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Water Security and Governance in Catchments

Edited by
Fernando António Leal Pacheco and
Luís Filipe Sanches Fernandes

Printed Edition of the Special Issue Published in *Water*

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This is a reprint of articles from the Special Issue published online in the open access journal *Water* (ISSN 2073-4441) (available at: www.mdpi.com/journal/water/special_issues/Water_Security_Governance).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-4110-5 (Hbk)
ISBN 978-3-0365-4109-9 (PDF)

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About the Editors

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Prof. Fernando A.L. Pacheco was born in 1967 in Mozambique. He holds a Ph.D. degree in Hydrogeology (2001) from the Trás-os-Montes and Alto Douro University (UTAD, Portugal) and an Aggregation title in Environmental Geochemistry (2011) from the UTAD. He was heading the Geology Department of UTAD from 2013 to 2021. He joined the Vila Real Chemistry Research Centre of UTAD in 2005, where he still develops most of his research. He published over 100 research papers in International journals. He is Editor at various scientific journals (e.g., Science of the Total Environment, Water, Sustainability, International Journal of Environmental Research and Public Health, Arabian Journal of Geosciences). Prof. Pacheco is actively involved in scientific cooperation on land management and water security projects, with several Brazilian institutions: Federal Institute of Triângulo Mineiro (IFTM), Regional Coordination of Environmental Justice Prosecutors in the Paranaíba and Baixo Rio Grande River Basins (MPMG), Minas Gerais Institute for Water Management (IGAM), and the San Paulo State University (UNESP).

Prof. Pacheco research interests and expertise cover the topics of hydrologic models coupled with weathering algorithms, especially in areas with significant anthropogenic pressure; multivariate statistical and environmental analyses of surface and groundwater databases, with focus on the prevention of surface and groundwater contamination; land degradation and management, as well as the negative impacts of inadequate land uses on soil erosion, surface and groundwater quality; water security issues, such as conjunctive use of surface and groundwater sources in public water supply systems, or the attenuation of hydrologic extremes (floods, droughts) through implementation of detention basins and decentralized rainwater harvesting systems in catchments.

Luís Filipe Sanches Fernandes

Prof. Luís Filipe Sanches Fernandes was born in 1968 in Portugal. He holds a Ph.D. degree in Civil Engineering from University of Minho (Portugal) since 1993. He is a Professor in the Engineering Department (Civil Engineering) in the area of Hydraulics, Water Resources and Environment of the University of Trás-os-Montes e Alto Douro (UTAD), where he teaches since 1995. He is full member of the Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), where he was a member of the executive committee for approximately 5 years. He also holds a MSc in Municipal Engineering from University of Minho since 1998. The PhD thesis was entitled "A model for simulating hydrographs in river basins using neural networks" and defended at UTAD. His Aggregation title was in Territorial and Environmental Engineering Sciences, specialization in Civil Engineering, and defended in the University of Évora (Portugal). Prof. Sanches Fernandes is a Member of The Portuguese Association of Water Resources and senior member of Order of Engineers. He has a 31 h-index Scopus with more than 100 articles published in the fields of hydraulics, water resources and environment. He has written 6 book chapters and more than 100 conference proceedings and communications (oral and poster). He has participated in 10 financed projects, being the leader in 2. He has supervised or co-supervised 4 PhD thesis and 35 master dissertations, and is responsible for several university extension projects with high funding values. He was a member of 2 terms in pedagogical councils, 2 terms in scientific councils and 1 term in general council in University of Trás-os-Montes and Alto Douro.

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Editorial

Water-Secure River Basins: A Compromise of Policy, Governance and Management with the Environment

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Citation: Pacheco, F.; Melo, M.; Pissarra, T.; Fernandes, L. Water-Secure River Basins: A Compromise of Policy, Governance and Management with the Environment. *Water* **2022**, *14*, 1329. https://doi.org/10.3390/w14091329

Received: 21 March 2022
Accepted: 11 April 2022
Published: 20 April 2022

Water-secure basins are a lifesaving goal of society that can be accomplished if political and water authorities, stakeholders, and the general public are networked and committed to effectively improve water security, river basin management, and water resource policies and governance. The United Nations defined water security as the "capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [1]. This definition comprises the elements of water security but does not direct the concept to a specific geographic space. If, as usual, the geographic space is a watershed, then water security overlaps the scope of river basin management as the later contributes to the former through a "coordination amongst operating and water management entities within a river basin, with a focus on allocating and delivering reliable water-dependent services in an equitable manner" [2]. The implementation of river basin management requires the preparation of a master plan reflecting sector plans and offering the most efficient use of water; the involvement of stakeholders for the sharing of basin-wide datasets and knowhow; the technical and scientific capacitation of involved human resources; and the implementation of monitoring and evaluation plans to identify the needs for adjusting management strategies; among others. However, even with these operational conditions ensured, river basin management can only succeed if political will and innovative water resource policies and governance approaches are capable to create a favorable legal atmosphere and respond to current water-born challenges. In the latter case, the response should help balancing the conflict between water demand and healthy ecosystems [3]; resolving water infrastructure finance constraints [4], bringing the payment for water resource services and ecosystem services into the equation; and implementing water-saving and green technologies through field rainwater harvesting [5], intelligent irrigation [6], wastewater treatment and reuse [7], desalinization [8], and education of population on efficient domestic and industrial water use [9]. The goal of understanding this complex imbrication and interplay between water security, river basin management, and water policies and governance, motivated the launch of a Special Issue on "Water Security and Governance in Catchments", which was edited with great enthusiasm.

During the working period, many submissions were received, which provided significant contributions for the main topics of this special issue. However, only 12 high-quality papers were accepted after several rounds of strict and rigorous review. These 12 contributions are summarized in the forthcoming paragraphs, being integrated into a coherent narrative. In brief, contributions 1–4 [10–13] discussed water security from the standpoints of quantity and quality, contributions 5–7 [14–16] addressed water hazard risks (floods and droughts), contributions 8–10 [17–19] looked into hazard mitigation measures and. Finally, contributions 11 [20] and 12 [21] focused on governance-related matters.

A key element of water security is availability, namely of surface water and groundwater. At the catchment scale, these parcels of total freshwater are frequently estimated by hydrologic models such as the SWAT. Contribution 1 [10] used this model to investigate the impact of current land uses, as well as of simulated land changes, on the runoff, groundwater storage and evapotranspiration, within the Uberaba River basin, Minas Gerais, Brazil. A scenario of extensive reforestation led to increasing groundwater storage but also to amplified water losses through evapotranspiration as well as decreasing contributions to the surface compartment through decreased runoff. Another vital element of water security is quality, namely the compliance of raw water with legal standards. In multiple-use watersheds where many activities can concur to water quality degradation, evaluation of security from the quality standpoint requires the continuous searching for effective evaluation methods. Contribution 2 [11] proposed a new method to estimate *Escherichia coli* load reduction in river basins, considering different flow regimes and seasons. The method is based on Load Duration Curves and the study area comprised the Piracicaba and Piranga basins (Minas Gerais, Brazil). The results made evident that the loading of raw sewage directly into the rivers was a leading cause of *Escherichia coli* contamination regardless of flow regime. Thus, the first mitigation measure of *Escherichia coli* pollution should be the installation of wastewater treatment plants in the basins. The presence of fecal coliforms as most serious alteration to the quality of Brazilian streams was corroborated in the study of an anthropized rural area located in the municipality of Igarassú, state of Pernambuco, presented as contribution 3 [12] in the special issue. Land use or occupation are not the sole human pressures capable to affect stream water quality in catchments. Damming is another frequent cause of water quality declines, especially if dam lakes receive contaminant-rich drainage from upstream agriculture or urban watersheds. Contribution 4 [13] studied the impact of damming on stream water quality of Lerez, Umia, Ulla and Mandeo rivers (Galicia, Spain), but found no evidence of degradation, probably due to the fact that the riparian habitat was in general classified as good quality or close to natural conditions around the studied reservoirs.

As entailed in the United Nations definition, a water-secure basin must ensure protection against water-related disasters, namely droughts and floods. Water scarcity is a worldwide problem aggravated by climate variations (especially in arid regions). Contribution 5 [14] showed how the expansion of the Dunhuang Oasis irrigation district and planting structure changes from 1987 to 2015 affected the oasis stability, as assessed by a ratio of precipitation over evapotranspiration. The stability dropped to a dangerously unstable level from 1985 to 2010, while the Dunhuang city and surrounding cropland were expanding. It recovered slightly from 2010 to 2015 with the implementation of water-saving measures, but a water-transfer project is viewed as the most practical measure to bring the oasis back to full stability in the future. Floods were also tackled in the Special Issue. Contribution 6 [15] created a water hazard risk map along the "Belt and Road" zone through combined flood and drought data from 1985. The Belt and Road Initiative is a global infrastructure development strategy adopted by the Chinese government in 2013, aiming to promote economic development and inter-regional connectivity within the nearly 70 countries involved. With regards to floods, the results showed that South-Eastern Asia, southern China and eastern Southern Asia are areas with the most abundant precipitations, while floods in these areas are also the most serious. Contribution 7 [16] addressed the long-term impacts of flood protection measures in Bangladesh. The authors tested whether the construction of an embankment in the Meghna–Dhonagoda region has affected the rural communities over time, benefiting those living inside more than those living outside the flood detention structure, but did not find a significant difference based on welfare, migration, or mortality indicators.

