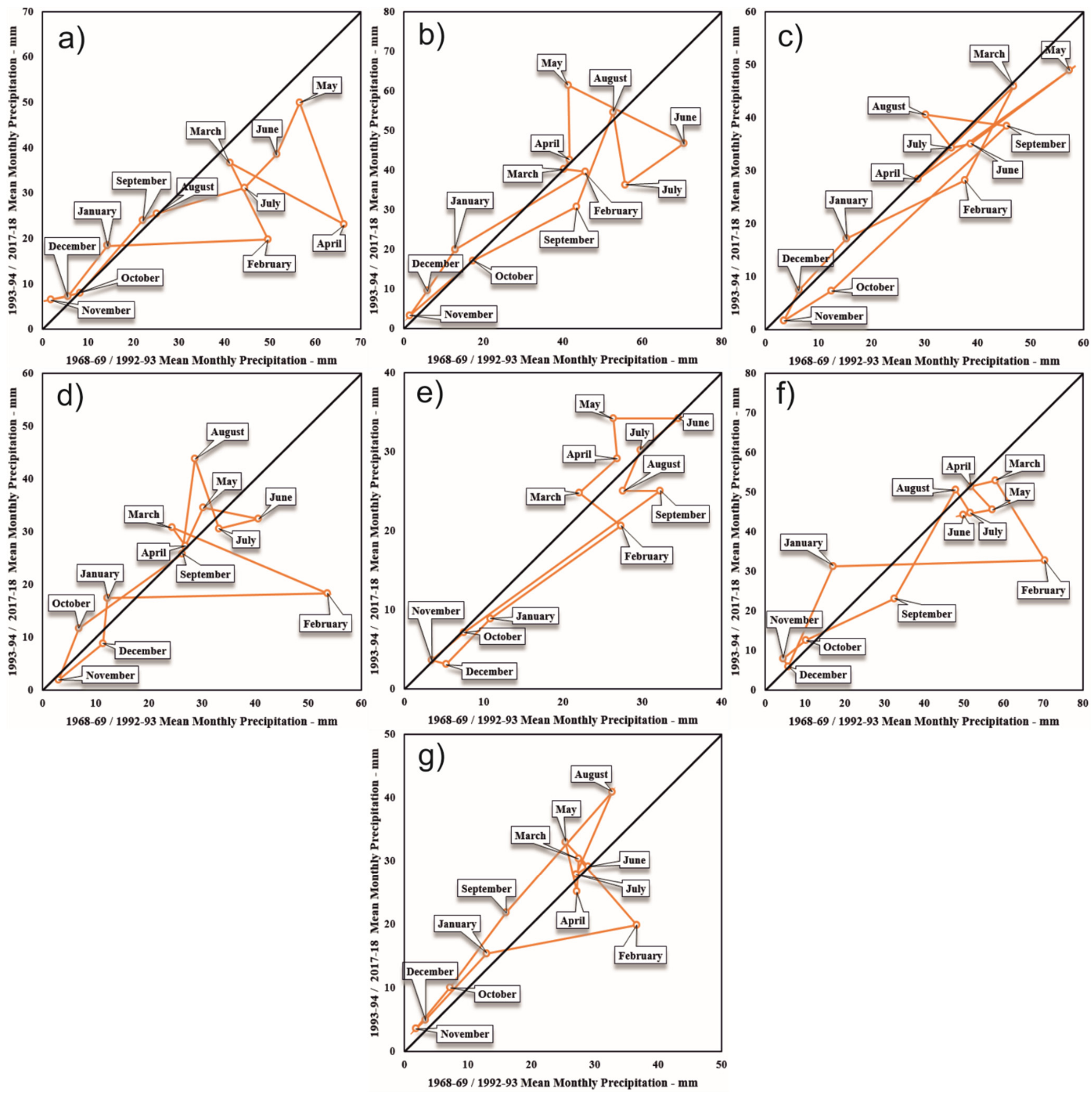

Figure 4. Innovative Polygon Trend Analysis Method graphics of standard deviation analysis results for each station: (**a**) Souk El Had, (**b**) Bordj Bou Naama, (**c**) Ain Lellou, (**d**) Ouled Ben A.E.K., (**e**) Oued Sly, (**f**) Saadia, and (**g**) Sidi Yakoub Bge.

As in Figure 3, IPTA graphs of other stations except for Bordj Bou Naama station in Figure 4 do not show a regular polygon. This is due to the fact that the standard deviation of the monthly total precipitation data is not constant and the data does not change systematically. However, the fact that there is only one polygon at Bordj Bou Naama station, although not a regular one, indicates that the standard deviation of the monthly total precipitation data is generally stable. When the IPTA graph of this station is examined in detail on a monthly basis, it is seen that the months without a trend are October, March, and April. While an increasing trend is observed in November, December, January, May, and August, decreasing trends are observed in the remaining 4 months. In addition, in the autumn–winter period (October–January), the standard deviation trend of the mean monthly precipitation is less than in spring and summer months. In fact, during summer, precipitation is scarce but during summer, precipitation has high intensities, thus standard deviation of monthly precipitation is higher than in the rest of the year. In this season, the Azores anticyclone moves north but when the anticyclone retreats south, it lets in the ocean disturbances affecting North Africa [51].

A synthesis of the results showed in Figure 4 is given in Table 4.

Table 4. General evaluation of standard deviation analysis results for each station.

Stations	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Souk El Had	↗	↘	↗	↗	↗	↘	↘	↘	↘	↘	↘	→
Bordj Bou Naama	↘	→	↗	↗	↗	↘	→	→	↗	↘	↘	↗
Ain Lellou	↘	↘	↘	→	↗	↘	→	→	↘	↘	→	↗
Ouled Ben A.E.K.	→	↗	→	↘	↗	↘	↗	→	→	↘	↘	↗
Oued Sly	↘	→	→	↘	↘	↘	↗	↗	↗	→	→	↘
Saadia	↘	↗	↗	→	↘	↘	↘	→	↘	↘	↘	↗
Sidi Yakoub Bge	↗	↗	↗	↗	↗	↘	↗	↘	↗	→	→	↗

↘: Decreasing Trend. ↗: Increasing Trend. →: No Trend.

Generally, increasing trends of standard deviations have been observed in January and August in five stations. An interesting behavior as observed in February with a decreasing trend of standard deviation monthly precipitations in all the stations. The more stable conditions were observed in April, where the majority of the stations did not evidence trends. As a result, the analysis of standard deviation trends of monthly precipitation evolution showed significant variability typical of the Mediterranean climate [52].

Statistical values of the arithmetic mean (AM) and the standard deviation (SD) for the seven stations are given in Tables 5 and 6, respectively. Results indicate transition between months. The maximum values are considered as an abrupt transition between 2 months.

Detailed results of the statistical values of the arithmetic mean (Table 5) for the Souk El Had station evidenced that the maximum trend length is 31.95 mm in the transition November–December, while a maximum trend slope of 21.17 was identified in February–March. For the Bordj Bou Naama station, the maximum trend length and slope are respectively 43.25 mm (April–May) and 3.32 (October–November). A maximum trend length of 34.78 mm and a maximum trend slope of 3.00 were detected in the Ain Lellou Mf station for the transitions December–January and October–November, respectively. As regards the Ouled Ben A.E.K. station, the maximum trend length was identified in September–October (30.35 mm), while the maximum trend slope was in October–November (−24.42). For the Oued Sly station, the maximum trend length is 22.10 mm (May–Jun.), and maximum trend slope is calculated as −40.54 (Jan.–Feb.). In the Saadia station, in March–April, a maximum trend length of 44.61 mm and a maximum trend slope of −25.76 in December–January were evaluated. Finally, in October–November, a maximum trend length of 24.49 mm and maximum trend slope of 2.11 were identified in the Sidi Yakoub Bge station.

Table 5. Statistical values of arithmetic mean for each station.

		Sep.–Oct.	Oct.–Nov.	Nov.–Dec.	Dec.–Jan.	Jan.–Feb.	Feb.–Mar.	Mar.–Apr.	Apr.–May	May–Jun.	Jun.–Jul.	Jul.–Aug.	Aug.–Sep.
S1	Length (mm)	26.44	23.01	31.95	17.49	17.81	14.22	17.76	22.3	23.46	3.61	1.55	19.25
	Slope	0.36	8.76	−0.28	5.49	0.78	21.17	0.5	0.35	0.94	0.58	1.6	1.72
S2	Length (mm)	32.22	26.52	13.98	15.9	20.17	4.95	5.14	43.25	27.13	9.7	2.26	21.68
	Slope	0.58	3.32	−0.18	−2.71	−2.27	−1.36	0.77	1.05	0.48	0.87	0.91	2.18
S3	Length (mm)	27.05	31.55	11.7	34.78	29.52	13.49	30.21	24.39	29.48	5.83	2.34	21.59
	Slope	0.61	3	−1.64	0.59	0.57	−0.25	0.46	1.56	0.78	0.68	1.48	1.71
S4	Length (mm)	30.35	28.93	11.7	6.44	3.79	12.72	17.16	20.39	27.09	7.79	3.18	19.37
	Slope	0.04	−24.42	−1.35	−3.32	0.23	−1.13	−0.1	1.12	0.94	1.58	0.86	3.22
S5	Length (mm)	21.78	21.54	6.21	9.04	2.2	15.49	20.42	8.99	22.1	5.18	0.71	10.64
	Slope	0.98	1.29	−1.14	−4.08	−40.54	−2.31	0.4	1.72	0.92	0.54	0.31	1.19
S6	Length (mm)	34.82	34.95	17.13	14.03	10.06	12.38	44.61	29.54	20.68	6.44	0.49	32.06
	Slope	0.26	3.22	0.02	−25.76	−8.05	−2.31	0.28	1.54	0.91	1.48	8.25	2.34
S7	Length (mm)	16.77	24.49	14.08	10.98	4.28	4.38	6.93	24.36	23.04	6.24	1.72	15.75
	Slope	0.48	2.11	−3.57	1.55	0.36	−1.77	−0.78	1.24	1	0.85	0.98	1.98

Table 6. Statistical values of standard deviation for each station.

		Sep.–Oct.	Oct.–Nov.	Nov.–Dec.	Dec.–Jan.	Jan.–Feb.	Feb.–Mar.	Mar.–Apr.	Apr.–May.	May–Jun.	Jun.–Jul.	Jul.–Aug.	Aug.–Sep.
S1	Length (mm)	35.36	18.79	28.57	28.56	12.43	10.24	20.15	3.35	21.22	6.51	3.78	14.13
	Slope	0.04	−2.01	−0.54	−2.72	2.27	1.04	0.29	0.51	1.15	0.24	0.23	1.27
S2	Length (mm)	38.28	5.47	2.77	18.79	32.63	17.99	18.58	25.61	29.39	21.08	7.62	12.51
	Slope	0.59	−0.12	1.78	−59.02	−0.50	0.71	−5.94	2.60	0.52	0.87	1.41	1.51
S3	Length (mm)	24.79	20.11	25.16	35.18	23.24	3.72	7.91	15.48	45.38	10.62	6.37	13.31
	Slope	0.49	1.93	0.98	0.72	0.74	0.21	−1.28	−0.14	0.94	0.63	2.02	1.08
S4	Length (mm)	41.41	31.88	4.35	7.92	10.69	7.75	14.01	18.20	24.14	10.44	10.83	8.64
	Slope	0.02	−0.43	−1.33	2.23	−0.20	0.25	−3.00	7.56	0.72	2.62	0.84	9.53
S5	Length (mm)	20.24	6.71	6.44	5.04	8.19	6.23	5.58	4.70	30.57	5.39	1.90	8.03
	Slope	0.71	−0.79	0.93	−11.14	0.01	0.83	2.37	−0.01	0.72	0.87	−0.28	1.05
S6	Length (mm)	53.28	23.71	6.38	8.01	7.45	1.82	6.86	31.43	24.63	7.46	2.34	27.72
	Slope	0.03	−1.64	0.24	−1.08	0.18	0.24	−1.56	1.77	0.48	0.79	−1.38	2.24
S7	Length (mm)	24.07	13.97	5.22	8.05	5.29	2.24	14.22	25.40	14.74	8.41	2.04	14.20
	Slope	0.19	−1.15	16.40	−4.38	−1.09	0.64	2.28	1.14	1.34	1.20	0.93	1.07

As regards the standard deviation (Table 6), in the Souk El Had station a maximum trend length of 35.36 mm and a maximum trend slope of −2.72 were detected in September–October and December–January, respectively. Results for the Bordj Bou Naama station evidenced that the maximum trend length is 38.28 mm in September–October, while the maximum trend slope is −59.02 in December–January. As regards the Ain Lellou Mf station, the maximum trend length was identified in May–June. (45.38 mm), while the maximum trend slope is in July–August (2.02). A maximum trend length of 41.41 mm and a maximum trend slope of 9.53 were detected in the Ouled Ben A.E.K. station for the transitions September–October and August–September, respectively. In the Oued Sly station, the maximum trend length and slope were identified in May–June (30.57 mm) and December–January (−11.14), respectively. In the Saadia station, in September–October, a maximum trend length of 53.28 mm and a maximum trend slope of 2.24 in August–

September were evaluated. Finally, in the Sidi Yakoub Bge station, a maximum trend length of 25.40 mm in April–May and a maximum trend slope of 16.40 in November–December were detected.

3.2. Comparison between the IPTA Method Results and Other Tests Results

The MK and Theil-Sen incline estimator tests were applied at monthly and annual time scales to each station. The MK test statistics ($\alpha = 0.05$) show increasing ($Z > 0$) and decreasing ($Z < 0$) trends. Table 7 presents the results of trend analysis for monthly and annual sums of precipitation based on the following methods: Mann–Kendall test (MK) and Sen's slope estimator.

Table 7. Results of MK and Sen's slope (SS) methods on monthly and annual scales at the study area.

		Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Year
S1	MK	1.263	0.351	1.506	−2.125 *	−1.104	−0.427	−1.623	−2.484 *	−0.895	−0.402	0.050	0.928	−1.606
	SS	0.156	0.054	0.467	−0.907	−0.495	−0.211	−0.557	−0.650	−0.041	0.000	0.000	0.000	−2.565
S2	MK	2.158 *	0.552	1.280	−0.309	1.205	0.443	−0.017	−1.882 +	−0.770	−0.694	0.443	−0.059	0.368
	SS	0.197	0.098	0.466	−0.140	0.544	0.188	−0.025	−0.683	0.000	0.000	0.000	0.000	0.629
S3	MK	0.995	−0.017	2.091 *	0.393	0.284	0.167	−1.054	−1.246	−0.795	−1.113	−0.945	−0.243	−0.167
	SS	0.105	−0.005	0.827	0.090	0.122	0.074	−0.347	−0.358	0.000	0.000	0.000	0.000	−0.245
S4	MK	1.305	−0.309	0.363	−1.288	0.000	0.301	−1.188	−1.121	−0.418	−0.485	−1.113	−1.690 +	−0.452
	SS	0.145	−0.047	0.384	−0.360	0.000	0.095	−0.420	−0.283	−0.059	0.000	0.000	0.000	−0.531
S5	MK	0.243	0.460	0.602	−1.179	0.151	0.560	−0.803	−0.711	−0.903	−1.062	−0.159	−0.326	−0.368
	SS	0.012	0.064	0.158	−0.387	0.039	0.160	−0.245	−0.150	−0.075	0.000	0.000	0.000	−0.353
S6	MK	1.322	0.402	1.690 +	−0.728	−0.619	−0.652	−0.770	1.113	1.489	2.233 *	2.183 *	2.359 *	−0.435
	SS	0.140	0.090	0.681	−0.430	−0.284	−0.265	−0.340	0.128	0.051	0.026	0.000	0.000	−1.064
S7	MK	1.263	0.703	1.874 +	−1.330	−0.728	0.142	−0.075	−1.096	−0.703	−1.380	−4.065 ***	−2.166 *	−0.084
	SS	0.122	0.109	0.504	−0.380	−0.141	0.037	−0.018	−0.262	−0.135	−0.005	0.005	−0.029	−0.124

+: significance level 0.1; *: significance level 0.05; significance level 0.01; ***: significance level 0.001.

Figure 5 shows, as an example, the sums of monthly (September, December, and March) and annual precipitation in the Oued Sly station, where no statistically significant trends were detected. A figure with all the months (Figure A1) can be found in Appendix A. This variability is well shown by modeling the precipitation by a moving average (MA) of a period of 3 years. This figure shows that trends of monthly sum of precipitation are well reflected by IPTA method (Figure 3 and Table 3), with similar trend signs. Considering the monthly sums of precipitation, a high variability is visible; conversely, in the case of annual sums, seasonality of precipitation is noticeable. The statistical significance trend of monthly precipitation was detected only with the MK test, while the trend magnitude was evaluated with the Sen's slope method. Only in the S5 station, the MK method did not detect any statistically significantly trends of monthly precipitation. In two stations, S6 and S7, located in the middle of the Wadi basin, a statistically significant trend was detected in 4 and 3 months, respectively. In the remaining stations, statistically significant trends were identified mainly in 2 months, in November and August, when the statistically significant trends were detected three times. Moreover, increasing trends were visible more often than decreasing trends. In fact, from the comparison of the results of Table 7, an increasing trend of monthly precipitations in almost all stations in September and November is evident, while in December, March, April, and May, a decreasing trend of precipitation is shown.

As regards the Sen's slope estimator, this method identified a further lack of trends than other methods. In the case of the annual sum of precipitation, in all stations decreasing and statistical insignificantly trends of precipitation were detected. The only exception is station S2, where an increasing non-significant trend was identified. A similar comparison of the IPTA method with commonly used MK test showed Alifujiang et al. [53], where they did not detect significant differences between both methods. Moreover, they concluded that the IPTA method allows more detailed interpretations about trend analysis, like benefits for identifying hidden variation trends of precipitation in comparison to commonly used methods. Also, Saplıoğlu and Kilit [54] detected a strong correlation between results from the IPTA method in the MK test and examined discharged data in the Western Mediterranean Basin.

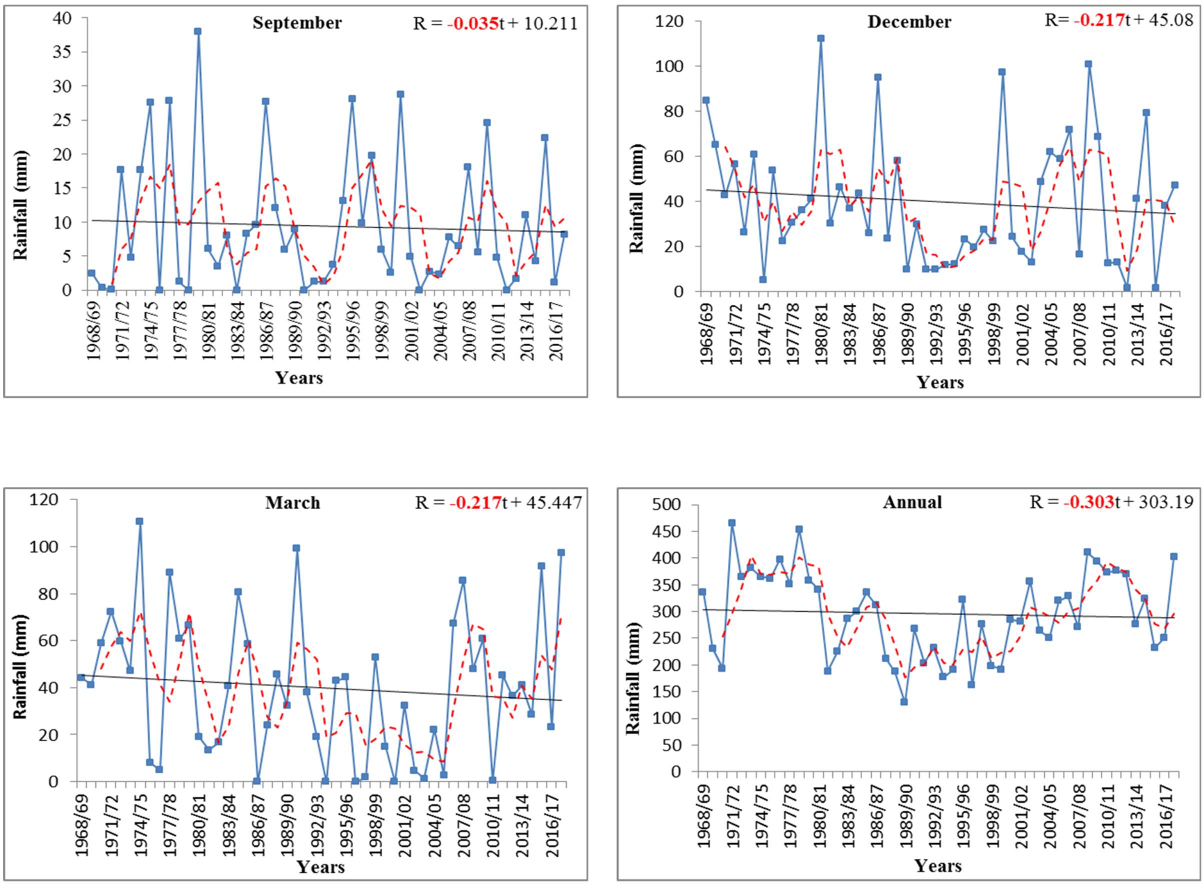

Figure 5. Sums of monthly and annual precipitation in the Oued Sly station.

From the comparison of the results obtained with the IPTA method (Tables 3 and 4) with the ones obtained with commonly used methods for trend detection (Table 7), a good agreement emerges. In fact, as Rathnayake [55] showed, results of the trend analyses for time series data with different resolutions performed with the Innovative Trend Analysis technique can give similar results to the ones obtained with the classical statistical trend analysis techniques. The author concluded that the Innovative Method is easy to perform and has low computational cost in comparison to other methods. Therefore, the technique can be widely used to identify the trends. Indeed, as mentioned earlier, the IPTA method is very simple to use from a practical point of view and has no flaws when compared to commonly used statistical tests. The method can indicate transition between analyzed months that can lead to deep analysis behavior of analyzed data. However, this technique does not provide any numerical value of the trend. Based on Şan et al. [56], it can be concluded that the IPTA method is more sensitive in detecting trends in comparison to the Mann–Kendall (MK) test. The disadvantages according to IPTA are that MK does not show a trend slope and that MK shows a holistic trend. The IPTA method has some advantages in comparison to other commonly used tests. In fact, the method is less sensitive to the influence of outlier values on final results. For example, Zittis [57] studied trends of monthly precipitation and showed that the Kruskal–Wallis test is sensitive to an outlier value. Also, the assessment of trends using commonly known methods in the characteristics of precipitation is complicated by the quality of the observations and by the intrinsic noisiness of the records [58]. Moreover, null hypothesis significance tests have a logically flawed rationale coming from ill posed and theoretically unfounded hybridization of Fisher significance tests and Neyman–Pearson hypothesis tests. They do not allow conclusions about the truth or falsehood of any hypothesis, and do not apply to exploratory non-randomized studies [30]. In addition, statistical significance does not imply physical significance because the former depends on the sample size, and almost every test assigns statistical significance to physically negligible differences for very large samples. On the other hands, Serinaldi et al. [59], based on numerical experiments, detected many flaws of ITA methods (the IPTA is a modified version of the ITA method) like: (1) " ... ITA diagrams are equivalent to well-known two-sample quantile-quantile (q–q) plots; (2) when applied to finite-size samples, ITA diagrams do not enable the type of trend analysis that it is supposed to do; (3) the expression of ITA confidence intervals quantifying the uncertainty of ITA diagrams is mathematically incorrect; and (4) the formulation of the formal tests is also incorrect and their correct version is equivalent to a standard parametric test for the difference between two means. Overall, we show that ITA methodology is affected by sample size, distribution shape, and serial correlation as any parametric technique devised for trend analysis". Despite many advantages, the IPTA method has similar flaws like ITA methods. Due to this reason, the IPTA method should be used only as a qualitative tool to support other methods when detecting the trend of hydrometeorological data.

4. Conclusions

In this study, the Innovative Polygon Trend Analysis Method was applied to total monthly precipitation data of seven stations in the Wadi Sly Basin in a 50-year period (1969–2018). As a result of the study, IPTA graphics were created for each station. In addition, trend lengths and trend slopes of monthly total precipitation data of each station were calculated. Additionally, results from the IPTA method were compared to two non-parametric tests: Mann–Kendall and Sen's slope estimator. After these analyses, the following evaluations were made:

- Size of trend lengths and trend slopes show the variability between months. For example, for Bordj Bou Naama Station, maximum trend lengths for arithmetic mean and standard deviation are 43.25 mm and 38.28 mm, respectively, while values of 3.32 and −59.02 are obtained for the maximum trend slopes, respectively. These values show that the transition between 2 months is severe.
- Results from the IPTA method have good agreement with commonly used non-parametric tests for each month.
- The IPTA method can be used to quantitively analyze and detect trends and can support results from other commonly used methods. The results from Man–Kendall test and Sen's estimator are quite similar. The directions of the trend are the same in most cases in both methods.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

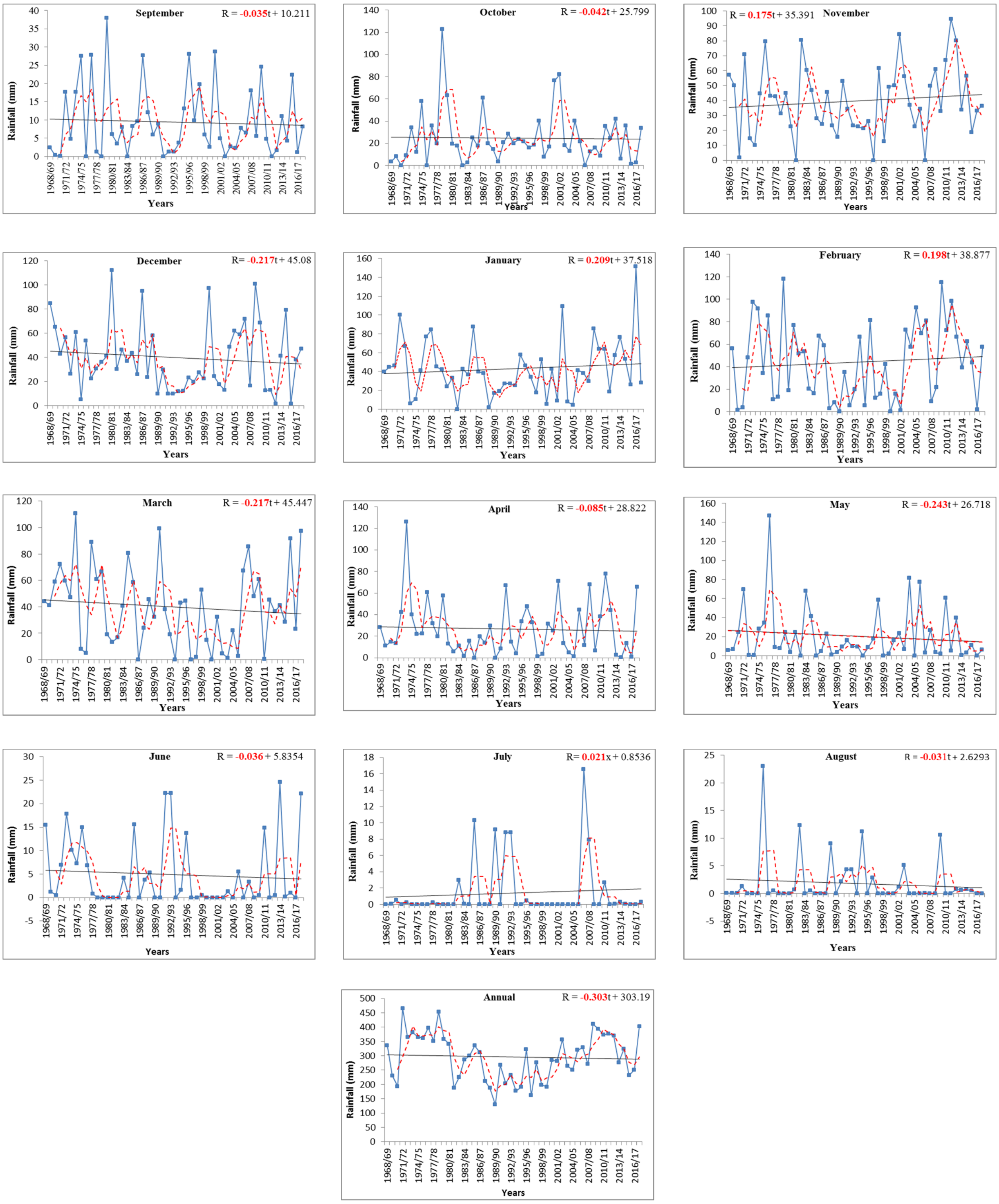

Figure A1. Sums of monthly and annual precipitation in the Oued Sly station.

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Fragmented Forest Patches in the Indian Himalayas Preserve Unique Components of Biodiversity: Investigation of the Floristic Composition and Phytoclimate of the Unexplored Bani Valley

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Abstract: Subtropical and temperate forests are amongst the most threatened habitats of Asia, due to large-scale habitat loss and the fragmentation of landscapes. Inspite of these, the Asiatic regions preserve their endemic biodiversity, and provide a favorable environment for the abundant growth of vegetation. In the Himalayas, many interior regions are still unexplored from a biodiversity perspective, due to remote locations and high snow-clad mountains. In this study, we investigated the unexplored Bani Valley in order to reduce the gap of uninventorized areas of rich biodiversity in the Himalayas and formulate plant conservation and management strategies. Thirteen field expedition tours were undertaken during 2017 and 2020 for data collection in different growing seasons in the study area. All plant species were collected as voucher samples, identified, and deposited in the internationally recognized Janaki Ammal Herbarium (acronym RRLH). GPS points were recorded in order to study the forest types and vegetation components of the study area. A total of 196 plant species belonging to 166 genera and 68 families were identified in Bani Valley, covering a total area of 2651 km^2. Approximately 70.62% of the species were native and 29.38% were non-native. In total, 46% of species were Indo-Malayan, followed by 22% Palearctic species. In angiosperms, dicotyledon species (68.37%) dominated. *Poales* were the most dominant order, with 38 species (19.38%). The most abundant families were *Poaceae* with 29 species (14.79%), *Fabaceae* (17, 8.67%), *Rosaceae*, *Cyperaceae*, and *Asteraceae* (9, 4.59% each). The life form analysis showed 50% of species as phanerophytes, followed by therophytes (25.77%). The leaf size spectra show mesophyllous species (34.69%) as the dominant group. The IUCN Red List of Threatened Plants categorized *Ailanthus altissima* as endangered (EN), *Aegle marmelos* and *Quercus oblongata* as near threatened (NT), *Ulmus wallichiana* and *Plantago lanceolata* as vulnerable (VU), *Taxus baccata* and 75 other species as least concern (LC), and 2 species as data deficient (DD). The remaining 113 species of plants had not been evaluated according to the IUCN Red List of Threatened Species. This study will help to shape conservation and management plans for threatened species for future implementation, and will help in biodiversity conservation. This study will serve as a database for future reference materials in terms of biodiversity management.

Keywords: biodiversity conservation; biological spectrum; phenology; leaf spectra; IUCN; native plants; Himalayas

1. Introduction

The origin of life on earth is a fascinating subject that can be studied through observations made today, and these observations, coupled with climate change over time, can provide answers as to how biodiversity has changed over time [1]. High-altitude mountainous belts safeguard important biodiversity and the scenic, aesthetic value of landscapes [2–5], provide ecosystem services to benefit human well-being, and are essential for a sustainable world [6–8]. Plant adaptation adjusts a life form to certain ecological conditions; thus, it has been widely used in the analysis of flora and vegetation [9]. The forms and structures of plant communities can be explored by classifying the species involved into categories reflecting their environmental relationships [10–13], and thus, plant communities can also be categorized in terms of leaf size and leaf form [14,15]. It has been shown that studying the biological spectrum is useful in comparing geographically separated plant communities, and is regarded as an indicator of changing environments [16]. Large-scale patterns of plant distribution are very well known, but regional- or local-scale study of plant assemblage is important for local action in biodiversity conservation [17]. Raunkiaer's classification, interlinked to climatic conditions and developed for the climate, is usually the temperate season, as the winter frost ends the plants' growing season [17–19]. Under this system, the life-forms were classified into five main groups, i.e., phanerophytes, chamaephytes, hemicryptophytes, cryptophytes, and therophytes [20]. This is supported by the observation that grassland vegetation in high-altitude regions is usually dominated by hemicryptophytes [21]. Raunkiaer's normal spectrum indicates a phanerophyte community, and the deviation determines the phytoclimatic nature of the vegetation composition of any particular given region [22]. Determining the difference between Raunkiaer's normal spectrum and the biological spectrum of life-forms allows us to discover the dominant lifeform that characterizes the phytoclimate of the study area in question [23]. Therefore, the life form study is an important factor in ecological studies and vegetation description, ranking next to floristic composition and biodiversity surveys [24,25].

High mountain areas occupy 3% of the world's surface, wherein there are about 10,000 plant species, which represents approximately 4% of the total species diversity of the planet [26]. However, as one ascends a mountain, a reduction in the number species is observed, due to the harsh environmental conditions [27]. On the other hand, the mountainous regions (including the valleys and the lowlands that surround the reliefs) show a great species richness, despite the species poverty of their peaks. This can be explained by considering that the maximum slope of an area can be understood as a proxy of its environmental heterogeneity [28]. In addition, mountains have great conservation value, harboring numerous endemic, rare, and/or threatened taxa and ecosystems [29]. However, this natural heritage is threatened by changes in landuse and by climate change [21]. The climatic changes are related to changes in the distribution of species [30]. Thus, their altitudinal changes are reliably reflected in changes in temperature [31], responding more quickly to climate warming than other regions [32,33]. For this reason, research in mountainous areas—including the botanization of species, carefully registering the collection altitudes—is of great interest [34]. It is on the southern slopes of the Himalayas that the greatest unevenness is recorded globally. In addition, this was the pioneer mountain range in the series of tectonic movements that wiped out the Paleo-Tethys Ocean. This movement is still ongoing, and will culminate in the closure of the Strait of Gibraltar. A comparison of the general patterns obtained in the Himalayas (Bani Valley) and other places in this group of "circum-Tethys" ranges would enrich future research. At the other extreme, around the Strait of Gibraltar, are located the Betic ranges (Spain) and the Rif and Atlas Mountains (Morocco), whose endemic flora were studied by Pérez-García et al. [35]. Compared to the flora of the Himalayas (Bani Valley), it is observed that the Betic and Rif Mountains' flora have a lower weight than the *Poaceae*, in exchange for a large increase in *Asteraceae*, *Caryophyllaceae*, *Fabaceae*, and *Lamiaceae*. In addition, they show a greater presence of hemicryptophytes and chamaephytes, in exchange for a lower proportion of therophytes and phanerophytes.

In India, there are four major biodiversity hotspots: the Himalayas, the Western Ghats, Indo-Burma, and Sundaland. Of the reported 18,532 species of angiosperms from the country (ENVIS, 2021), about 50% of species are recorded in the Himalayas [36]. A lot of floristic and ecological research works have been carried out in geographic regions of Jammu and Kashmir (J&K) at different times [37–39]; however, there are still lots of unexplored pockets in the Himalayas, which may be unexplored due to their extreme climate, unapproachable terrain, and the fear of cross-border terrorism issues [40–43]. Plant collection and the dissemination of data on the floristic composition and phytoclimatic variables can impart a lot of knowledge to mankind, and fill the gap of unexplored regions. The Kathua district of J&K is recognized as "the Gateway to the Union Territory (UT)"and is bestowed with varied topography and mountainous climatic conditions [44]. It covers a total area of 2651 km^2, whose altitude varies from 350 to 6000 m above mean sea level (AMSL). The region is surrounded by the Jammu district to the northwest, the Doda and Udhampur districts to the north, the state of Himachal Pradesh to the east, and the state of Punjab to the south. The terrain is very diverse, consisting of rich agricultural areas along the Punjab border, plains sweeping eastward to the foothills of the Himalayas, and the mountainous alpine region in the northeast [44]. The Indian Census of 2011 recorded the total population as 191,988 (available at https://censusindia.gov.in, accessed on 10 February 2021). The climatic conditions vary depending on the geographical location and altitude; plains areas experience a subtropical climate, and the mountainous region to the north experiences a temperate climate. Bani Valley is a mountainous part of this district that lies towards the extreme north of India, is a part of the Northwestern Himalayan Region, and is categorized as a region of the Shivalik range. The region is under-explored from a floristic point of view, and there is no literature available to date on its plant diversity or phytoclimatic conditions. Therefore, our aim was to undertake a detailed floristic investigation of the Bani Valley. The Bani Valley presents a unique climate, bestowed with natural beauty, vegetation, and topography for studying the biodiversity (especially for medicinal plants) of the Northwestern Himalayan Region. The present study of the vegetation composition of the Bani Valley could be used as an example in India for other similar vegetation types, and for phytoclimatic study in particular.

2. Materials and Methods

2.1. Study Area

Bani Valley (Figure 1) is situated in the interior region of the Kathua district (J&K). It lies between latitude 32°52′33.15″ N and longitude 75°48′14.53″ E, and the elevation ranges from 1200 to 2001 m AMSL, covering a total area of 468 km^2. The region is part of Western Himalaya, and the valley is situated at the bank of the SewaRiver, representing one of the northernmost parts of the Kathua district. This area is 85 km from the Basohli tehsil, and approximately 152 km from the town of Kathua and about 236 km from the UT capital, Jammu. The only way to reach the Bani Valley is by road.

The climate of the study region ranges from subtropical to temperate climates. The high mountainous hills of the Bani Valley are covered with snow and ice for 2–3 months per year. The different seasons prevailing in Bani Valley can be divided into four distinct intervals: summer, spring, rainy, and winter. The summer temperature varies from 18–45 °C, and the winter temperature from 0–15 °C. The annual rainfall varies from 1200–1530 mm. About 85% of rainfall is received in the monsoon season, i.e., from July to September. The sudden cloud burst and heavy rainfall can cause landslides, and these sometimes block the route to the Bani Valley. The heavy rainfall and landslides combined with stream waters cause havoc for the people.

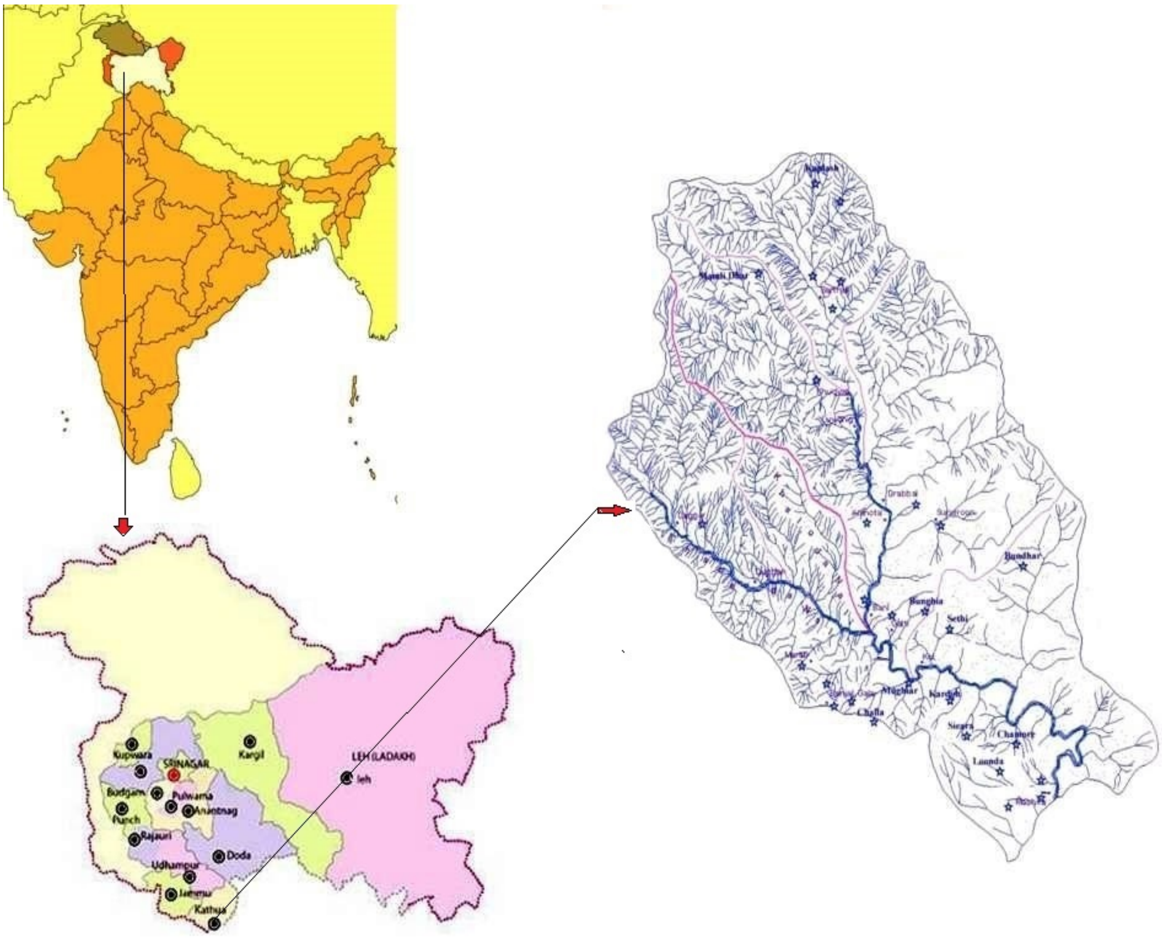

Figure 1. Location map of the Bani Valley (Jammu and Kashmir), Western Himalaya, India.

Using Champion and Seth's classification of forest types in India [45] as a reference, along with our own field observations, the forest types of Bani Valley can be divided into two categories, i.e., subtropical and temperate forests (Figure 2). The subtropical forests were sub-divided into two types—subtropical dry deciduous forests, and subtropical evergreen chir-pine forests. At lower altitudes, the trees were dominated by subtropical dry deciduous scrubs. The major dominant tree species of subtropical dry deciduous vegetation were *Mallotus philipensis* (Lam.) Müll.Arg., *Terminalia bellirica* (Gaertn.) Roxb., *Ficus hispida* L.f., *Trema orientale* (L.) Blume, *Melia azedarach* L., *Toona sinensis* (Juss.) M.Roem., *Butea monosperma* (Lam.) Kuntze, *Syringa emodi* Wall. ex Royle, and *Lyonia ovalifolia* (Wall.) Drude. The major shrub species of subtropical dry deciduous vegetation were *Debregeasia saeneb* (Forssk.) Hepper and J.R.I. Wood, *Colebrookea oppositifolia* Sm., *Ototropis multiflora* (DC.) H.Ohashi and K.Ohashi, *Strobilanthes wallichii* Nees, *Cissampelos pariera* Vell., and *Rubus idaeus* L. The dominant herbaceous species of subtropical dry deciduous vegetation were *Trifolium pratense* L., *Lespedeza juncea* (L.f.) Pers., *Pilea scripta* (Buch.-Ham. ex D.Don) Wedd., and *Urtica dioica* L. The above make up the vegetation in the foothills of the Himalayas.

The forests at elevations upto 1600 m are subtropical evergreen chirpine vegetation. *Pinus roxburghii* Sarg. is the most dominant tree species in chir-pine vegetation. The shrub species in evergreen chir-pine vegetation are *Rubus ellipticus* Sm., *Cotinus coggygria* Scop., and *Desmodium elegans* DC. The herb species found in evergreen chir-pine vegetation are *Oreoseris gossypina* (Royle) X.D.Xu and V.A.Funk, *Barleria cristata* L., *Rungia pectinata* (L.) Nees, *Persicaria capitata* (Buch.-Ham. ex D.Don) H.Gross, *Achyranthes aspera* L., and *Euphorbia hirta* L. The vegetation components above 1600 m are mostly temperate, and are dominated by *Cedrus deodara* (Roxb. ex D.Don) G.Don forests. Oak forests are also the dominant vegetation at these altitudes. The dominant tree species of these forests are

C. deodara, *Rhododendron arboreum* Sm., *Alnus nitida* (Spach) Endl., *Quercus oblongata* D.Don, *Acer caesium* Wall. ex Brandis, and *Celtis australis* L. The dominant shrubby vegetation of temperate climates is characterized by *Zanthoxylum armatum* DC., *Prinsepia utilis* Royle, *Rubus niveus* Thunb., *Isodon rugosus* (Wall. ex Benth.) Codd, and *Berberis lycium* Royle. The herb species of temperate vegetation are *Valeriana jatamansi* Jones ex Roxb., *Viola canescens* Wall., *Geranium wallichianum* D.Don ex Sweet, *Galium aparine* L., and some fern species, such as *Pteris vittata* L., *Pteris cretica* L., *Polystichum polyblepharum* (Roem. ex Kunze) C.Presl, and *Asplenium dalhousieae* Hook.

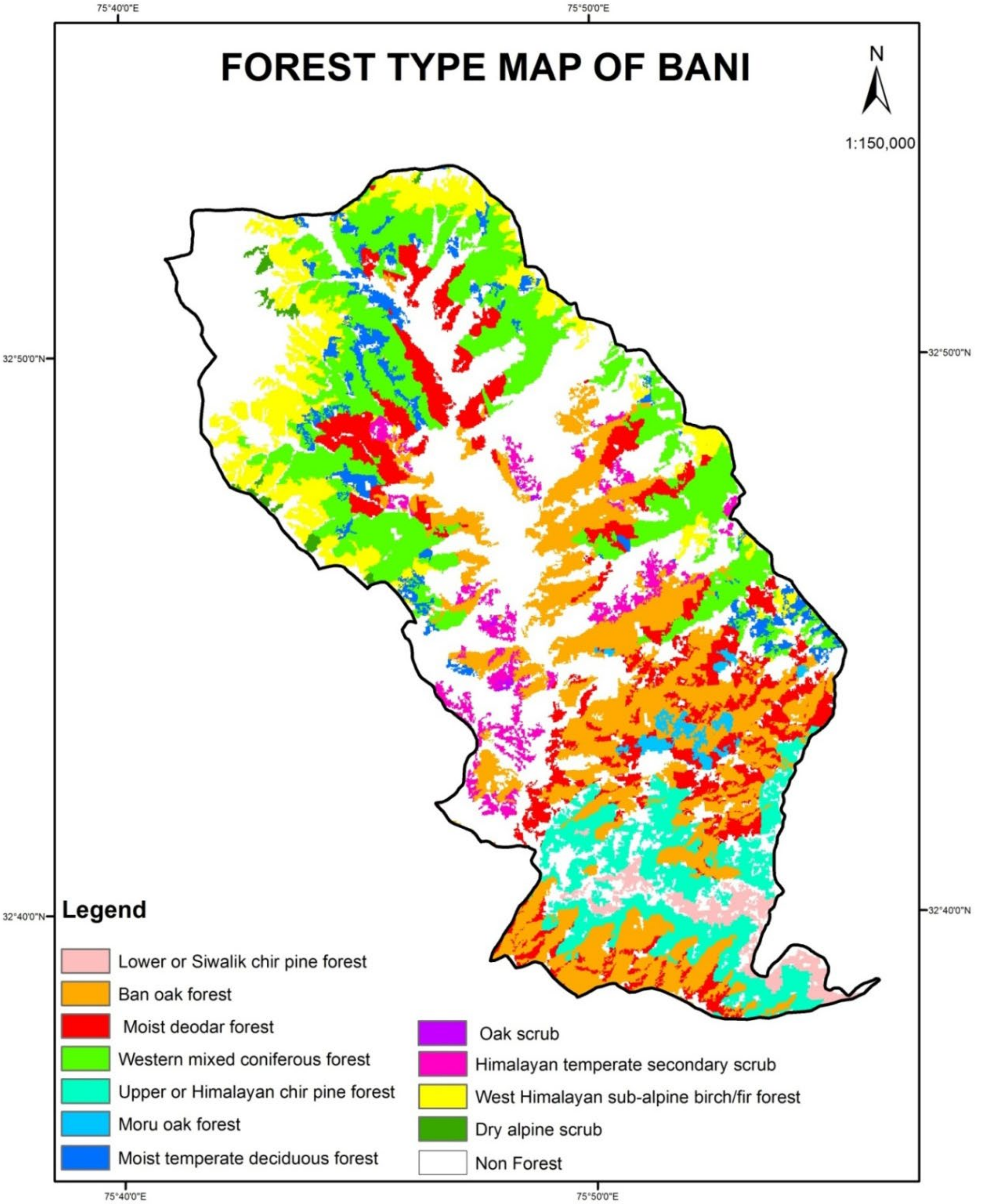

Figure 2. Forest types of the Bani Valley (Jammu and Kashmir), Western Himalaya, India.

A total of 33 villages and 8096 households fall in the jurisdiction of Bani Valley, representing 45,996 people, of whom 23,889 are male and 22,107 are female; the recorded population density is 250 km^{-2} (https://www.censusindia.co.in, accessed on 10 February 2021). The literacy rate is 44.27% (male: 57.16%; female: 42.84%). Bani tehsil is home to some Nomadic groups, such as Gujjars and Bakarwals. These are semi-pastoral ethnic communities of J&K. They always move seasonally here and there as they have no permanent settlements. On the arrival of summer, these communities start their journey towards high altitude areas along with their livestock. With the onset of unfavorable conditions, they come down and settle in the plains areas of the Bani Valley.

2.2. Data Collection

2.2.1. Field Surveys

Thirteen field surveys and exploration tours were undertaken in the Bani Valley from March 2017 to July 2020 in different seasons, in order to study the botanical and ecological aspects of the vegetation composition. Floristic surveys were carried out in order to collect plant samples (angiosperms, gymnosperms, and lycophytes and ferns) from different altitudes of the study area. Lower plants (e.g., bryophytes, algae, fungi, lichens, and mosses) were excluded from this study. A total of 24 plots were laid out by first measuring randomly selected, 50 m-long straight transects, with the help of a measuring tape, at different locations in the study area. Two altitude gradients (1201–1600 m a.m.s.l. for subtropical forest and 1601–2000 m a.m.s.l. for temperate forest) were selected. Flag-type points were marked and placed at 10 m intervals along the transect line, and also at distances of 10 m on both sides of the line, measured at right angles from the transect angle, thus marking off five 10 m $\times$ 10 m quadrats on each side. Small transect lines were selected because the area had fragmented forest patches due to the occurrence of high hills and valleys, steep slopes, and deep gorges in the study area. Within each quadrat, all stems (trees, shrubs, and herbs) were counted and recorded. A total of 240 quadrats (120 on each side of the 50-m line) for trees (10 m $\times$ 10 m), shrubs (5 m $\times$ 5 m), and herbs (1 m $\times$ 1 m) were used for the study. The diameters of the trees were measured using a diameter tape at 1 m height or above the buttress roots, and the trees' heights were recorded using clinometers. For multi-stem herbs (Poaceae), we divided the total stem number of the herbs by the mean number of stems per plant falling inside a 1 m $\times$ 1 m quadrat, and rounded up the value for the purpose of analysis. Our focus was to collect the maximum number of plant samples bearing flowers and fruits in different seasons. A number of the quantitative measures typically employed in biodiversity plot studies were calculated for the two types of studied forest plots—subtropical and temperate forests. These included stem density, frequency, basal area, relative density, relative dominance, relative frequency, and importance value index (IVI) [46–51]. Data on plot heterogeneity (diversity and evenness of species)—such as the Dominance, Shannon, and Evenness indices—were computed using PAST software Version 3.21 and presented. The specimens collected from the field tours were dried and processed as per the standard operating procedure of Jain and Rao's modern herbarium techniques [52]. GPS coordinates, along with the digital photographs of all plant species available in the study, were taken. Plant samples were collected in triplicate and herbarium-prepared as per standard protocols, and the specimens of the collected plants were pasted on herbarium sheets (42 cm $\times$ 28 cm $\pm$ 2 cm). Each plant was given an accession number. Finally, the plant specimens were deposited in the Janaki Ammal Herbarium (acronym RRLH) of the CSIR–Indian Institute of Integrative Medicine Jammu (India). The herbarium acronyms are in accordance with Thiers [53].

2.2.2. Presentation of Data

The vegetation composition of the study area is identified based on morphological characteristics. The species, along with their habitat and habit, life-span, phenological period, Raunkiaer's life-form system classification, leaf spectra, and the distribution of the flowering periods of the study area, were provided. Families were arranged according to

Angiosperm Phylogeny Group IV classifications [54]. Gymnosperms, and lycophytes and ferns, were placed after the flowering plants. The total number of orders, families, genera, and species under dicots and monocots identified from the study area was also prepared. IUCN Red List statuses were provided by consulting their website: www.iucnredlist.org.

2.2.3. Literature Sources

The identities of plants were confirmed from scientific studies published in journals, books, revisionary works, and monographs available in the libraries of CSIR–Indian Institute of Integrative Medicine (IIIM) and Jammu University. Plant species were botanically compared with the help of Flora of Udhampur [55], Flora of Jammu and Plants of Neighbourhood [56], Flora of Trikuta Hills [57], Handbook of Medicinal Herbs [58], and Illustration of Jammu Plants [59]. Angiosperm Phylogeny Group IV was used to classify the plant species, and the species list of the plants was checked using POWO (available at http://www.powo.org), the International Plant Names Index (available at http://www.ipni.org), and Tropicos (available at https://www.tropicos.org).

For each plant species, we attributed a life-form following Raunkiaer's classification, and a leaf size, as categorical variables: (1) leptophyllous (<25 mm^2); (2) nanophyllous (25–225 mm^2); (3) microphyllous (225–2025 mm^2); (4) mesophyllous (2025–4500 mm^2); and (5) megaphyllous (4500–1225 mm^2). A biological spectrum was prepared for the study area, which was subsequently compared with Raunkiaer's normal spectrum in order to determine the phytoclimate and vegetation composition of the study area.

For studying the phenological periods of different species, we categorized different months of the year as different seasons: summer (April–June); spring (January–March); rainy (July–September); and winter (October–December). Flowering periods were recorded from our field observations, and plant sample collection was performed over four continuous years of data collection from the study area.

3. Results and Discussion

3.1. Diversity of Taxa and Families

In the present study, a total of 547 sampled vouchers were collected, representing 196 species of 166 genera distributed in 68 families under 27 orders (Table 1). Sixty-eight percent of the species were dicotyledons, followed by monocotyledons (23.97%), lycophytes and ferns (5.10%), and gymnosperms (2.55%). The dominant orders of the angiosperms were *Poales* with 38 taxa (19.38%), *Rosales* (25, 12.75%), *Fabales* (16, 8.16%), *Sapindales* (15, 7.65%), *Lamiales* (13, 6.63%), *Asterales* (9, 4.59%), *Caryophyllales* (8, 4.04%), *Malpighiales* (7, 3.57%), *Ranunculales* (6, 3.06%), and *Cucurbitales* (5, 2.55%) (Table 1). All of the angiosperm species are arranged according to the APG IV system of classification [54], followed by gymnosperms, and lycophytes and ferns.

Table 1. Total diversity of plant taxa in the Bani Valley (Jammu and Kashmir), Western Himalaya, India.

Group	Orders	Families	Genera	Taxa			
				Herbs	Shrubs	Trees	Total
Dicots	20	52	117	48	34	52	134
Monocots	5	10	37	46	1	0	47
Lycophytes and ferns	1	4	8	10	0	0	10
Gymnosperms	1	2	4	0	0	5	5
Total	27	68	166	104	35	57	196

The top 10 dominant families reported in the study area in terms of species richness were *Poaceae* (29, 14.79%), followed by *Fabaceae* (17, 8.67%), *Rosaceae*, *Cyperaceae*, and *Asteraceae* (9, 4.59% each). A total of 11 families comprising 2 species (1.02%), 4 families comprising 3 species (1.53%), and 4 families comprising 4 species (2.04%) were also reported. Another 37 monotypic families comprising single species were also identified in the study area. In terms of the highest number of genera, the 10 most dominant plant families were

Poaceae (23, 13.93%), *Fabaceae* (17, 10.30%), *Asteraceae* (9, 5.45%), *Acanthaceae* (6, 3.63%), *Cyperaceae*, *Lamiaceae*, *Rosaceae* and *Urticaceae* (5, 3.03% each), *Pteridaceae* (4, 2.42%), and *Polygonaceae* (2, 1.21%).

Floristic studies carried out by Dhar and Kachroo [60] in the Kashmir Himalayas have shown a somewhat similar pattern of diversity of plant taxa. According to their work, *Asteraceae*, *Lamiaceae*, *Poaceae*, *Rosaceae*, and *Polygonaceae* were dominant plant families, similar to our own research findings. Similarly, Sharma et al. [61] carried out similar studies in the Sangla Valley of the Northwestern Himalayan Region, and reported *Asteraceae*, *Rosaceae*, *Apiaceae*, and *Ranunculaceae* as the dominant families. Our findings were also supported by the dominance of *Poaceae* and *Asteraceae* reported in the flora of the Lahaul–Spiti and Bhaba Valleys of Western Himalaya and Himachal Pradesh [62,63]. Species richness was similar at the same altitude and climatic conditions. Zent and Zent [64] studied the floristic composition, structure, and diversity of forest plots in the Sierra Maigualida, Venezuelan Guayana, and reported 533 species, of which *Fabaceae* represents the most dominant family. There are other, similar studies that support our findings, including the studies carried out by Agrawal [65], Shaheen et al. [66], and Haq et al. [67].

The genus *Cyperus* L. comprises five species, and was the most dominant monocot, whereas the genera comprising three species were *Ficus* Tourn. ex L., *Persicaria* Mill., *Rubus* L., and *Setaria* P.Beauv. The 19 well-represented genera containing 2 species were *Asplenium* L., *Carex* L., *Chrysopogon* Trin., *Clematis* L., *Commelina* Plum. ex L., *Cymbopogon* Spreng., *Euphorbia* L., *Galium* L., *Isodon* (Schard. ex Benth.) Spach, *Pilea* Lindl., *Pinus* L., *Prunus* L., *Pteris* L., *Pyrus* L., *Rumex* L., *Saccharum* L., *Solanum* L., *Thalictrum* Tourn. ex L., and *Terminalia* L. The remaining 139 taxa, belonging to monotypic genera, were also recorded. In a similar environment, a study on floristic diversity and the distribution patterns of plant communities along altitudinal gradients was carried out by Sharma et al. [61] in the Sangla Valley of the Northwestern Himalayan Region, and reported *Artemisia* L., *Polygonum* Juss., *Saussurea* DC., *Berberis* L., *Thalictrum* Tourn. ex L., *Geranium* Tourn. ex L., *Juniperus* L., *Nepeta* L., *Potentilla* L., *Poa* L., *Rosa* L., and *Salix* L. as the dominant genera. There are other similar studies which support our findings, including the studies carried out by Chawla et al. [62], Chowdhery and Wadhwa [63], Agrawal [65], Shaheen et al. [66], Dhaliwal and Sharma [68], and Haq et al. [69].

3.2. Species Diversity in Different Growth Form

The present floristic and vegetative composition analysis of the study area shows a total of 134 dicots (68.37%), 47 monocots (24.23%), 10 lycophytes and ferns (5.15%), and 5 gymnosperms (2.57%). Among these, 104 of the identified taxa were herbs (53.06%), followed by shrubs (17.85%) and trees (29.08%). Amongst the total dicot taxa, herbs, shrubs, and tree habits were represented by 48, 34, and 52 taxa, respectively, whereas the total monocot group of plants, herbs and shrubs, comprised of 46 and 1 species, respectively. No tree species of monocots were recorded in the study area. The epiphytes recorded were not included while studying the quadrat data for analysis of different diversity indices.

The results of 240 quadrats indicated that the subtropical forests of the Bani Valley were characterized by 415 trees, 480 shrubs, and 96,000 herbs, representing 45, 23, and 42 species of trees, shrubs, and herbs, respectively. The temperate forest plots indicated 400 trees (19 species), 355 shrubs (20 species), and 162,800 herbs (59 species) (Table 2). The Dominance, Shannon, and Evenness indices analyzed for these two types of forests (subtropical and temperate forests) of the Bani Valley are also presented in Table 2.

Table 2. Qualitative analysis of plant diversity of the Bani Valley (Jammu and Kashmir), Western Himalaya, India.

Habit		Number of Taxa	Number of Individuals	Dominance Index	Shannon Index	Evenness Index
A. Subtropical forests (1201–1600 m)	Trees	45	415	0.41	3.51	0.74
	Shrubs	23	480	0.08	2.75	0.68
	Herbs	42	96,000	0.06	3.01	0.76
B. Temperate forests (1601–2000 m)	Trees	19	400	0.11	2.53	0.66
	Shrubs	20	355	0.12	2.31	0.76
	Herbs	59	162,800	0.03	3.77	0.77

At low altitudes in the subtropical forests of the study area in the Bani Valley, angiosperm taxa were dominant. The gymnosperms were mostly confined to high-altitude regions of the study area. Monocots, especially *Poaceae*, were mostly confined to the higher elevations. Trees and shrubs were mostly confined to lower elevations. The earlier research carried out on the species diversity in Western Himalaya shows a somewhat similar pattern. Comparing these research findings with earlier works, such as that of Mir et al. [70] in the Kashmir Himalayas, shows similarity in findings mostly regarding the dominant coniferous forests. Similarly, Dogra et al. [71] studied plant diversity in the western Himalayas of Himachal Pradesh in similar climatic conditions and elevations, and our research shows similarities in terms of family composition and dominant species. Gaston et al. [72] also carried out similar studies in the western Himalayas, which showed a similar type of species diversity in similar types of vegetation. Other researchers, such as Gairola et al. [73], have performed floristic analysis in the western Himalayas of the Garhwal division of Uttarakhand, and the species richness and different growth forms were similar to the present findings.

3.3. Life Span

In the study area, 50 taxa of annual plants, representing 25.51%, were therophytes. Some of the common annual plants growing in the study area were *Juncus bufonius* L., *Poa annua* L., *Solanum virginianum* L., *Cyperus rotundus* L., *Euphorbia thymifolia* L., etc. A total of 146 were perennial plants, comprising 74.49% of the total flora of the study area, which could survive in the most unusual and unfavorable conditions. These perennial plants were mostly trees and shrubs, which were more dominant at low altitudes in warm, moist, subtropical forests. Some of the common perennial plants growing in the study area were *Commelina benghalensis* L., *Rubus paniculatus* Sm., *Clematis graveolens* Lindl., *Carex brunnea* Thunb., *A. nitida*, *C. deodara*, etc. At higher altitudes most of the plant life forms were therophytes, hemicryptophytes, and chamaephytes, and this could be the result of climatic factors and dry conditions favoring the growth of such species. Similar conditions are not inclusive for other groups, such as megaphanerophytes and nanophanerophytes.

The data on life-span findings from the Bani Valley were observed to be similar to those of Subramani et al. [74], who have carried out life-span studies in the Northwestern Himalayan Region. Another botanist, Saha [75] came across similar dominant life-forms in the Darjeeling regions of the northeastern Himalayas. In J&K, Rawat and Adhikari [76] studied the Changthang plateau of the Ladakh region based on altitudinal gradients, and recorded similar observations. Other studies, such as those of Namgyal et al. [77], Klimes [78], and Pharswan et al. [79], also attained similar research findings in Western Himalaya. Nautiyal et al. [80] conducted similar studies at similar altitudes and climatic conditions in the Tungnath area of the Kumaon Himalayas.

3.4. Life Form and Biological Spectrum

The biological spectrum of the Bani Valley shows that phanerophytes, with 96 taxa (48.97%), were the dominant group, followed by therophytes (50, 25.51%), hemicryptophytes (30, 15.31%), chamaephytes (16, 8.16%), and geophytes (4, 2.04%) (Figure 3). Among phanerophytes, megaphanerophytes (61, 31.12%) were more dominant than nanophanerophytes (35, 17.86%). This research reveals that phanerophytes, chamaephytes, and therophytes constituted higher percentages of 48.97, 8.16, and 25.51%, respectively, than in Raunkiear's normal spectra, exhibiting a "phanero-phamae- therophytic phytoclimate" (Figure 4). Furthermore, the plant life forms, i.e., hemicryptophytes (15.31%) and geophytes (2.04%), were comparatively smaller in percentage than in Raunkiaer's normal spectra (Table 3). The dominant three groups (phanerophytes, therophytes, and hemicryptophytes) constituted 89.79% of the total plant's life.

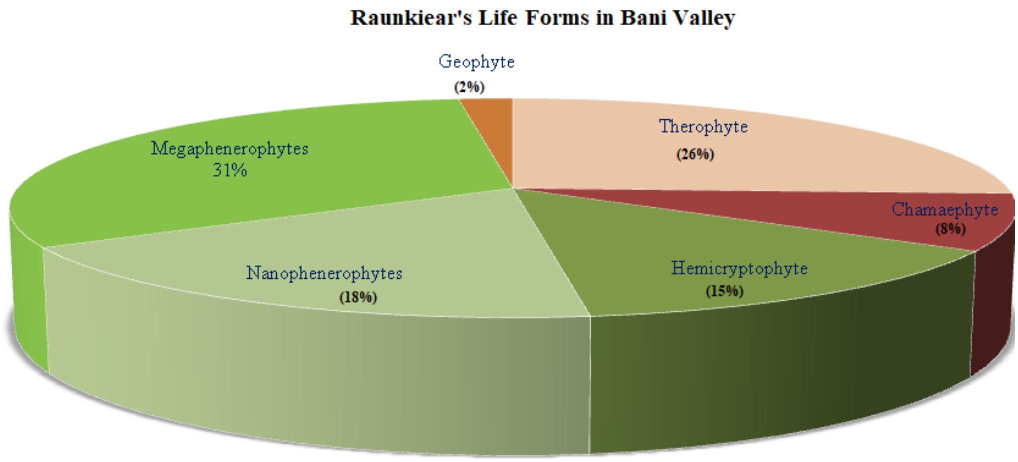

Figure 3. Biological spectra of the taxa recorded in the Bani Valley (Jammu and Kashmir), Western Himalaya, India, based on Raunkiaer's system of classification.

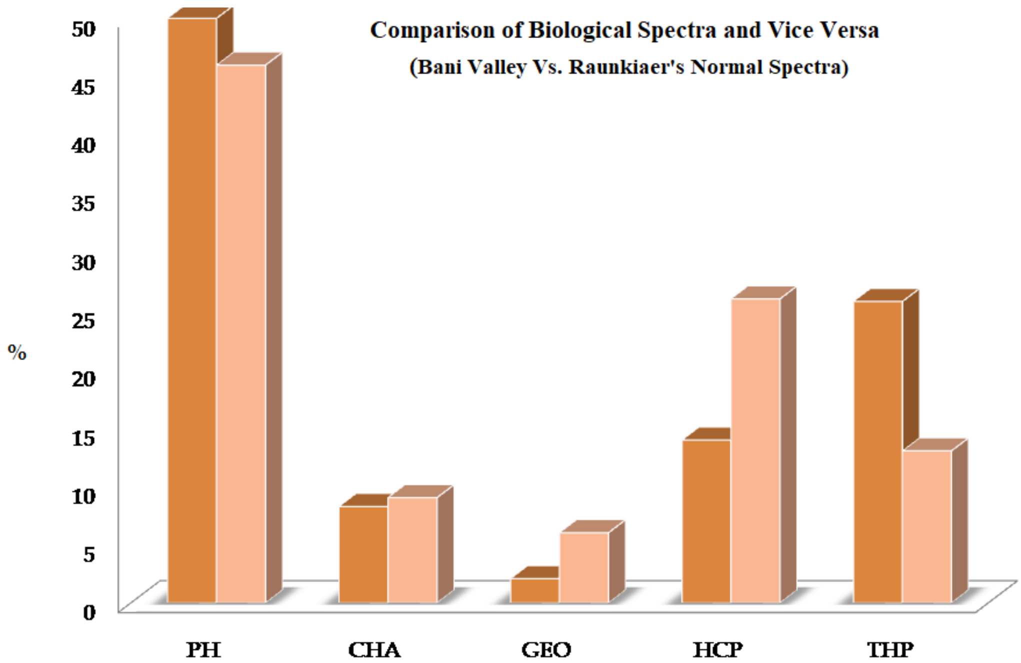

Figure 4. Comparison of the biological spectra of the taxa recorded in the Bani Valley (Jammu and Kashmir), Western Himalaya, India, with Raunkiaer's Normal Spectra (PH: Phanerophytes; CHA: Chamaephytes; GEO: Geophytes; HCP: Hemicryptophytes; THP: Therophytes).

Table 3. Biological spectra (% of all life forms) of the study area and its comparison with Raunkiaer′s normal spectra.

Raunkiaer ′s Life Forms	Total No. of Species	Biological Spectra (%) of the Bani Valley	Raunkiaer′sNormal Spectra (%)	Deviation = (Raunkiaer′s Normal Spectra–Biological Spectra)
PH	96	48.98	46.00	2.98
CHA	16	8.16	9.00	−0.84
GEO	4	2.04	6.00	−3.96
HCP	30	15.31	26.00	−10.69
THP	50	25.51	13.00	12.51
Total	196	100.00	100.00	0.00

(Note:PH: Phanerophytes; CHA: Chamaephytes; GEO: Geophytes; HCP: Hemicryptophytes; THP: Therophytes).

Therophytes growing in the Bani Valley showed the maximum divergence from Raunkiaer′s normal spectra. The dominance of phanerophytes indicates that the study area was under mild biotic pressure. Many plant species were decreasing in the area at an alarming rate [81,82]. Therefore, we feel that it is the responsibility of the local people and forest departments to protect the plant species and unique vegetation composition of the Bani Valley.

Studies reveal that megaphanerophytes and nanophanerophytes were dominant in warmer, moist subtropical forests, whereas therophytes and hemicryptophytes are mostly present in the high-altitude regions of the Bani Valley. Similar studies were also carried out in Western Himalaya earlier by many botanists. Saxena et al. [83] performed studies on life forms at high altitudes in the Kumaon Himalayas. The results of our study were similar to their research findings. Other botanists, such as Singh and Bedi [84], and Das et al. [85], have also carried out similar research in different pockets of Western Himalaya, and when comparing the present research with earlier research findings, we find similar results.