Prevention anticipates while mitigation responds to water-related hazards. Both initiatives are crucial to keep basins secure and were investigated in the special issue. Contribution 8 [17] presented the results of a restoration project that combined civil with soft soil engineering procedures and revegetation, aiming to mitigate the impacts of long-lasting dredging in the estuary of Lima river (in the northwest of Portugal), namely the collapse of banks and consequent destruction of riparian vegetation. The built structures, composed of an interconnected system of groynes, deflectors and rip-rap/gabion mattress, detained erosion but failed to trap sediments as much as expected. Contribution 9 [18] also addressed mitigation, but in the context of crop production systems. The authors reviewed resource-conservation technologies developed in the Eastern Gangetic Plain as a response to concerns about agricultural sustainability, with basic principles of rebuilding the soil, optimizing inputs for crop production, increasing food production, and optimizing profits. Conservation agriculture and water-saving measures were among the developed technologies, which had the benefit of reducing energy and nutrients usage and of reducing agrochemical leaching, being scale-invariant and intuitively clear. The anticipation of water scarcity was addressed in contribution 10, which was focused on wastewater reuse as an opportunity to meet the freshwater demand, and proposed a shift of paradigm from "safe treatment and discharge of wastewater" to "transforming used water to fit-for-purpose water".

Although related to the prevention of freshwater scarcity, contribution 10 [19] was more a reflection about governance of wastewater reuse. In their paper, the authors enumerated the steps that are necessary to take before practicing responsible water reuse, namely the assessment of water demand and availability, identification of reuse applications, evaluation of health and safety including water treatment, and the setup of a governance approach. The last two contributions included in the special issue also addressed water governance issues. Contribution 11 [20] compared various water governances with the purpose to identify the best approach to regulate integrated river basin management. The governances included in the comparison were the experimental, corporate, polycentric, metagovernance, and adaptive. The comparison was based on the governance dimensions of effectiveness, efficiency and trust, and engagement, as defined by the OECD (Organization for Economic Co-operation and Development). A combination of adaptative and metagovernance was elected the best approach to regulate integrated river basin management. The last contribution (no. 12) [21] was concerned with the link between implementation of new government strategies and water-related research. The authors investigated the impact of Jordan's 2008–2022 government strategy for water on the research conducted in the Azraq Basin. The results showed an increase in the number of water-related research papers, but the increase was not different from the increasing trend in research production in Jordan generally. Besides, the documents aligned with the water strategy goals were not larger than 80%.

In brief, the 12 papers covered most elements of water security at catchment scale, namely water quantity and quality or water-related hazards, besides establishing links with management actions such as prevention and mitigation of flood or drought risk, as well as with governance approaches such as the alignment of water-related research with governments' strategy for water. Taken altogether, the papers form an interesting view over the challenges of building water-secure river basins.

Funding: For the author integrated in the CITAB research centre, this work was supported by National Funds of FCT–Fundação para a Ciência e Tecnologia, under the project UIDB/04033/2020. This author is also integrated in the Inov4Agro–Institute for Innovation, Capacity Building and Sustainability of Agri-food Production. The Inov4Agro is an Associate Laboratory composed of two R&D units (CITAB & GreenUPorto). The author integrated in the CQVR received FCT funds under the projects UIDB/00616/2020 and UIDP/00616/2020.

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

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Article

Potential Impacts of Land Use Changes on Water Resources in a Tropical Headwater Catchment

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Citation: Martins, M.S.d.M.; Valera, C.A.; Zanata, M.; Santos, R.M.B.; Abdala, V.L.; Pacheco, F.A.L.; Fernandes, L.F.S.; Pissarra, T.C.T. Potential Impacts of Land Use Changes on Water Resources in a Tropical Headwater Catchment. *Water* **2021**, *13*, 3249. https://doi.org/10.3390/w13223249

Academic Editor: Athanasios Loukas

Received: 27 July 2021
Accepted: 12 November 2021
Published: 16 November 2021

Abstract: The main objective of this study was to investigate the relationships between land use and future scenarios of land changes on water runoff and groundwater storage in an Environmental Protection Area (EPAs) watershed. The methodology was based on the application of the Soil and Water Assessment Tool (SWAT) hydrological modelling to investigate flow simulations in current land use and in two future scenarios (forest and pasture). The performance of goodness-of-fit indicators in the calibration (NSE = 0.82, R^2 = 0.85, PBIAS = 11.9% and RSR = 0.42) and validation (NSE = 0.70, R^2 = 0.72, PBIAS = −4% and RSR = 0.55) was classified as good and very good, respectively. The model accurately reproduced the inter-annual distribution of rainfall. The spatial distribution of average annual surface flow, lateral flow, and groundwater flow were different between sub-basins. The future scenario on land use change to forest (FRSE) and pasture (PAST) differed during the year, with greater changes on rainy and dry seasons. FRSE increase of 64.5% in area led to decreased surface runoff, total runoff, and soil water; and increased lateral flow, groundwater, and evapotranspiration. The effect of the natural vegetation cover on soil moisture content is still unclear. The hydrological model indicated the main areas of optimal spatial water flow. Considering economic values, those areas should encourage the development of government policies based on incentive platforms that can improve environmental soil and water sustainability by establishing payment for environmental services (PES).

Keywords: flow; water discharge; land use; land change; SWAT model

1. Introduction

The extent of land use land changes (LULC) in tropical headwater catchment can result in the deterioration of many natural materials as a result of a human actions that directly affect the water and soil resources. Therefore, the increasing demand for production lands modify the water cycle and soil properties, which causes intense environmental degradation [1–4]. Understanding the LULC impacts by using future projections of scenarios from natural vegetation cover and the human alteration of landscapes is a major concern for the development of socioeconomic functions and sustainability [5–11]. Each land use production unit varies in its effect on environmental attributes [12], and impact the hydrologic cycle, affecting people's living.

Population growth and needs have been subjected to most environmental changes in studies over the last century to detect the critical processes that drive most changes. During the last few decades there has been an increase in world population and LULC impact on soil and water resources [6,9,11,12], and a better improved land organization is important to better distinguish the watershed factors of the ecosystem balance. Understanding the potential impacts on water and soil resources is challenging and enables consideration of the aspects on how LULC varies in space and time to apply better management practices.

Landscape properties interact with global climate change [6–9,13] and other land use policy issues [14], so, to apply hypothetical scenarios of methodology in watershed environment is important for several reasons. Research into forecasters of land use interests can inform policy and contribute to the development of economic decisions to prepare for landowners' agricultural and livestock demand. Furthermore, understanding the nature of assessing potential impacts of the land use changes scientifically explains the alterations in a watershed hydrology and river discharge [2,4,8,9], which may permit the private landowners' decisions to allocate economic land uses to increase water storage in spring catchment areas. The retention capabilities of soil systems were analyzed by [11]; urban areas contribute to decreased water capacity in catchments and causes the high percentage of natural land use in the upper part of the catchment to increase.

The land-use catchment hydrology effects have great local and temporal variability. The dominant vegetation type in deforested areas results in great difference in scale between the clime information resulting from the resolution of hydrological downscaling of dynamic and statistical models that use regional atmospheric data. For global models to reproduce, hydrological change needs to use large-sized grids (low spatial resolution). However, for impact, vulnerability, adaptation, and resilience studies, greater detail is necessary as these studies are generally local in specific watersheds [6–11,13].

Assessing the potential impact of eventual land-use changes of the analyzed area on a spatially distributed assessment criteria permit identification variables and quantify them to compare and estimate LULC on a watershed scale. The study of the main impacts provides relative importance to farm land-use policies. A quantitative investigation explores the effect of two land uses: Pasture and natural forest on the water resource management of a tropical catchment. Hypothetical simulation of land use scenarios have attracted interest [2,6–11] and investigations of the hydrological regime on climate change and urbanization scenarios based on the coupling of a stochastic weather generator with a land use change model in a basin-scale; water balance components will show the main changes of the scenarios evaluated [13,15–17].

The generated future scenarios were successively used to force a physically based and spatially distributed hydrological model to reconstruct the basin response under different conditions. The authors of [11,18] showed that urban expansion around protected areas will continue to be a major threat. On the other hand, the increases in ecological areas and crop/pasture lands in protected areas can limit the potential recovery of natural vegetation [19]. By modeling the land uses and water in river basins, it is possible to analyze and predict the effect of the LULC on natural resources. The authors of [20–22] installed a monitoring system in a small agricultural and forested catchment in an intensive livestock production area to obtain new information on the effect of livestock production systems on water cycles. In this way, it is possible to monitor the water dynamics and from there, estimate, with mathematical models, the causes that interfere in the environment, to understand the water cycle in the basin system to apply the best forms of management [23,24].

SWAT (Soil and Water Assessment Tool) is a semi-distributed, comprehensive river basin model [25]. This is a tool that assists the surface modeling of watersheds that aims to predict the impact of soil management on water resources [26]. The SWAT tool also infers several scenarios with different types of management and conservation practices, quickly and with low cost. The uncertainty, calibration, and parameter sensitivity analysis is used to provide statistics for goodness-of-fit and to obtain a better understanding of the overall hydrologic processes [25]. After a long period of change of land use from forest to pasture, the storm flow increased 17 times, while surface flow doubled in pastured areas, associated with the storm flow [27,28].

The farmers in these units must be conscious that the water requirements of the growing population are essential and it is necessary to acquire parcels of the terrain in the upper lands where preservation of vegetation is imperative [17,28]. Therefore, threatened springs, streams, and rivers should be identified and protected so that the population and agriculture can have enough water of better quality. Thus, the identification of areas of hydrological ecosystem services on units for protection is essential for the conservation of natural resources [14,29–32].

The main objective of this research was to analyze an environmental modeling system for some phases of watershed hydrology on land use future scenarios in the Environmental Protection Areas (EPAs), from Portuguese: 'Áreas de Proteção Ambiental (APA)' of the Uberaba River basin using the SWAT model to guarantee the improvement, soil management, and the conservation of the natural resources of this ecosystem.