3.5. Leaf Size Spectrum

The overall leaf size spectra of the Bani Valley were: 10 leptophyllous (5.10%), 63 nanophyllous (32.14%), 41 microphyllous (20.92%), 68 mesophyllous (34.69%), and 14 megaphyllous (7.14%). Among the leaf size spectra, mesophyllous was found to be highest among plant species, followed by nanophyllous, microphyllous, megaphyllous, and leptophyllous. The results analysis of the leaf spectra of the Bani Valley concerning the Raunkiaer′s life forms system is shown in Table 4. We observed that the taxa with large leaves occur in warmer, moist climatic conditions, while the plants with smaller leaves are characteristic of cold and dry climatic conditions. Wright et al. [86] studied leaf data for 7670 plant species, along with climate data from 682 sites across the world, and concluded that large-leaved species predominate in wet, hot, and sunny environments, whereas small-leaved plant species were found in high-altitude areas [63]. In the present study, the plant species with microphyllous and nanophyllous leaves were confined to higher altitude regions, and this findingis consistent with the work carried out by Haq et al. [67]. The plant species with mesophyllous and megaphyllous leaves represent the characteristic vegetation in the low-altitude regions. A study carried out in the Keran Valley of the Kashmir Himalayas generated similar results [67]. The herbaceous flora were dominant at the upper reaches in both studies. This is because of similar altitudes and climatic conditions. Similarly, studies carried out by Shaheen et al. [87] in the Western Himalayan alpine regions of Kashmir show similar patterns of life forms.

Table 4. Analysis by leaf size of life forms in the study area.

Raunkiaer's Life Forms	Leptophyllous	Megaphyllous	Mesophyllous	Microphyllous	Nanophyllous	Total
CHA	0	0	6	3	7	16
GEO	0	1	2	0	1	4
HCP	1	0	10	7	12	30
PH	5	12	37	20	22	96
THP	4	1	13	11	21	50
Total	10	14	68	41	63	196

(Note: PH: Phanerophytes; CHA: Chamaephytes' GEO: Geophytes; HCP: Hemicryptophytes; THP: Therophytes).

3.6. Phenological Periods

The taxa showed flowering and fruiting in different seasons. The phenological periods of the plants of the Bani Valley were divided into four different groups of the year. From January to March, 17 taxa were recorded as being in the flowering stage (8.67%), followed by 106 taxa flowering in April–June (54.08%), 63 taxa from July to September (32.14%), and 10 (5.10%) from October to December (Figure 5). Most taxa from the study area were found to be in the flowering stage from April to June. The majority of the taxa bloomed from May to June. The Bani Valley falls under the temperate zone of the Northwestern Himalayan Region, and experiences vivid snowfall in most parts of the region. The perennating buds of the plants growing in such a climate remain dormant in order to overcome these adverse climatic conditions. This is the reason that leads to plants blooming in the spring and summer seasons. Even from July to September, many plant species were found to be in the flowering stage, and during this period the region experiences maximum rainfall. High rainfall allows the plants to grow and bloom. The findings of the present study correlate with similar studies undertaken by earlier researchers [88–93], which reached similar research findings.

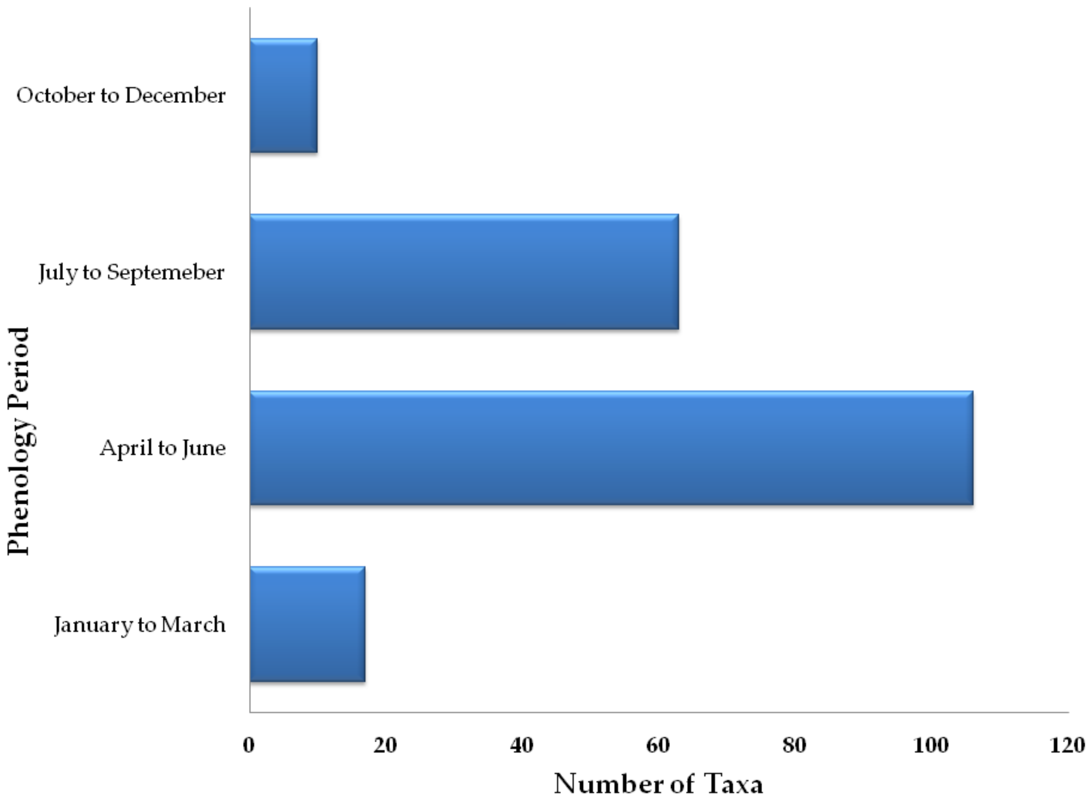

Figure 5. Analysis of the total number of taxa in different phenological periods of the year.

3.7. Invasive Species

Out of a total of 196 species inventorized from the Bani Valley, 30% (59 species) are alien/invasive species, while 70% are native to the Asian or Himalayan regions. These invasive species also show affinities of European, Eurasian, African, and American origin. Most of these alien species are cultivated or introduced as garden plants by the local people in the study area. The most common invasive plant species found to be growing in the region include species such as *Ageratum conyzoides* L., *Argemone mexicana* L., *Arthraxon lancifolius* (Trin.) Hochst., *C. brunnea*, *Cynodon dactylon* (L.) Pers., *Euphorbia thymifolia* L., *Galinsoga parviflora* Cav., *J. bufonius*, *Malvastrum coromandelianum* (L.) Garcke, *Panicum virgatum* L., *Parthenium hysterophorus* L., *Prunus domestica* L., *R. idaeus*, *Setaria flavida* (Retz.) Veldkamp, *Setaria italica* (L.) P.Beauv., and *Solanum americanum* Mill. (Table 5). These invasive plants also are reported as potential invaders in other parts of the Himalayas [69]. Alien plant species tend to have more phenotypic plasticity than native plants, and are usually superior to native plants in numerous fitness components; for this reason, they can colonize disturbed areas and natural habitats more resourcefully than native species [94–96]. *Asteraceae*, *Poaceae*, *Brassicaceae*, *Fabaceae*, and *Lamiaceae* are the families with the most invasive plant species found in India [97], and these families of invasive species are consistent with the findings of Wu et al. [98] for China, Lambdon et al. [99] for Europe, Khuroo et al. [100] for India, Randall [101] for Australia, and Diez et al. [102] for New Zealand. Out of all of the species recorded inthe Bani Valley, 30.41% are alien, most of which thrive in anthropogenically disturbed habitats. These values are comparable with those reported by Kohli et al. [103] from the Himachal Pradesh region of the Indian Himalayas. Khuroo et al. [104] reported that 8.5% of Indian flora (1599 species belonging to 842 genera and 161 families) were alien plant species, most of which belonged to the *Asteraceae* (134 spp.), *Papilionaceae* (114 spp.) and *Poaceae* (106 spp.) families. Another study carried out by Haq et al. [69] reported *Anthemis cotula* L., *Convolvulus arvensis* L., *Carduus onopordioides* Fisch. ex M.Bieb., *Datura stramonium* L., *Erigeron canadensis* L., and *Sisymbrium loeselii* L. as the most invasive plant species growing in the Jammu and Kashmir Himalayas, and reported that climate change and biological invasions in the form of alien species are major drivers affecting biodiversity and ecosystem services.

3.8. Conservation Status and IUCN Categories

Among these 196 taxa of plants (Table 5), 113 had not been evaluated according to the IUCN Red List of Threatened Species [105]. There were 76 plant taxa mentioned under least concern (LC), 1 as endangered (EN), 2 as near-threatened (NT), 2 as vulnerable (VU), and 2 as data deficient (DD). *Ailanthus altissima* (Mill.) Swingle was the endangered species identified from the study area, whereas *Ulmus wallichiana* Planch. and *Plantago lanceolata* L. were the vulnerable species. *Aegle marmelos* (L.) Corrêa and *Q. oblongata*—categorized as NT—were also found to be growing in the Bani Valley. *Taxus baccata* L. and 75 other species are LC species recorded in the study area. Earlier works, such as that of Bijlwan et al. [106], studied the natural regeneration status of endangered plants i.e., *T. baccata* in the Northwestern Himalayan Region. Similarly, Lanker et al. [107] and Paul et al. [108] studied the genus *Taxus* L. in the northeast Himalayas, where this species was mentioned as a highly threatened plant due to anthropogenic factors and its use in medicine. The phytosociological analysis with ecological information reveals a study area that is floristically rich and, at the same time, under pressure from human activity. This research highlights the status and ecological distribution of the species in the study area, the ecological characteristics necessary for their survival, and the threats faced by some of the taxa designated by following the criteria devised by the IUCN. Various factors caused the depletion of the native flora from the study area. Anthropogenic activities were the major cause. Deforestation and overgrazing by livestock were other factors leading to the destruction of plant species.

Table 5. List of plant taxa in the Bani Valley of Kathua district, Jammu and Kashmir, Western Himalaya, India.

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
I. MONOCOTS												
Acorales Martinov												
Acoraceae Martinov												
Acorus calamus L.	RRLH54665	H	P	May–June	Streamside	GEO		MES	Ensiform	LC	Native to Asia	N
Alismatales R.Br. ex Bercht. & J. Presl												
Potamogetonaceae Bercht. & J.Presl												
Potamogeton nodosus Poir.	RRLH55286	H	P	Jul–Aug	Aquatic	CHA		NP	Lanceolate	LC	Native to North America	E
Araceae Juss.												
Arisaema flavum (Forssk.) Schott	RRLH55268	H	P	July–Aug	Forest slopes	GEO		MES	Oblong to lanceolate	NA	Native to Asia	N
Juncaceae Juss.												
Juncus bufonius L.	RRLH55278	H	A	May–Jun	Streamside	THP		MES	Elliptic	LC	Native to North America	E
Smilacaceae Vent.												
Smilax vaginata Decne.	RRLH54673	S	P	May–Aug	Forest thickets	PH	NPH	LEP	Ovate	NA	Native to Asia and Afghanistan	N
Asparagales												
Asparagaceae Juss.												
Asparagus adscendens Roxb.	RRLH55270	H	P	Nov–Dec	Forest thickets	PH	NPH	MIC	Spiny	NA	Native to India	N
Orchidaceae Juss.												
Rhynchostylis retusa (L.) Blume	RRLH55205	H	A	May–Jun	Epiphytic	THP		LEP	Lorate	NA	Native to Asia	N
Commelinales Mirb. ex Bercht. & J. Presl												
Commelinaceae Mirb.												
Commelina benghalensis L.	RRLH54667	H	P	Apr–May	Wet places	CHA		MES	Ovate	LC	Native to Asia	N
Commelina communis L.	RRLH54941	H	A	Apr–May	Moist places	THP		MES	Lanceolate	NA	Native to Asia	N
Poales Small												
Cyperaceae Juss.												
Cyperus alulatus J. Kern	RRLH54630	H	A	Jun–Jul	Forest slopes	THP		NP	Elliptic	LC	Native to the Indian subcontinent	N
Carex brunnea Thunb.	RRLH55270	H	P	Jun–Jul	Mountain slopes	HCP		NP	Lanceolate	NA	Native to Africa	E
Carex muricata L.	RRLH55271	H	P	May–Jun	Hill slopes	HCP		MIC	Lanceolate	NA	Native to North America	E
Cyperus niveus Retz.	RRLH54667	H	A	Sep–Oct	Stream margins	THP		MIC	Elliptic	NA	Native to Asia	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Cyperus paniceus (Rottb.) Boeckeler	RRLH55274	H	P	Apr–May	Grasslands	HCP		NP	Oblong	LC	Native to Africa	E
Cyperus rotundus L.	RRLH52669	H	A	May–Jun	Grasslands	THP		MIC	Elliptic	LC	Native to Africa and Eurasia	E
Eleocharis palustris (L.) Roem. & Schult.	RRLH55276	H	P	Jun–Jul	Stream margins	HCP		MIC	Linear	LC	Native to North America	E
Eriophorum comosum (Wall.) Nees	RRLH54904	H	P	May–Jun	Rock crevices	THP		NP	Linear	LC	Native to Asia	N
Schoenoplectus lacustris (L.) Roem. & Schult.	RRLH55288	H	P	Jun–Jul	Swampy areas	HCP		NP	Linear	LC	Native to Europe	E
Poaceae Barnhart												
Alopecurus arundinaceus Poir.	RRLH54668	H	P	Jul–Aug	Grasslands	CHA		NP	Linear	LC	Native to Eurasia	E
Arthraxon lancifolius (Trin.) Hochst.	RRLH52617	H	A	Sep–Oct	Rocky surfaces	THP		NP	Elliptic	LC	Native to Eurasia	E
Arundinella pumila (Hochst.) Steud.	RRLH55269	H	P	Aug–Sep	Grasslands	HCP		MES	Linear to lanceolate	NA	Native to Asia	N
Brachiaria ramosa (L.) Stapf	RRLH52615	H	A	May–Jun	Grasslands	THP		MIC	Lanceolate	LC	Native to tropical Africa	E
Cenchrus ciliaris L.	RRLH54626	H	A	May–Jun	Wastelands	HCP		MES	Linear	LC	Native to tropical Africa	E
Chrysopogon fulvus (Spreng.) Choiv.	RRLH54960	H	A	Jun–Jul	Moist places	THP		MES	Linear	NA	Native to Asia	N
Chrysopogon gryllus (L.) Trin.	RRLH55273	H	P	Aug–Sep	Moist places	HCP		NP	Linear	NA	Native to Eurasia	E
Cymbopogon distans (Nees ex Steud.) W.Watson	RRLH54669	H	P	Jun–Jul	Open, grassy places	HCP		MES	Linear to filiform	NA	Native to India and China	N
Cymbopogon jwarancusa (Jones) Schult.	RRLH54670	H	P	Mar–May	Mountain slopes	HCP		MIC	Linear	NA	Native of Africa	E
Cynodon dactylon (L.) Pers.	RRLH54671	H	P	Jan–Dec	Roadsides	HCP		NP	Linear	NA	Native to Africa	E
Echinochloa stagnina (Retz.) P.Beauv.	RRLH55275	H	P	May–Jun	Moist places	HCP		NP	Linear	LC	Native to Africa	E
Isachne himalaica Hook.f.	RRLH54971	H	P	May–Jun	Swampy places	HCP		NP	Linear	NA	Native to the Himalayas	N
Leersia hexandra Sw.	RRLH55279	H	P	May–June	Streamside	HCP		NP	Linear	LC	Native to America	E
Melinis minutiflora P.Beauv.	RRLH54627	H	P	Jul–Aug	Field margins	HCP		MES	Linear	NA	Native to Africa	E
Microstegium nudum (Trin.) A.Camus	RRLH55280	H	A	Aug–Sep	Field margins	THP		NP	Linear	NA	Native to Africa	E

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Miscanthus nepalensis (Trin.) Hack.	RRLH55281	H	P	Aug–Sep	Mountain slopes	HCP		MES	Linear	NA	Native to the Himalayas	N
Oplismenus burmanii (Retz.) P.Beauv	RRLH55282	H	P	Sep–Oct	Moist places	HCP		NP	Lanceolate	NA	Native to Africa	E
Panicum virgatum L.	RRLH54628	H	P	Jul–Aug	Cultivated	THP		NP	Linear	LC	Native to North America	E
Paspalum vaginatum Sw.	RRLH54986	H	P	Jun–Jul	Swampy areas	HCP		MIC	Linear	LC	Native to North America	E
Pennisetum flaccidum Griseb.	RRLH55283	H	P	Jul–Aug	Grasslands	HCP		MIC	Linear	LC	Native to the Himalayas	N
Poa annua L.	RRLH55284	H	A	Apr–May	Moist places	THP		MES	Linear	LC	Native to America	E
Polypogon fugax Nees ex Steud.	RRLH55285	H	A	Jun–Aug	Moist places	THP		NP	Linear	NA	Native to South America	E
Saccharum filifolium Steud.	RRLH55287	H	P	Apr–May	Grasslands	HCP		MIC	Linear	NA	Native to the Himalayas	N
Saccharum spontaneum L.	RRLH54953	H	P	Jul–Aug	Mountain slopes	HCP		NP	Linear	LC	Native to the Indian subcontinent	N
Setaria flavida (Retz.) Veldkamp	RRLH55290	H	P	Jul–Aug	Roadsides	HCP		MES	Linear to lanceolate	NA	Native to Africa	E
Setaria italica (L.) P.Beauv	RRLH55291	H	A	May–Jul	Cultivated	THP		NP	Linear	NA	Native to Eurasia	E
Setaria viridis (L.) P.Beauv	RRLH55292	H	A	May–Jun	Roadsides	THP		LEP	Linear	NA	Native to Asia	N
Thysanolaena latifolia (Roxb. ex Hornem) Honda	RRLH54952	H	P	May–Dec	Hillsides	HCP		NP	Lanceolate	NA	Native to Asia	N
Tragus racemosus (L.) All.	RRLH55294	H	P	May–Jun	Roadsides	THP		NP	Linear	NA	Native to Eurasia and Africa	E
II. EUDICOTS Ranunculales Juss. ex Bercht. & J.Presl												
Ranunculaceae Juss.												
Clematis grata Wall.	RRLH55388	S	P	Jul–Aug	Forest margins	PH	NPH	NP	Ovate	NA	Native to the Himalayas	N
Clematis graveolens Lindl.	RRLH55336	S	P	Apr–May	Forest thickets	PH	NPH	NP	Ovate	NA	Native to Afghanistan and India	N
Thalictrum foliolosum DC.	RRLH55367	S	P	May–Jun	Montane forests	PH	NPH	MIC	Elliptic to ovate	NA	Native to the Indian subcontinent	N
Thalictrum virgatum Hook.f. & Thomson	RRLH55245	S	P	Jun–Jul	Forest margins	PH	NPH	MIC	Rhombic	NA	Native to the Himalayas	N
Berberidaceae Juss.												

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Berberis lycium Royle	RRLH55359	S	P	Apr–May	Forest margins	PH	NPH	NP	Oblanceolate	NA	Native to the Himalayas	N
Platanaceae T.Lestib.												
Platanus orientalis L.	RRLH55215	T	P	Mar–May	Cultivated	PH	MPH	NP	Ovate	DD	Native to Europe	E
Buxales Takht. ex Reveal												
Buxaceae Dumort.												
Sarcococca saligna (D.Don) Müll.Arg.	RRLH55268	S	P	May–Jun	Evergreen forests	PH	NPH	MES	Lanceolate	NA	Native to India and Pakistan	N
Papaveraceae Juss.												
Argemone mexicana L.	RRLH54671	H	A	Mar–Apr	Streamside	THP		MIC	Oblanceolate	NA	Native to North America	E
Menispermaceae Juss.												
Cissampelos pareira L.	RRLH54662	S	P	Mar–Apr	Forest margins	PH	NPH	NP	Ovate	NA	Native to Asia	N
Tinospora cordifolia (Willd.) Hook.f. & Thomson	RRLH54670	S	P	May–Jun	Forest thickets	PH	NPH	MES	Cordate	NA	Native to Asia	N
Piperales Bercht. & J.Presl												
Piperaceae Giseke												
Peperomia tetraphylla (G.Forst.) Hook. & Arn.	RRLH55254	H	P	Feb–Mar	Epiphytes	GEO		NP	Elliptic	NA	Native to Asia	N
Laurales Juss.												
Lauraceae Juss.												
Neolitsea umbrosa (Nees) Gamble	RRLH54992	T	P	Mar–May	Forest margins	PH	MPH	MES	Oblong	NA	Native to the Himalayas	N
III. CORE EUDICOTS SUPERROSIDS												
Saxifragales Bercht. & J. Presl												
Crassulaceae J.St.–Hil.												
Rosularia adenotricha (Wall. ex Edgew.) C.-A.Jansson	RRLH54904	H	A	May–Jun	Rock crevices	THP		MIC	Obovate	NA	Native to the Himalayas	N
Fabales Bromhead												
Fabaceae Lindl.												
Acacia concinna (Willd.) DC.	RRLH54925	S	P	April–Jun	Forest thickets	PH	NPH	MIC	Ovate	NA	Native to Asia	N
Albizia chinensis (Osbeck) Merr.	RRLH54675	T	P	Mar–May	Open areas	PH	MPH	MIC	Oblong	NA	Native to Southeast Asia	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Argyrolobium roseum (Cambess.) Jaub. & Spach	RRLH55372	H	A	May–Jun	Forest margins	THP		MIC	Obovate	NA	Native to India and Pakistan	N
Bauhinia purpurea L.	RRLH55373	T	P	May–Jun	Cultivated	PH	MPH	MIC	Suborbicular	LC	Native to the Indian subcontinent	N
Biancaea decapetela (Roth.) O.Deg.	RRLH55374	S	P	Apr–May	Roadsides	PH	NPH	MIC	Ovate	NA	Native to Asia	N
Butea monosperma (Lam.) Kuntze	RRLH54676	T	P	Mar–Apr	Forest margins	PH	MPH	NP	Obovate	LC	Native to Asia	N
Cassia fistula L.	RRLH55375	T	P	Aug–Sep	Roadsides	PH	MGP	MES	Ovate	LC	Native to the Indian subcontinent	N
Chamaecrista mimosoides (L.) Greene	RRLH55611	S	P	Apr–May	Wastelands	PH	NPH	MEG	Linear	LC	Native to Africa	E
Dalbergia sissoo Roxb. ex DC.	RRLH54931	T	P	Mar–Apr	Cultivated	PH	MPH	MEG	Ovate	LC	Native to India	N
Delonix regia (Bojer ex Hook.) Raf.	RRLH55375	T	P	Jun–Jul	Cultivated	PH	MPH	NP	Oblong	LC	Native to Madagascar	E
Erythrina indica Lam.	RRLH55376	T	P	Apr–May	Field margins	PH	MPH	MES	Lanceolate	LC	Native to Africa and Asia	N
Grona triflora (L.) H.Ohashi & K.Ohashi	RRLH54905	S	P	May–Jun	Forest thickets	PH	NPH	MIC	Obovate	NA	Native to America	E
Lespedeza juncea (L.f.) Pers.	RRLH54636	H	P	Jul–Aug	Forest thickets	HCP		NP	Oblanceolate	LC	Native to Asia	N
Ototropis multiflora (DC.) H. Ohashi & K. Ohashi	RRLH55363	S	P	Jul–Aug	Mountain slopes	PH	NPH	MIC	Elliptic	NA	Native to the Indian subcontinent	N
Phyllodium elegans (Lour.) Desv.	RRLH54987	S	P	May–Jun	Forest thickets	PH	NPH	NP	Ovate	LC	Native to the Himalayas	N
Robinia pseudoacacia L.	RRLH54602	T	P	May–Jun	Cultivated	PH	MPH	MES	Oblong	LC	Native to North America	E
Senegalia modesta (Wall.) P.J.H.Hurter	RRLH54674	T	P	Mar–May	Cultivated	PH	MPH	MES	Ovate	NA	Native to the Indian subcontinent	N
Rosales Bercht. & J.Presl												
Cannabaceae Martinov												
Cannabis sativa L.	RRLH54915	H	A	May–Jun	Wastelands	THP		NP	Lanceolate	NA	Native to Asia	N
Celtis australis L.	RRLH55360	T	P	Mar–May	Field margins	PH	MPH	NP	Ovate	LC	Native to the Mediterranean region and West Asia	E
Elaeagnaceae Juss.												
Elaeagnus umbellata Thunb.	RRLH55354	T	P	Apr–May	Forest thickets	PH	MPH	MIC	Obovate	LC	Native to Asia	N
Rosaceae Juss.												

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Prinsepia utilis Royle	RRLH55224	S	P	Apr–May	Wastelands	PH	NPH	MIC	Ovate to lanceolate	NA	Native to the Western Himalayas	N
Prunus domestica L.	RRLH55390	T	P	May–Jun	Cultivated	PH	MPH	NP	Elliptic	DD	Native to North America	E
Prunus persica (L.) Batsch.	RRLH55391	T	P	Apr–May	Cultivated	PH	MPH	MIC	Elliptic	LC	Native to Asia	N
Pyrus pashia Buch.-Ham. ex D.Don	RRLH54901	T	P	Mar–May	Forest thickets	PH	MPH	MES	Ovate	LC	Native to the Himalayas	N
Pyrus pyrifolia (Burm.f.) Nakai	RRLH55392	T	P	May–Jun	Field margins	PH	MPH	MES	Ovate toelliptic	NA	Native to Southeast Asia	N
Rosa moschata Herrm.	RRLH55393	S	P	Jun–Jul	Forest thickets	PH	NPH	MES	Oblong to lanceolate	NA	Native to Iran and Afghanistan	E
Rubus ellipticus Sm.	RRLH54951	S	P	Mar–Apr	Mountain slopes	PH	NPH	MES	Ovate	LC	Native to Asia	N
Rubus idaeus L.	RRLH55210	S	P	May–Jun	Forest thickets	PH	NPH	NP	Ovate to lanceolate	NA	Native to Eurasia	E
Rubus paniculatus Sm.	RRLH55292	S	P	Jun–Jul	Forest thickets	PH	NPH	NP	Ovate to lanceolate	NA	Native to the Himalayas	N
Rhamnaceae Juss.												
Ziziphus mauritiana Lam.	RRLH55389	T	P	Aug–Sep	Forest thickets	PH	MPH	MES	Ovate	LC	Native to India	N
Ulmaceae Mirb.												
Trema orientalis (L.) Blume	RRLH55370	T	P	Mar–Apr	Mountain slopes	PH	MPH	NP	Lanceolate to ovate	LC	Native to Asia and Africa	N
Ulmus wallichiana Planch.	RRLH55400	T	P	Apr–May	Field margins	PH	MPH	MES	Ovate	VU	Native to the Himalayas	N
Moraceae Gaudich.												
Ficus auriculata Lour.	RRLH55383	T	P	Aug–Sep	Forest margins	PH	MPH	MES	Ovate to cordate	LC	Native to Asia	N
Ficus hispida L.f.	RRLH55383	T	P	Jun–Jul	Forest margins	PH	MPH	MES	Ovate to oblong	LC	Native to Asia	N
Ficus palmata Forssk.	RRLH55224	T	P	May–Jun	Roadsides	PH	MPH	MES	Ovate	NA	Native to the Indian subcontinent	N
Morus alba L.	RRLH55385	T	P	Apr–May	Cultivated	PH	MPH	MES	Ovate	LC	Native to North America	E
Urticaceae Juss.												
Debregeasia saeneb (Forssk.) Hepper & J.R.I.Wood	RRLH54948	S	P	Mar–Apr	Shady places	PH		MES	Lanceolate	NA	Native to the Himalayas	N
Elatostema sessile J.R.Forst. & G.Forst.	RRLH54662	H	P	May–Jun	Forest margins	CHA		NP	Linear	NA	Native to the Indian subcontinent	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Fleurya interrupta (L.) Gaudich	RRLH54663	H	A	Jul–Aug	Moist places	THP		MES	Ovate	NA	Native to Asia and Australia	N
Pilea scripta (Buch.- Ham. ex D.Don) Wedd.	RRLH54664	H	P	Jun–Jul	Shady places	PH		MIC	Elliptic	NA	Native to the Himalayas	N
Pilea umbrosa Wedd. ex Blume	RRLH55664	H	P	Jul–Aug	Shady places	CHA		MES	Ovate	NA	Native to the Himalayas	N
Urtica dioica L.	RRLH54991	H	P	Jun–Jul	Forest thickets	HCP		MES	Ovate	LC	Native to Eurasia	E
Fagales Engl.												
Fagaceae Dumort.												
Castanea sativa Mill.	RRLH55272	T	P	Apr–May	Forest margins	PH	MPH	MES	Elliptic	LC	Native to Europe	E
Lithocarpus henryi (Seemen) Rehder & E.H.Wilson	RRLH55377	T	P	Aug–Sep	Mixed forests	PH	MPH	MES	Oblong	LC	Native to the Himalayas	N
Quercus oblongata D.Don	RRLH54684	T	P	May–Jun	Mixed forests	PH	MPH	MES	Oblong	NT	Native to Asia	N
Betulaceae Gray												
Alnus nitida (Spach) Endl.	RRLH55302	T	P	Mar–Apr	Forest margins	PH	MPH	MIC	Elliptic	LC	Native to the Himalayas	N
Juglandaceae DC. ex Perleb												
Juglans regia L.	RRLH54857	T	P	Apr–May	Cultivated	PH	MPH	MES	Elliptic	LC	Native to Eurasia	E
Cucurbitales Juss. ex Bercht. & J.Presl												
Cucurbitaceae Juss.												
Solena amplexicaulis (Lam.) Gandhi	RRLH54604	S	P	Apr–May	Forest thickets	PH	NPH	MIC	Ovate	NA	Native to Asia	N
Combretaceae R.Br.												
Terminalia bellirica (Gaertn.) Roxb.	RRLH55361	T	P	Mar–Apr	Field margins	PH	MPH	MEG	Obovate	NA	Native to Asia	N
Terminalia chebula Retz.	RRLH54361	T	P	May–Jun	Forest margins	PH	MPH	MEG	Elliptic	LC	Native to Asia	N
Lythraceae J.St.-Hil.												
Punica granatum L.	RRLH55379	S	P	May–Jun	Cultivated	PH	NPH	MEG	Elliptic to oblanceo-late	LC	Native to Iran and India	N
Woodfordia fruticosa (L.) Kurz	RRLH54914	T	P	Jan–Feb	Forest slopes	PH	MPH	NP	Lanceolate	LC	Native to Asia	N
Malpighales Juss. ex Bercht. & J.Presl												
Hypericaceae Juss.												

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Hypericum perforatum L.	RRLH54665	H	P	Jun–Jul	Grassland slopes	PH		NP	Oblong	NA	Native to Eurasia	E
Violaceae Batsch.												
Viola odorata L.	RRLH55218	H	P	Apr–May	Forest Slopes	THP		NP	Ovate	NA	Native to Asia	N
Euphorbiaceae Juss.												
Euphorbia hirsuta L.	RRLH54944	H	A	Jun–Jul	Roadsides	HCP		MIC	Lanceolate to ovate	NA	Native to India	N
Euphorbia thymifolia L.	RRLH54920	H	A	Jun–Jul	Roadsides	THP		NP	Lanceolate	NA	Native to America	E
Phyllanthus emblica L.	RRLH52672	T	P	Apr–May	Open areas	PH	MPH	NP	Oblong	LC	Native to India	N
Triadica sebifera (L.) Small	RRLH55371	T	P	May–Jun	Forest slopes	PH	MPH	NP	Rhomboid to ovate	LC	Native to China and Taiwan	E
Salicaceae Mirb.												
Flacourtia indica (Burm.f.) Merr.	RRLH55395	S	P	Jan–Feb	Mixed forests	PH	NPH	MEG	Oblong	LC	Native to Africa and Asia	N
Populus ciliata Wall. ex Royle	RRLH55396	T	P	May–Jun	Roadsides	PH	MPH	MES	Ovate	LC	Native to the Himalayas	N
Xylosma longifolia Clos	RRLH55397	T	P	Apr–May	Mountain forests	PH	MPH	MES	Elliptic	LC	Native to the Indian subcontinent	N
Sapindales Juss.												
Sapindaceae Juss.												
Aesculus indica (Wall. ex Cambess.) Hook.	RRLH55368	T	P	Apr–May	Field margins	PH	MPH	MEG	Oblong	LC	Native to the Himalayas	N
Acer caesium Wall. ex Brandis	RRLH42643	T	P	May–Jun	Forest margins	PH	MPH	MEG	Obovate	LC	Native to the Himalayas	N
Rutaceae Juss.												
Murraya koenigii (L.) Spreng.	RRLH52649	S	P	Mar–Apr	Mixed forests	PH	NPH	MES	Ovate	NA	Native to India and Sri Lanka	N
Aegle marmelos (L.) Corrêa	RRLH52641	T	P	Jul–Aug	Mixed forests	PH	MPH	MES	Ovate	NT	Native to the Indian subcontinent	N
Zanthoxylum armatum DC.	RRLH55226	T	P	Apr–May	Forest margins	PH	MPH	MIC	Lanceolate	LC	Native to the Himalayas	N
Anacardiaceae R.Br.												
Cotinus coggygria Scop.	RRLH54912	T	P	Feb–mar	Forest thickets	PH	MPH	MIC	Elliptic	LC	Native to Eurasia	E
Simaroubaceae DC.												
Ailanthus altissima (Mill.) Swingle	RRLH55398	T	P	Apr–May	Mixed forests	PH	MPH	MEG	Ovate	EN	Native to Asia	N
Meliaceae Juss.												
Melia azedarach L.	RRLH55382	T	P	Mar–Apr	Field margins	PH	MPH	MIC	Ovate	LC	Native to Asia	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Toona sinensis (Juss.) M.Roem.	RRLH55381	T	P	May–Jun	Forest margins	PH	MPH	MES	Lanceolate	LC	Native to the Indian subcontinent	N
Malvaceae Juss.												
Abutilon indicum (L.) Sweet.	RRLH54666	H	P	July–Oct	Wastelands	CHA		MIC	Ovate	NA	Native to Asia	N
Bombax ceiba L.	RRLH55364	T	P	Mar–Apr	Field margins	PH	MPH	MES	Oblong	LC	Native to Asia	N
Grewia optiva J.R.Drumm. ex Burret	RRLH55380	T	P	Jun–Jul	Field margins	PH	MPH	MES	Elliptic	NA	Native to the Indian subcontinent	N
Malvastrum coromandelianum (L.) Garcke.	RRLH54667	H	P	May–Jun	Wastelands	GEO		MEG	Ovate	NA	Native to North America	E
Thymelaeaceae Juss.												
Daphne papyracea Wall. ex G.Don	RRLH55215	S	P	Nov–Dec	Forest thickets	PH	NPH	MES	Ovate	NA	Native to Asia	N
Brassicales Bromhead												
Capparaceae Juss.												
Crateva adansonii DC.	RRLH54671	T	P	Jun–Jul	Roadsides	PH	MPH	NP	Elliptic	LC	Native to Asia	N
Caryophyllales Juss. ex Bercht. & J. Presl												
Amaranthaceae Juss.												
Achyranthes aspera L.	RRLH52653	H	P	Jun–Aug	Wastelands	CHA		NP	Obovate	NA	Native to South America	E
Aerva sanguinolenta (L.) Blume	RRLH52658	H	P	April–Jun	Forest margin	CHA		NP	Ovate toelliptic	NA	Native to Asia	N
Dysphania ambrosioides (L.) Mosyakin & Clemants	RRLH54988	H	A	Mar–Apr	Field margins	THP		MIC	Oblong	NA	Native to South America	E
Polygonaceae Juss.												
Persicaria capitata (Buch.-Ham ex D.Don) H.Gross	RRLH54910	H	P	May–Jun	Forest slopes	CHA		NP	Ovate	NA	Native to Asia	N
Persicaria maculosa Gray	RRLH54928	H	A	Jun–Jul	Streamside	THP		MES	Lanceolate	LC	Native Asia	N
Rumex dentatus L.	RRLH54700	H	A	May–Jun	Mountain slopes	THP		MES	Oblong	NA	Native to Asia	N
Rumex hastatus D.Don	RRLH54975	H	P	Apr–May	Rocky crevices	CHA		MIC	Hastate	NA	Native to the Himalayas	N
IV. ASTERIDS												
Santalales												
Santalaceae R.Br.												
Viscum album L.	RRLH55295	S	P	Nov–Dec	Parasitic	PH	NPH	MIC	Obovate	NA	Native to Eurasia	E
Ericales												

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Ericaceae Durande												
Lyonia ovalifolia (Wall.) Drude.	RRLH55355	T	P	May–Jun	Forest thickets	PH	MPH	MES	Ovate	LC	Native to the Himalayas	N
Rhododendron arboreum Sm.	RRLH55204	T	P	May–Jun	Forest slopes	PH	MPH	MES	Oblong	LC	Native to Asia	N
Primulaceae Batsch ex Borkh.												
Lysimachia arvensis (L.) U.Manns & Anderb.	RRLH55387	H	A	May–Jun	Wastelands	THP		MEG	Ovate	NA	Native to Asia	N
Gentianales Juss. ex Bercht. & J.Presl												
Rubiaceae Juss.												
Galium asperuloides Edgew.	RRLH55213	H	P	Apr–May	Mountain slopes	CHA		MIC	Elliptic	NA	Native to the Indian subcontinent	N
Galium aparine L.	RRLH55394	H	A	Mar–Apr	Forest thickets	THP		MIC	Linear	NA	Native to South America and Eurasia	E
Rubia cordifolia L.	RRLH54625	H	A	Aug–Sep	Forest margins	THP		NP	Lanceolate	NA	Native to India	N
Apocynaceae Juss.												
Holarrhena antidysenterica Wall.	RRLH52631	T	P	Apr–Jul	Mixed forests	PH	MPH	MEG	Ovate	LC	Native to India	N
Boraginaceae Juss.												
Cordia dichotoma G. Forst.	RRLH52610	T	P	Feb–Mar	Field margins	PH	MPH	MEG	Ovate	LC	Native to India	N
Solanales Juss. ex Bercht. & J.Presl												
Convolvulaceae Juss.												
Argyreia nervosa (Burm.f.) Bojer	RRLH55363	S	P	Mar–Apr	Mixed forests	PH	NPH	MES	Cordate	NA	Native to the Indian subcontinent	N
Solanaceae Juss.												
Solanum americanum Mill.	RRLH54619	H	A	Nov–Dec	Wastelands	THP		MES	Ovate	NA	Native to North America	E
Solanum virginianum L.	RRLH54927	H	A	Oct–Dec	Moist places	THP		MES	Ovate to oblong	NA	Native to the Indian subcontinent	N
Solanum xanthocarpum Schrad.	RRLH52367	H	P	Nov–Dec	Moist places	THP		MES	Ovate	LC	Native to the Indian subcontinent	N
Lamiales Bromhead												
Oleaceae Hoffmanns. & Link												
Syringa emodi Wall. ex Royle	RRLH55386	T	P	May–Jun	Mixed forests	PH	MPH	MES	Ovate	NA	Native to the Himalayas	N
Plantaginaceae Juss.												
Plantago lanceolata L.	RRLH55365	H	P	May–Jun	Wastelands	HCP		MES	Lanceolate	VU	Native to Eurasia to Asia	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Acanthaceae Juss.												
Barleria cristata L.	RRLH52605	H	P	May–Jun	Forest slopes	CHA		MES	Elliptic	NA	Native to Asia	N
Dicliptera bupleuroides Nees	RRLH52611	H	A	Jun–Jul	Roadsides	THP		NP	Ovate	NA	Native to Asia	N
Justicia adhatoda L.	RRLH52653	H	P	Jan–Feb	Roadsides	PH		MES	Ovate toelliptic	NA	Native to the Indian subcontinent	N
Lepidagathis cuspidata Nees	RRLH52619	H	P	Mar–May	Forest thickets	CHA		MES	Elliptic	NA	Native to India	N
Rungia pectinata (L.) Nees	RRLH54924	H	P	Nov–Dec	Wastelands	THP		MES	Oblong	NA	Native to Asia	N
Strobilanthes wallichii Nees	RRLH54997	S	P	Jun–Jul	Open forests	PH	NPH	NP	Elliptic	NA	Native to the Himalayas	N
Lamiaceae Martinov												
Colebrookea oppositifolia Sm.	RRLH54908	S	P	Jan–Mar	Forest thickets	PH	NPH	NP	Oblong	NA	Native to the Indian subcontinent	N
Isodon japonicus (Burm.f.) H.Hara	RRLH55224	S	P	Jul–Aug	Forest thickets	PH	NPH	NP	Ovate	NA	Native to Asia	N
Isodon rugosus (Wall. ex Benth.) Codd	RRLH55225	S	P	Jul–Aug	Forest thickets	PH	NPH	MEG	Ovate	NA	Native to Asia	N
Leucas ciliata Benth.	RRLH54903	H	P	Jul–Oct	Roadsides	THP		NP	Lanceolate	NA	Native to Asia	N
Scutellaria discolor Wall. ex Benth.	RRLH55289	H	P	Jun–Jul	Forest margins	CHA		MES	Elliptic to ovate	NA	Native to the Himalayas	N
Vitex negundo L.	RRLH55378	S	P	Apr–May	Forest thickets	PH	NPH	NP	Lanceolate	LC	Native to Asia and Africa	N
Scrophulariaceae Juss.												
Buddleja paniculata Wall.	RRLH55369	S	P	Mar–Apr	Forest thickets	PH	NPH	MES	Elliptic	NA	Native to Asia	N
Asterales Link												
Asteraceae Bercht. & J.Presl												
Ageratum conyzoides L.	RRLH55357	H	A	Jan–Dec	Field margins	THP		NP	Ovate	NA	Native to South America	E
Bidens biternata (Lour.) Merr. & Sherff	RRLH54650	H	A	Sep–Oct	Roadsides	THP		NP	Ovate	NA	Native to the tropical and subtropical Old World	E
Elephantopus scaber L.	RRLH55258	H	A	Jul–Aug	Forest margins	THP		MES	Oblanceolate	NA	Native to the Indian subcontinent	N
Galinsoga parviflora Cav.	RRLH54630	H	A	Jul–Aug	Field margins	THP		MIC	Elliptic	NA	Native to South America	E
Gynura angulosa (Wall.) DC.	RRLH54609	H	P	Sep–Oct	Forest slopes	CHA		NP	Obovate	NA	Native to Asia	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Jacobaea nudicaulis (Buch.-Ham. ex D.Don) B.Nord.	RRLH55277	H	A	Mar–Apr	Grassy slopes	THP		NP	Oblong	NA	Native to Asia	N
Oreoseris gossypina (Royle) X.D.Xu & V.A.Funk	RRLH55385	H	P	May–Jun	Rocky slopes	CHA		MES	Oblanceolate	NA	Native to the foothills of the Himalayas	N
Parthenium hysterophorus L.	RRLH54947	H	A	Apr–May	Wastelands	THP		NP	Ovate toelliptic	NA	Native to South America	E
Blainvillea acmella (L.) Philipson	RRLH52646	H	A	Mar–May	Moist places	THP		MES	Elliptic	NA	Native to Brazil	E
Apiales Nakai												
Araliaceae Juss.												
Hedera nepalensis K.Koch	RRLH55356	S	P	Oct–Nov	Mixed forests	PH	NPH	MIC	Lanceolate	NA	Native to Asia	N
GYMNOSPERMS												
Pinales Gorozh.												
Pinaceae Spreng. ex F.Rudolphi												
Cedrus deodara (Roxb. ex D.Don) G.Don	RRLH55222	T	P	May–Jun	Coniferous forests	PH	MPH	MES	Linear	LC	Native to the Himalayas	N
Juniperus recurva Buch.-Ham. ex D.Don	RRLH55225	T	P	Apr–May	Coniferous forests	PH	MPH	LEP	Linear	LC	Native to the Himalayas	N
Pinus roxburghii Sarg.	RRLH55223	T	P	Sep–Oct	Coniferous forests	PH	MPH	LEP	Linear	LC	Native to the Himalayas	N
Pinus wallichiana A.B.Jacks.	RRLH55224	T	P	May–Jun	Coniferous forests	PH	MPH	LEP	Linear	LC	Native to the Himalayas	N
Taxaceae Gray												
Taxus baccata L.	RRLH55293	T	P	Aug-Dec	Coniferous forests	PH	NPH	LEP	Linear	LC	Native to the Himalayas	N
LYCOPHYTES AND FERNS												
Polypodiales												
Dennstaedtiaceae Pic.Serm.												
Microlepia nepalensis (Spreng.) Fraser-Jenk., Kandel & Pariyar	RRLH54681	H	A	May–Jun	Forest slopes	THP		MIC	Ovate	NA	Native to Asia	N
Pteridaceae E.D.M. Kirchn.												
Adiantum capillus-veneris L.	RRLH54676	H	A	May–Jun	Shady places	THP		NP	Elliptic	LC	Native to the Indian subcontinent	N
Cheilanthes subvillosa Hook.	RRLH54679	H	A	Mar–Apr	Moist places	THP		NP	Lanceolate	NA	Native to the Indian subcontinent	N

Table 5. *Cont.*

Plant Groups (APG IV)	Voucher Number	Habit	Life Span	Phenology Period	Habitat	Raunkiaer's Life Forms	Sub-type of Raunkiaer's Life Forms	Leaf Spectrum	Leaf Shape	Conservation Status (IUCN)	Specific Distribution	Native (N)/ Exotic (E)
Onychium japonicum (Thunb.) Kunze	RRLH54682	H	A	May–Jun	Moist places	THP		MIC	Ovate	NA	Native to Asia	N
Polystichum polyblepharum (Roem. ex Kunze) C.Presl	RRLH54683	H	P	Mar–Apr	Shady places	HCP		LEP	Lanceolate	NA	Native to North and South America	E
Pteris cretica L.	RRLH54684	H	P	Mar–Apr	Forest margins	HCP		MES	Obovate	NA	Native to Africa and Eurasia	E
Pteris vittata L.	RRLH54685	H	P	Mar–Apr	Forest margins	HCP		MES	Elliptic	LC	Native to Asia	N
Aspleniaceae Newman												
Asplenium adiantum–nigrum L.	RRLH54677	H	A	May–Jun	Rocky crevices	THP		LEP	Ovate	NA	Native to Eurasia	E
Asplenium dalhousiae Hook.	RRLH54678	H	A	May–Jun	Rocky surfaces	THP		NP	Ovate	NA	Native to India	N
Selaginellaceae Willk.												
Selaginella eurynota A.Br.	RRLH54686	H	A	Mar–Apr	Shady places	THP		LEP	Elliptic to ovate	NA	Native to Asia	N

(Abbreviations—Habit: H = herb; S = shrub; T = tree. Life span: A = annual; P = perennial. Raunkiaer's Life Forms: CHA = chamaephyte; GEO = geophyte; HCP = hemicryptophyte; HDP = hydrophyte; MPH = megaphaneropyte; NPH = nanophanerophyte; PH = phanerophyte; THP = therophyte. Leaf spectra: LEP = leptophyllous; MEG = megaphyllous; MES = mesophyllous; MIC = microphyllous; NP = nanophyllous. Conservation status: LC = least concern; EN = endangered; VU = vulnerable; DD = data deficient; NT = near-threatened; NA = not available on the IUCN Red List of Threatened Species'website/not assessed. Nativeness: E = exotic; N = native/indigenous).

4. Conclusions

Scientific findings have proven that floristic analysis is a good indicator of the ecological wealth of the ecosystem within the given setup of the prevailing microhabitat conditions of a particular geographical region. The inventory of the floristic composition of India and elsewhere in the world would help in bridging the geographical knowledge gaps in invasion biology research. The inventory can serve as a scientific baseline for investigating the patterns, pathways, extent, impacts, and effective management of plant invasions in India. Studying floristic composition and associated ecological parameters in the Himalayas is a necessity for biodiversity conservation, because it provides scientific data pertaining tothe environment for wildlife, and simultaneously contributes to the sustainable management of unique regional natural resources. The Bani Valley in the Northwestern Himalayan Region is floristically abundant with natural resources, which is evident from the occurrence of 196 different species of plants. The surprising levels of diversity recorded in the subtropical and temperate forest plots, as well as the low levels of similarity between these forests, suggest that the Bani Valley may harbor forests richer in plant species than previously imagined. More extensive explorations and inventories throughout the Himalayan regions are needed in order to get a better idea of just how diverse these forests may be. Analysis of life forms gives a clear picture of the biological spectrum of the Bani Valley, which in times to come will serve as baseline information for ecologists and environmentalists. In the present study, phanerophytes, therophytes, and hemicryptophytes share importance in depicting the "phanero-thero-hemicrypto phytic"phytoclimate. This study can provide baseline data for use by policymakers and wildlife departments to develop conservation plans for the sustainable use of plant resources in the Himalayas, particularly for the subtropical and temperate species. It also suggests that biotic factors play an important role in shaping the vegetation of a landscape; therefore, anthropogenic stress can be minimized. Accordingly, we suggest that rich-diversity forests such as those found in the Bani Valley should be given higher priority in conservation planning than is presently the case. Finally, it is worthwhile to point out that the Bani Valley is rather close to several indigenous communities, which therefore means that these areas are inhabited, exploited, and intervened in by humans, although such impacts are very low. In times to come, conservation programs could be started in order to protect economically valuable flora by educating the native communities residing there.

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sustainability

Article

The Importance of Keeping Alive Sustainable Foraging Practices: Wild Vegetables and Herbs Gathered by Afghan Refugees Living in Mansehra District, Pakistan †

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† This paper is dedicated to the memory of first author's father (Afsar Khan Manduzai), who, as many others Afghans, fled to Pakistan in 1980; Afsar has been one of the key study participants of this survey and unexpectedly passed away on 18 December 2020, while this paper was in its final preparation phase.

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Abstract: The issue of foraging for wild food plants among migrants and relocated communities is an important one in environmental studies, especially in order to understand how human societies rearrange their practices linked to nature and how they adapt to new socioecological systems. This paper addresses the complexity of Traditional/Local Environmental Knowledge (LEK) changes associated to wild vegetables and herbs across four different groups of Afghan refugees living in Mansehra District, NW Pakistan, since 1985. Via interviews with eighty study participants, forty-eight wild vegetables and herbs were recorded, representing both the past and present wild plant gastronomic heritage. The majority of the quoted wild plant ingredients were only remembered and no longer actively used, thus suggesting an important erosion of LEK. Moreover, the number of wild vegetables and herbs currently used by Afghan Pashtuns engaged in farming activities is much higher than those reported by the other groups. The findings indicate that practiced LEK, i.e., knowledge that is continuously kept alive via constant contact with the natural environment, is essential for the resilience of the biocultural heritage, which is, however, also influenced by the rearrangement of social life adopted by refugees after relocation.

Keywords: wild food plants; herbal teas; ethnobotany; LEK; Afghans; refugees; Pakistan; cultural adaptation

1. Introduction

The ethnobotany of migrants, i.e., the exploration of wild plants and herbal teas used by relocated communities has become the focus of an increasing number of studies during the past two decades, aimed at exploring how Traditional/Local Environmental Knowledge (LEK, [1]) and attached gastronomic heritage [2] change after relocation.

During the past two decades, several scholars have undertaken the task of exploring the food systems of migrants (for example [3–7]), and specifically their plant-related knowledge and practices ([8], and references therein), particularly in the USA [9–11], Latin America [12–15], the UK [16,17], and the European Union [18–22], as well as in Northern Africa [23]. To our knowledge, no research has thus far considered the LEK of migrants forcibly relocated because of war, and very few studies have addressed the issue of migrants' plant knowledge in Asia [24].

Northwest Pakistan has undergone profound changes in its social structure over the past several decades due to the arrival of a significant number of war refugees from Afghanistan beginning in 1979; however, little attention has been paid to the analysis of their customs, especially in terms of LEK systems. In 2017, 1.4 million registered Afghan refugees were living in Pakistan [25]. Since the late 1990s, a considerable number of Afghan refugees have moved out of refugee camps to peri-urban areas, and in 2011, 67% of them lived in urban or rural areas, while the remaining 33% still resided in 54 refugee camps [26]. The majority of the Afghan diaspora lives in Khyber Pakhtunkhwa (KP), the Northwest Province of Pakistan, which borders Afghanistan and has both environmental and socio-cultural configurations similar to those of that country. Moreover, in this province, the geoclimatic and environmental conditions (i.e., the presence of Pakistan's most extensive forest as well as mountain pastures) make possible the continuation of some pastoralist activities, which were performed by the refugees before having to leave their native country.

This paper aims to fill the gap in the environmental, anthropological, and ethno-biological literature, focusing attention on Afghan war refugees and the effects of their forced migration on their foraging practices and wild plant use/gastronomy. In doing so, the paper documents and compares the uses of wild food plant ingredients among four distinct ethnic Afghan refugee groups in Mansehra in order to assess how different cultural adaptation strategies may have affected their LEK linked to wild plants.

The objectives of this study were to record the wild plant portion of the LEK and gastronomic heritage, i.e., the wild food plants and herbal teas as remembered or still used, among four groups of Afghan refugees in Mansehra District, to compare the data among the four communities, and to discuss possible explanations for differences among the diverse strategies of cultural adaptation that the considered communities adopted.

2. Materials and Methods

2.1. Study Area and Communities

The study was conducted in Mansehra District, NW Pakistan, from January to March 2020 (Figure 1). The district occupies an area of 4579 square kilometers, consisting of mainly plains and hills. Mansehra is located between 34°14′ and 35°11′ latitude and 72°49′ and 74°08′ longitude. Mansehra District is surrounded by lush green high mountains and plain agricultural land. Mountain elevation varies between 2000 m in the South to over 4500 m in the North. In Mansehra, the climate is moist temperate: the mean maximum and minimum temperatures recorded are 34 °C and 2 °C, respectively.

Administratively, the Mansehra District belongs to the Hazara Division of the Khyber Pakhtunkhwa (KP) Province of Pakistan. According to the 2017 census, the total population of Mansehra District is approximately 1.5 million [27] and the predominant language, according to the 1981 census, is Northern Hindko, with Pashto spoken by about 15% of the population [28]. The population is largely Muslim, with a small number of Hindus and Sikhs.

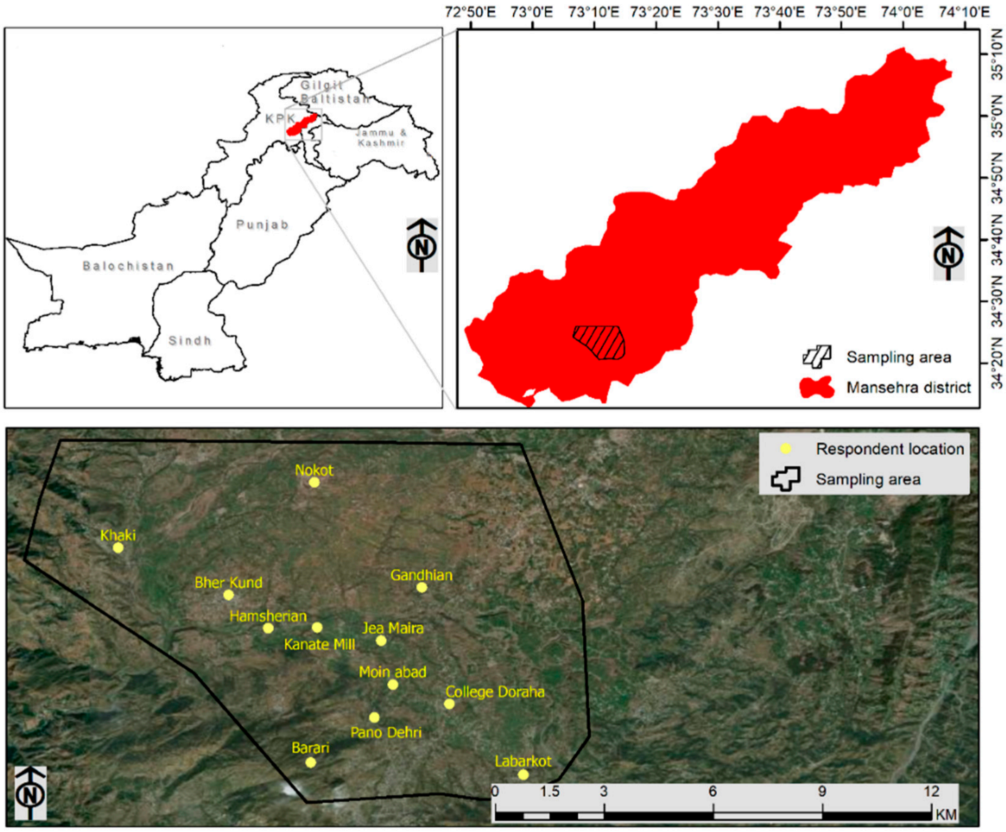

Figure 1. Map of the study area and visited valleys.

2.2. Informant Selection and Field Study

A total of 80 interviews with individuals ranging between 50 and 80 years of age were conducted among the four major refugee groups, belonging to three distinct ethnic groups, residing in the area of Mansehra District. They included: Pashtun Afghans who live outside refugee camps (PAs), Pashtun Afghans still living inside camps (PCs), Kochi Pashtun Afghans (KOs), and Uzbek Afghans (UZs). All the refugees arrived in Pakistan from diverse areas of Afghanistan, mainly from the areas of Balkh and Kunduz in the North and the areas of Logar, Jalalabad, and Paktika in the East, at the beginning of the 1980s, following the Russian invasion of Afghanistan. The interviewee sample is further described in Table 1.

Study participants were selected by snowball sampling, starting from elderly community members, who could be perceived as LEK holders. All the interviews were conducted by the first author (Figure 2) in the spring of 2020, in the two main local languages spoken by the community members (Pashto and Farsi/Persian). The ethnobotanical information was gathered from in-depth interviews after obtaining prior verbal informed consent and the *Code of Ethics* of the International Society of Ethnobiology (ISE) [29] was strictly followed. The interviews focused on current and past uses of wild vegetables and other herbal ingredients, which included information on plant folk names, details of use, and procurement. Mushrooms as well as wild fruits were excluded in the current survey, because they are cognitively well separated from the category "herbs" in the local folk taxonomy and because of the difficulties in eliciting information about food items, which are normally not collected during the spring. Particular attention was paid to record the medicinal perception of wild plant-based preparations [30,31].

Table 1. Characteristics of the study participants.

Group	Pashtuns Living Outside Refugee Camps (PAs)	Pashtuns Living Inside Refugee Camps (PCs)	Pashtun Kochis (KOs)	Uzbeks (UZs)
Arrival in the present area	1979–1985	1979–1985	1979–1985	1979–1985
Approx. number of community members	10,000	6000	4000	2000
Living environment	Plain area	Plain area	Plain areas in winter, mountain pastures in the summer	Plain area
Native language	Pashto	Pashto	Pashto	Uzbek
Other known languages	Persian	Persian	Persian	Pashto and Persian
Religion	Sunni Islam	Sunni Islam	Sunni Islam	Sunni Islam
Marriages	Strictly endogamic	Strictly endogamic	Strictly endogamic	Strictly endogamic
Subsistence economy	Horticulture	Foreign remittances	Pastoralism	Horticulture and butcher's shops
Estimated socioeconomic status	Middle low	Middle low	Low	Low
Number of interviewed study participants (males/females)	20 (14/6)	20 (19/1)	20 (20/0)	20 (20/0)

Figure 2. First author interviewing Kochi study participants.

2.3. Botanical Identification

The wild plant specimens that could be collected during the field survey were identified by taxonomists at COMSATS University. The nomenclature follows World Flora Online [32], while family assignments follow the Angiosperm Phylogeny Group (APG) IV [33]. The herbarium specimens were deposited at the herbarium of COMSATS University Islamabad (Abbottabad Campus). For the quoted wild plants for which no specimens could be collected, identification was hypothesized on the basis of photographs, plant descriptions, and similarity of the recorded folk plant names with those previously recorded in field ethnobotanical and plant ethnolinguistic surveys conducted in Persian/Dari- and Pashto/Pathan-speaking areas [34–43].

2.4. Data Analysis

Data on the recorded wild plant ingredients among the four considered groups were represented using a Venn diagram and the Jaccard (similarity) Index (JI) for each pair of datasets [44]. JI was calculated using the following formula:

JI = number of plants used by both group A and group B/total number of plants used by groups A and B.

3. Results

3.1. The Wild Food Plants of the Afghan Diaspora in NW Pakistan

The recorded wild plant ingredients used in the past or currently used are reported in Table 2; the table also includes also two specific cultivated plants (*Papaver* and *Brassica* spp.), whose quoted food/herbal use remarkably diverge from their "usual" ones in both the Middle East/South Asia and "the West".

Table 2. Wild vegetables and herbal teas recorded among the Afghans living in NW Pakistan.

Botanical Family, Taxon, and Voucher Specimen Code	Vernacular Name	Procurement	Used Parts	Preparation and Perceived Healthy Properties (Treated Diseases)	FQ PAs	FQ PCs	FQ KOs	FQ UZs
Achillea santolinoides Lag. and possibly other *Achillea* spp.#, Asteraceae	Zawal	fA	Aerial parts	B: boiled in milk, anti-cough	++ *		+ *	
Alkanna tinctoria (L.) Tausch., Boraginaceae, CUHA205	Surkhakay	Bm	Roots	F: powdered, sprinkled on crude or fried egg, and given to eat to a mother who just gave a baby, believed to be a reconstituent and relieving internal wounds; decoction, topically applied for earaches	++		+ *	
Allium carolinianum DC. #, Amaryllidaceae	Piazake	fP	Leaves	F: boiled and then fried (sometimes mixed with other greens), or sometimes consumed raw	+		+++	
Allium rosenbachianum Regel #, Amaryllidaceae	Kheza	fA	Leaves	F: fried	+ *	+ *	++ *	
Amaranthus hybridus L. and possibly other *Amaranthus* spp.#, Amarathaceae	Qarqarra	fP	Leaves	F: boiled, then fried with onions and tomatoes, and eventually chilies (in mixtures with other greens)	+++	++		
Artemisia scoparia Waldst. & Kitam., Asteraceae, CUHA10	Tarkha	fA	Whole plant	B: cold macerate (let macerate one whole night outside under the stars), abdominal pains *	+ *	+ *	++ **	
Berberis lycium L., Berberidaceae, CUHA204	Kwaray	bm	Roots	B: cold macerate, drunk, as a remedy against backache, headache, bone aches, stomachache, anti-cough, to heal internal/external wounds, heel cracks	+++	++	++	

Table 2. *Cont.*

Botanical Family, Taxon, and Voucher Specimen Code	Vernacular Name	Procurement	Used Parts	Preparation and Perceived Healthy Properties (Treated Diseases)	FQ PAs	FQ PCs	FQ KOs	FQ UZs
Berberis sp.#, Berberidaceae	Spar aghzye	fA	Aerial parts	B: decoction, menorrhagia	+ *			
Brassica rapa L., Brassicaceae, CUHA206	Teepar	cultivated	Seeds	B: roasted (wrapped in piece of cloth and placed inside burning embers) and then consumed as a galactagogue	++			
Calotropis procera (Aiton) Dryand#, Apocynaceae	Spalmai	fA	Leaves	B: crushed and topically applied, anti-lice	+ *			
Camellia sinensis (L.) Kuntze#, Theaceae	Sheen Chai	bm	Leaves	B: tea is used to lower cardiovascular complications and body fats	+++	++	++	++
Cannabis sativa L., Cannabaceae, CUHA16	Da bhang bootay	bm	Hashish (*charas*)	SM: smoked and inhaled, aphrodisiac	+ *		++ *	++
Capparis spinosa L.#, Capparaceae	Kevera	fA, br	Young leaves and flower buds	F: boiled, then fried with onions, tomatoes, and eggs; sometimes preserved dried	+	+ *	++ *	
Capsella bursa- pastoris (L.) Medik., Brassicaceae, HUP9204	Pathosnara	fP	Leaves	F: boiled and then fried (in mixture with other greens)	++			
Caragana ambigua Stocks#, Fabaceae	Makhey	fA	Young fruits	F: eaten raw			++ *	
Centaurea sp.#, Asteraceae	Kuragh	fA	Aerial parts	B: decoction, antidiabetic	++ *		+ *	
Chenopodium album L., Amaranthaceae, CUHA21	Shorakay	fP	Leaves and young shoots	F: boiled, then fried with onions and tomatoes, and eventually chilies (in mixtures with other greens)	++			
Cichorium intybus L.#, Asteraceae	Shamakay, Shenguly	fA	Seeds	B: decoction, anti-pyretic	+*	+ *	++ *	
		fP	Leaves	F: boiled, then fried (mixed with other vegetables)	++			
Cuminum setifolium (Boiss.) Koso-Pol.#, Apiaceae	Krawsay	fA	Leaves	B: tea, anti-cough, esp. in cows and sheep		++ *		
Descurainia sophia (L.) Webb ex Prantl., Brassicaceae, CUHA207	Khaksher	fA	Seeds	B & F: decoction or seeds consumed as such, as an antipyretic and cold reliever in children	++ *			
Ephedra sp.#, Ephedraceae	Mauraze	fA	Leaves	B: tea, sometimes considered anti-cough	+ *		+++ *	
Ferula sp.#, Apiaceae	Khore	fA	Young shoots	F: boiled and fried	+ *		++ *	
Fumaria indica (Hausskn.) Pugsley., Fumariaceae, CUHA188	Pappra	fA	Fresh plant juice	B: crushed, macerated in cold water, left overnight under the stars/sky, and drunk in a small glass before breakfast, as an antidiabetic and blood purifier	++ *		+ *	

Table 2. *Cont.*

Botanical Family, Taxon, and Voucher Specimen Code	Vernacular Name	Procurement	Used Parts	Preparation and Perceived Healthy Properties (Treated Diseases)	FQ PAs	FQ PCs	FQ KOs	FQ UZs
Heliotropium sp.#, Boraginaceae	Ajdum	bm	Roots	B: decoction, aphrodisiac, backache, joint aches	++			
Lamium amplexicaule L., Lamiaceae, HUP9208	Char gul bootay	fP	Leaves and flowers	F: boiled, then fried (mixed with other greens)	++			
Malva nicaeensis All., Malvaceae, HUP9201	Panderak	fP	Leaves	F: boiled, then fried (alone or with mixed greens), often considered a strengthening food for women during pregnancy; preserved dried	+++	++	+	
Medicago arabica (L.) Huds., Fabaceae, HUP9202	Peshtaray	fP	Leaves	F: boiled, then fried with onions (mainly mixed with other greens); preserved dried	+++	++	++	++
Myrtus communis L.#, Myrtaceae	Maloogan	bm	Leaves	SM: dry leaves are placed on embers—the resulting smoke is considered an anti-Evil-Eye mean (esp. for those babies and children, who are most beloved)	+			
Olea europaea subsp. *cuspidata* (Wall. & G.Don) Cif.#, Oleaceae	Khowan	fP	Leaves	F: leaves were used to prepare tea in times of famine	+ *			
Paliurus spina-christi Mill.#, Rhamnaceae	Zrerra	fA	Roots and seeds	B: decoction, hepatitis		++ *		
Papaver somniferum L., Papaveraceae, CUHA211	Post/Ghoza	cultivated	Pericarp and latex	B: decoction of the pericarp, as an anti-cough; the latex is ingested as an aphrodisiac and anti-insomnia	+ *	+ *	+ *	++
Peganum harmala L., Nitrariaceae, CUHA150	Spelanay	bm	Seeds	SM: seeds are sprinkled on embers and their smoke is considered able to counteract the Evil-Eye F: seeds with white sugar are ingested as anti-cough	++	++ *	+ *	
Plantago lanceolata L., Plantaginaceae, HUP9207	Bartang	fA	Seeds	B: boiled in milk drunk as an anti-diarrheal, anti-cough, and for curing bronchitis	++ *			
Plantago ovata Forssk., Plantaginaceae, CUHA153	Asphagoul	bm	Seeds	F: consumed raw with white sugar in order to treat dysentery and hematuria	+++	+	++	++
Polygonum sp.#, Polygonaceae	Bandakey	fA	Young shoots	F: fried	++ *			
Portulaca oleracea L., Portulacaceae, CUHA72	Warkharay	fP	Aerial parts	F: boiled and then fried (in mixture with other greens)	++	+ *	++ *	
Punica granatum L., Lythraceae, CUHA78	Annar	bm	Fruits	B: decoction of the fruit epicarp is used as anti-diarrheal for children; F: fruit pulp with seeds are consumed as blood purifier *	++		+	++

Table 2. *Cont.*

Botanical Family, Taxon, and Voucher Specimen Code	Vernacular Name	Procurement	Used Parts	Preparation and Perceived Healthy Properties (Treated Diseases)	FQ PAs	FQ PCs	FQ KOs	FQ UZs
Quercus baloot Griff., Fagaceae	Serei	fA	Seeds	B: decoction, anti-pyretic	+ *			
Rosa spp.#, Rosaceae	Gulab	fA	Leaves	B: cold macerate, thrust quencher	+ *			
Rumex crispus L., Polygonaceae, HUP9205	Shalkhay	fP	Leaves	F: boiled and then fried, sometimes considered as a remedy for treating constipation	+++	+	++ *	
Salvia spp.#, Lamiaceae	Gulbakhor	bm	Aerial parts	B: decoction, aphrodisiac for females	++			
Stellaria media (L.) Vill., Caryophyllaceae, HUP9203	Kashi	fP	Leaves	F: boiled, then fried (with other greens)	+			
Trachyspermum ammi (L.) Sprague., Apiaceae, CUHA203	Sperkai	bm	Fruits	B: tea, abdominal cramps and dysentery (also for sheep and cows *)	+++	++	+	+ *
Trigonella foenum-graecum L., Fabaceae, CUHA209	Malkhawaze	bm	Seeds	F: eaten raw for relieving gastric troubles *	+		+	
Vitex negundo L.#, Lamiaceae	Marwandaie	fA	Leaves	B: decoction, aphrodisiac for females	+ *			
Withania coagulans (Stocks) Dunal., Solanaceae, CUHA170	Khamzoora	fA, fP	Seeds	F: rennet for making cheese	+ *	+ *	+++	
			Leaves	B: tea, anti-cough/cold *		+		
Unidentified taxon	Sukre	fA	Whole plant	B: cold macerate, blood purifier	++ *			

#: identification conducted upon pictures, folk names, and plant description only; bm: ingredient bought at the local market; br: brought from the home country; f: foraged; A: in Afghanistan; P: in Pakistan; * uses only remembered from the past in Afghanistan; B: beverage; F: food; SM: smoked; FQ: frequency of quotation; PAs, PCs, KOs, UZs: see Table 1; + rarely quoted (less than 10% of study participants); ++ commonly quoted (10–40% of study participants); +++ very commonly quoted (more than 40% of study participants).