2. Material and Methods

2.1. Study Area

The experimental area is the EPA of the Uberaba River located in Minas Gerais state, Brazil, between longitudes 47°45′ W and 48°00′ W and latitudes 19°35′ S to 19°45′ S (Figure 1). Altitudes varying from 700 m to 1050 m, the basin area covers 525 km^2, around 30% of the Uberaba River basin. The Uberaba River flows into Grande River and this into Paraná River.

The EPAs are protected areas defined by the Brazilian Government, regulated by Law 9985, 18 July 2000 [33], that establishes the National System of wildlife protected areas management (SNUC, in Portuguese) aimed to conserve Units of Conservation (UC) to protect the biodiversity and genetic resources within the national territory and waters under the Brazilian jurisdiction. The creation of EPAs has been encouraged as the most effective way to conserve forest remnants [34,35], and especially water recharge areas. Therefore, it is linked to the use of natural resources and, at the same time, to improve the connection of human beings with nature [36].

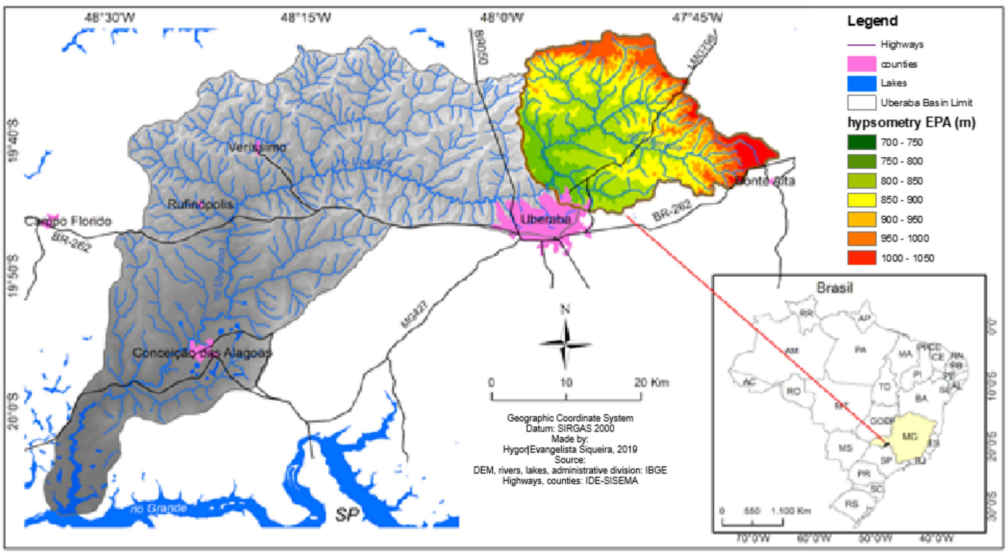

Figure 1. Experimental area of the EPA of the Uberaba River. Map Source: [37].

The area was established as an EPA due to its environmental importance in the region. The area represents the upper portion of the Uberaba River basin that supplies water to Uberaba City, Uberaba Municipality, Minas Gerais state, Brazil. The upper spring supply is a provision of water direct from drainage net to a number of consumers, and is also a source of groundwater to large supplies that are managed by water companies and serve entire communities. According to the Brazilian Institute of Geography and Statistics [37,38] the estimated population of Uberaba City in 2019 was 333,783 people. The area is subdivided into 17 sub-basins and has a drainage net with approximately 454 first-order watercourses, and according to the 'Mineiro' Water Management Institute [39], the water is classified as class 2, favoring the use of these waters for public supply, in addition to other uses.

The climate of the region is classified as a semi-dry tropical type, with dry season during April to September and a rainy season from October to March, representing six months of drought [40]. Its average annual precipitation was 1659.3 mm in the period from 1979 to 2013, according to data from 'Instituto Nacional de Meteorologia do Ministério da Agricultura, Pecuária e Abastecimento' [41]. The greatest precipitation usually occurs from December to March with values ranging between 253.8 mm and 316.4 mm in March and January, respectively [42,43]. The average minimum and maximum monthly temperature for the same period (from 1979 to 2013) were 17.7 °C and 28.7 °C, respectively (Figure 2).

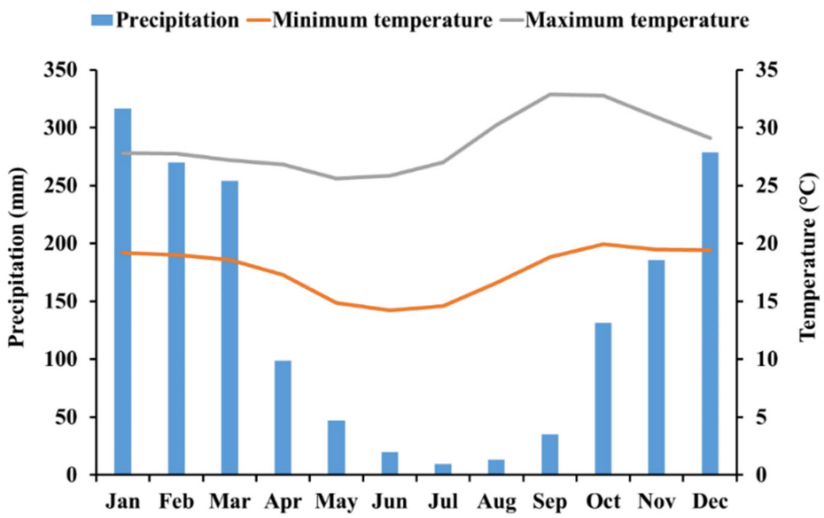

Figure 2. Average monthly precipitation and average minimum and maximum monthly temperature between 1979–2013 at the EPA of the Uberaba River.

The geology (A), soil (B), geomorphology (C), and land use (D) of the EPA at the Uberaba River basin are presented on Figure 3.

The geology is mainly in the northeast portion of the Paraná Sedimentary basin, under the geological features of the Central Plateau, formed by the Uberaba formation (k2bub), Marília formation (k2bm), and Serra Geral formation (k1 delta sg) (Figure 3A), [44–46]. The soil is formed by organic and inorganic compounds, formed by horizons and change according to climatic influences in a pedological differentiation concerning the source material and the pedogenetic processes [46–50]. The soils were identified in three types, as can be seen in Figure 3B: Red Latosol (Oxisols), Red Yellow Latosol, and Red Yellow Argisol [48]. The geomorphology of the EPA of the Uberaba River basin is characterized by four compartments, which are identified by the tops of the Pediplano, the headwaters, smooth–wavy surface with the convex top, and wavy surface with the sharp top [44–50] (Figure 3C), occupying 11.13%, 6.56%, 66.68%, and 15.63% of the area, respectively. The main land use of land cover are: agriculture, forestry (eucalyptus), natural landscape (native forest), mining, and urban areas (Figure 3D). Pasture for livestock is predominant, [51,52], and since the 1990s this activity has lost areas to agriculture, which has been gradually advancing in the region. The term agriculture was used for land cover type, "crops", and meant for cultivation or growing of certain vegetable species to produce food and energy, such as food crops (maize, rice), cash crops (sugarcane, cotton, oilseeds), plantation crops (coffee and rubber) and horticulture crops (fruits and vegetables).

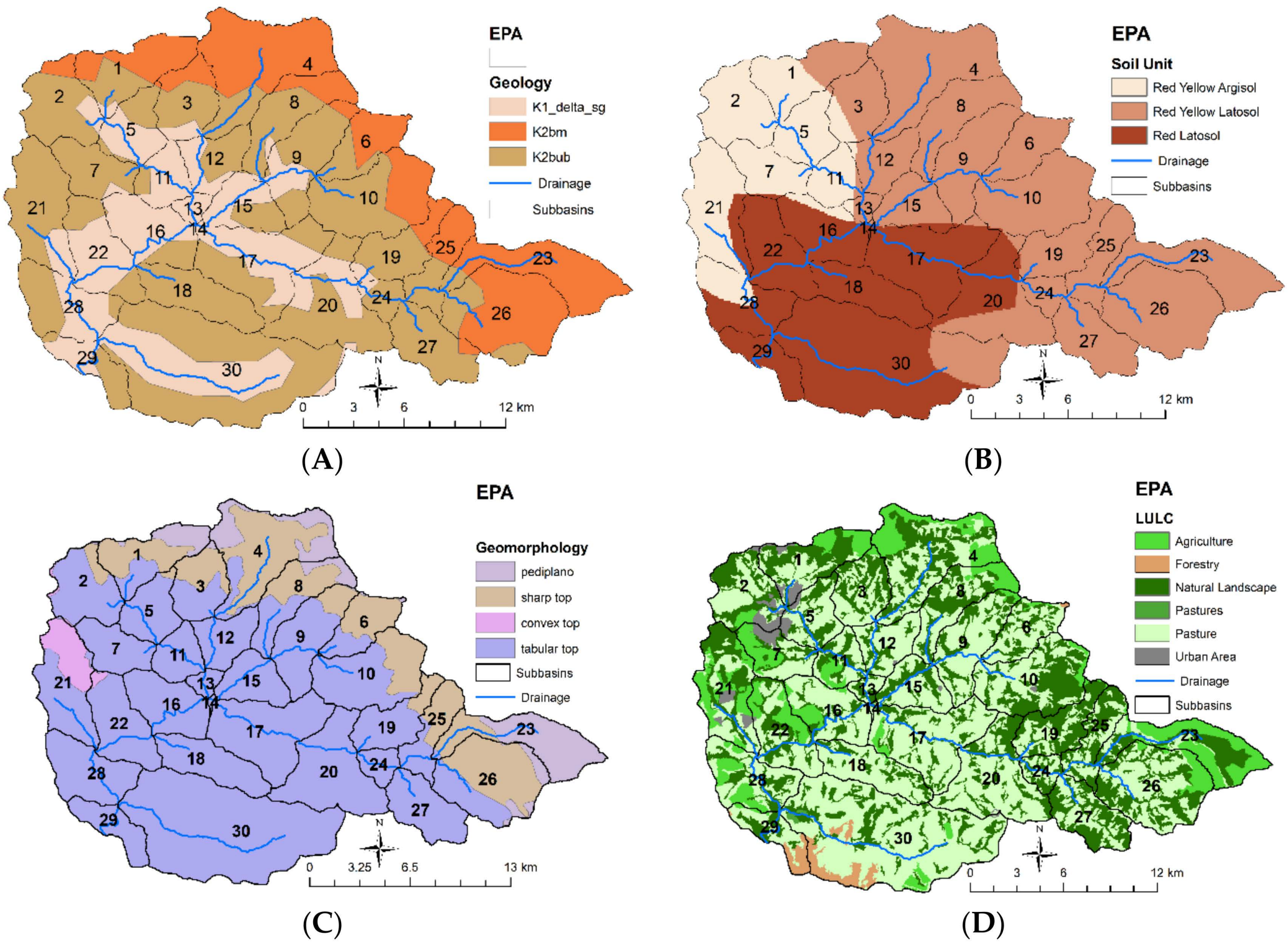

Figure 3. Geology (**A**), soil (**B**), geomorphology (**C**), and land use (**D**) at the EPA of Uberaba River. Source (**A**): The author, adapted from [44].