A total of forty-eight plants were recorded, of which two could not be identified, since they refer to wild ingredients, which were only used in the past in Afghanistan and no specimens, pictures, or very detailed descriptions of them could be obtained. Table 2 presents the recorded ingredients along with their plant origin, local names, procurement, preparations, uses, and quotation frequencies among the four considered groups.

Very few wild vegetables were used as *edible medicines* ([30,31]: ad hoc prepared dishes consumed in order to obtain a specific healing effect), while most quoted herbal teas were also used therapeutically. Study participants did not report any adverse effects linked to the use of the quoted wild plants.

Most of the quoted ingredients were only remembered (Figure 3), while most of the quoted plants were foraged (during the past in Afghanistan and currently in Pakistan), although an important number—especially dried wild herbal teas—were bought from markets in the host country. The most frequently quoted ingredients were wild amaranth (*Amaranthus* spp.), *Berberis lyceum*, ajwain (*Trachyspermum ammi*), spotted medick (*Medicago arabica*), and psyllium (*Plantago ovata*).

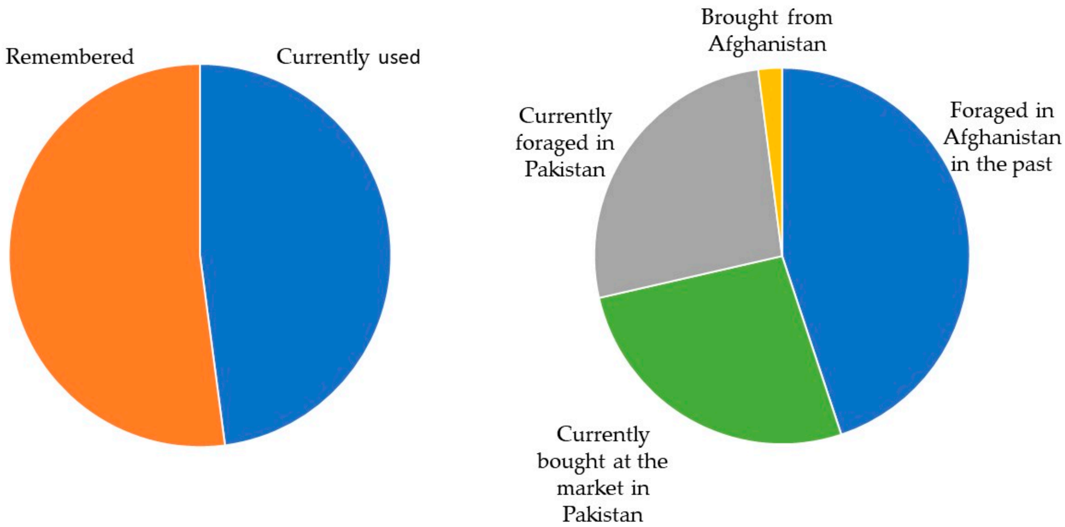

Figure 3. Remembered vs. currently used wild ingredients and their procurement.

Figure 4 and Table 3 show the overall comparison of the wild plant ingredients quoted by the four considered groups, in which we can observe that the diversity of wild plant ingredients quoted by Pashtuns living outside the camps (n = 46, 25 currently used) was much higher than that of wild plants quoted by Kochis (n = 27, 11 currently used), by the Pashtuns living in refugee camps (n = 19, 9 currently used), and by Uzbeks (n = 7, 6 currently used). In particular, the JI between PAs and KOs overall wild ingredients was remarkable and higher (JI = 0.55) than that between both Pashtun groups (JI: 0.36).

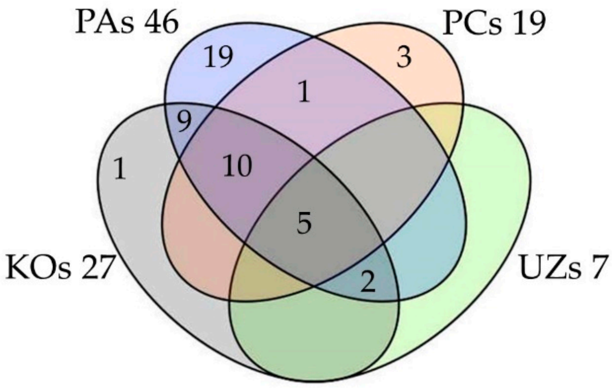

Figure 4. Venn diagram showing the cross-cultural comparison of the overall quoted wild food plants.

Table 3. Jaccard Similarity Indexes (JI) of the quoted wild food plants quoted by the four considered groups (the highest value is marked in bold).

	PAs	PCs	KOs	UZs
PAs	-	0.36	**0.55**	0.15
PCs	0.36	-	0.48	0.24
KOs	**0.55**	0.48	-	0.26
UZs	0.15	0.24	0.26	-

The following paragraphs will try to address some possible explanations for this remarkable difference, assuming that before relocation the refugees had a similar life and socioeconomic profile, and that the LEK of the four groups while living in Afghanistan was similar. This assumption is reasonable given the fact that, four decades ago, Afghans were engaged in small-scale subsistence agropastoral activities, both in the rural north and in the east of their country, areas from which most of the study participants moved.

3.2. Wild Vegetables

Interviews revealed a remarkable resilience of foraging practices among Pashtuns with regard to farming activities, exclusively related, however, to wild leafy vegetables growing close to courtyards. Women are the main foragers of widely available weeds, which they gather, using just their hands, from anthropogenic areas close to cultivated plots. Once the wild vegetables are brought home, they are washed with water several times and then boiled in hot water for 10–20 min; after boiling, the water is drained and the boiled vegetables are fried with tomatoes, onions, garlic, and possibly chilies (*gadwad saba*). Generally, this second stage takes about 10–15 min and the dish is served with whole wheat bread (*tandoori nan*), normally baked by elderly women at home in clay ovens.

Moreover, boiled wild vegetables are often also used as a filling for the national Afghan dish called *bolani* (a flat-bread, normally baked with a vegetable filling, Figure 5).

Figure 5. Foraged weeds (*Amaranthus*, *Chenopodium*, and *Portulaca* spp.) and *bolani* filled with them.

In addition, study participants also revealed that they sometimes use a combination of wild vegetables with some cultivated leafy vegetables, most commonly spinach (*Spinacia oleracea*). Furthermore, most of the informants living outside the refugee camps reported the preservation of some wild vegetable plants such as mallow and alfalfa (*Malva* and *Medicago* spp., respectively), which are dried on mats in direct sunlight; after drying, these vegetables are stored in a porous cloth bag or a piece of cloth for use in the off season, just putting them back in water.

Dried wild vegetables are especially used during the winter and times of financial insecurity as well.

The majority of the study participants from the community of Afghan Pashtuns living outside the refugee camps also reported a few wild plants used as *edible medicines*; in particular, cooked dock leaves (*Rumex* sp.) are considered a remedy for constipation, while processed mallow (*Malva* sp.) leaves are considered to be a strengthening food for pregnant women. The most popular homemade beverage among all Afghans living in the study area is green tea (sheen chai), which is additionally recognized as a medicine for lowering body fat and cardiovascular problems. Moreover, the Kochi community used to prepare green tea with wild *Withania* leaves and Pashtuns living outside the camps wild *Olea* leaves.

Overall, the plant knowledge of Afghan refugees seems to have been heavily affected by their relocation. The data show an overarching reduction in foraged wild plants growing in the mountains due to their transfer into a new (plain) natural environment.

The wild plants still regularly foraged by Pashtun refugees living outside the refugee camps are for the most part weeds, i.e., synanthropic species growing in anthropogenic environments (*Chenopodium*, *Lepidium*, *Lamium*, *Malva*, *Medicago*, *Portulaca*, *Rumex*, and *Stellaria* spp.); they are easily accessible around the settlements in the fields and sometimes in the corner of courtyards, and the continual practice of foraging them has kept the LEK attached to weeds alive. In fact, despite the occurrence of weeds in their settlements as well, Pashtuns living inside the refugee camps no longer retain much LEK.

Another reason could be that they “do not need” to gather wild vegetables, as they mainly live on remittances sent from abroad. A 71-year-old woman from this community underlined her view in this way:

“*These wild plants are normally used as fodder for animals; I don't like to eat the animal food, it's an embarrassing food for us. We don't use wild food plants anymore and their consumption is a story of former times*”.

This statement seems to also entail an internalized bias possibly derived from the majority of inhabitants living in urban environments, according to whom the eating of weeds is a custom of a poor and turbulent past that has to be eliminated. This latter aspect deserves a more detailed discussion concerning the role played by trauma in keeping gastronomic heritage linked to everyday domestic cuisine (and not to festival dishes).

In Caruth's psychoanalytic theory of trauma, for example, it is not the experience itself that produces a traumatic effect, but rather the remembrance of it [45]. Active forgetfulness, in this case, is a dynamic ability to overcome traumatic and negative memories, which is a necessary condition for the culture of a minority group to support and develop itself further [46]. Aarelaid-Tart (2006) argued that, in a situation of cultural trauma, people inhabiting an unfamiliar cultural space start to speak of traditions not being kept, or for which no one is able to practice them under the new circumstances [47]. Our findings could potentially explain the increase in cultural disorganization and disorientation among the studied Afghan Diaspora as a direct result of traumatic cultural changes. Recent systematic reviews demonstrated that experiencing forced resettlement due to war conflicts and acute political crises was a traumatic event for relocated residents [48–50]. Traumatogenic social changes are not limited to their destructive effect on society at the macro level, as they also directly affect functioning at a micro-scale, specifically on the knowledge and practices of individuals. Wartime displacement from Afghanistan to neighboring Pakistan involved a significant disruption of the everyday life of relocated ethnic groups, the collapse of social networks, threats to beliefs and values, the loss of a familiar environment, disconnection from the local community, and especially a concentrated loss of resources. On the other hand, according to Hunt and Gekenyi [51], refugees are often traumatized more by their arrival and reception in the unknown country than they are by the events they witnessed or experienced in their home country. Positive adaptation in the face of forced relocation, therefore, may be drawn from individual strength, local community support, strong culture roots, and broader social and political forces of the host country [52].

Moreover, the LEK retained by Uzbek Afghan refugees, who relocated to semi-urban areas and mainly work as butchers, dramatically declined. This group quoted the lowest number of wild ingredients (Figure 4). One of the study participants (51-year-old man) from this community commented:

“*Since foraging requires time, I prefer easily accessible vegetables in the market*”.

This shows that this group possibly went through an acculturation to the urban mainstream, also given the fact that several male community members run butchers' shops.

Also Kochis, who are mobile pastoralists [53], do not substantially forage anymore, as they ironically buy cultivated vegetables from the market when they live in the plains during the cold months and take these vegetables with them to the pastures when they move there with their herds in the spring.

Among the four considered groups, Kochis therefore also had the highest proportion of remembered plants (Table 2), possibly because their relocation to Pakistan heavily affected the opportunity of practicing their LEK in the mountain environments where they keep their herds, which in Afghanistan were higher and much more extensive. This group seems to have opportunistically kept their mobile pastoralism (in a semi-mobile, transhumant way in Pakistan) in order to be able to trade animals as a survival strategy, but they seem to have lost many foraging practices that they used to have in their home country.

The memories and narratives of wild food plants are also different among the four studied groups. The community that mostly engaged in foraging (Pashtuns living outside refugee camps) remembers with nostalgia those wild food plants that they can no longer find in Pakistan. A 45-year-old woman stated:

"*I wish I could find my home country wild vegetables here in Mansehra, I cannot forget their delicious taste*".

Only one of these wild food ingredients (wild caper), which seems to not be available in Pakistan, is procured from Afghanistan relying on a network of relatives and attached informal exchanges still ongoing to and from Afghanistan, as a 60-year-old man explained:

"*A few days ago I asked my daughter on a phone call to bring me some dried wild capers from Afghanistan and upon her arrival she gave them to me. I fried these along with a few eggs and they tasted delicious*".

After four decades of living in the new host environment, Afghan refugees highlighted as remembered fifteen wild food plants, of which the identity of a few of them could only be hypothesized on the basis of their folk names and plant descriptions: this was the case, for example, for plants referred to as *bandakey* (*Polygonum* sp.) and *kheza* (*Allium rosenbachianum*).

3.3. Herbal Teas

Considering herbal ingredients, adaptation to the new socioecological environment in Pakistan involved a deeper loss of LEK. This may also be due to the accessibility to pharmaceuticals in Mansehra District. Afghan refugees currently use a very small number of plants in comparison with what they remembered from their home country.

The large majority of the quoted herbal teas have been evaluated by modern pharmacological and phytotherapeutical studies; the most common currently utilized herbal ingredients included *Trachyspermum*, *Berberis*, *Alkanna*, *Brassica*, *Cannabis*, *Pegamum*, *Plantago*, *Myrtus*, and *Heliotropium* spp., while slightly more than half of the quoted herbs were only remembered as being used in the past in Afghanistan. The few currently used herbal ingredient plants quoted by the refugees are, however, rarely gathered from the wild and more often bought in dried form from Pakistani markets.

Looking closely at the dynamics of the four groups, it also emerges that in this domain Pashtuns living outside the refugee camps partially continue to use a number of medicinal plants. As pointed out by one informant, a 50-year-old Pashtun man living outside the camps:

"*I use to buy available medicinal plants in the local market; I believe these plants are safe and are better than modern science based medicines*".

A 40-year-old male Afghan Pashtun refugee living in a camp instead commented:

"*We prefer modern science instead of herbs since the effect of medicines is fast and they are readily available*".

A 60-year-old male Uzbek Afghan study participant confirmed this view:

"*We prefer to go to doctor nearby in case of ailment and distress*".

The LEK regarding the use of herbal ingredients among pastoralist Kochi refugees has also been eroded and they are nowadays completely dependent on pharmaceuticals. As one of the informants (28-year-old man) pointed out:

"*Our forefathers used these medicinal plants, in this present time we mostly prefer to go to private clinics when we are in the plains, while we take cough and fever syrups with us when we move to mountain pastures*".

Refugees procure a number of dried herbal ingredients for teas from their homeland. These include *Heliotropium* sp., an indigenous plant from the home country that is perceived to relieve back and joint pain and act as an aphrodisiac for both men and women, *Alkanna tinctoria*, which is considered an important external and internal wound healer, and *Salvia* spp. that are strongly perceived as aphrodisiacs for women.

Despite the importance of the transnational flow, the interviewees pointed out that the possibility of obtaining plant materials from Afghanistan has decreased drastically in recent years, due to the new border policy shaped by Pakistani authorities, who allow only Afghans having a passport with a valid visa to move into Pakistan. A 54-year-old male Afghan refugee described this phenomenon:

> "*When it was financially feasible I used to travel to my home country regularly, and on my journey back I used to bring some dried medicinal plants and even dried wild vegetables, but since the new borders policy changed I have been unable to travel regularly to my home country; it is very costly now, thus I have abandoned the use of these plants*".

The analysis of this procurement strategy and its recent changes, therefore, suggests a progressive weakening of the tie that binds refugees with their motherland, which proceeds hand in hand with a greater reliance on the resources present in the new location, especially in local Pakistani markets. This phenomenon has a further impact on the process of transformation and erosion of the LEK of the refugees.

The majority of the study participants interviewed shared very little information about the use of herbal and other domestic ingredients for treating domestic animals. The most commonly quoted herbal teas still used by the study participants included *Trachyspermum*, *Glycyrrhiza*, *Paeonia* spp., and an unidentified lichen. The majority of the veterinary plants and other domestic remedies were quoted by less than one-third of the informants, mainly pastoralist Kochis, thus suggesting that this kind of biocultural heritage is seriously threatened. One possible reason for the loss of traditional knowledge regarding the use of natural remedies to treat domesticated animals may be that most diasporic Afghans—apart from Kochis—keep very few animals at home.

3.4. Socioeconomic Factors Influencing the LEK of Refugees

The data presented in the tables and the figures should, however, be contextualized into a broader discussion about the changes undergone by LEK and read in light of the complex process of resettlement of refugee communities. This process entails environmental, physical, economic, and sociocultural factors, and in particular a radical change in household economy [54], in particular for Pashtun refugees. The present situation sees a substantial continuation of the kind of activities conducted in the homeland for Uzbek Afghans, who have historically played a crucial role in urban areas and in particular as traders [55], and for the Kochis, who have been historically linked with pastoralism and nomadism [53]. Pashtun refugees faced the biggest economic and cultural challenge. While relocation of communities is still a key political topic for the future of both Afghanistan and Pakistan [56], most of the informants were farmers forced from their lands and relocated in refugee camps. In the new, difficult environment [57], adaptation strategies have involved different solutions that are epitomized by the distinction between Pashtuns living inside and outside the camps. Nowadays, while Pashtuns living in camps and also Uzbeks base their daily life on an urban economy, Pahstuns living outside camps and Kochi pastoralists continue their main occupations in the host country conducting horticultural and pastoralist activities, respectively. The preservation of greater LEK among the latter groups suggests the importance of everyday exposure and dependence on the environment and its biodiversity, whereas the other two groups have relied more on what market relationships can provide.

The importance of frequent exposure to the natural environment in retaining LEK is also demonstrated by the gap in LEK that emerges among the different groups. Pashtun women living outside refugee camps gather wild plants and possibly acquire knowledge by doing this, while in the other communities, women mostly stay at home and no longer forage.

The difference is seen not only on the level of currently collected wild food plants, but also those that are just a remembrance of the name. Of nineteen remembered wild plants, 10 were remembered solely among the Pashtuns living outside the camps, the group that has retained everyday contact with nature. The relationship of farmers to their land and the natural environment is embedded in their culture, and when this tie is broken, by removing the person from everyday interaction with nature, "signs and stories" related to the place [58] are rearranged and newly written. Foraging and the use of wild plant ingredients belong to tacit knowledge, described by Hungarian philosopher Michael Polanyi (1966, [59]) as a skill that connects the mind with the body and, in our case, the environment in which the body functions. The lack of interaction with the natural environment prevents tacit knowledge from not only developing further (both in the natural environment and in the kitchen), but even continuing to thrive close to the level it did while nature was still present in the semi-sphere of the person. Ecosemioticians Timo Maran and Kalevi Kull have highlighted that "human culture is a part of the ecosystem" [60]; from that, the ecosystem shapes human culture.

All the Afghan refugees are similarly affected by the Pakistani cultural environment, in terms of economic expectation, cultural models, and social practices [61]. Yet, the most urbanized groups (Pashtuns in camps and Uzbeks) are experiencing a tremendous erosion of their LEK, i.e., they have lost the opportunity to interact with the natural environment in the new host country. The results of this study clearly indicate that if people are removed from a familiar ecosystem and not provided something comparable in return, communication between the culture of those people and the environment ceases to exist, which affects not only current environmental and culinary practices and relationships, but also the memories of past relationships. The trauma of relocation magnifies the withdrawal from the natural environment, changing even past cultural codes related to the environmental domain. As culture is rooted in nature, without these roots culture is in danger of collapse.

Our research points out that the expectations of modernity [62] have lured the younger generations away from an agropastoralist economy, causing a rapid disintegration of their daily interactions with the environment and a loss of gastronomic heritage as well. The hegemonic effect [63] of Pakistani culture is also evident in the marginalization of traditional herbal practices, which are preserved in an active form very rarely and especially only by those refugees (i.e., Kochis) who live for many months far from healthcare centers and urban facilities.

4. Conclusions

The data presented in the current article show that the four Afghan refugee communities living in NW Pakistan still practice a few foraging activities and these are linked to their gastronomic heritage too. This knowledge-practices-beliefs system, which, however, is mainly alive in the memories of refugees, should be valorized, preserved, or even re-activated with the aim of fostering social sustainability and inclusion.

The study shows also that Afghan refugees, who share a similar migration history and live in the same natural environment, do not necessarily forage and subsequently utilize wild vegetables and herbs in the same way. The cultural makeup of communities is critical to the articulation of the links among their social dimension, the wild food systems, and the local flora.

More importantly, this study suggests that continued exposure to the new natural environment plays a crucial role in keeping foraging and wild food plants-centered gastronomic practices alive, and that, conversely, a long-stay in refugee camps or engaging in urban activities may lead to the erosion of LEK. These findings suggest that policy-makers should pay particular attention in shaping strategies linked to migrants and refugees. Long stays in refugee camps in particular may be detrimental for their cultural heritage and ultimately for their empowerment and well-being and should therefore be avoided. Finally, the study shows also that the rearrangement of refugees' social life has a significant effect on their nature knowledge.

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Article

Adding the Mureş River Basin (Transylvania, Romania) to the List of Hotspots with High Contamination with Pharmaceuticals

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Abstract: *Background*: The Mureș River Basin is a long-term heavily polluted watershed, in a situation of climate changes with decreasing water flow and related decreasing dilution capacity. Here, a mixture of emerging pollutants such as pharmaceuticals were targeted to reveal potential risks regarding the natural lotic ecosystems. Due to the continuous discharge into the environment, pharmaceuticals are gaining persistent organic pollutant characteristics and are considered emerging pollutants. Based on the hazard quotient, this research highlights the dangerous concentrations of carbamazepine, ibuprofen, furosemide, and enalapril in river water. *Results*: High levels of four pharmaceutical compounds (carbamazepine, ibuprofen, furosemide, and enalapril) and some of their derived metabolites (enalaprilat, carboxyibuprofen, 1-hydroxyibuprofen, and 2-hydroxyibuprofen) were reported in our study in the Mureș River Basin. Overall, pharmaceutical concentrations were found to be highest in the wastewater treatment plant (WWTP) effluent, median downstream of the WWTP, and lowest upstream of the WWTP, as was expected. For all pharmaceutical compounds tested, we recorded concentrations above the limit of quantification (LOQ) in at least one of the sites tested. Carbamazepine exhibited the highest mean values upstream, downstream, and at the WWTP. As expected, the highest concentrations for all the studied pharmaceutical compounds were detected in the WWTP effluent. All Hazard Quotient (HQ) values were below one (on a logarithmic scale in base 10), with the highest values in the WWTP and the lowest in the river upstream of the WWTP. The HQ intervals were in the same range for furosemide, carbamazepine, and ibuprofen at each of the three different sites: upstream WWTP effluent, and downstream. The interval for enalapril stands out as having the lowest HQ at all three sites. *Conclusions*: Based on these results, the large and complex hydrographical system Mureș River Basin was transformed from a grey area, with little information about pharmaceutical contamination, to a hotspot in terms of contamination with emerging pollutants. Pharmaceutical compound concentrations were found to be the highest in WWTP effluents. The WWTP effluent concentrations were among the highest in Europe, indicating that treatment plants are the primary source of water pollution with pharmaceuticals compounds. The detected levels were higher than the safety limit for carbamazepine and ibuprofen. The determined HQ values imply that the measured levels do pose a threat to the environment for the studied pharmaceuticals. Based on the obtained results, human communities can assess, monitor, predict, and adapt in time to these already-present regional challenges and risks for sustainable use of natural resources, including water and associated products and services.

Keywords: wastewater treatment plants; emerging pollutants water contamination; hazard quotient; carbamazepine; ibuprofen; furosemide; enalapril; liquid chromatography; triple quadrupole mass spectrometry

1. Background

Pharmaceuticals are chemical compounds prepared or dispensed in pharmacies and hospitals and used in the medical treatment of humans and animals. They come in the form of prescription, over the counter, veterinary, or therapeutic pharmaceuticals. Due to industrialized production, there are many pharmaceuticals that became relatively largely accessible worldwide on the free market, including in terms of prices [1,2]. In the last decade, the unintentional presence of pharmaceuticals in the aquatic ecosystems (water, sediment, and biota) has become increasingly apparent in concentrations that can have a negative impact on the aquatic organisms and ecological processes. Due to their presence in the environment, pharmaceuticals are starting to be considered emerging pollutants: compounds not yet included in water-quality regulations, with unknown or poorly understood effects, and pose a potential threat to the ecosystems and human safety and health [3].

In the Lower Danube Basin, footprints of human presence go back in history to 180,000 BC, with noticeable increasing damaging effects on the environment throughout time [4–6]. One of the large-scale second-order tributaries of the Danube is the Mureş River; its upper and middle sectors are located in the amphitheater-like Transylvanian depression, ringed by the South-Eastern Carpathians, and inhabited by over seven million people [7], making it a zone containing important human activities causing adverse effects [8].

The Mureș River is the largest tributary of the Tisza River (Danube Basin), with a length of 761 km and a watershed with an area of 28,319 km^2, located in the central and western part of Romania (longitude: 20°11′ west and 25°44′ east and latitude: 45°14′ south and 47°08′ north). This basin relief varies significantly; mountains cover 25% of the surface, while 55% of the surface consists of hills and plateaus, 15% valleys and meadows, and 5% plains [9,10].

The Mureş Basin was chosen for this study for several reasons: the relatively large surface/importance in the Danube Basin [6], the relatively significant human population living in the basin area including in large cities [9,11], the important historical and present human impact including pollution problems in the basin [12,13], the presence of numerous WWTPs (wastewater treatment plants) along the river using similar technology (all 15 WWTPs included in this study have mechanical, biological, and chemical processes used for the treatment of wastewater), the diversity of habitats in the watershed, the total lack of pharmaceutical-aquatic ecosystems related data in this basin, etc.

Pharmaceutical compounds have been investigated and found in the sewerage system's contaminated waters, permanently affected by effluents from hospitals, residential, office, and production areas of Mureş River and its main tributaries. These compounds come from different pharmaceutical classes, such as non-steroidal anti-inflammatory (ibuprofen), psychotropic (carbamazepine), cardiovascular (enalapril), and diuretic pharmaceuticals (furosemide). Besides their presence in water environments, these pharmaceuticals have been characterized according to their water solubility, predicted no-effect concentration (PNEC), and pKa or log K_{ow} (Table 1). Alongside the parent pharmaceuticals, it is interesting to look at their metabolites. For example, enalapril and the ibuprofen metabolites (carboxyibuprofen, 1-hydroxyibuprofen, and 2-hydroxyibuprofen) can be found in the environment. Of the above-listed compounds, carbamazepine is identified as a future emerging pollutant priority candidate, while ibuprofen is a proposed addition to this list [14]. One reason carbamazepine has been thoroughly investigated is its ubiquitous presence (94%) in analyzed rivers. This presence is not so much due to its high use but more likely due to its slow degradation rate and ability to be extracted efficiently from contaminated samples or efficient extraction methods [15,16].

Table 1. Properties of the studied pharmaceuticals.

Substance	CAS Number	Molecular Weight	Water Solubility	pKa	Log K_{ow}	PNEC
Enalaprilat	76420-72-9	348.399 g/mol	0.876 mg/mL	3.13	−0.94 [17]	NA
Enalapril	75847-73-3	376.453 g/mol	16.4 g/L [18]	3.67	4.22	184 μg/L [19]
Furosemide	54-31-9	330.739 g/mol	73.1 mg/L [20]	4.25	2.03	6.2 μg/L [19]
Carbamazepine	298-46-4	236.274 g/mol	0.152 mg/mL	15.96	2.45	7.7 μg/L [19]
Ibuprofen	15687-27-1	206.285 g/mol	21 mg/L [20]	5.3 [21]	3.97	2.3 μg/L [19]
Carboxyibuprofen	15935-54-3	236.267 g/mol	0.3 g/L	3.97	2.78 [22]	NA
1-hydroxyibuprofen	53949-53-4	222.284 g/mol	0.51 g/L	4.55	2.69 [22]	NA
2-hydroxyibuprofen	51146-55-5	222.284 g/mol	0.3 g/L	4.63	2.37 [22]	NA

CAS—chemical abstracts service. pKa—acid dissociation constant. Log K_{ow}—octanol/water partition coefficient. PNEC—predicted no-effect concentration. NA—not available.

1.1. Pollution Sources and Environmental Hazards of Studied Pharmaceutical Compounds

It has been reported that some pharmaceuticals that are present in surface waters, groundwater, and the discharge from WWTPs pose a severe environmental problem, since these compounds could affect non-target and susceptible species because they are biologically active [23,24]. Furthermore, these compounds have potentially toxic effects (or could determine behavioral alteration) in the aquatic trophic nets, affecting the food chain organisms such as phytoplankton [25], amphipods [26] and crustaceans [27], fish [28,29], and finally, mammals [30]. When looking specifically at the pharmaceuticals of interest, it is observed that carbamazepine induces a stress response in rainbow trout individuals (*Oncorhynchus mykiss*) [28]. At the same time, ibuprofen negatively affects the health of African catfish (*Clarias gariepinus*) individuals [29].

Due to their polar nature (Table 1), these compounds stay in the solution and do not adhere to soil and particles; therefore, they are mobile in the environment. Another downside of pharmaceuticals is the continuous release into the aquatic environment, which gives them the characteristic of persistent organic pollutants (POPs) regarding their high detection rate. These characteristics make the studied pharmaceutical compounds likely to reach drinking water sources, posing a serious problem for human safety and health in places dependent on recycled water. The problem has been reported in France [23], the United States [31], and Australia [32]. In Romania, the effluent from WWTPs is not reused as drinking water and is discharged back into rivers [33]. This effluent mixes with the hyporheic water and can potentially influence other downstream water sources. When considering the dilution of the pharmaceuticals, the human risk is lowered, but there are still problems when mixtures are involved [34], and new compounds are added to the mixture every day. On the other hand, the threat to the environment is problematic, and high interest is accorded to pharmaceutical's presence and their effects on flora and fauna [35]. From this point of view, the studied basin is a grey area, with few reports about pharmaceutical concentrations [36–38], a relatively common situation, especially in the southeastern part of Europe, but not only.

The two primary biological sources of pharmaceuticals in the studied environment are derived from veterinary and medical uses, through animal and human excretion of active metabolites consisting of a mixture of metabolized and conjugated compounds and unmetabolized compounds [3]. Humans excrete mainly 55 to 80% unmetabolized compounds (with few exceptions) through urine and partially through feces [39–41]. The following can be different sources of aquatic environment contamination: WWTP discharges, hospital effluents, direct disposal of unused or expired pharmaceuticals, manufacturing, landfill leachates, livestock activities, aquaculture, and soil fertilization with sewage sludge and livestock waste [42–44]. Among the mentioned sources, WWTPs are considered the most problematic source of contamination [45]. This is because the fact that WWTPs do not effectively eliminate all the pharmaceutical compounds from the WWTP influents during the procedures of removing pollutants [46–58]. Examples of inadequate removal of pharmaceuticals at the WWTP are carbamazepine, with a low (10–20%) to no removal efficiency [53,54], and furosemide, with a removal efficiency under 42% [55]. Pharmaceuticals could have long-term effects on biota and could exhibit bioaccumulation, and the presence of different pharmaceutical mixtures, which could have additive and synergistic effects [3]. In terms of avoiding pharmaceutical contamination of water, a series of methods have been proposed and implemented, such as physical adsorption processes, biological degradation processes, chemical processes, advanced oxidation processes, and various combined methods [56]. Alongside these methods, a series of procedures limiting the disposal of surplus pharmaceuticals should also be considered.

Very few studies investigated the occurrence of pharmaceuticals in river waters in Romania [57–61]; even fewer studies mention parts of the investigated area and pharmaceuticals [36–38].

1.2. Aim

This study focuses on the occurrence, distribution, and fate of several pharmaceuticals that are on the emerging pollutants list or that are commonly used in the Mureș River Basin, where no large-scale data about them are widely available. This study aims to assess the potential risk of the investigated pharmaceuticals in the environment. One way of tackling this problem is using the hazard quotient (HQ: ≥1 indicates a potential for negative impact on the lotic ecosystem, <1 low ecological risk), i.e., the ratio between the measured environmental concentration (MEC) and predicted no-effect concentration (PNEC). HQ is the measure of the potential exposure to a substance for which no adverse effect is expected.

2. Material and Methods

2.1. Sampling

Water samples were collected from 15 sites in the Mureș River Basin in 2018. The sampling sites are located from the river source to the Mureș River exit from the Romanian territory (Figure 1). The Mureș River is located in the central and western part of Romania (longitude: 20°11′ west and 25°44′ east and latitude: 45°14′ south and 47°08′ north). Sites were selected around WWTPs: upstream, downstream, and at the WWTPs effluents. The distance from the upstream site and WWTP effluent or the downstream site and WWTP effluent were 100 m. For each site, three replicates were collected. Water was collected in plastic (polyethylene terephthalate) bottles, capped, and maintained at 4 °C for a maximum of two weeks. Pharmaceuticals of interest were extracted from the water samples.

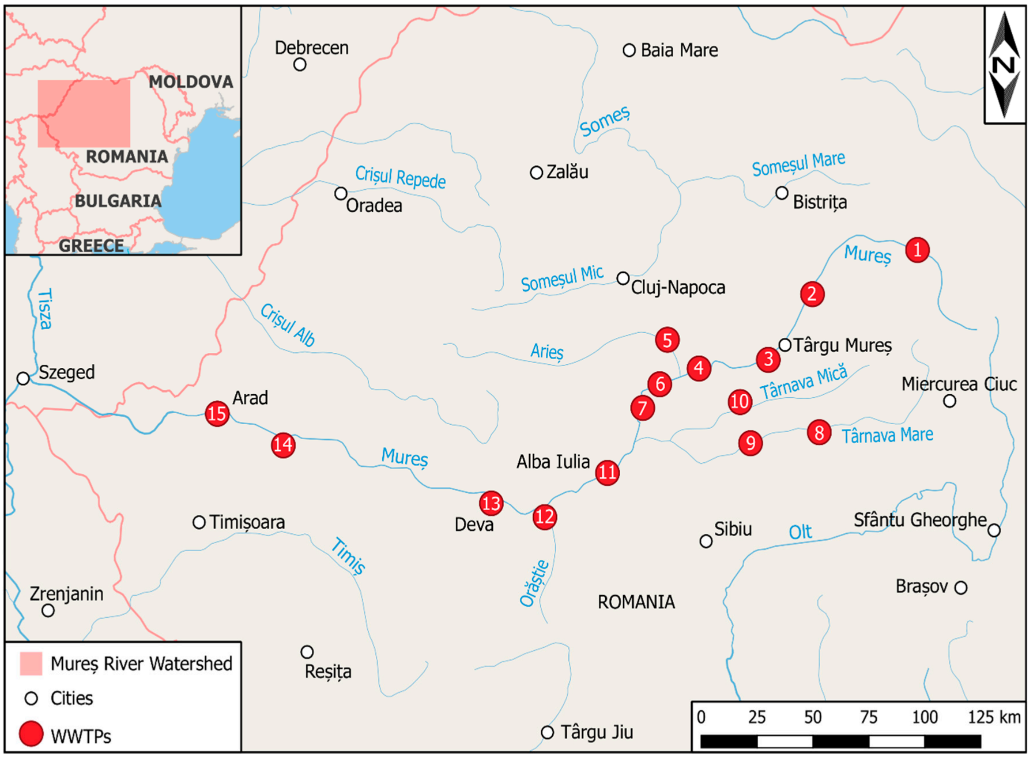

Figure 1. Map showing sampling locations at the wastewater treatment plant (WWTP) effluent: 1—Toplița (46°56′5.348″ north, 25°19′9.469″ east), 2—Reghin (46°45′19.458″ north, 24°42′35.128″ east), 3—Cristești (46°29′57.012″ north, 24°27′46.418″ east), 4—Luduș (46°27′22.9″ north, 24°3′42.274″ east), 5—Câmpia Turzii (46°33′40.518″ north, 23°52′18.372″ east), 6—Ocna Mureș (46°23′25.08″ north, 23°50′11.396″ east), 7—Aiud (46°17′50.1″ north, 23°44′36.799″ east), 8—Sighișoara (46°13′44.818″ north, 24°46′16.341″ east), 9—Mediaș (46°10′43.403″ north, 24°22′29.74″ east), 10—Târnăveni (46°20′3.826″ north, 24°18′25.189″ east), 11—Alba Iulia (46°2′.657″ north, 23°33′15.112″ east), 12—Orăștie (45°51′41.152″ North, 23°12′17.798″ East), 13—Deva (45°54′15.869″ north, 22°53′36.243″ east), 14—Lipova (46°4′35.256″ north, 21°40′38.161″ east), 15—Arad (46°10′40.152″ north, 21°16′37.829″ east).

2.2. Reagents

All the reagents were purchased from BioAqua (Târgu Mureș, Romania) and were of HPLC analytical grade (water, acetonitrile, and methanol), except for the formic and acetic acids of 98% purity. Carbamazepine (99.5%) and 10,11-dihydrocarbamazepine (99,5%) were obtained from Dr. Ehrenstorfer reference standards producer (Germany), enalapril (97%) and furosemide (97%) were purchased from Alfa Aesar (Lancashire, UK), enalaprilat (98%) was obtained from Cayman Chemical Company (Ann Arbor, MI, USA), and ibuprofen (98%), carboxyibuprofen (98%), 1-hydroxyibuprofen (98%), 2-hydroxyibuprofen (98%), and ibuprofen-d3 (98%) were purchased from Merck (Darmstadt, Germany). The Oasis HLB 500 mg cartridges were purchased from Waters (Wilmslow, UK).

2.3. Sample Extraction

Compounds of interest were extracted using the solid phase extraction (SPE) method on 500 mg Oasis HLB cartridges [44] installed on a vacuum manifold (Phenomenex) and conditioned with 5 mL of HPLC grade methanol at 5 mL/min. The cartridges were then equilibrated with 5 mL of 0.1% (acetic acid) acidulated HPLC grade water at 5 mL/min. Afterward, 1 L of acidulated (0.1% acetic acid) river water sample was passed through the cartridge at 10 mL/min. After the sample passage, the sample bottles were rinsed with 10 mL HPLC grade water flowed through the cartridges. A full vacuum was used for 30 min to dry the cartridges. The elution was done first with 5 mL of HPLC grade methanol and then with 5 mL of a 1:1:1 solution of methanol:acetonitrile:isopropanol. The eluate was concentrated to 0.5 mL under a gentle stream of air at 40 °C and stored in 1.5 mL clean vials (Agilent) until analysis.

2.4. Liquid Chromatography

Compounds of interest were separated with a 1200 HPLC (Agilent) on a Zorbax SB-C18 (2.1 × 100 mm, 3.5 μm, Agilent) HPLC column [48]. Pharmaceuticals were divided into two groups, and each group was analyzed by a different method. The first group contained: carbamazepine, 10,11-dihydrocarbamazepine, furosemide, enalapril, and enalaprilat. For this group of pharmaceuticals, the mobile phases were HPLC grade water (solvent A) and HPLC grade acetonitrile (solvent B), both with 0.1% formic acid. The flow rate was set to 0.8 mL/min, and the mobile phase gradient was set to rise from 5% solvent B to 15% B in 3 min, held at 15% B for 1 min, raised to 35% B in 3 min, and then raised to 70% B in 3 min with 5 μL injection volume. The second group of pharmaceuticals contained: ibuprofen, carboxyibuprofen, 1-hydroxyibuprofen, 2-hydroxyibuprofen, and ibuprofen-d3. For this group, the mobile phases were HPLC grade water (solvent A) with 0.1% acetic acid and HPLC grade methanol (solvent B). The flow rate was set at 0.8 mL/min with the mobile phase gradient set to rise from 5% solvent B to 100% solvent B in 8 min with a 2 min hold at 100%, and the injection volume was set to 10 μL. The retention times (RT) are presented in Table 2.

2.5. Triple Quadrupole Mass Spectrometry

For triple quadrupole mass spectrometry (QqQ MS) [51], we used a G6410B system (Agilent) with a multimode ESI-APCI source installed. The capillary was set to 4 kV for positive mode and 2.5 kV for negative mode. We have used nitrogen for drying (325 °C at 5 L/min) and nebulizing (40 psi). The MS heaters were set at 100 °C, both while nitrogen was used for collision-induced dissociation (CID). All pharmaceuticals were first analyzed in SCAN mode to determine the retention time and then in product ion mode to determine the best fragmentor voltage and collision energy. The MS/MS was operated in multiple reaction monitoring (MRM) mode to detect and quantify the compounds of interest (Table 2). For each pharmaceutical, the most abundant ion transition was selected for quantification (Q), while a second ion transition was chosen for qualification (q), where possible.

Table 2. Details regarding the column separation and detection of investigated pharmaceuticals.

Substance	RT	Ion Mode	Ion Transition	Fragmentor (V)	Collision Energy (V)
Enalaprilat	3.808	Positive	Q 349.2→206.2	135	15
		Positive	q 349→303.2	135	12
Enalapril	7.201	Positive	Q 377.3→234.2	70	17
		Positive	q 377.3→303.3	70	12
Furosemide	7.593	Negative	Q 329→285.1	120	10
		Negative	q 329→204.7	110	20
Carbamazepine	7.917	Positive	Q 237→194	110	15
		Positive	q 237→191.9	110	35
* 10,11-dihydrocarbamazepine	8.052	Positive	Q 239.1→196	110	25
		Positive	q 239.1→180.1	110	25
Ibuprofen	7.240	Negative	Q 205→161	75	5
Carboxyibuprofen	5.516	Negative	Q 235→191	75	5
1-hydroxyibuprofen	5.811	Negative	Q 221→159	75	5
2-hydroxyibuprofen	5.526	Negative	Q 221→177	75	0
* Ibuprofen-d3	7.239	Negative	Q 208→164	75	0

Q—quantifier transition. q—qualifier transition. RT—retention time. * internal standards.

LOD (limit of detection) and LOQ (limit of quantification) were determined from the standard deviation of 10 replicate injections, where LOD was three times the standard deviation. At the same time, LOQ was calculated as 10 times the standard deviation (Table 3) [62,63]. The standard curve linearity (R^2) was higher than 0.998 for all the analyzed pharmaceuticals.

Table 3. Instrument LOD and LOQ values for the studied pharmaceuticals.

Substance	Quantification Transition	LOD ppb	LOQ ppb
Enalaprilat	349.2→206.2	0.592	1.972
Enalapril	377.3→234.2	0.625	2.084
Furosemide	329→285.1	0.868	2.894
Carbamazepine	237→194	0.355	1.183
Ibuprofen	205→161	0.806	2.687
Carboxyibuprofen	235→191	0.795	2.648
1-hydroxyibuprofen	221→159	0.736	2.453
2-hydroxyibuprofen	221→177	0.686	2.287

LOD—limit of detection. LOQ—limit of quantification.

2.6. Data Analysis

The concentrations were calculated relative to the internal standards. For carbamazepine, enalapril, enalaprilat, and furosemide, we used 10.11-dihydrocarbamazepine as the internal standard. While ibuprofen-d3 was used as the internal standard for ibuprofen, carboxyibuprofen, 1-hydroxyibuprofen, and 2-hydroxyibuprofen. The arithmetic mean of the three replicates was used for statistical analyses. We have investigated the data distribution by employing the Shapiro-Wilk normality test implemented in the base R 3.5.2 package. A Spearman's rank-order correlation was used to assess the correlation between treated water from the WWTP on river water quality, while the corrplot package [64] was used to generate the correlograms using R 3.5.2 package. GraphPad Prism version 6.0 was used for designing concentration and HQ graphs. The HQ was quantified as the ratio between the MEC of the pharmaceutical and PNEC. The PNEC values used are listed in Table 1. The map (Figure 1) was generated using QGIS 3.6 software [65], the Natural Earth Data maps, and the WGS 84 sampling site coordinates.

2.7. Method Validation

To test our ability to extract the selected pharmaceuticals from river water and determine the method's precision and accuracy, eight recovery experiments were undertaken. For this, we sampled 10 L of water from a single location and distributed the water into two blinds and eight recoveries of 1 L each. River water samples (recoveries) were spiked with concentrations close to those expected in the river and extracted using the specified SPE method. River water that was not spiked (blinds) with pharmaceuticals served as a control for the pharmaceutical amount in the environment and was used to subtract the native contamination from the recoveries. The mean recoveries are as follows: 99% for enalaprilat, 101% for enalapril, 99% for furosemide, 109% for carbamazepine, 98% for carboxyibuprofen, 97% for 2-hydroxyibuprofen, 100% for 1-hydroxyibuprofen, and 97% for ibuprofen. The relative standard deviation (RSD) was also calculated, and the values are as follows: 11% for enalaprilat, 8% for enalapril, 14% for furosemide, 4% for carbamazepine, 9% for carboxyibuprofen, 1% for 2-hydroxyibuprofen, 2% for 1-hydroxyibuprofen, and 3% for ibuprofen. Negative controls (solvent blanks) were analyzed at each extraction and quantification to rule out possible contamination of solvents with the tested pharmaceuticals and the presence of background noise acquired during detection and quantification. No compounds of interest were detected in the blanks.

3. Results

3.1. Concentrations

Concentrations of four pharmaceuticals, enalapril, furosemide, carbamazepine, and ibuprofen, as well as those of some of their metabolites, enalaprilat for enalapril and carboxyibuprofen, 1-hydroxyibuprofen and 2-hydroxyibuprofen for ibuprofen, were determined in river water upstream, downstream, and in the WWTP effluent for 15 WWTPs along the Mureș River Basin. All the reported concentrations were higher than the LOQ. Overall, pharmaceutical concentrations are highest in the WWTP effluent, median downstream of the WWTP, and lowest upstream of the WWTP, as was expected (Table 4, Table 5).

We next analyzed the minimum quantifiable, maximum, median, and average concentrations measured at the 15 locations tested for each pharmaceutical upstream, downstream, and at the WWTP (Table 4). For all pharmaceuticals tested, we measured concentrations above the LOQ in at least one of the sites tested (Table 5). Carbamazepine exhibited the highest average measured upstream, downstream, and at the WWTP. As expected, the highest concentrations for all the pharmaceuticals were detected in the WWTP effluent (Table 4).

3.2. Correlations

We found a strong, positive correlation between upstream WWTP concentrations and downstream concentrations for enalaprilat and furosemide, which was statistically significant (r_s (2) = 0.94, $p < 0.01$ for enalaprilat and r_s (3) = 1, $p < 0.001$ furosemide). In case of furosemide, carboxyibuprofen, and ibuprofen, a moderate, positive correlation between WWTP effluent concentrations and downstream concentrations was determined (r_s (108) = 0.62, $p < 0.05$ for furosemide, r_s (80) = 0.72, $p < 0.01$ for carboxyibuprofen, and r_s (8) = 0.85, $p < 0.05$ for ibuprofen) (Figure 2). For the rest of the investigated relevant pairing of pharmaceuticals, no correlation between upstream, downstream, or WWTP effluent concentrations was determined.

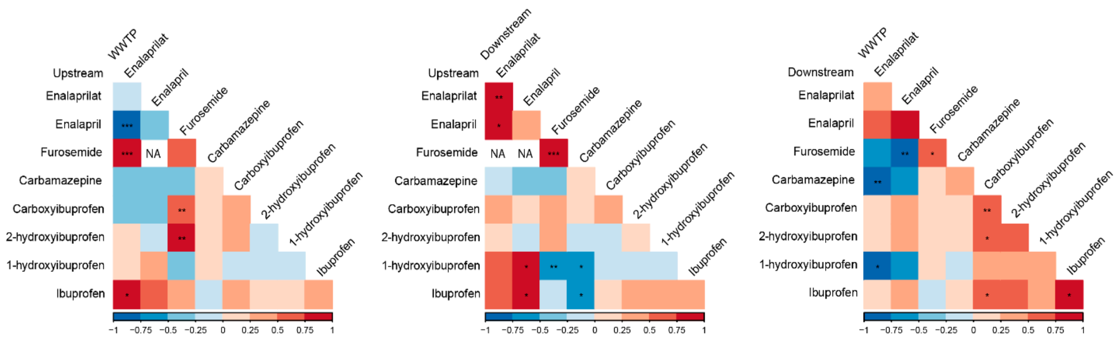

Figure 2. Spearman's rank-order correlograms highlight the pharmaceutical correlations between locations. Positive (1) and negative (−1) correlations are represented as a color gradient, while the p values are represented with asterisks (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$). NA depicts situations where there were not enough values to compute the correlation.

We also measured correlations between pharmaceuticals and their metabolites at the different sampling sites. We found a strong, positive correlation between enalapril and enalaprilat at each of the three sites, upstream, downstream, and WWTP effluent (r_s (4) = 1, $p < 0.001$ upstream, r_s (12) = 0.78, $p < 0.05$ downstream, r_s (10) = 0.82, $p < 0.05$ in the WWTP effluent). For ibuprofen and its metabolites, a positive correlation has been observed in the following situations: ibuprofen and carboxyibuprofen in the upstream sites (r_s (44) = 0.8, $p < 0.01$), ibuprofen and carboxyibuprofen in the downstream sites (r_s (68) = 0.69, $p < 0.05$), ibuprofen and 1-hydroxyibuprofen in the upstream sites (r_s (116) = 0.59, $p < 0.05$), ibuprofen and 2-hydroxyibuprofen in the upstream sites (r_s (106) = 0.62, $p < 0.05$), ibuprofen and 2-hydroxyibuprofen in the downstream sites (r_s (22) = 0.9, $p < 0.001$), and finally, ibuprofen and 2-hydroxyibuprofen in the WWTP effluent sites (r_s (10) = 0.82, $p < 0.05$) (Figure 3).

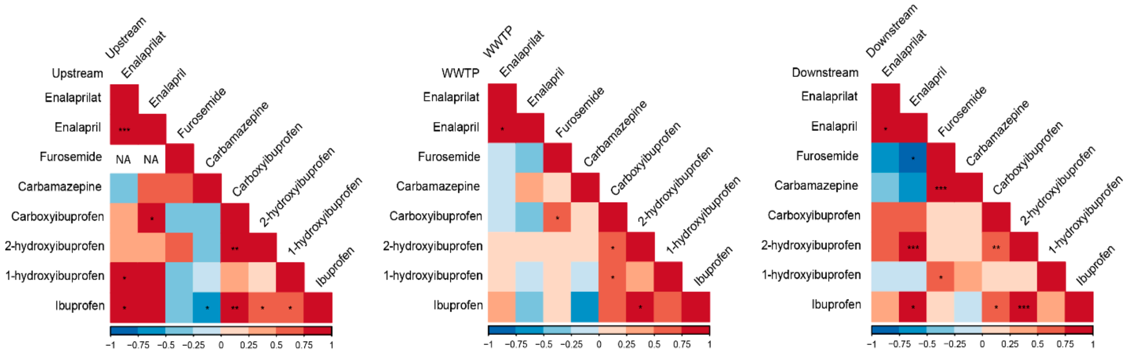

Figure 3. Spearman's rank-order correlograms highlight the pharmaceutical correlations within locations. Positive (1) and negative (−1) correlations are represented with color gradients, while the p values are represented with asterisks (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$). NA represents situations where there were not enough values to compute the correlation.

3.3. Hazard Quotient (HQ)

To address the impact of the investigated pharmaceutical compounds on the aquatic ecosystem, we quantified the HQ for the four pharmaceuticals tested: enalapril, furosemide, carbamazepine, and ibuprofen (Figure 4). All HQ values are below one (on a logarithmic scale in base 10), with the highest values in the WWTP effluent and the lowest in the river upstream of the WWTP. The HQ intervals were in the same range for furosemide, carbamazepine, and ibuprofen at each of the three different sites: upstream, WWTP effluent, and downstream. The interval for enalapril stands out as having the lowest HQ at all three sites (Figure 4).

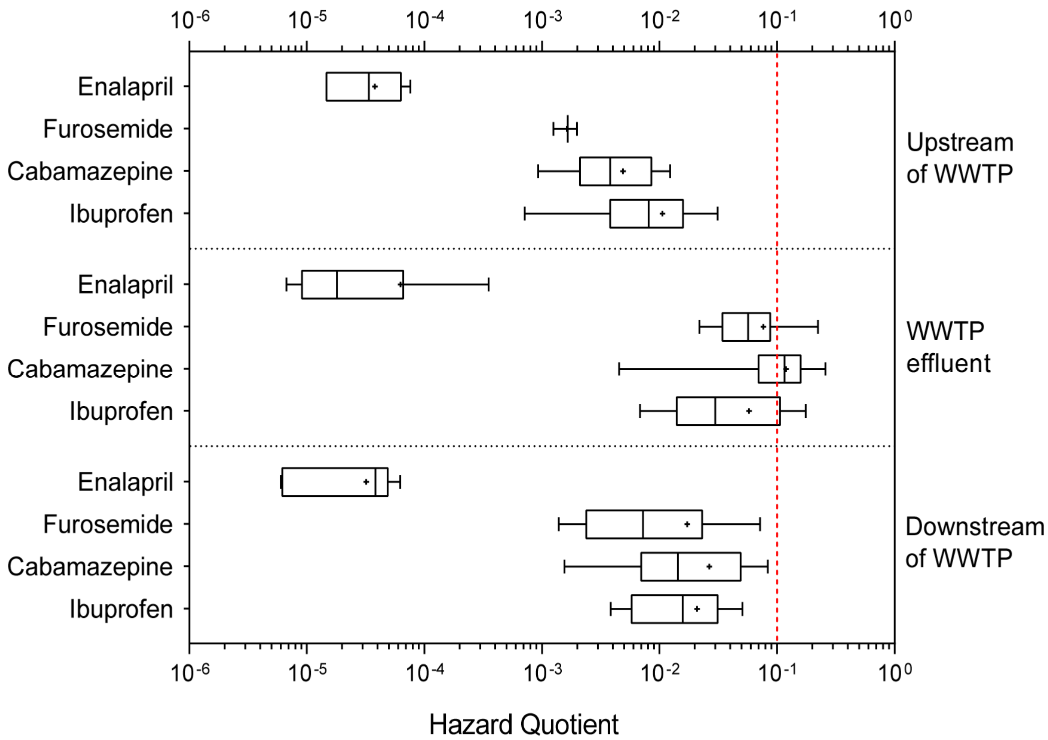

Figure 4. Chart representing the Hazard Quotient (HQ) of the investigated pharmaceuticals. The results are plotted on a base 10 logarithmic scale, as box plots with whiskers at the minimum and maximum values, while the box is delimited by the 25th and 75th percentile, the median is shown as a line and the mean as a plus sign. The red dotted line represents the limit of 0.1 HQ.

4. Discussion

In the Water Framework Directive (WFD) [66], there are two types of water environmental quality standards (EQS) concerning pharmaceuticals: the annual average concentration (AA-EQS) based on chronic toxicity data and the maximum acceptable concentration (MAC-EQS) [67]. These values are 0.5 μg/L (AA-EQS) and 1600 μg/L (MAC-EQS) for carbamazepine [67] and 1 μg/L (AA-EQS) and 40 μg/L (MAC-EQS) for ibuprofen [68]. There are no values calculated for enalapril, enalaprilat, furosemide, 1-hydroxyibuprofen, 2-hydroxyibuprofen, and carboxyibuprofen. We found the maximum concentration of carbamazepine in the downstream sample to be above the annual average environmental quality standard but lower than the maximum accepted. However, the situation worsens in the WWTP effluent, where the concentration average is higher than the AA-EQS for carbamazepine. Because the average and median concentrations for carbamazepine in the downstream sample are less than half of the average accepted value, these concentrations do not pose a threat as of yet. Still, they should be monitored closely so as to not rise above the annual accepted average through accumulation.

We found that the HQ is lower than one for all the pharmaceuticals tested, in all the sampling sites, both in the WWTP effluent and in the river. The values we found are similar to values already reported [19] or slightly lower than those values. Ibuprofen has been found to have the highest HQ in the WWTP [19], while in our study, furosemide and carbamazepine seem to have slightly higher HQs. The HQ values that range from 0.1 to 1 are considered low hazard with potential adverse effects; between 1 and 10, the adverse effects and hazard are probable, while for values higher than 10, hazard are anticipated [19,69,70]. These results imply that for the pharmaceuticals studied, the measured levels pose a threat to the environment, especially for the effluent. Although WWTPs do not have designated methods for removal of the studies pharmaceuticals, it has been reported that some of them degrade during wastewater treatment. Using reported percentages of WWTP clean-up of pharmaceuticals, 42% for furosemide [55], 20% for carbamazepine [53], 80% for ibuprofen [71], and 95% for enalapril, we calculated the putative influent concentration (Figure 5). The results show much higher concentrations in the influent compared with the effluent (Figure 5). These concentrations could be potentially hazardous, especially during heavy rain periods when WWTPs overflow and discharge the effluent at a higher rate than normal.

Moreover, we considered the impact of these high concentrations of pharmaceuticals on the bacteria contained in the activated sludge and the possibility that they would be killed or inhibited. When comparing the MECs of pharmaceuticals in the WWTP with known concentrations that impact bacterial survival, we find them to be at least three orders of magnitude lower than concentrations that would impact bacterial survival [72]. Even if we extrapolate the putative influent concentrations, we do not obtain values over the risk concentrations. Enalapril, which had the highest degradation/removal rate, has a putative concentration in the influent lower than the rest of the pharmaceuticals investigated. Therefore, we do not anticipate a negative impact caused by this singular pharmaceutical's presence on the biological processes taking place in the WWTP.

Our measurement that in the majority of cases the downstream contamination is lower than the effluent contamination, coupled with the correlations observed between downstream and effluent concentration, leads us to believe that the WWTPs are primary sources of river pollution with pharmaceuticals. The underlying concentration that appears in the river (upstream sites) is not high enough to hint at other sources of contamination that could topple the effect of the WWTPs. The fact that enalaprilat and furosemide concentrations are correlated between the upstream and downstream of WWTP sites could mean that these compounds could quickly traverse the river's length between the WWTP sites before precipitating out of the solution or being degraded. This is backed up by their higher solubility in water compared to the other pharmaceuticals, calculated through the Log K_{ow} parameter (Table 1). The fact that the concentrations of ibuprofen and 2-hydroxyibuprofen are positively correlated in all the investigated cases (upstream, downstream, and WWTP effluent), while concentrations of ibuprofen and carboxyibuprofen are positively correlated in two cases (upstream and downstream) could be due to the metabolization of ibuprofen in humans, for which 2-hydroxyibuprofen and carboxyibuprofen are final products and 1-hydroxyibuprofen is an intermediary step to carboxyibuprofen [73]. Therefore, it is conceivable that 2-hydroxyibuprofen and carboxyibuprofen would have higher concentrations than 1-hydroxyibuprofen, which appears to be the case (Table 4).

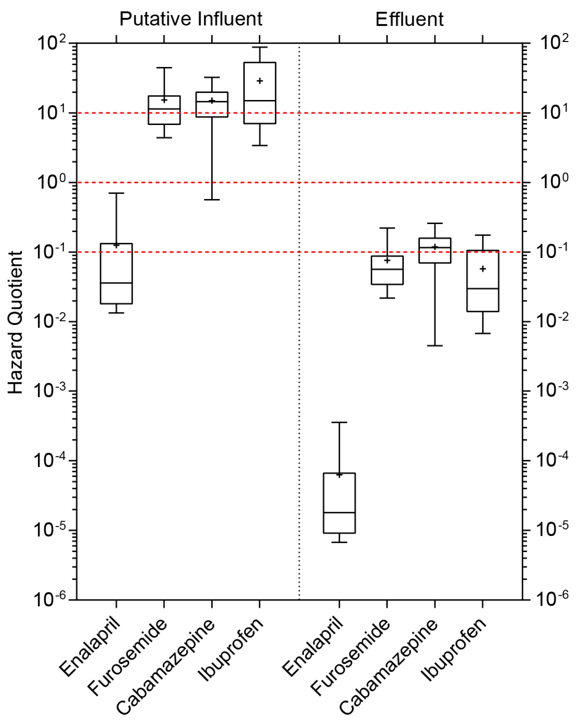

Figure 5. Estimation of the influent concentration of pharmaceuticals in the WWTP based on the degradation/removal rate. The results are plotted on a base 10 logarithmic scale as box plots with whiskers at the minimum and maximum values, while the box is delimited by the 25th and 75th percentile, with the median shown as a line and the mean as a plus sign. The red dotted lines represent the limits of 0.1, 1, and 10 HQ.

The frequency of detection was above 50% both in the WWTP effluent and downstream from it, reaching 100% for some of the pharmaceuticals (Table 4). Enalapril and its metabolite enalaprilat had the lowest frequency of detection overall. The rest had low frequencies in the upstream samples, with the frequencies rising above 80% for most pharmaceuticals in the WWTP effluent and downstream from it. Carbamazepine had the highest detection level, with 93% upstream, 93% downstream, and 100% at the WWTP. This high frequency of detection points to several things: it shows the level of pollution with the tested pharmaceuticals, it confirms our ability to measure the presence of these pharmaceuticals in the river water, and it shows the slow degradation rate and persistence of this pharmaceutical in the environment [74].

Table 4. Summary of pharmaceutical concentrations measured upstream, downstream, and at the WWTP effluent.

Location	Substance	Min (ng/L)	Max (ng/L)	Median (ng/L)	Average (ng/L)	N	F
Upstream	Enalaprilat	1.19	23.16	7.66	9.02	6	40%
	Enalapril	2.70	14.00	6.22	6.96	5	33%
	Furosemide	7.78	12.30	10.27	10.12	3	20%
	Carbamazepine	7.16	95.11	29.38	37.72	14	93%
	Carboxyibuprofen	6.74	111.61	26.30	31.30	13	87%
	2-hydroxyibuprofen	2.27	49.49	2.27	2.27	15	100%
	1-hydroxyibuprofen	0.28	4.66	2.19	2.39	13	87%
	Ibuprofen	1.65	71.85	18.59	24.39	12	80%
WWTP effluent	Enalaprilat	2.54	146.66	7.93	24.82	9	60%
	Enalapril	1.24	64.93	3.31	11.54	9	60%
	Furosemide	135.92	1379.37	352.43	473.62	14	93%
	Carbamazepine	34.95	1992.43	893.94	918.99	14	93%
	Carboxyibuprofen	17.84	2036.70	91.36	431.01	12	80%
	2-hydroxyibuprofen	15.94	826.16	85.29	221.64	12	80%
	1-hydroxyibuprofen	1.30	84.22	7.82	22.85	13	87%
	Ibuprofen	15.68	403.06	68.66	132.62	8	53%
Downstream	Enalaprilat	1.83	19.07	8.83	8.90	8	53%
	Enalapril	1.11	11.50	7.07	5.90	7	47%
	Furosemide	8.63	444.63	44.84	106.81	12	80%
	Carbamazepine	11.99	643.31	110.26	204.15	15	100%
	Carboxyibuprofen	6.76	166.28	22.38	51.74	15	100%
	2-hydroxyibuprofen	11.92	85.68	33.23	43.28	15	100%
	1-hydroxyibuprofen	0.16	11.24	2.80	4.14	14	93%
	Ibuprofen	8.84	117.14	36.17	47.88	11	73%

N—number of occurrences. F—frequency of detection.

Table 5. Concentrations of pharmaceuticals in different locations along the Mureș River Basin.

	Location	ENA	ENP	FUR	CBZ	CarboxyIBP	2-hydroxyiIBP	1-hydroxyIBP	IBP
1	Upstream	4.88	NA	NA	20.32	6.74	21.57	NA	NA
	Downstream	7.13	NA	NA	22.45	6.79	27.56	NA	NA
	Effluent	10.55	3.31	150.26	444.73	25.19	548.05	6.99	271.60
2	Upstream	NA	NA	NA	17.47	NA	2.89	2.86	NA
	Downstream	NA	NA	68.65	477.26	14.90	29.04	2.84	NA
	Effluent	4.32	NA	135.92	1224.15	25.20	69.87	3.07	NA
3	Upstream	NA	NA	NA	30.25	NA	32.10	0.28	1.65
	Downstream	NA	NA	143.36	377.68	93.31	74.65	0.16	NA
	Effluent	NA	NA	441.74	1230.86	254.44	226.54	1.30	NA
4	Upstream	NA	NA	12.30	95.11	13.24	22.09	2.47	9.93
	Downstream	NA	NA	21.04	146.56	14.18	27.44	2.79	14.07
	Effluent	NA	NA	298.53	1079.31	391.16	320.95	27.08	43.14
5	Upstream	1.73	2.71	NA	8.97	27.96	43.24	1.77	24.00
	Downstream	1.83	2.61	294.59	254.64	6.76	56.40	11.24	63.69
	Effluent	NA	3.20	847.10	568.59	37.55	84.94	21.94	92.47
6	Upstream	NA	NA	7.78	71.37	15.34	21.97	2.78	15.63
	Downstream	NA	NA	8.63	85.65	13.57	17.85	2.44	16.35
	Effluent	6.51	NA	214.79	1701.62	22.72	15.94	3.98	15.68
7	Upstream	NA	NA	NA	71.23	7.57	15.77	2.16	8.32
	Downstream	NA	NA	14.44	110.26	8.39	16.81	2.54	8.84
	Effluent	NA	NA	241.95	876.52	17.84	32.34	8.53	28.67
8	Upstream	23.16	14.00	NA	12.59	53.54	30.13	2.55	44.05
	Downstream	19.07	11.50	NA	94.46	166.28	85.68	9.02	107.35
	Effluent	NA	NA	NA	NA	1646.56	NA	84.22	403.06
9	Upstream	12.73	9.17	10.27	28.52	48.25	49.49	4.23	71.85
	Downstream	13.34	8.93	15.91	88.20	50.50	65.68	4.55	64.87
	Effluent	7.93	7.29	325.29	1194.42	NA	85.64	2.22	44.84
10	Upstream	10.45	6.22	NA	7.16	26.30	37.13	2.19	36.95
	Downstream	13.25	7.07	17.11	53.88	22.38	42.91	2.68	36.17
	Effluent	31.17	17.04	1379.37	1992.43	542.88	321.89	61.52	NA

Table 5. *Cont.*

	Location	ENA	ENP	FUR	CBZ	CarboxyIBP	2-hydroxyiIBP	1-hydroxyIBP	IBP
11	Upstream	NA	NA	NA	63.70	33.74	31.19	1.62	15.26
	Downstream	3.15	1.14	444.63	643.31	25.60	33.23	7.00	NA
	Effluent	3.65	1.24	439.93	663.75	NA	NA	NA	NA
12	Upstream	NA	2.70	NA	NA	8.10	2.27	NA	NA
	Downstream	10.52	8.97	11.21	11.99	161.05	68.29	1.39	117.14
	Effluent	146.6	64.93	207.04	225.99	NA	NA	NA	NA
13	Upstream	1.19	NA	NA	38.64	45.85	26.10	1.66	21.54
	Downstream	2.93	1.11	101.57	234.56	29.76	11.92	2.81	13.33
	Effluent	10.04	3.49	414.28	717.23	26.65	61.82	7.82	NA
14	Upstream	NA	NA	NA	25.61	111.61	40.23	4.66	35.12
	Downstream	NA	NA	NA	32.43	20.47	28.60	2.26	13.09
	Effluent	NA	1.27	1154.93	34.95	145.17	65.59	3.97	NA
15	Upstream	NA	NA	NA	37.14	8.64	10.74	1.80	8.34
	Downstream	NA	NA	140.53	428.90	142.12	63.09	6.25	71.84
	Effluent	2.54	2.08	379.57	911.36	2036.70	826.16	64.42	161.47

1—Toplița, 2—Reghin, 3—Cristești, 4—Luduș, 5—Câmpia Turzii, 6—Ocna Mureș, 7—Aiud, 8—Sighișoara, 9—Mediaș, 10—Târnăveni, 11—Alba Iulia, 12—Orăștie, 13—Deva, 14—Lipova, 15—Arad. The concentrations are reported in ng/L. NA—under the limit of quantification. ENA—enalaprilat. ENP—enalapril, FUR—furosemide. CBZ—carbamazepine. IBP—ibuprofen.

There is no apparent rise in concentrations from the source of the river towards the exit from Romania to Hungary, which could be the result of a high rate of precipitation out of the solution due to the low level of solubility of the investigated pharmaceuticals. Another reason could be the short half-life of these pharmaceuticals, which are hours to days for ibuprofen [75] and 63 days [76] or 38 days [77] for carbamazepine; this could be an indication of the high degradation rate of these compounds. One way of identifying the accumulation of pharmaceuticals in the river is to look at the river sediment, which could be an interesting topic for future research.

In Romania, the concentration of ibuprofen has been reported between 61.3 and 115.2 ng/L in the Someș River in 2006 [57], between 9 and 63 ng/L at different main localities in the Someș River in 2007 [58], and between 16 and 63 ng/L at the WWTP effluent in the Someș River in 2008 [59]. Concentrations were in the range of 1.65–71.85 ng/L for the upstream sites, 15.68–403.06 ng/L for WWTPs, and 8.84–117.14 ng/L for the downstream sites (Table 4). For carbamazepine, it has been reported that the concentrations ranged from 67 to 75 ng/L in the Someș River in 2006 [57] and 38 to 56 ng/L in 2008 [58] and 20–49 ng/L in the Danube River, while a maximum concentration of 140 ng/L was detected in the Argeș River [76]. In 2015, it was also reported that the concentration of carbamazepine was situated in the interval of 4 to 40 ng/L in the Danube River and some tributaries [61] and the interval of 5 to 25 ng/L for some major Romanian rivers (Prahova, Timiș, Danube, Siret, Prut, and Jijia) [60]. The previously reported concentrations have a maximum that is lower than the concentrations reported in this study, at all the investigated sites (upstream, WWTP, and downstream) (Table 4). The only exception is for the concentration of ibuprofen from the Târgu Mureș WWTP, which was investigated in three studies [36–38] and have identified high concentrations, up to 7600 ng/L. These results point to a problematic situation of the Mureș River as a hotspot, with levels of carbamazepine in the WWTP effluent reaching a maximum of 1992.43 ng/L. These high concentrations could be due to sampling the effluent, where higher concentrations are to be expected. Another explanation for these high MECs is the fact that Mureș River has a smaller volume of water than the Danube, which makes detecting higher concentrations of pharmaceuticals more likely, as already pointed out [60]. The fact that we detected these pharmaceuticals in high concentrations does not come as a surprise, especially given that a European wide study in 2009 has detected ibuprofen and carbamazepine, among others, as compounds with the highest maximum concentrations in the range of μg/L [77]. Taking into consideration the 90th percentile and the proposed indicative warning levels mentioned in 2009 [77], we can see that the concentrations that we detect are well above the threshold for carbamazepine (limit of 100 ng/L) when looking at the average concentrations of all the substances detailed in this paper in the WWTP effluent and downstream of the WWTP, and ibuprofen (limit of 200 ng/L) in the WWTP effluent when looking at the maximum detected concentration. In this respect, the Mureș River Basin can be considered polluted, and these results warrant further investigation.

The potential synergic effects of these pharmaceutical compounds with other pollutants present in the basin, such as POPs [12,13,78], can raise the area's risk potential for natural and semi-natural ecosystems and human settlements health and welfare, which increases the importance of monitoring in the catchment basin of rivers receiving wastewater [79,80]. The problem with high levels of pharmaceuticals in the environment is tied directly to human exposure. In this case, the concentrations to which we are exposed could be higher, especially when the individuals are under treatment with the investigated pharmaceuticals.