2.2. SWAT Model Data

The ArcSWAT model is an ArcGIS interface tool for soil and water assessment that is a physically-based continues-event hydrologic model developed by the USDA Agricultural Research Service (ARS) [53]. The setup working directory and geodatabases were created to store the parameters needed for SWAT model run. The EPA watershed and sub basins delineation was performed using the Digital Elevation Model (DEM) by Embrapa Relevo Project [54], interpolated to 20 m of spatial resolution converted to SIRGAS 2000, and the slope of the terrain were reclassified into four classes as flat (0–3%), smooth–wavy (3–8%), undulating (8–20%), and mountainous (20–45%) according to [48,49].

The stream definition function was made in the entire area by a watershed delineator method based in a discretization of the Basin areas into smaller increments, such as sub-basins [55–57]. The number of sub-basins created was 30, and each one possesses a geographic position in the watershed and is spatially related to one another. The drainage network, the stream juncture points, and the contours (divisors) of each sub-basin were displayed on the map of the Basin (Figure 3). The model incorporates regression equations to describe the relationship between the input and output variables [26].

The following soil classes are found in the basin Red Latosol, Red Yellow Latosol, and Red Yellow Argisol (Figure 3B). The vector files of the soil classes were prepared by

Embrapa on a scale of 1:250,000 and acquired from the IBGE database. The data of the tropical soil parameters were inserted into the SWAT database for each soil type.

The runoff volume, as SCS curve number procedure to runoff equation was an empirical model involving rainfall–runoff relationships from small rural watersheds across the U.S. [58]. The model provided a consistent basis for estimating the amounts of runoff under varying land use and soil types [48,49,58]. The retention parameter varies spatially, due to changes in soils, land use, management, and slope; and temporally, due to changes in soil water content.

Daily and monthly climatic data on precipitation, air temperature, relative humidity, wind speed, and solar radiation were obtained from the World Climate Data (USGS). The data were sampled by two automatic meteorological stations of the National Institute of Meteorology—INMET, located in the mesoregion of the Triângulo Mineiro—MG state, Brazil: Conceição das Alagoas meteorological station (A520), at an altitude of 573 m, and the Uberaba weather station (A568), at an altitude of 778 m. To calculate the evapotranspiration, the Penman–Monteith equation was used with monthly climatic data between 1979 and 2013.

The climatic data were precipitation (mm), minimum and maximum air temperature (°C), relative humidity (%), wind speed (ms^{-1}), and solar radiation (MJ/m^2 day). To analyze the climate data on the coefficient of variation, the Coefficient of Variation Classification methodology [59], described by Technical Norm No. 171 of November 1989, of the Institute for Forest Research and Studies (IPEF), was used. The climate in EPA of Uberaba River provides indications of the humidity and energy data that control water balance and determine the relative importance of the components of hydrological cycles [26]. To calculate the runoff, the SWAT uses a modified Soil Conservation Service Curve Number (SCS CN) methodology. The SCS CN is a function of the soil permeability, land use, and antecedent soil water conditions and is calculated by the cover, hydrologic soil group, land use, treatment or practice, and hydrologic condition A, B, C, and D [38].

The land use map was made by The Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas), from Brazilian 1985-2020 database, located at https://mapbiomas.org/en/project, accessed on 14 February 2020. Land use data were determined considering the coverage of the predominant rural area and the coverage of the urban area, considering the land uses described on [60,61], described in Table 1, and Figure 3D.

Table 1. Land use land cover at the EPA of the Uberaba River.

Symbol—Soil Use	Concept
AGRL—Agriculture	Both perennial and annual agriculture were considered in this class.
URMD—Urban	The region presents the expansion of the urban network, but this is still concentrated close to the water executory of the EPA of Uberaba River.
FRST—Natural Landscape	The term "FRST" was designed to natural native forest and permanent preservation areas.
UIDU—Mining	Mining activity is basalt mining.
PAST—Pasture	Land use predominant at the EPA of Uberaba River.
EUCA—Silviculture and/or exposed soil	The term "EUCA"was designed for forest farming in a woodland as Pine and Eucalyptus. Less predominant land use at the EPA of Uberaba River

To model purposes [60–66], the SWAT model divided the watershed into a sub-basin and, in turn, into the hydrologic response units (HRUs) [26]. Each HRU was a homogeneous unit that comprised the unique land cover, soil, and slope attributes.

The SWAT quantified the relative impacts of vegetation, soil, management, and climate change within each HRU. The output of the hydrological model (e.g., runoff, sediments, and nutrients) was calculated in each HRU and then summed to another HRU of the same sub-basin to compute the total loading from the sub-basin. The SWAT model was executed on a monthly basis with a warm-up period of 3 years (from 1979 to 1981) with the aim of (i) helping to minimize the model values for the initial hydrological conditions, and (ii) ensuring the establishment of basic flow conditions and hydrologic process equilibriums [24].

All LULC parameters were obtained from the SWAT database, excepted the BLAI (maximum leaf area index), GSi (canopy stomatal conductance), and OV_N (Manning coefficient for the soil surface) of the vegetation covers. These parameters were changed to better represent the tropical conditions (Table 2).

Table 2. Modified vegetation parameters as Maximum leaf area index (BLAI), Canopy stomatal conductance (GSi) and Manning's "*n*" for the surface (OV_N) from the SWAT model's database.

Vegetation Cover	BLAI (Maximum Leaf Area Index) ($m^2 \cdot m^{-2}$)	GSi (Canopy Stomatal Conductance) ($m \cdot s^{-1}$)	OV_N (Manning's "*n*" for the Surface) ($s \cdot m^{-1/3}$)
Native vegetation (Atlantic Forest)	7.5 [60]	0.033 [61]	0.3 [62]
Eucalyptus	4.0 [60]	0.01 [60]	0.17 [62]
Pasture	3.0 [63]	0.01 [64]	0.23 [65]
Agriculture	7.0 [63]	0.0095 [66]	0.14 [62]

The hydrological cycle is based on water balance equations [62,66] and the results provide, in addition to the physical description of the compartments, the total runoff value of the EPA of the Uberaba River sub-basins. When the rains fall, the drops are intercepted according to the morphometric characteristics of the vegetation cover. The redistribution component of the SWAT model uses a rainwater tracking technique to predict the flow of water entering the system on the hydrological cycle processes.

2.3. Model Calibration and Uncertainty Analysis

2.3.1. Calibration and Validation of Streamflow Data

For the calibration and validation of the SWAT model, we used streamflow data of the website of the National Water Agency [67], from the Uberaba fluviometric station, identified by code 61794000 corresponding to the point flow, under the coordinates 19°43′48″ S and 47°58′48″ W. This hydrometric station was located approximately 4.8 km from the mouth of the Uberaba River and was used for the calibration and validation of the SWAT model from 1982 to 1987 and 2006 to 2010, respectively. The discharge was calibrated at a monthly time step rather than a daily time step because, despite the precipitation being available at the daily scale, the observed streamflow had daily data with gaps but is complete and reliable at the monthly scale. Despite monthly water balance models not performing as well as daily water balance models in simulating monthly runoff, the research developed by [68,69] showed that monthly calibration is particularly valuable for applications where one is primarily interested in monthly, seasonal, and annual streamflow volumes, and is a viable alternative to daily calibration when no daily streamflow data are available. Finally, the monthly calibration has the advantage of making the calculation process faster, so it is possible to quickly carry out a large number of simulations for parameter sensitivity and uncertainty analyses [69,70].

2.3.2. Parameter Selection

Model calibration was focused on optimizing seven parameters, which were identified using the sensitivity analysis tool. This method combines Latin-Hypercube and one-factor-at-a-time sampling. The parameters are ranked according to their sensitivities and the first three parameters (GWQMN, EPCO, and GW_DELAY) had a significant influence on calibration ($p \leq 0.05$) (Table 3).

Table 3. The parameters used in the calibration procedure of streamflow between 1982 and 1987, in the Uberaba River basin. In the legend of methods, R is relative and V is the replacement value. The asterisk (*) represent the parameters statistically significant ($p \leq 0.05$).