The potential risk associated with these pharmaceuticals can rise in the present situation. The climate changes [81] tend to reduce the minimum, average, and maximum dilution flow [5] in the Danube Basin too, and the increasing human water consumption will put supplementary pressure on this respect as well.

5. Conclusions

Based on this study's results, the large and complex hydrographical system Mureș River Basin was transformed from a grey area to a hotspot in contamination with emerging pharmaceuticals. Pharmaceutical concentrations were found to be the highest in WWTP effluents, indicating that the treatment plants are the primary source of water pollution in this case. The detected levels are higher than the safety limit for carbamazepine in the annual average environmental quality standards, and are higher than the limits proposed in 2009 [77] for carbamazepine and ibuprofen. The determined HQ values imply that the measured levels for the studied pharmaceuticals do pose a threat to the environment.

Pharmaceuticals have become a norm in every household, and unfortunately, this has resulted in the highlighted contamination problem for environmental waters. Since pharmaceuticals are necessary for human and household animal health, and their consumption cannot be eliminated, there should be methods put in place that take care of their disposal, release into the environment, and ecotoxicological effects. Among these methods, an organized monitoring system for out of date pharmaceuticals, a designated treatment at the WWTPs for degradation of these pharmaceuticals, introduction of phytoremediation, depuration stations along the river, and better human population education for the use and disposal of pharmaceuticals should be a priority.

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Abbreviations

HQ	Hazard Quotient
WWTP	Wastewater Treatment Plants
PNEC	Predicted No Effect Concentration
MEC	measured environmental concentration
CAS	Chemical Abstracts Service
HPLC	High-Performance Liquid Chromatography
SPE	Solid Phase Extraction
RT	Retention Times
QqQ MS	Triple Quadrupole Mass Spectrometry
ESI	Electrospray Ionization
APCI	Atmospheric Pressure Chemical Ionization
CID	Collision Induced Dissociation
MRM	Multiple Reaction Monitoring
Q	Quantification Ion
q	Qualification Ion
LOD	Limit of Detection
LOQ	Limit of Quantification
RSD	Relative Standard Deviation
WFD	Water Framework Directive
EQS	Environmental Quality Standards
AA-EQS	Annual Average Concentration
MAC-EQS	Maximum Acceptable Concentration
ENA	Enalaprilat
ENP	Enalapril
FUR	Furosemide
CBZ	Carbamazepine
IBP	Ibuprofen
POPs	Persistent Organic Pollutants

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Evolution of Clustering Quantified by a Stochastic Method—Case Studies on Natural and Human Social Structures

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Abstract: Clustering structures appearing from small to large scales are ubiquitous in the physical world. Interestingly, clustering structures are omnipresent in human history too, ranging from the mere organization of life in societies (e.g., urbanization) to the development of large-scale infrastructure and policies for meeting organizational needs. Indeed, in its struggle for survival and progress, mankind has perpetually sought the benefits of unions. At the same time, it is acknowledged that as the scale of the projects grows, the cost of the delivered products is reduced while their quantities are maximized. Thus, large-scale infrastructures and policies are considered advantageous and are constantly being pursued at even great scales. This work develops a general method to quantify the temporal evolution of clustering, using a stochastic computational tool called 2D-C, which is applicable for the study of both natural and human social spatial structures. As case studies, the evolution of the structure of the universe, of ecosystems and of human clustering structures such as urbanization, are investigated using novel sources of spatial information. Results suggest the clear existence both of periods of clustering and declustering in the natural world and in the human social structures; yet clustering is the general trend. In view of the ongoing COVID-19 pandemic, societal challenges arising from large-scale clustering structures are discussed.

Keywords: clustering evolution; natural clustering; social clustering; spatiotemporal clustering; scale development; stochastic analysis

1. Introduction

«αἰὲὶ τὸν ὁμοῖον ἄγει θεὸς ὡς τὸν ὁμοῖν» (Οδύσσεια, ϱ 218) [1]

"All ever, the god is bringing like and like together." (Homer-Odyssey)

Seen from a stochastic viewpoint, both the evolution of the natural and the anthropogenic world are marked by the emergence of various types of clustering in space, increasing and decreasing in time. The existence of clustering can be claimed to be ubiquitous in the physical world, as it is found in galaxies, in ecosystems, in the societies of humans and animals and even in the mere biological organization of life. Indeed, we can see living creatures as the evolution of cells' clustering: from the appearance of bacteria (~3.6 billion years ago), protozoa (~1.7 billion years ago), fish (~0.45 billion years ago), to dinosaurs (~0.25 billion years ago) to todays mammals (~0.22 billion years ago). [2–5]. Observing the omnipresent character of clustering structures, a first natural question that arises is: *Is clustering useful in life*? complemented by the more central one: *If yes, does it have a limit?*

The first question has a seemingly straightforward answer. The plots in Figure 1 give a first positive reply to it. The average elephant, the biggest currently living animal on land, requires remarkably less energy per mass than a mouse in order to survive (Figure 1a) as the bigger the animal, the more efficiently it uses energy [6,7]. Larger scales also seem to increase efficiency for mammals in terms of water consumption for survival (Figure 1b). Clustering is also useful in human societies, as clustering of humans created what we now know as civilization. The clustering of human social processes along with their increase in spatial scale, is a primary principle for the societal world. This is because human clustering and interdependence structures enhance communication, promote science and exchange of ideas, boost trade and reduce the cost of basic social goods (such as access to water and energy), thereby improving the overall quality of human life [8–10]. In financial terms, the advantageous features of increased clustering are expressed through the classic concept of "economies of scale" [11].

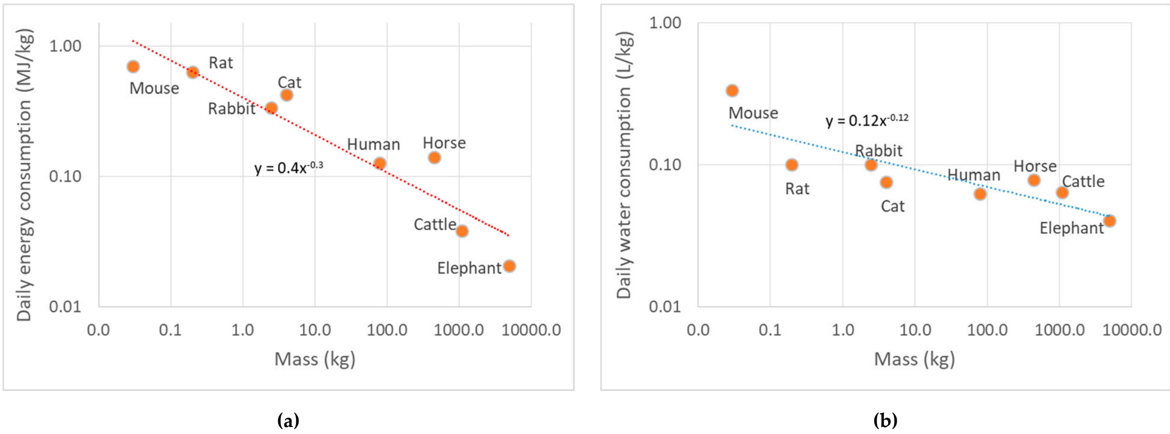


Figure 1. Daily energy consumption of mammals (**a**), Daily water consumption of mammals (**b**) data from [12–15].

A more holistic inspection of natural evolution however reveals hidden elements of clustering, which suggest that the second question also has a positive answer. Dinosaurs were the biggest living creatures on earth but about 66 million years ago they disappeared. Smaller animals such as mammals survived because of "Being small. If you're small you probably have a large population and thus a wider genetic diversity." [15]. Similar considerations might be drawn for human societies regarding the rise and fall of civilizations, the population and depopulation of large cities, followed by analogous trends in economic and agricultural activities over various spatial scales. The reasons behind the reverse trend in the clustering tendency might be less discernible for the anthropogenic world, however it becomes clear in this case as well that there is no single direction in terms of clustering but rather there is a certain stochastic element dominating its evolution.

With the stochastic tool 2D-Climacogram (2D-C), clustering is quantified from each image through cumulative variability over various scales, and a methodology is developed to allow the characterization of its temporal evolution. In the literature, there are many approaches to quantify clustering, calibrated for application in different fields as biology and ecosystems [16,17], life sciences [18–21], neural networks [22], physics and physical phenomena [23,24], maps [25,26] and more [27], yet there is no approach proposing a unifying stochastic view of 2D clustering in terms of variability vs. scale. Moreover, while the presence of 2D clustering is studied as a behavior, its temporal evolution is less explored as until recently, there was a scarcity of spatial information in time. Using various sources of spatial information, such as animated maps [28,29] and satellite images, an effort is made to characterize and interpret certain spatial aspects of the evolution of the natural and human world that provide quantitative insights for understanding the past. This understanding might serve as a basis for large-scale decision making for the future. This paper presents a stochastic methodology that quantifies clustering in 2D space and its temporal evolution by analyzing image sequences of the spatial structures over time.

We show the applicability of our tool in different fields by providing case studies from the analysis of clustering in ecosystems i.e., the evolution of forests and water bodies, of human structures, i.e., in terms of urbanization and urban expansion as well as in terms of cosmological simulations. The latter provide a very relevant quantification of clustering as the evolution of clustering in universe is widely studied [30–34] and it can be viewed as a macroscopic picture of clustering in nature.

We conclude our work with a theoretical discussion on the role of clustering in the human social structure. In view of the COVID-19 pandemic, we discuss the risk dynamics stemming from large-scale human clustering. Furthermore, by considering the way the latter was mitigated, i.e., through the destruction of large-scale social clustering structures, we draw wider considerations on the existence of an "optimal" scale and spatial distribution for human organization and society development.

2. Methodology

2.1. Stochastic Analysis of Clustering in 2D Space: The 2D-C Tool

The mathematical field of Stochastics has been introduced on the opposite side of deterministic approaches, as a way to model the so-called random, i.e., complex, unexplained or unpredictable, fluctuations observed in non-linear geophysical processes [35,36]. Stochastics helps to develop a unified perception of natural phenomena and expel dichotomies like random vs. deterministic. From the viewpoint of stochastics, there is no such thing as a "virus of randomness" that infects some phenomena to make them random, leaving other phenomena uninfected. Instead, both randomness and predictability coexist and are intrinsic to natural systems which can be deterministic and random at the same time, depending on the prediction horizon and the time scale [37]. This research aims to develop a stochastic analysis method to quantify both the spatial structures in terms of clustering and the temporal evolution thereof.

A stochastic computational tool called 2D-Climacogram, abbreviated as 2D-C [38,39], is used to study the clustering in 2D space, using images from various sources. 2D-C measures the degree of variability (change in variability vs. scale) in images using stochastic analysis. Here, we refer to spatial scale, defined as the ratio of the area of $k \times k$ adjacent cells (i.e., scale k) that are averaged to form the (scaled) spatial field, over the spatial resolution of the original field (i.e., at scale 1).

Image processing typically begins with filtering or enhancing an image using techniques to extract more information from the images [40] and image segmentation is one of the basic problems in image analysis. The importance and utility of image segmentation has resulted in extensive research and numerous proposed approaches based on intensity, color, texture etc. that are both automatic and interactive [41].

This analysis for image processing is based on a stochastic tool called climacogram. The term climacogram [42,43] comes from the Greek word climax (meaning scale). It is defined as the (plot of) variance of the averaged process (assuming stationary) versus the averaging scale k and is denoted as $\gamma(k)$. The climacogram is useful for detecting both the short- and the long-term change (or else dependence, persistence and clustering) of a process, with the latter emerging particularly in complex systems as opposed to white-noise (absence of dependence) or Markov (i.e., short-range dependence) behavior [44].

In order to quantify the image variability, each image was first digitized in two dimensions (2D) based on the grayscale color intensity (thus, studying the brightness of an image), and the climacogram was calculated based on the geometric scales of adjacent pixels. Assuming that our sample is an area $n\Delta \times n\Delta$, where n is the number of intervals (e.g., pixels) along each spatial direction and Δ is the discretization unit (determined by the image resolution, e.g., pixel length), the empirical classical estimator of the climacogram for a 2D process can be expressed in equation 1 as:

$$\underline{\hat{\gamma}}(\kappa) = \frac{1}{n^2/\kappa^2 - 1} \sum_{i=1}^{n/\kappa} \sum_{j=1}^{n/\kappa} \left(\underline{x}_{i,j}^{(\kappa)} - \overline{\underline{x}} \right)^2 \tag{1}$$

where the '^' over γ denotes an estimate, κ is the dimensionless spatial scale, $\underline{x}_{i,j}^{(\kappa)} = \frac{1}{\kappa^2}\sum_{\psi=\kappa(j-1)+1}^{\kappa j}\sum_{\xi=\kappa(i-1)+1}^{\kappa i}\underline{x}_{\xi,\psi}$ represents a local average of the space-averaged process at scale κ, and at grid cell (*i*,*j*), $\underline{\overline{x}} \equiv x_{1,1}^{(n)}$ is the global average and the underlined variables represent random variables as opposed to regular ones. Note that the maximum available scale for this estimator is *n*/2. The difference between the value in each element and the field mean is raised to the power of 2, since we are mostly interested in the magnitude of the difference rather than its sign, and in particular, in the variance estimation. Therefore, the 2D-C expressed the diversity in the color intensity among the different elements at each scale by quantifying the variability of their brightness intensities.

An important property of stochastic processes which characterizes the variability over scales is the Hurst–Kolmogorov (HK) behavior (persistence), which can be represented by the Hurst parameter [45]. This parameter can be estimated by minimizing the fitting error between the empirical (observed) and the modeled (Equation (2)) climacogram, both of which are derived from the large-scale values, i.e., the last 50 scales are used in the presented applications. The isotropic HK process with an arbitrary marginal distribution, i.e., the power-law decay of variance as a function of scale, can be defined for a 1D or 2D process as:

$$\gamma(k) = \frac{\lambda}{(k/\Delta)^{2d(1-H)}} \tag{2}$$

where λ is the variance at scale $k = \Delta$, Δ is the time or space unit, d is the dimensionality of the process/field (i.e., for a 1D process $d = 1$, for a 2D field $d = 2$, etc.) and H is the Hurst parameter ($0 < H < 1$). For $0 < H < 0.5$ the HK process exhibits an anti-persistent behavior, $H = 0.5$ corresponds to the white noise process and for $0.5 < H < 1$ the process exhibits persistence (i.e., clustering). In the case of clustering behavior due to heterogeneity of the brightness of the image, the high variability in brightness persists even in large scales. This clustering effect may substantially increase the diversity between the brightness in each pixel of the image, a phenomenon also observed in hydrometeorological processes (such as temperature, precipitation, wind etc. [36]), natural landscapes and music [46].

The algorithm that generates the climacogram in 2D was developed in MATLAB for rectangular images [47]. In particular, for the current analysis, the images are cropped to 400 × 400 pixels, 14.11 cm × 14.11 cm, in 72 dpi (dots per inch).

2.2. Temporal Evolution of 2D Clustering

The pixels analyzed are represented by numbers denoting their color intensity in grayscale (white = 1, black = 0). Figure 2 presents images from three timeframes of the evolution of the universe as generated by a cosmological model of evolution [48]: (a) 500 million years after Big Bang, an image with faint clustering; (b) 1000 million years after the Big Bang, an image with clustering and (c) 10,000 million years after the Big Bang, an image with intense clustering. Figure 3 presents the steps of analysis and shows grouped pixels at scales k = 2, 4, 8, 16, 20, 25, 40, 50, 80, 100 and 200 that were used to calculate the climacogram.

The presence of clustering is reflected in the climacogram, which shows a marked difference as clustering increases (Figure 4a,b). Specifically, the variance of the images is notably higher at all scales when clustering increases, indicating a greater degree of variability of the process.

For the integration of all information contained in the 2D climacogram of each timeframe, we evaluated the cumulative areas underneath each one for all scales (Figure 5a), i.e., the climacogram integral $\int_\Delta^k \gamma(x)/x\, \mathrm{d}x$, where Δ and k are the minimum and maximum scale and we have divided by x in order for the integral to converge for an arbitrarily high k ($k \to \infty$). In the discrete case, this can be approximated as in Equation (3):

$$\mathrm{CI}(k) = \sum_{i=1}^{n(k)-1} 2\gamma(x_i)\frac{x_{i+1} - x_i}{x_{i+1} + x_i} \tag{3}$$

where $n(k)$ is the number of integration intervals up to scale k. We evaluated $\mathrm{CI}(k)$ at the maximum available spatial scale, in order for it to be the best approximation of the limit $\mathrm{CI}(\infty)$.

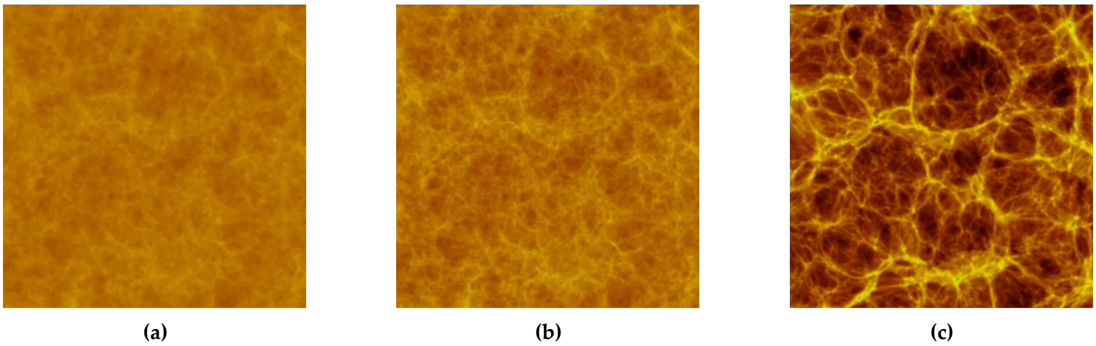


Figure 2. Benchmark of image analysis, evolution of the universe [48]: (**a**) an image of 500 million years after the Big Bang with faint clustering and an average brightness of 0.45; (**b**) an image of 1000 million years after the Big Bang with clustering and an average brightness of 0.44; (**c**) an image of 10,000 million years after the Big Bang image with intense clustering and an average brightness of 0.33 (snapshots from videos of cosmological simulations, [48,49]).

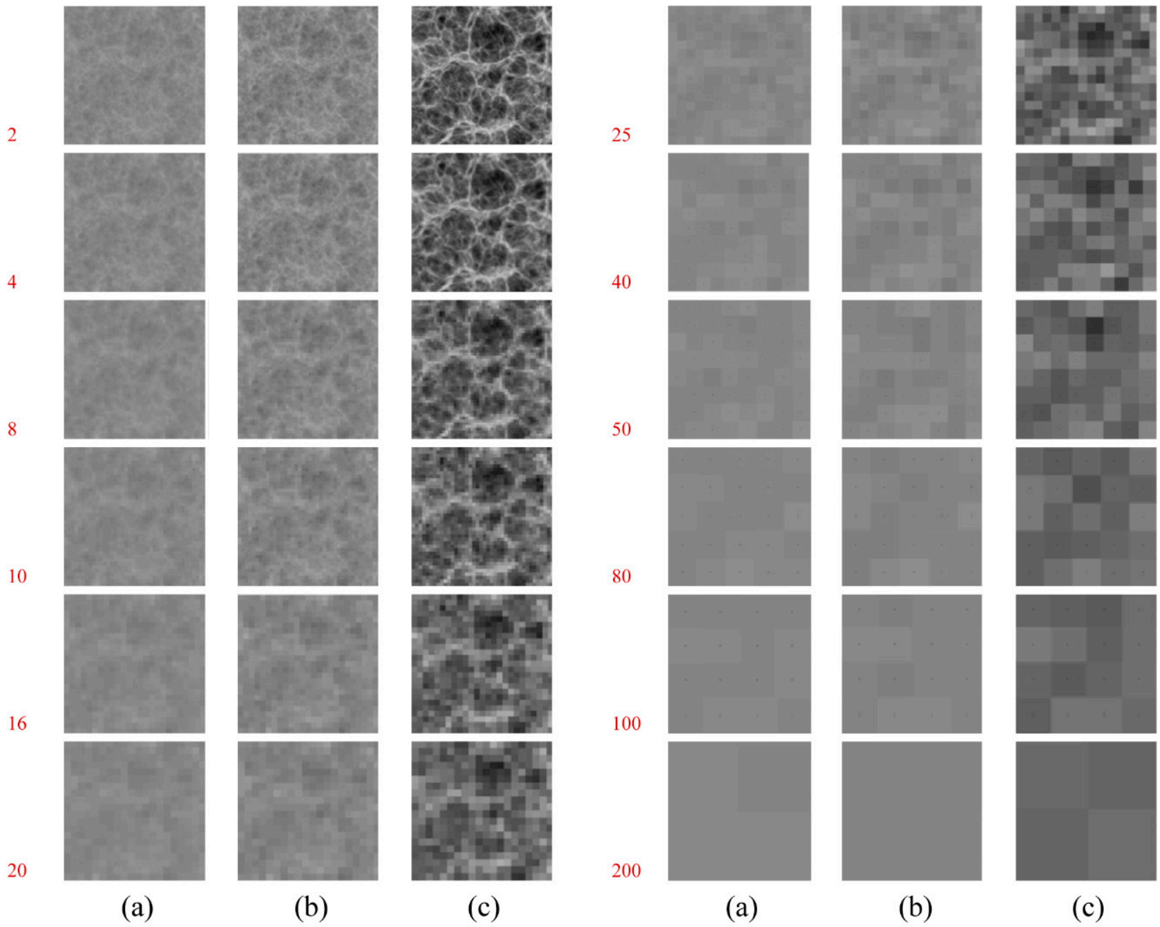
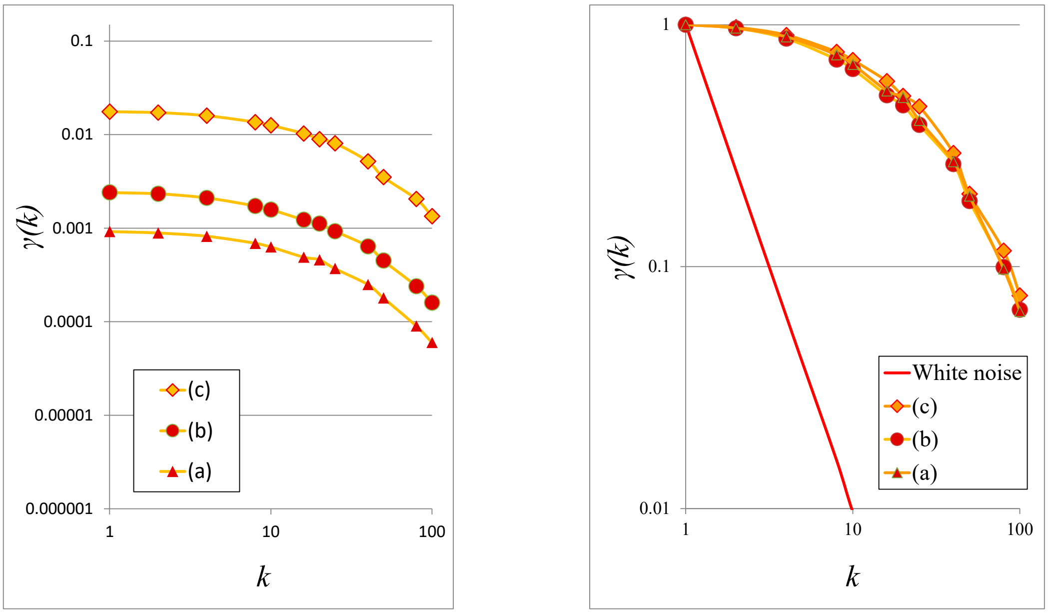
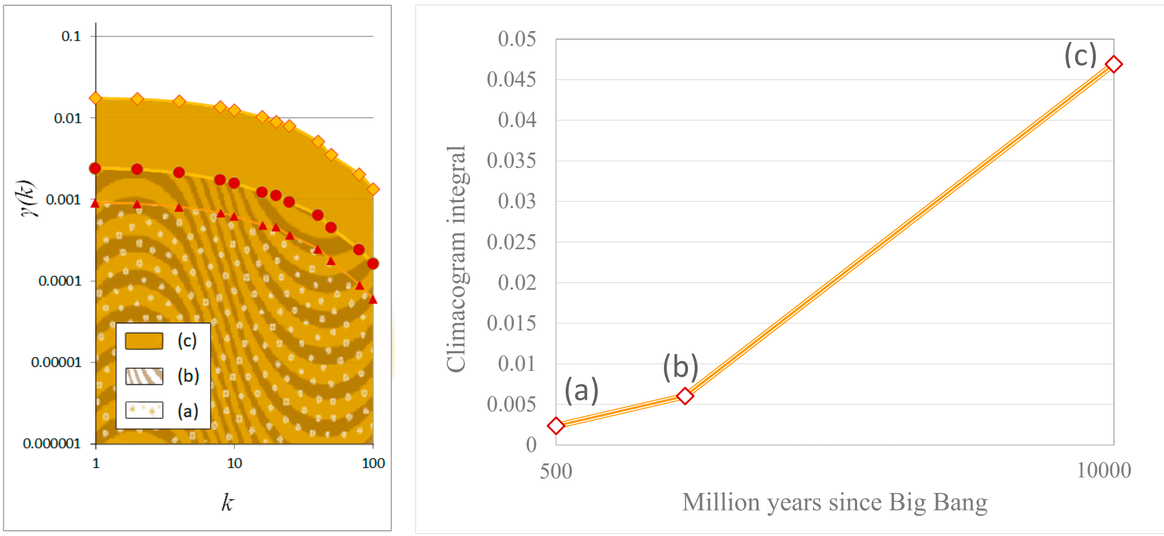


Figure 3. Example of stochastic analysis of a 2D picture, in escalating spatial scales, as shown on the left in red. Grouped pixels at different scales are used to calculate the climacogram: images (**a**), (**b**) and (**c**) correspond to times as given in Figure 2.



(a) **(b)**

Figure 4. (**a**) Climacograms of the benchmark images; (**b**) standardized climacograms of the benchmark images. A standardized climacogram is not helpful for evaluating the range of the evolution of clustering but is helpful to estimate curves' slopes for further stochastic analysis.



(a) **(b)**

Figure 5. (**a**) Cumulative areas underneath each climacogram for each scale; (**b**) Rate of alteration of clustering through time.

In Figure 5b, each climacogram is represented by the respective integral, thus we can evaluate the rate of alteration of clustering through time.

3. Case Studies

In order to present the applicability of our tool in different fields, we studied several examples as case studies illustrating clustering in nature from cosmological simulations as well as in ecosystems and human social structures such as the evolution of urbanization and urban expansion.

3.1. Evolution of Clustering in Nature

3.1.1. Cosmological Simulations

Some cosmological simulations of the growth of Black Holes and Galaxies [48] show that the evolution of the universe is characterized by a tendency for clustering through time [34]. We analyzed timeframes of a general view of one cosmological simulation model (Figure S1: General view of the direct Cosmological Simulations of the Growth of Black Holes and Galaxies [48,49]) and a closer zoom (Figure S3: Closer zoom in an area of the direct Cosmological Simulations of the Growth of Black Holes and Galaxies) using 2D-C plots (Figure S2: Climacograms of the Direct Cosmological Simulations of the Growth of Black Holes and Galaxies (Figure S1) and Figure S4: Climacograms of the closer zoom of Direct Cosmological Simulations of the Growth of Black Holes and Galaxies (Figure S2)). We evaluated the temporal evolution of clustering by following the methodology of Section 2, i.e., we found the cumulative areas underneath each time-referenced climacogram and plotted the temporal evolution of the integrals (Figure 6).

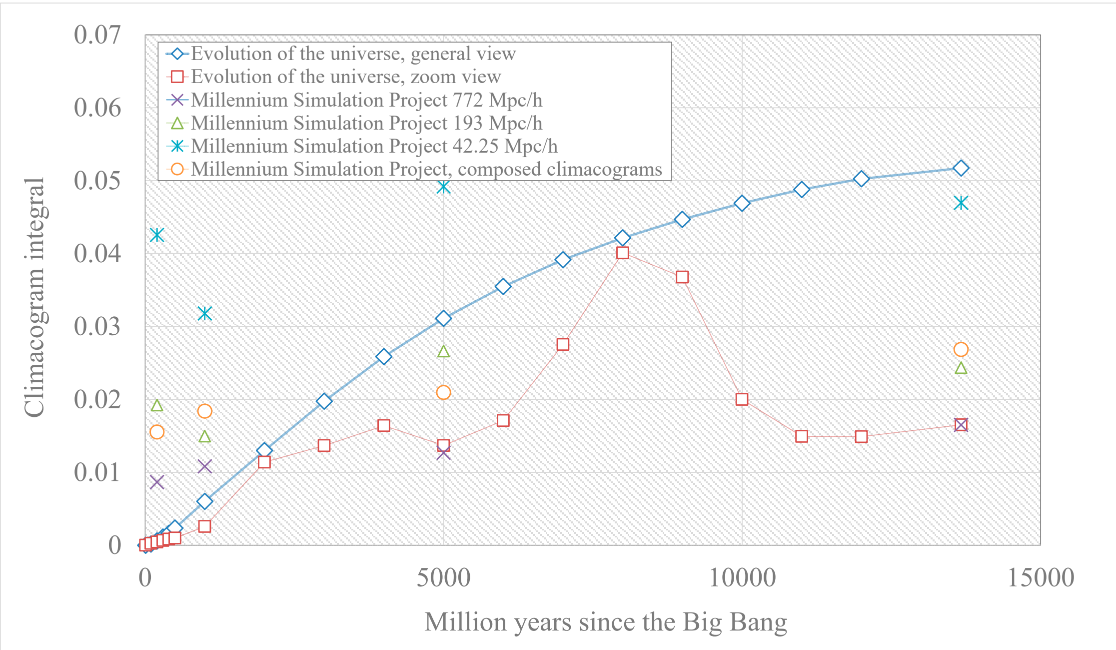


Figure 6. Rate of alteration of clustering through time of image series in Figures S1, S3, S5.

In addition, we evaluated the clustering behavior shown in the Millennium Simulation Project [50] (Figure S5: Evolution of the universe. Millennium Simulation Project [50]). Specifically, the Millennium simulation Project shows four timeframes of the evolution of a projected density field, with three different views. To unify the study of the stochastic behavior from the three distinct cosmological views of Millennium Simulation Project (772 Mpc/*h*, 193 Mpc/*h*, 48.25 Mpc/*h*) we employed the following procedure. For each scale, we formed the sample of empirical climacogram values estimated from each of the three series. For the range of scales at which the series overlap we matched the respective climacogram values with one another by minimizing the sum of their sample standard deviations for the given scales. For the (unconstrained) minimization we used the Generalized Reduced Gradient method [51,52] which is one of the most robust and reliable approaches to nonlinear optimization [53] (Figure S6: Fitting curves of composed climacograms of Millennium Simulation Project [50] (a) image series of 210 mil years after B.B.; (b) image series of 1000 mil years after B.B.; (c) image series of 4700 mil years after B.B.; (d) image series of 13,600 mil years after B.B.).

3.1.2. Ecosystems

Ecosystems are characterized by dynamic transformations involving spatial clustering. In order to show how the proposed stochastic tool could be applied in the study of ecosystems, we present the quantification of the evolution of clustering for three case studies:

- the deforestation of Borneo, Figures 7, 9a, S8: Deforestation in Borneo 1950–2005 (a) 1950; (b) 1985; (c) 2000 (d) 2005 [54], Figure S9: Climacograms of the deforestation in Borneo, Figure S10: Evaluation of climacograms and rhythm of clustering in demolition of fosters' clustering in Borneo,
- the deforestation of the Amazon, Figures 8, 9b, S11: Deforestation of Amazon, creation of clustering of dry land and urban areas inside forest [55], Figure S12: Climacograms of the deforestation in Amazon, Figure S13: Evaluation of climacograms and rhythm of clustering evolution of dry-lands' clustering in Amazon
- the evolution of water bodies in Greece, Figures 10, 11, S14: Greece, natural and artificial lakes (a) overview map of the area with natural and artificial lakes in 2020; (b) layer of the map; natural and artificial lakes 2020; (c) layer of the map; lakes 2020, Figure S15: Evolution of water bodies in Greece as new big dams are constructed and new artificial lakes are created, Figure S16: Climacograms of the evolution of water bodies in Greece.

In these examples, we can see the demolition of the forests' clustering in Borneo, and the evolution of clustering of dry lands and urban areas in the Amazon forest. An interesting insight is provided, showing the evolution of water bodies in Greece, as new artificial lakes are created, resulting in amplification of natural variability. Such an argument in favor of the integration of dams in the landscape was recently proposed [56]. Note that increasing clustering of water bodies is associated with the construction of large-scale dams and it is related to the economic growth; increasing clustering appears in periods of increasing Gross Domestic Product (GDP) (Figure 11).

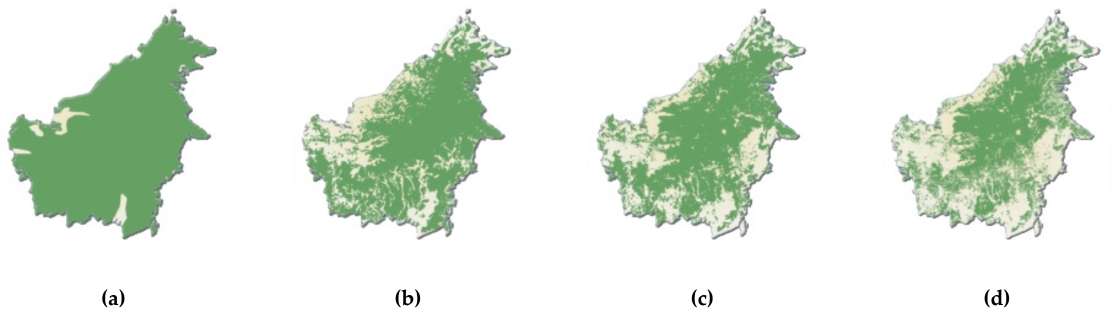
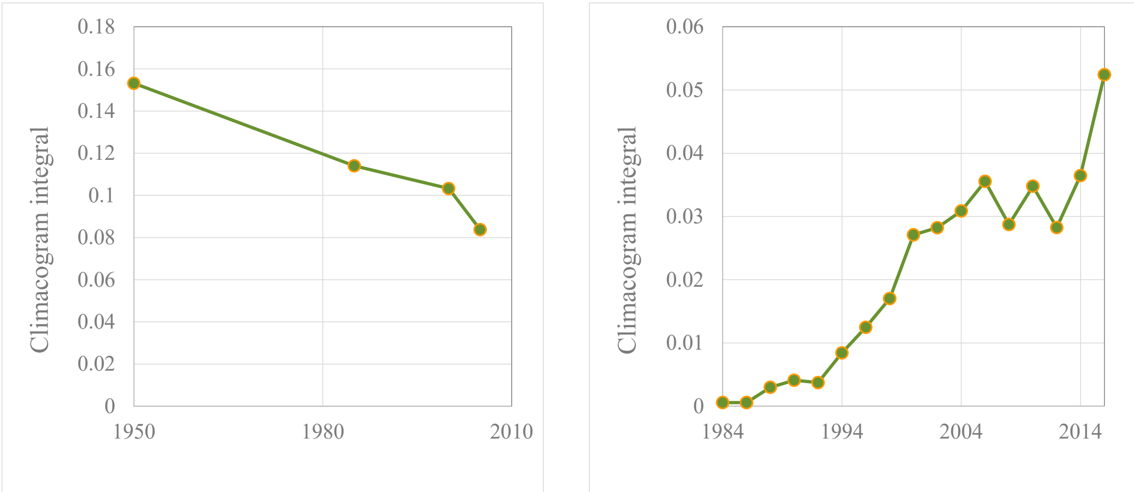


Figure 7. Deforestation in Borneo, declustering of forests 1950–2005 (**a**) 1950; (**b**) 1985; (**c**) 2000 (**d**) 2005 [54].

Figure 8. Deforestation of the Amazon, creation of clustering of dry land and urban areas inside a forest (**a**) 1984; (**b**) 1992; (**c**) 2000; (**d**) 2008; (**e**) 2016 [55].



(a) **(b)**

Figure 9. Rate of alteration of clustering through time of (**a**) demolition of fosters' clustering in Borneo; data from Figure S8 (**b**) evolution of dry-lands' clustering in the Amazon; data from Figure S11.

(a) **(b)** **(c)**

Figure 10. Evolution of water bodies in Greece as new artificial lakes are created (**a**) overview map of the area with natural and artificial lakes in 2020; (**b**) layer of the map: lakes in 1960; (**c**) layer of the map: lakes in 2020.

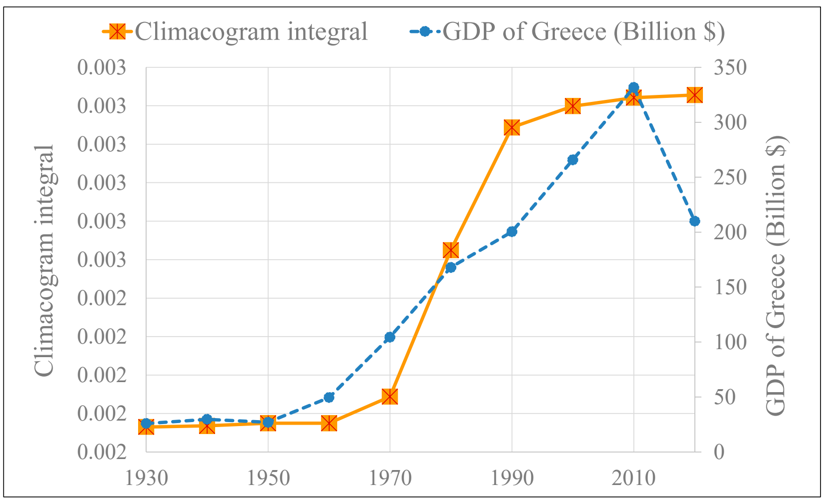


Figure 11. Rate of alteration of clustering through time of water bodies in Greece through the construction of large dams; related to the GDP of Greece; data from Figure S14.

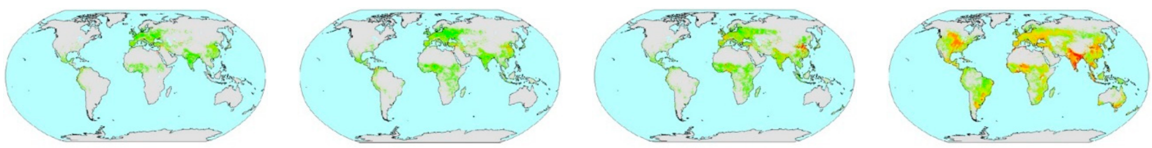
3.2. Evolution of Human Social Clustering

Large-scale infrastructure projects are necessary when the human population is clustered and organized in large units. In order to understand and describe the changing scale of infrastructures, it is necessary to first assess the evolution of human social clustering. This is facilitated through the investigation of spatial databases. To this aim, we employed our stochastic methodology to characterize the temporal evolution of spatial information regarding human social clustering.

The beginning of human civilization is signaled by the organization of systematic agriculture through the clustering of cropland areas (Figures 12, S18: Evolution of cropland area; historical data from 3000 BC to AD 2000. [57]) and the formation of human clustering structures, i.e., societies that stabilized in space forming cities and transforming their environment (Figures 13, S20: Evolution of London; historical data from 1 AD to 1950 AD. [58]). We evaluated related historical data to quantify the evolution of clustering at the global (Figures 14a, S19: Climacograms of cropland areas, Figure S22a: Evaluation of climacograms and rhythm of clustering of cropland land historical data) and local scale (Figures 14b, S21: Climacograms. Clustering of urbanization of London, Figure S22b: Evaluation of climacograms and rhythm of clustering and evolution of urbanization in London area).

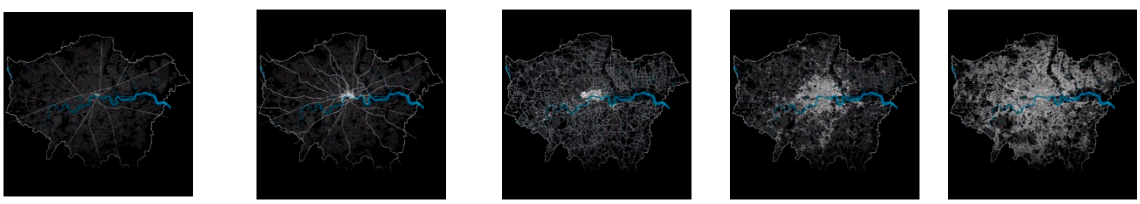
Figure 14a shows the evolution of cropland areas from 1000 BC to 2000 AD worldwide, derived from [57], whereas Figure 14b shows the evolution of settlements in London from 1 AD to 1900 AD, derived from [58]. It is interesting to note the radical increase in the rate of clustering occurring in both cases after 1700 AD (Figure 14), i.e., in the period after the industrial revolution.

It should be noted however that threats such as natural disasters and war demolish clustering of human social structures, as revealed by the inspection of satellite lights in Syria after the onset of the civil war (Figures 15, S40: Satellite night lights of Syria taken from Reference [59]; (**a**) 2012; (b) 2014; (**c**) Rate of alteration of clustering after the onset of the civil war).



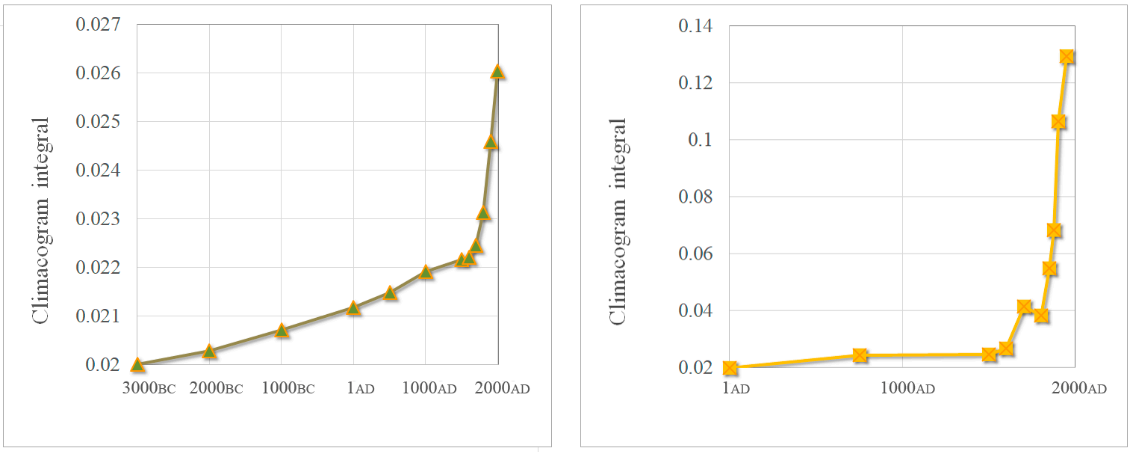
(**a**) (**b**) (**c**) (**d**)

Figure 12. Evolution of cropland area; historical data (**a**) 1000 BC; (**b**) 1000AD; (**c**) 1700AD (**d**) 2000 [57].



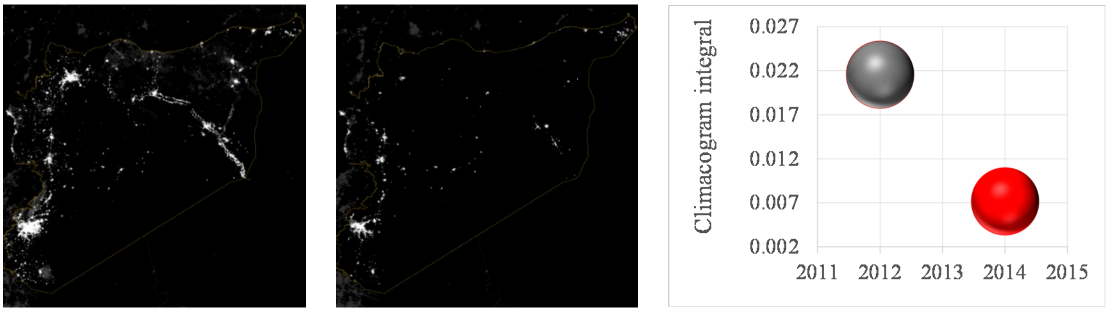
(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 13. Evolution of London; historical data (**a**) 1AD; (**b**) 1500AD; (**c**) 1700AD; (**d**) 1850AD; (**e**) 1900AD [58].



(a) **(b)**

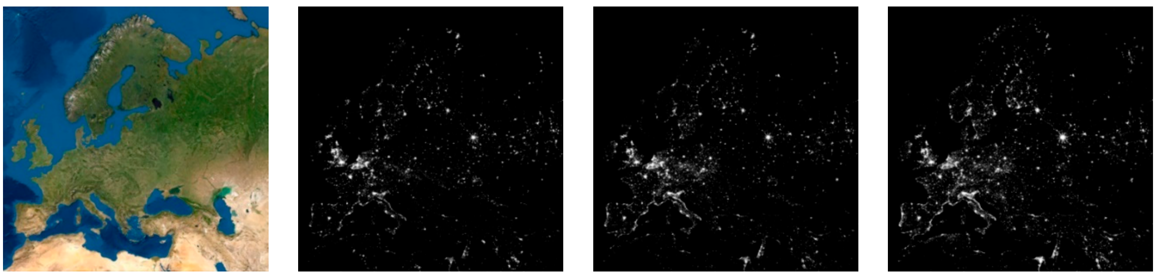
Figure 14. Rate of alteration of clustering through time of (**a**) cropland land historical data (**b**) evolution of urbanization in the London area.



(a) **(b)** **(c)**

Figure 15. Satellite night lights of Syria taken from Reference [59]; (**a**) 2012; (**b**) 2014; (**c**) Rate of alteration of clustering after the onset of the civil war.

Next, we explored spatial data pertaining to urbanization taking place in the past century. The first information source examined was the spatial distribution of satellite night lights. The night lights have been widely used as an index of the population and density of settlements [60], economic activity [61], consumption and distribution of electricity [62], poverty and development status [63] and human exposure to natural disasters such as floods [64]. An example showing satellite images from city lights in Europe is shown in Figure 16, while their respective climacograms are shown in Figure 17.



(a) **(b)** **(c)** **(d)**

Figure 16. (**a**) Europe and its night lights in (**b**) 1992, (**c**) 2002, (**d**) 2012.

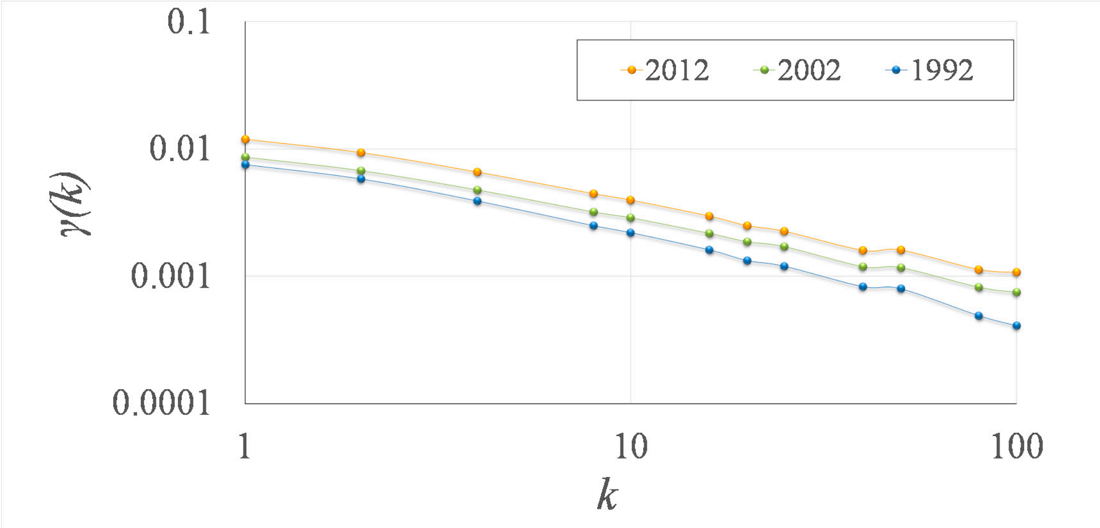


Figure 17. Climacograms of the images of night lights of Europe.

The second information source examined was the spatial dataset on land uses. Large-scale geospatial data, including land-cover types, were obtained from the Historical Database of the Global Environment, HYDE 3.1 [57], of the National Centers For Environmental Information at the National Oceanic And Atmospheric Administration (NOAA). HYDE datasets are based on Food and Agriculture Organization of the United Nations agricultural statistics and land use (FAOSTAT) over the period 1960–2010 [65], a variety of other historical information prior to 1960, datasets for wood harvest by FAO and urban land extent [57] in combination with assumptions of other land cover change (e.g., forest areas, which are estimated by MODIS equipped satellites). This dataset was chosen because it contains valuable temporal information on urbanization.

The land cover dataset was provided in form of NetCDF files at a spatial resolution of 0.5×0.5 degrees of latitude and longitude. Therefore, the size of each grid cell expands from 1.3475×10^7 m^2 to 3.088224×10^9 m^2. In addition, land cover geospatial data were provided at an annual time resolution using the WGS84 reference coordinate system. The longest record spans the years 1770–2010, but our studied period spans from 1900 to 2010. Land cover annual maps report the percentage of grid cell areas belonging to each of 28 land cover types, from which we focus on the urban land cover type. An example showing the extension of urban land cover in Europe is shown in Figure 18, while their respective climacograms are shown in Figure 19.

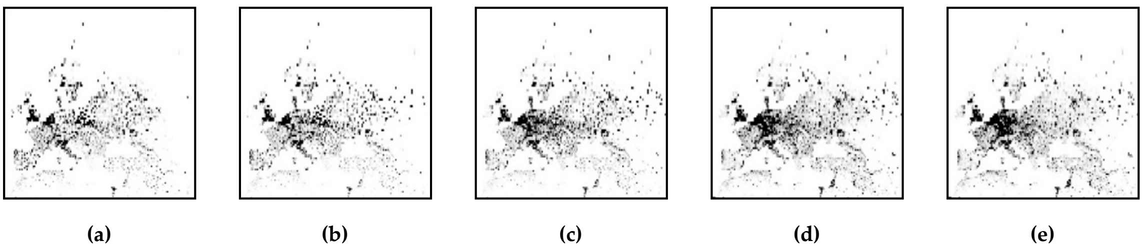


Figure 18. Europe in the Mercator projection of urbanization in (**a**) 1900; (**b**) 1930; (**c**) 1960; (**d**) 1990; (**e**) 2010.

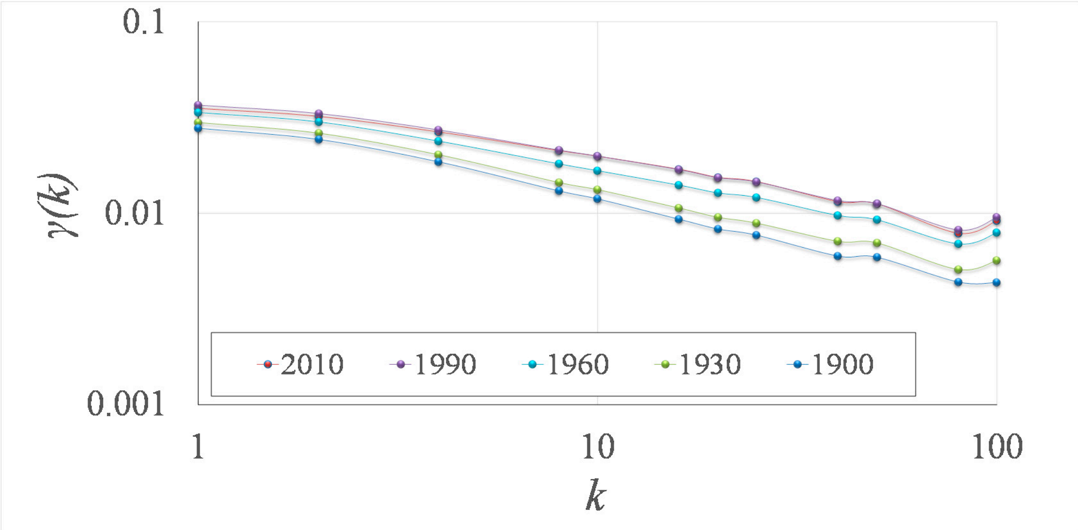


Figure 19. Climacograms of urbanization's images.

All studied images along with the complete climacogram analysis for Europe, Asia, America and the globe is presented in the Supplementary Material (Figures S23–S39) and summarized in Figure 20.

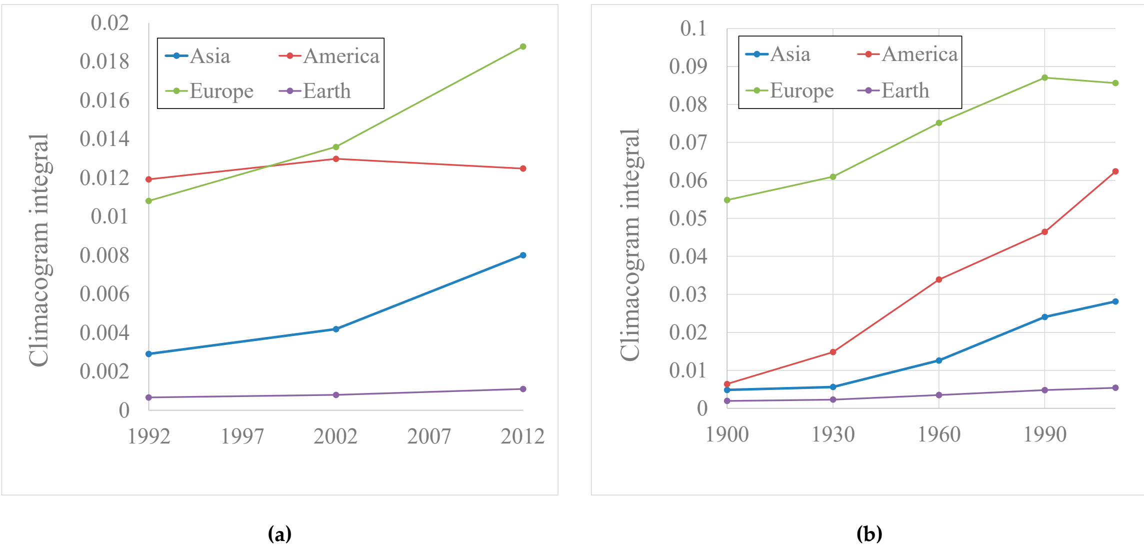


Figure 20. Temporal evolution of urban clustering from evaluation of (**a**) city lights and (**b**) urban land cover percentages.

The temporal evolution of human social clustering from both information sources is presented in Figure 20. Overall, the analyses support the case for increased human social clustering during the 20th century in all three continents, i.e., Asia, Europe and America. A few differences arise from the comparison of the period that the information sources overlap, i.e., from the 1992 to 2010. Namely, although urbanization appears increasing in terms of land use in America, this trend is not confirmed by the evaluation of night lights for the same period, which appear to have slightly decreased. In contrast, the night lights in Europe have majorly increased during this period, despite the relative stability in the urban land use cover. These differences indicate the virtue of considering both information sources, as night lights appear to be a better index of population density, whereas the land use cover is more reflective of the spatial expansion of urban land uses. From this point of view, it appears that urban expansion has been more prominent in America, whereas Europe has experienced increased population density. Last, Asia shows consistent increases in both information sources over the last few decades.

4. Discussion

4.1. Human Social Clustering as a Means for Development and Progress

The idea of economies of scale as developed by Adam Smith [66] is that with the increase of growth comes a decrease of the cost per unit [10]. The advantages of economies of scale have theoretical limits, i.e., when reaching the optimal design point where the cost per additional unit begins to increase. Economies of scale are related to scale development of infrastructures where there are also additional limits induced due to lack of funds, technical difficulties as well as public opposition [67] and resources accessibility. Large scales of infrastructure have risks [68] but are also advantageous for local economies [69]. Previous work [8] has shown that changing the scale of water infrastructures results to changes in the cost of water in agreement with the so-called "0.6 rule" in macroeconomics [8,70,71].

This relationship is also addressed by Wenban–Smith [72], who uses the term "density effects" to describe the clustering trend towards concentration of population and large scales infrastructures. For instance, in Greece we can see this clustering trend in terms of infrastructure in the construction of large-scale dams. Other emblematic examples of large-scale projects include the controversial "North American Water and Power Alliance" [73,74] (not constructed yet), Tehri Dam [75] (constructed in India) and the Three Gorges Dam [76] (constructed in China).

In order to solve the problem of the optimal scale of infrastructure, multi-criteria optimization is required. Despite the contributions of mathematicians, little progress has been made in this engineering problem until the last half of the 20th century, when high-speed digital computers made it possible to apply optimization techniques to large-scale structures with powerful and popular complex optimization methods [77]. Still, it is often the case that rather than cost-benefit optimization, political and aesthetical reasons (as the desire for creation of *civilization signals*), are the driving forces behind the choice of the scale of historical infrastructures; notable examples are shown in Figure 21.

(a) (b) (c)

Figure 21. (**a**) The Great Pyramid of Giza 2560 BC [78] (**b**) Notre-Dame de Paris, towers on the west facade 1220–1250 AD [79] (**c**) Eiffel Tower 1887–1889 [80].

What is common though in these large-scale projects, is the existence of an efficient state structure able to take the relevant decisions about political and administrative mechanisms for decisions clustering, as well as to impose and finance them. Thus, they reflect the presence of a stable social mechanism which, according to the theory of Tomas Hobbes [81], is represented by *Leviathan*. The latter metaphorically represents a central political entity that seeks to preserve law and peace by imposing a *utilitarian egoism* driven by the instinct of self-preservation (conatus) and the will to dominate, exercising absolute power only in favor of preserving social peace, i.e., the well-known *social contract*. *Leviathian* also undertakes the protection of citizens from external and internal factors, while also protecting citizens from the central entity itself. From this idea the Constitution originated as a self-limitation of power. As engineering development is intertwined with social peace and prosperity, we can assume that a form of centralized socio-political structure the likes of *Leviathan* is required in order to undertake decisions about large-scale development and infrastructure projects.

Another view on the creation of large infrastructure projects through centralized social structures is given by Aristotle [82]: *"...καὶ τὸ πένητας ποιεῖν τοὺς ἀρχομένους τυραννικόν, ὅπως μήτε φυλακὴ τρέφηται καὶ πρὸς τῷ καθ᾽ ἡμέραν ὄντες ἄσχολοι ὦσιν ἐπιβουλεύειν. παράδειγμα δὲ τούτου αἵ τε πυραμίδες αἱ περὶ Αἴγυπτον καὶ τὰ ἀναθήματα τῶν Κυψελιδῶν καὶ τοῦ Ὀλυμπίου ἡ οἰκοδόμησις ὑπὸ τῶν Πεισιστρατιδῶν, καὶ τῶν περὶ Σάμον ἔργα Πολυκράτεια (πάντα γὰρ ταῦτα δύναται ταὐτόν, ἀσχολίαν καὶ πενίαν τῶν ἀρχομένων)".* English translation [83]: "And it is a device of tyranny to make the subjects poor, so that a guard may not be kept, and also that the people being busy with their daily affairs may not have leisure to plot against their ruler. Instances of this are the pyramids in Egypt and the votive offerings of the Cypselids, and the building of the temple of Olympian Zeus by the Pisistratidae and of the temples at Samos, works of Polycrates (for all these undertakings produce the same effect, constant occupation and poverty among the subject people)". This example highlights the mutually dependent relation between central entities and large-scale development: the existence of the one often relies on the other.

4.2. Risks From Large-Scale Clustering

While human social clustering increases the chances for social progress and prosperity, it also increases exposure and vulnerability to different kinds of risk. For the first time in human history, more people live in cities than in rural areas. This rapid growth in the number of people living in cities and urban landscapes is increasing the world's susceptibility to natural disasters [84,85] and other threats [86]. For instance, in the case of war, large-scale infrastructure projects are important and common targets. Figure 22a depicts Serbian civilians, forming human shields to protect their country's infrastructure during the NATO bombing of Yugoslavia during the Kosovo War (1999). Large-scale infrastructures are also symbols of civilizations and this is why the World Trade Center was a target during the 9/11/2001 attack (Figure 22b).

On the other hand, modern large-scale infrastructure projects have a life of no more than 120 years due to aging of their materials and the difficulties in maintaining them [87]. As a simple example, consider the two collapses of large-scale bridges that have occurred in Italy in the past few years, causing fatalities and massive disruption of transportation [88,89]. Moreover, it is straightforward to see how a possible failure in large-scale water-supply infrastructures upon which societies are heavily reliant would create a vague gap in social functioning [88].

It is therefore evident that with the increase of the scale of the development along with the planned increase of benefits comes also an increase of risks, as the concentration of goods and services in one place makes the human communities more vulnerable to a destruction of this supply chain. Interestingly, metaphors on the existence of a limit in the scale of human works are present in various literature and theological works since antiquity, perhaps the most famous examples are found in the Holy Bible. In the latter the man is regarded as the crown of God's Creation and by the fall of man in Original Sin, the whole Creation falls (Genesis 3.17 [90], St Paul, Epistle to the Romans; 8.20-22. [91]). After the fall of humans, the environment became hostile and man had to do work to survive. In the famous myth of the Babel tower, the Holy Bible explicitly communicates the notion of an upper limit in the scale of human works (Genesis 11, Job 38:1-41 [90]).

(a) (b)

Figure 22. (**a**) Serbians protecting their country's infrastructure from bombing as human shields [92]; (**b**) The north face of Two World Trade Center (south tower) immediately after being struck by United Airlines Flight 175 [93].

Recently, due to the ongoing COVID-19 pandemic, we have been collectively reminded of how large-scale human social clustering increases the risk of pandemics. In the developed world, the majority of measures to mitigate the spread of the pandemic have been based on forms of social distancing, with lock-downs being the ultimate measure. Nearly three billion people were in quarantine in April 2020 [94]. In this respect, the Epicurean philosopher Lucretius says that if there is no immediate risk of death, people are not afraid of death [95], but the fear of death can lead people to make social divisions and suspend their personal growth [96]. Indeed, when people are afraid of dying, it is common to believe that the avoidance of social contact will help them avoid danger, illness and death altogether. This phenomenon is well documented in social fear management studies [97] and in this context, it can also be viewed as another implicit communication of the risks of social clustering.

5. Conclusions

It is argued herein that clustering is both a natural and a human social tendency that comes with different qualitative consequences with scaling, i.e., the properties of large scales cannot be derived from the ones of small scales. In these terms, as both the scales of current societies and that of engineering projects increase, it is of paramount importance to understand both the structure of spatial clustering and its temporal evolution. To this aim, this research develops a stochastic method of general applicability for the quantification of the temporal evolution of spatial clustering as a tool to assess, monitor and potentially predict elements of global changes.

The tool called 2D-C (2D-Climacogram) quantifies the variability of images through the variance of the brightness intensity in grayscale. Upon a careful selection of images representing spatial information, we can derive a quantification of clustering over time that is useful for either quantitatively characterizing known spatial changes, as urbanization, and tracking their temporal evolution, or even revealing spatial patterns that are less expected, i.e., pertaining to feedback loops between anthropogenic interventions and natural variability. We present a range of applications for (a) the natural sciences, in terms of the evolution of the universe as suggested by cosmological simulations and of ecosystems, such as forests and lakes, and (b) for human sciences dealing with social structures, as revealed by the evolution of worldwide cropland data, satellite images of night lights and spatial data on urban land cover.

Our results support the concept that there is a tendency for clustering both in the natural and anthropic world, yet this tendency is scale-dependent as beyond a certain scale it may as well be dissolved or replaced by a structure of another quality. We have seen that in the evolution of the universe clustering increases and decreases depending on the scale of view, and structures that have grown and seem at a certain scale to be merging (galaxies, clusters, super clusters, etc.), in other scales are moving apart. In biological life clustering is related to saving of energy resources, as in in mammals, but it is not always stable; for instance, dinosaurs disappeared. The case studies on ecosystems, namely the Borneo and Amazon forests and the lakes in Greece, show that the clustering method offers an effective characterization of the evolution of ecosystems revealing clustering and declustering patterns. In many cases, the interplay of natural and human-driven variability is difficult to discern and proves unpredictable in terms of evolution. Such a counterintuitive case is the found increase in ecosystem variability stemming from anthropogenic interventions such as dams.

Clustering and declustering periods are apparent in nature as also revealed by our case studies, as well as in human social structures. There are local examples of declustering, i.e., related to wars, famines or nuclear and natural disasters, but our case studies show an overall positive clustering trend. Specifically, in our study of long-term worldwide cropland data and London's evolution, we have found that the rhythm of clustering dramatically increased since the industrial revolution, whereas urbanization followed this overall positive trend till the present time. This is in accordance with the widespread belief that larger human clustering structures enhance efficiency (e.g., through economies of scale). Yet it is becoming increasingly evident that clustered human structures come with increased risks as well. For instance, in the economy increasing clustering comes with increase in systemic risks, while centralization of infrastructure and resources increases vulnerability of the population during failure or war. In this period, the society is forced to radically reassess the clustering structures in different social scales in order to tackle the risk from the COVID-19 pandemic.

Despite the vast benefits resulting from centralized social structures during the last centuries as presented in Figures 14 and 20, at this point in time, it is tempting to consider an alternative social distribution in space, perhaps a sparser and more decentralized one, taking example of the evolution of natural structures that are driven by uncertainty. The COVID-19 circumstance presents an opportunity to reconsider the trade-offs resulting from our natural tendency to cluster in space. In addition, it is an opportunity to revise the criteria for selecting the optimal scale for development, as well as the meaning that terms such as *sustainability* bear under unprecedented conditions.

In any case, the answer to the question of an optimal scale of social organization and development, is a fascinating problem that engineers among others, are urged to set and solve [98–100]. *Homo Sapiens* survived the natural selection being a (small-scale) mammal and not a (large-scale) dinosaur. Yet humans were ultimately able not only to adapt to new conditions but also to shape new conditions and modify their environments through science and technology.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/19/7972/s1, Figure S1. General view of the direct Cosmological Simulations of the Growth of Black Holes and Galaxies [1,2], Figure S2. Climacograms of the Direct Cosmological Simulations of the Growth of Black Holes and Galaxies (Figure S1), Figure S3. Closer zoom in an area of the direct Cosmological Simulations of the Growth of Black Holes and Galaxies [1], Figure S4. Climacograms of the closer zoom of Direct Cosmological Simulations of the Growth of Black Holes and Galaxies (Figure S2), Figure S5. Evolution of the universe. Millennium Simulation Project [3], Figure S6. Fitting curves of composed climacograms of Millennium Simulation Project [3] (a) image series of 210 mil years after B.B.; (b) image series of 1000 mil years after B.B.; (c) image series of 4700 mil years after B.B.; (d) image series of 13,600 mil years after B.B., Figure S7. Rate of alteration of clustering through time of image series in Figures S1, S3, S5, Figure S8. Deforestation in Borneo 1950–2005 (a) 1950; (b) 1985; (c) 2000 (d) 2005 [4], Figure S9. Climacograms of the deforestation in Borneo, Figure S10. Evaluation of climacograms and rhythm of clustering in demolition of fosters' clustering in Borneo, Greece, natural and artificial lakes (a) overview map of the area with natural and artificial lakes in 2020; (b) layer of the map; natural and artificial lakes 2020; (c) layer of the map; lakes 2020, Figure S11. Deforestation of Amazon, creation of clustering of dry land and urban areas inside forest [5], Figure S12. Climacograms of the deforestation in Amazon, Figure S13. Evaluation of climacograms and rhythm of clustering evolution of dry-lands' clustering in Amazon, Figure S14. Greece, natural and artificial lakes (a) overview map of the area with natural and artificial lakes in 2020; (b) layer of the map; natural and artificial lakes 2020; (c) layer of the map; lakes 2020., Figure S15. Evolution of water bodies in Greece as new big dams are constructed and new artificial lakes are created, Figure S16. Climacograms of the evolution of water bodies in Greece, Figure S17. Rate of alteration of clustering through time of water bodies in Greece through the construction of large dams, related to GPD of Greece, Figure S18. Evolution of cropland area; historical data from 3000 BC to AD 2000. [6], Figure S19. Climacograms of cropland areas, Figure S20. Evolution of London; historical data from 1 AD to 1950 AD. [7], Figure S21. Climacograms. Clustering of urbanization of

London, Figure S22. Evaluation of climacograms and rhythm of clustering (a) cropland land historical data (b) evolution of urbanization in London area, Figure S23. (a) Mercator projection of earth and its night lights in (b) 1992; (c) 2002; (d) 2012., Figure S24. Climacograms of the images of night lights of the earth, Figure S25. Earth in Mercator projection of urbanization in (a) 1900; (b) 1930; (c) 1960; (d) 1990; (e) 2010, Figure S26. Climacograms of urbanization's clustering in worldwide, Figure S27. (a) Mercator projection of Europe and its night lights in (b) 1992; (c) 2002; (d) 2012, Figure S28. Climacograms of the images of city lights of Europe, Figure S29. Europe in Mercator projection of urbanization in (a) 1900; (b) 1930; (c) 1960; (d) 1990; (e) 2010, Figure S30. Climacograms of urbanization's clustering in Europe, Figure S31. (a) Mercator projection of North America and its night lights in (b) 1992; (c) 2002; (d) 2012., Figure S32. Climacograms of the images of city lights of Europ, Figure S33. North America in Mercator projection of urbanization in (a) 1900; (b) 1930; (c) 1960; (d) 1990; (e) 2010, Figure S34. Climacograms of urbanization's clustering in America, Figure S35. (a) Mercator projection of Asia and its night lights in (b) 1992; (c) 2002; (d) 2012., Figure S36. Climacograms of the images of city lights of Asia, Figure S37. Asia in Mercator projection of urbanization in (a) 1900; (b) 1930; (c) 1960; (d) 1990; (e) 2010, Figure S38. Climacograms of urbanization's clustering in Asia, Figure S39. Evaluation of climacograms and rhythm of clustering (a) city lights (b) urbanization, Figure. 40. Satellite night lights of Syria taken from Reference [59]; (**a**) 2012; (b) 2014; (**c**) Rate of alteration of clustering after the onset of the civil war, Figure S41. Climacograms, declustering of urbanization in Syria.

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