Method and Parameter	Description	Units	Minimum Value	Maximum Value	Fitted Value
V_GWQMN.gw *	Flow threshold depth of water in shallow aquifer	mm	0	5000	357.676
V_EPCO.hru *	Plant uptake compensation factor	–	0	1	0.022
V_GW_DELAY.gw *	Groundwater delay	days	0	500	258.819
V_RCHRG_DP.gw	Flow deep aquifer percolation coefficient	–	0	1	0.247
R_CN2.mgt	Curve number for moisture condition II	–	−0.1	0.1	0.069
V_ESCO.hru	Soil evaporation compensation factor	–	0	1	0.943
V_ALPHA_BF.gw	Baseflow alpha factor	1/days	0	1	0.298

To calibrate the hydrological model, it was necessary to change the parameters that govern (i) the surface water processes, including the curve number (CN), (ii) both evapotranspiration and soil moisture including the parameters of the soil evaporation compensation factor (ESCO) and plant uptake compensation factor (EPCO), and (iii) the parameters that control the subsurface water processes, including the flow threshold depth of water in a shallow aquifer (GWQMN), groundwater delay (GW_DELAY), and deep aquifer percolation fraction (RCHRG_DP), and Baseflow alpha factor (ALPHA_BF) [55–72].

The CN2 parameter was raised during calibration, which has the effect of increasing the amount of surface runoff generated from rainfall. The ESCO parameter remained close to the maximum value (0.943) meaning that the predicted streamflow values became closer to the observed streamflow when the ESCO value was at its maximum. This parameter controlled the soil evaporative demand that was to be met from different depths of the soil [70]. Thus, raising the ESCO value decreased the soil depth to which SWAT can satisfy potential soil evaporative demand [69–71], thus decreasing soil evaporation and ET and increasing total water yield, streamflow, and baseflow [71,72]. In turn, the EPCO parameter was lowered (0.022) because the water uptake demand for plants was met by higher layers in the soil. This way, less water was transferred from the lower layers in the soil to atmosphere through evapotranspiration [24–28].

The shallow aquifer contributed baseflow to the main channel or reached within the sub-basin. Baseflow was allowed to enter the reach only if the amount of water stored in the shallow aquifer exceeded a threshold value specified by the user which was defined by GWQMN parameter [73]. For a low value of GWQMN, SWAT produced more base flow. The effect of this parameter on baseflow influenced the streamflow as well [72]. The low value of GWQMN (357 mm) corresponded to high streamflow, which was in accordance with observed streamflow values. The ALPHA BF described the rate at which groundwater entered a stream. The approximate value of 0.3 was estimated in this study. Compared with commonly used values, which range from 0.3 to 1 [74], the baseflow recession constant of 0.3 was small, suggesting slow drainage and major storage in shallow aquifers. To adjust the baseflow, it was also necessary to raise the value of GW_DELAY, i.e., increase the time delay between water exiting the soil profile and entering the shallow aquifer (about 260 days). Indeed, this value can be considered reasonable because the soils present in the catchment are deep and have Red-Yellow Argisol (PVA) which is characterized by low hydraulic conductivity. Finally, for an optimal model, adjustment was necessary to increase the deep percolation (RCHRG_DP = 0.247). The RCHRG_DP is a fraction of the total daily re-charge that can be routed to the deep aquifer. The amount of water moving from the shallow aquifer due to percolation into the deep aquifer was correlated to the aquifer percolation coefficient, i.e., the amount of recharge entering both aquifers [62,73].

2.3.3. The SUFI-2 Procedure and the Statistical Evaluation Criteria

The Sequential Uncertainty Fitting (SUFI-2) routine, which is linked to SWAT under the platform of SWAT Calibration and Uncertainty Programs (SWAT-CUP) 2012 [75], was used to model the calibration and estimation of both parameter and predictive uncertainty at the EPA of the Uberaba River basin. SWAT-CUP 2012 is a standalone computer program developed for calibration and validation of SWAT model [75] and SUFI-2 is acknowledged as a powerful tool for making calibration and uncertainty analysis of the SWAT model [75–77]. In SUFI-2, parameter uncertainty is reported using a multivariate uniform distribution in a parameter hypercube, while the model output uncertainty is derived from the cumulative distribution of the output variables [77,78].

The objective function selected as the calibrated parameter set was the Nash–Sutcliffe Efficiency (NSE). It was also used as the coefficient of determination (R2) and the percent bias (PBIAS) and standardized RMSE (RSR) to assess the model performance. The NSE is commonly used for reflecting the overall fit of a hydrograph because it is very sensitive to high extreme values (due to the squared differences) [24,66]. NSE values vary from $-\infty$ to 1, with a value of 1 indicating that the simulated and observed discharge data are perfectly matched. This way, NSE values greater than 0.5 means that the model is appropriate and good for the simulation of maximum streamflow [79]. The goodness-of-fit indicator, R2, describes the proportion of the variance in measured data explained by the model. R2 ranges from 0 to 1, with higher values indicating less error variance. This indicator has been widely used for model evaluation, and values granter than 0.5 and 0.75 have been considered satisfactory and very good performance of the model, respectively [78].

The PBIAS values indicate the deviations between the mean simulated and observed streamflow, expressed as a percentage. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. A positive value of PBIAS indicates an underestimation bias while a negative value indicates an overestimation one [75,79]. The RSR is the ratio of the root mean square error (RMSE) to the standard deviation of measured data (STDEVobs). The RSR varies from 0 to a large positive value. The optimal value is 0 which indicates zero RMSE or residual variation and therefore perfect model simulation [79]). In general, these goodness-of-fit indicators are considered satisfactory whenever R2 and NS are greater than 0.5, RSR less than 0.7 and PBIAS ranges between less than $\pm$25% for the streamflow [79,80].

2.4. *Afforestation and Pasture Scenarios*

The land use scenarios were selected in order to verify the phenomena of replacement of land occupation in natural landscapes. Anthropogenic actions contribute to the degradation of natural resources, including water resources. Originally created by Law 6902/1981, environmental protection areas are now regulated by Law 9.985/00, the National System of Nature Conservation Units (SNUC). The EPA can be established in areas of public or private domain, by the Union, States, or municipalities, without the need for expropriation of private lands. The status of the EPA is an area for protection and conservation of the sustainable land use category as the law allows for human occupation and sustainable production. Therefore, there was not yet an orderly human occupation of the area and the sustainable use of its natural resources.

The activities and uses developed in these areas are subject to specific rules and the owner must establish the conditions for research and public visitation, subject to legal requirements and restrictions. To evaluate the hydrological response to land use changes at the EPA of the Uberaba River basin, two scenarios were considered. Forest Scenario supposes that all current PAST and AGRL will be changed to FRST representing a 97% increase in FRST area over the entire catchment.

The scenarios of the land uses changed from 32.6% to 97.1%—forest or 53.3% to 97.1%—pastures, and the areas were investigated to better understand the environmental conditions or watershed potential as the land use modifies to pasture or crops scenarios.

Pasture Scenario supposes that all current FRSE and AGRL will be converted to PAST, representing a 97% increase in PAST area over the entire catchment. Meanwhile, the rest of the land covers, Residential-Medium Density (URMD), Industrial (UIDU), and Eucalyptus (EUCA), will remain unchanged.

The scenarios were chosen due to the link between process studies of hydric balance change and impact assessments to analyze the indication of what the future might achievably be like. At the EPA, the land uses are changed in environmental systems of watershed from natural landscape transformed in pasture lands emphasizing the functional role of land for economic activities.

The study will show basic assumptions to ensuring sustainable conditions and might also trigger feedback to the system and vulnerability conditions, such as the forest management nexus in the EPA versus pasture consequences on water resources. These two land use change scenarios (i.e., afforestation and pasture) were based on present land use conditions and potential future land use. The percentage areas of the current land use and the change scenarios are shown in Figure 4.

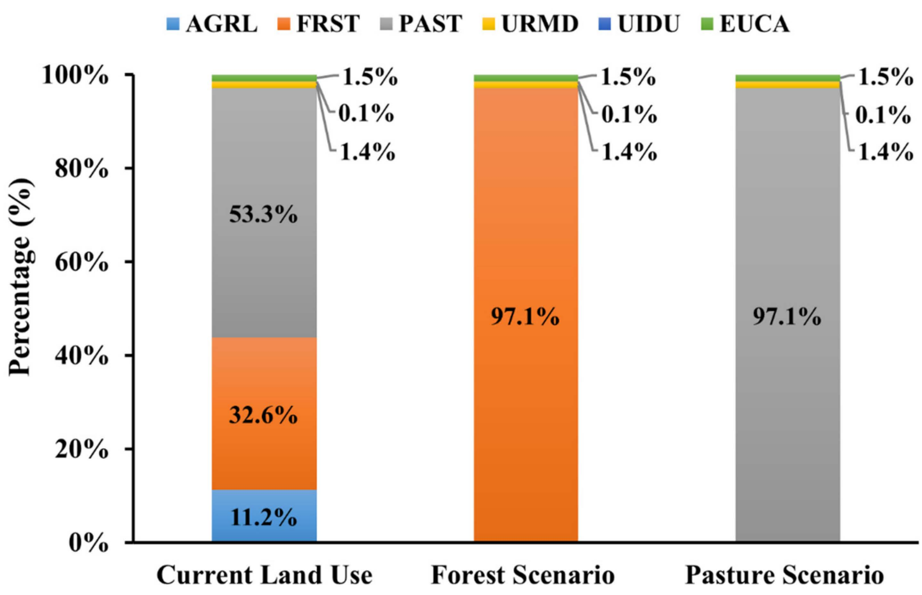

Figure 4. Land use proportions for current land use and the scenarios of forest and pasture in the Uberaba River basin. In the forest scenario, Agricultural Land-Generic (AGRL) and Pasture (PAST) change to Forest-Mixed (FRST), and in the pasture scenario, Agricultural Land-Generic (AGRL) and forest-evergreen (FRSE) change to Pasture (PAST). Legend: Residential-Medium Density (URMD), Industrial (UIDU) and Eucalyptus (EUCA).

3. Results

3.1. Calibration and Validation of the Streamflow

The streamflow was calibrated to a 5-year period (1982–1987) and validated to a 4-year period (2006–2010), both monthly. Figure 5 shows the agreement between the observed and the simulated streamflow for both calibration and validation periods. The visual analysis of the simulated hydrograph reproduced the measured discharge reasonably well and closely replicated the temporal variation, as well as the mean monthly precipitation. Table 4 depicts the goodness-of-fit indicators for the streamflow calibration and validation based on the NSE, R^2, PBIAS, and RSR. The goodness-of-fit indicators for the streamflow show good and very good performance of the model in both calibration and validation. The analysis of the NSE values is 0.82 (very good) and 0.70 (good) for both calibration and validation respectively. The R^2 shows good and very good performance of the model with values of 0.85 and 0.72 for calibration and validation, respectively [78]. The PBIAS values indicate some deviations between the mean simulated and observed streamflow. In calibration, it shows an underestimation of 12% of simulated streamflow, and in validation a slight overestimation in 4% of cases. These values mean that the performance of the SWAT model in estimating the mean streamflow is satisfactory and very good in both calibration and validation, respectively (Figure 5) [79]. The analysis of the RSR shows values of 0.42 (very good) and 0.55 (good) for calibration and validation, respectively [79].

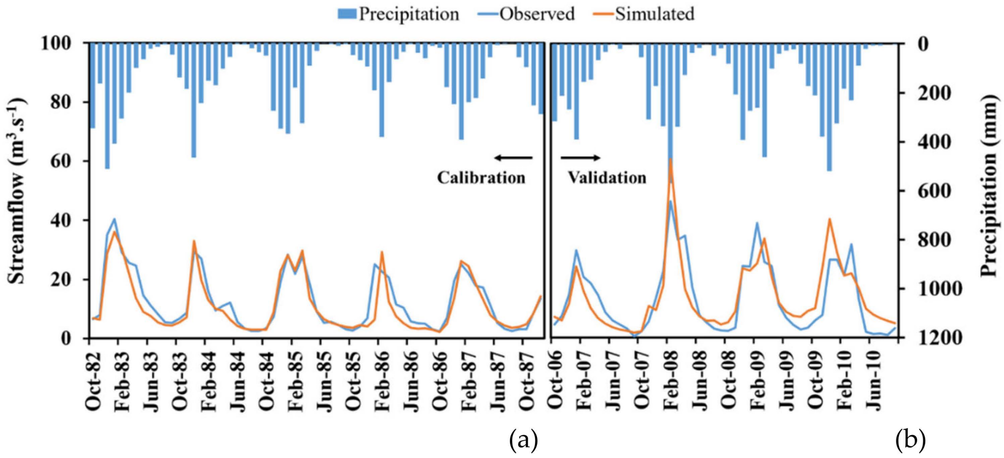

Figure 5. Comparison of observed and simulated monthly streamflow during (**a**) the calibration (between 1982 and 1987); and (**b**) validation (between 2006 and 2010) in the Uberaba River basin.

Table 4. Goodness-of-fit indicators for monthly calibration between 1982 and 1987 and the validation of streamflow between 2006 and 2010 in the Uberaba River basin.

Measures	Values	Acceptable Ranges
Calibration		
NSE (Nash–Sutcliffe Efficiency)	0.82	≥0.75 very good
R^2 (Coefficient of determination)	0.85	≥0.75 very good
PBIAS	11.9%	±10–±15 good
RSR (Standardized RMSE)	0.42	≤0.5 very good
Validation		
NSE (Nash–Sutcliffe Efficiency)	0.70	0.65–0.75 good
R^2 (Coefficient of determination)	0.72	0.65–0.75 good
PBIAS	−4%	≤±10 very good
RSR (Standardized RMSE)	0.55	0.5–0.6 good

3.2. Water Balance of the Current Land Use

The water balance of the Uberaba River basin is presented in Table 5. The streamflow and actual evapotranspiration (ET) represented 44% and 51% of the precipitation respectively and the remaining 5% percolate to the deep aquifer. The largest amount of water that reaches the river comes from the lateral flow (48%), and the remaining flow is from the surface and groundwater with 25% and 27%, respectively (Table 5). Figure 6 shows the spatial distribution (in each sub-basin) of surface runoff (SURQ), lateral runoff (LATQ), and groundwater (GWQ) in the current land use. The values of flow components are expressed in mm and are an average annual between 1982 and 2013 in the Uberaba River basin. The spatial distribution of flow components in the catchment is very uneven, i.e., the average annual of surface flow was greater in the western sub-basins (>300 mm/year), while the lateral flow is major in the eastern and northern sub-basins (>450 mm/year) and the groundwater flow is higher in the southern sub-basins (>300 mm/year).

Table 5. Water balance ratios simulated by SWAT between 1982 and 2013 with current land use of the Uberaba River basin.

Water Balance Ratios	Current Land Use
Streamflow/Precipitation	0.44
Surface runoff/Total flow	0.25
Lateral flow/Total flow	0.48
Groundwater flow/Total flow	0.27
Percolation/Precipitation	0.16
Deep recharge/Precipitation	0.04
Evapotranspiration/Precipitation	0.51

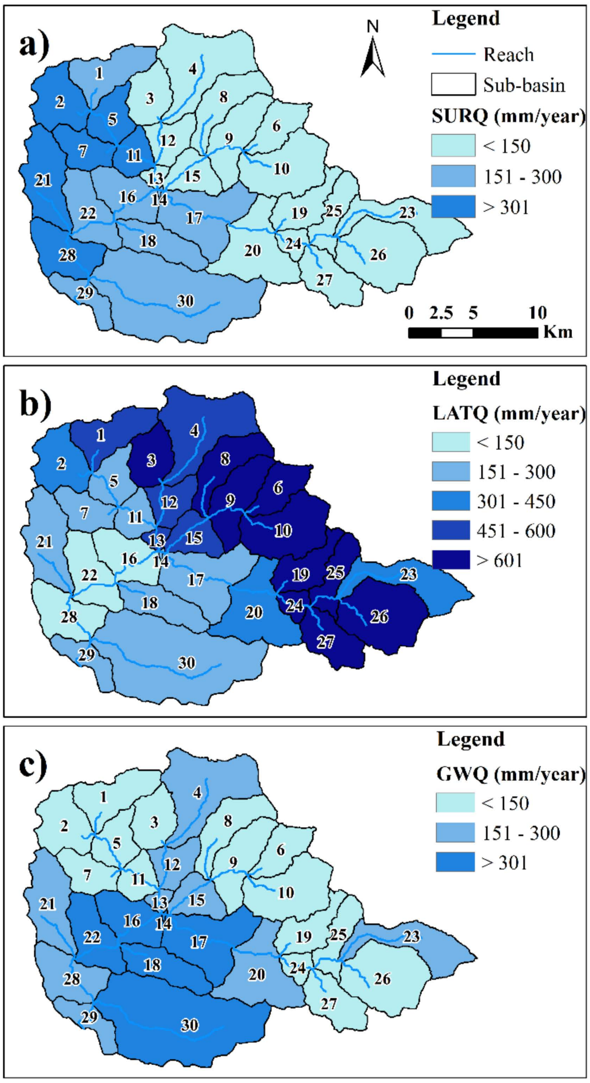

Figure 6. SWAT output maps of the surface flow (**a**); the lateral flow (**b**); and the groundwater flow (**c**). The values are expressed in mm per year between 1982 and 2013 with current land use of the Uberaba River basin.

3.3. The Current Land Use, and Forest and Pasture Scenarios

The calibrated SWAT model was applied to simulate the monthly SURQ, LATQ, GWQ, total runoff, ET, and soil water (SW) under the current land use, and the scenarios of forest and pasture (Figure 7). The results show that all components of water balance presented monthly variations, with values generally greater between December and May, which corresponds to the wet season (Summer and Autumn), and minor values between June and November, which corresponds to the dry season (Winter and Spring) (Figure 7). The monthly SURQ of the forest scenario was the component that showed high differences under land-use scenarios, with the most changes occurring during the wet season from December to May. Less remarkable changes were observed in other components of water balance in the forest scenario, and all components in the pasture scenario (Figure 7). Table 6 summarizes the average annual values of current land use, and the average annual values change and percentage change of both scenarios for the same components analyzed in Figure 7. The 64.5% increase in FRSE area led to a decrease of 71.1 mm (45.3%) in the surface runoff, 11 mm (4.8%) in total runoff, and 48.5 mm (7.1%) in soil water; and an increase of 21 mm (5.7%) in lateral flow, 17.1 mm (2.6%) in groundwater, and 23.2 mm (2.9%) in evapotranspiration (Table 6). The 43.8% increase in PAST area led to an increase of 1 mm (3%) in surface flow, 2.1 mm (2%) in groundwater, 2.5 mm (0.2%) in evapotranspiration, and 48.3 mm (6.8%) in soil water; and a decrease of 5.4 mm (1.5%) in lateral flow and 0.8 mm (0.6%) in total runoff.

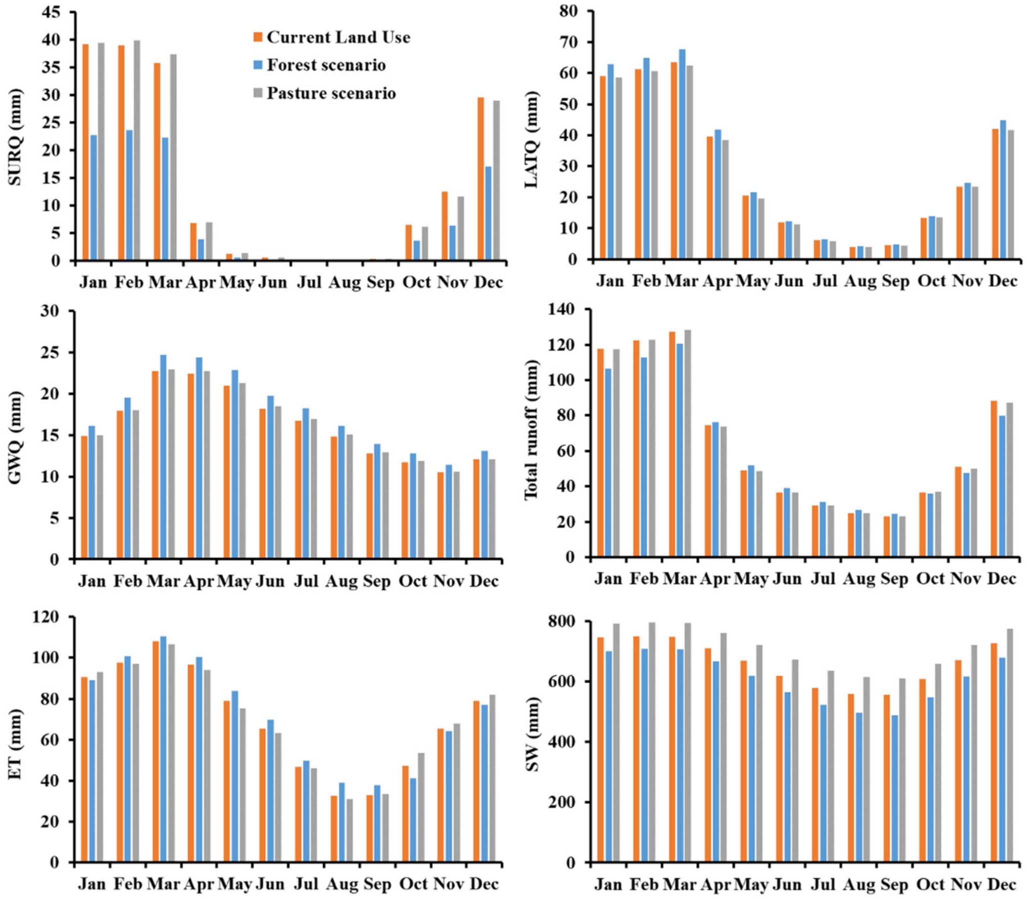

Figure 7. Monthly surface runoff (SURQ), lateral runoff (LATQ), groundwater (GWQ), water yield, actual evapotranspiration (ET), and soil water (SW) using calibrated SWAT model in current land use and the forest and pasture scenarios. The data are between 1982 and 2013 of the Uberaba River basin.

Figure 8 shows the spatial distribution (in each sub-basin) and annual average of total runoff and GWQ in current land use, and the changes under forest and pasture scenarios. The spatial distribution of total runoff and GWQ in current land use is distinct. While the total runoff is greater in the northern sub-basins (>790 mm), the GWQ is higher in the southern sub-basins (>230 mm) (Figure 8a,d). In the forest scenario, the decreased total runoff observed in Figure 8b and Table 6 is found evenly distributed across the basin, being that most sub-basins show between −20 and −40 mm. The increase of GWQ observed in Figure 8e and Table 6 is found in the western and southern sub-basins (until 60 mm).

Contrarily, in the northern sub-basins we detected a decrease until −20 mm of GWQ. In the pasture scenario, the decreased total runoff observed in Figure 8c and Table 6 only occurred in the western and some northern sub-basins (until −32 mm); in the remaining sub-basis we observed an increase (until 22 mm). Contrary to total runoff, the GWQs observed in Figure 8 and Table 6 increase, but the spatial distribution shows that the increase only occurs in the northern sub-basins (until 21 mm), while in the southern sub-basins we observed a decrease (until −21 mm).

Table 6. The average annual values of current land use and the average annual values change and percentage change of both scenarios (Forest and Pasture) for the components: surface runoff (SURQ), lateral runoff (LATQ), groundwater (GWQ), total runoff, evapotranspiration (ET), and soil water (SW). The data are between 1982 and 2013 of the Uberaba River basin.

Current Land Use/Scenarios	SURQ	LATQ	GWQ	Total Runoff	ET	SW
Current land use						
Value (mm)	171.92	349.03	195.95	238.97	840.79	726.61
Forest scenario						
Value (mm)	100.84	370.01	213.03	227.96	863.99	678.09
Value change (mm)	−71.08	20.97	17.08	−11.01	23.20	−48.52
Percentage change (%)	−45.27	5.68	2.56	−4.77	2.88	−7.05
Pasture scenario						
Value (mm)	172.94	343.60	198.03	238.19	843.32	774.94
Value change (mm)	1.02	−5.44	2.08	−0.78	2.53	48.33
Percentage change (%)	−3.01	−1.45	1.97	−0.57	0.21	6.84

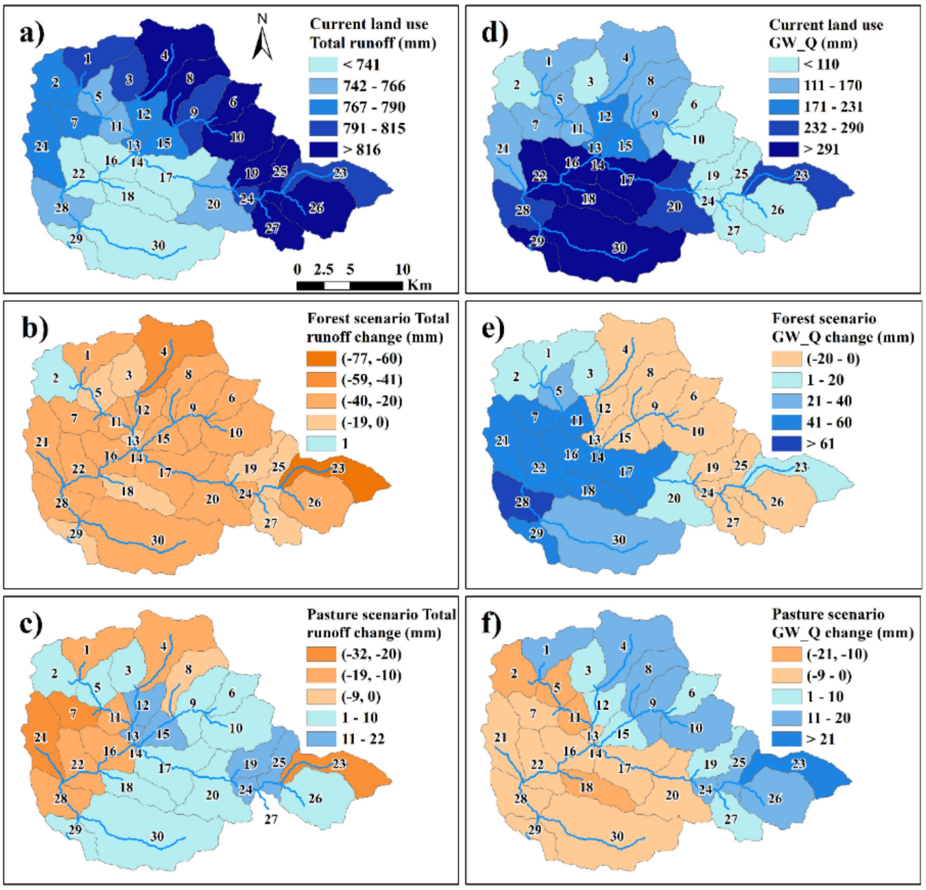

Figure 8. Spatial distribution of the average annual total runoff (mm) (**a**–**c**) and groundwater flow (GW_Q) (mm) (**d**–**f**) under current land use (**a**,**d**), in forest (**b**,**e**) and pasture (**c**,**f**) scenarios. The values are expressed in mm and are an average annual between 1982 and 2013 of the Uberaba River basin.

4. Discussion

4.1. Limitations of the Simulation

Although calibration results are considered good, there are some factors that compromise the model performance. In this work, the two factors that seem to most influence the flow estimation are the rain gauge density and the accuracy of the hydrometric gauges. The performance of hydrological modeling depends largely on the quality of the rainfall data and the density of rain gauges. The authors of [80,81] analyzed the effect of the high variability in rainfall on the uncertainty of the calibrated model, and they suggest that the high variability in rainfall can be attributed to the low rain gauge density. In fact, the density of the rainfall input data contributes significantly to the level of uncertainty in the simulated streamflow because as the variability in rainfall increases, the uncertainty of calibrated model also increases. Thus, reducing the variability in rainfall input data and accurately estimating the rainfall data used for calibrating the model could lead to a significant improvement in simulated streamflow thereby reducing the level of uncertainty of the model. In addition, this low density difficultly represents the orographic effect on the precipitation, i.e., some climate stations are within lower altitude values and consequently cannot represent the orographic effect on the precipitation rates. In the study area, the rain gauges are located at an altitude of 573 and 778 m, i.e., in valleys, within the orographic "shadow" of the surrounding mountains that reach 1043 m of altitude.

4.2. Water Balance Analysis

The spatial distribution of the surface flow, lateral flow, and groundwater flow in current land use are not equal in the entire basin and their variability has different sources. The spatial distribution of the surface flow is similar to the soil type map (Figure 3c), while the lateral flow represents the different slopes that occur in the basin, and the groundwater represents both the soil type and slope. Indeed, the higher surface flow in the western sub-basins of the catchment occurs under Red-Yellow Argisol (PVA). This soil has poor aeration during the rainy season due to low hydraulic conductivity at the top of the Bt horizon, resulting in high surface runoff and high erodibility [82]. Meanwhile, in the southern and northern/eastern sub-basins there is Red Latosol (LV) and Red-Yellow Latosol (LVA), respectively. These soils are characterized by good internal drainage that is attributed to their great porosity. As a whole, they have low erodibility associated with low flow potential superficial [82].

The spatial distribution of lateral flow is a faithful representation of the slope, being that it is greater in the eastern and northern sub-basins of the catchment where it is a predominantly steep slope. Indeed, the slope has an important role in streamflow and sediment yield. Several authors, in their works, also obtained the similar results [83,84]. Ref. [83] using the SWAT in the Upper Danube Basin (which covers about 132,000 km^2 across Austria, Germany, Czech Republic, and Slovakia) showed that default hillslope length (the SWAT method) resulted in large overestimations of lateral flow. In addition, [84] reported that the SWAT for the calculation of lateral flow velocity, in HRUs, overestimates the amount of lateral flow in steep slopes. The same authors argue that the SWAT also drives an increasing underestimation of surface runoff in increasing slope gradients.

The spatial distribution of groundwater flow reflects the soil type in the southern and western sub-basins and the slope in the eastern and northern sub-basins of the catchment. In the southern sub-basins, the major groundwater flow is associated with Red Latosol due to its good internal drainage. In the eastern and northern sub-basins, the lower groundwater flow is associated with a steep slope. Indeed, the higher lateral flow drives a decrease in the amount of soil water that is available for percolation to the groundwater. This observation can explain the lower groundwater flow in steep slope sub-basins. The same results were obtained by the authors [83,84].

In the EPA of the Uberaba River basin, the streamflow and ET represented 44% and 51% of the precipitation, respectively (Table 5). These values are different from work developed by [66] in Atlantic Forest of the Pomba River basin, located in Minas Gerais state and Rio de Janeiro states. They performed tests on water balance in SWAT and the values of ET were 69% and 63% for calibration and validation respectively, and 27% and 30% for calibration and validation of the streamflow, respectively. In addition, the percentage of water that reaches the river by surface, lateral, and groundwater flows were different. They presented a similar percentage of lateral and groundwater flows, between 46% and 48% for calibration and validation. They obtained 6% of the streamflow from the surface flow for calibration and validation against 25% in the EPA of the Uberaba River basin and the opposite for groundwater flow, with approximately 48% in the Pomba River Basin against 27% in the EPA. Only the lateral flow presented an equal percentage near 48% in both basins. The differences between both basins can be due to major area of forest and eucalyptus in the Pomba River basin that leads to an increase of infiltration and consequently less surface flow and major ET. In addition, the Red-Yellow Latosol with good internal drainage as dominant type soil in Pomba River basin contributed to less surface flow.

The uncertainties represent limitations for decision making with respect to the mitigation of impacts, based on a paradigm of optimization. Nevertheless, the rural farmers need the integration of knowledge that they consider the multiple stressors that condition the environment of decision of the EPA. Application of exploratory analysis, which consider multiples scenarios, systematically explores the implications of a wide range of hydrological conditions and policies [5–11].

4.3. Components of the Water Balance of the Current Land Use Forest and Pasture Scenarios

The Uberaba River basin is inserted in a summer rainfall-dominant region, that occurs between December and May, and a predominantly dry winter that occurs between June and November (Figure 8). This inter-annual distribution of rainfall is well represented by the monthly variations in SURQ, LATQ, GWQ, total runoff, ET, and SW simulated by SWAT in the current land use. In addition, the changes under forest and pasture scenarios differed across months. The greater changes occurred during the wet season (December–May) and the SURQ, LATQ, GWQ, and total runoff were the components that best represented these changes. In the forest scenario, a decrease of the surface flow, total runoff, and soil water, and an increase of the lateral flow, groundwater flow, and evapotranspiration were observed. Between all components, the surface flow presented the major percentage change (average of −45%) at annual time scales (Table 6).

The increases of infiltration were due to increases in soil organic matter improved by the forest. Indeed, the increase in the lateral flow and groundwater flow, in the study area, indicates that the Atlantic Forest contributes to an increase of water infiltration into the soil. The results showed that the increase of infiltration does not necessarily drive the increases in total runoff and soil water: on the contrary, they decreased. This occurs because trees with their deep root systems can extract more water from shallow aquifer storage, and, can transpire more due to larger leaf area [85–87]. However, the effect of the vegetation cover on soil moisture content is still questionable. This is because if it is true that the increase of vegetation cover increases the transpiration loss and the rainfall interception, it also triggers the decreases of evaporation loss through shading. This way, the shading of canopy vegetation reduces the direct radiation absorption, leading to lower soil temperature and soil evaporation rates, followed by greater soil moisture [88]. The same authors argue that the effect of vegetation cover on the soil water content may be due to climate and the length of dry or wet periods.

The EPA of the Uberaba River Basin protected area was created by the local municipal government with the main goal of bringing environmental benefits to Uberaba's society. Concerning preservation policy, the local actors established a unit of conservation within an economic interest as agricultural and livestock production systems, following the Brazilian Forest Code to land use regulation in rural estate properties and the improvement of policies on economic and ecological zoning (ZEE) [29].

The water environmental interests should have strong incentives to seek better management at the EPA of the Uberaba River Basin. This study also shows a way of looking at the effect of land use change in watersheds on the volume of water available, as a subsidy to payments for ecosystem services (PES) system, that can come about with the establishment of catchments on springs, and the hydrological benefits that will come from productive pasture potential of land to be changed into forest land with more biodiversity and hydrological functioning. Those incentives should encourage groups of rural producers to adopt policy platforms and lobbying strategies that can improve the environmental soil and water sustainability. The environmental interests of land use, land changes, and the preservation of natural lands may benefit from at least some of the owners of rural properties over conservation units for preserving the natural ecosystem in a biological function. The social and economic functions of the land are stronger when the land is used. The government should create a protected area seeking the needs of major local production systems as main industries and subnational efforts to reconcile competing interest yields on average weaker environmental policy at a local level of government. The creation of payment for environmental service policies need to consider the water production in each area along rivers and springs along with the areas that must be preserved by the Brazilian Forest Code. The PES schemes are relatively new and policies are needed to support positive environmental externalities through the transfer of financial resources from beneficiaries of certain environmental services to those who provide these services or are fiduciaries of environmental resources. The area of the EPA of the Uberaba River Basin is a perfect area to start those policies to benefit local rural producers and water uses in the Uberaba municipality which, according to data from the Brazilian Institute of Geography and Statistics (IBGE), has approximately 337,000 inhabitants.

5. Conclusions

The hydrological discharge of headwater sub-basins showed space–time variation in magnitude on the 30 sub-basins at EPA of the Uberaba River basin. The SWAT-T model was used to analyze the hydrological sensitivity of a tropical catchment in Minas Gerais state, Brazil. To better represent the vegetation types for tropical areas, the parameters BLAI, GSi, and OV_N were changed. After that, we created land use changes on forest and pasture scenarios.

The land use changes on forest and pasture scenarios showed that all components of water balance presented monthly variations. The greater changes occurred during the wet season (December–May) in the monthly SURQ of the forest scenario. The results showed that a 64.5% increase of FRSE area led to a decrease of 71.1 mm in surface runoff, 11 mm in total runoff, and 48.5 mm in soil water; and an increase of 21 mm in lateral flow, 17.1 mm in groundwater, and 23.2 mm in evapotranspiration. The 43.8% increase in PAST area led to an increase of 1 mm in surface flow, 2.1 mm in groundwater, 2.5 mm in evapotranspiration, and 48.3 mm in soil water; and a decrease of 5.4 mm in lateral flow and 0.8 mm in total runoff.

The hydrological model indicated the main areas of spatial optimal water flow. Considering economic values, those areas should encourage the government's policy of incentive platforms that can improve environmental soil and water sustainability. The creation of payment for environmental service (PES) policies should consider the water production and the areas further along with the areas that must be preserved by the Brazilian Forest Code and the Conservation Units should be an environmental protection area to hydrological economic interests. Furthermore, the methodology employed in this study can be further applied to other tropical catchments for LULC impact assessments on water resources.

Information processing models suggest that a variety of scenario characteristics may affect watershed ecosystems in hypothetical testing scenarios in ways that can influence the degree to which a landowner engages with and carefully considers information about the land uses of pasture and forest. Examinations of the SWAT Processing Model suggest that details underscoring the importance of and accountability for a land use decision lead to the application of better management practice on rural lands. For example, hypothetical scenarios of pasture and forest might include information linking the hydrological cycle to a sub-basin unit, thereby increasing the sustainability management of forest and forest livestock will be a better choice for management practices. The management of forest and pasture areas and the accountability of a better land use policy are important to consider, as they are more likely to naturally occur in a watershed ecosystem, as opposed to hypothetical scenarios where the influence of forest and pasture are often absent.

Author Contributions: Conceptualization, M.S.d.M.M., T.C.T.P. and C.A.V.; methodology, T.C.T.P. and R.M.B.S.; software, L.F.S.F., T.C.T.P. and R.M.B.S.; validation, T.C.T.P. and R.M.B.S.; formal analysis, F.A.L.P., T.C.T.P. and M.Z.; investigation, M.S.d.M.M., T.C.T.P. and C.A.V.; resources, M.S.d.M.M. and T.C.T.P.; data curation, M.S.d.M.M., T.C.T.P. and R.M.B.S.; writing—original draft preparation, M.S.d.M.M., T.C.T.P., R.M.B.S., M.Z. and T.C.T.P.; writing—review and editing, F.A.L.P., M.S.d.M.M., V.L.A., T.C.T.P. and R.M.B.S.; visualization, F.A.L.P. supervision, T.C.T.P. and L.F.S.F.; project administration, T.C.T.P. and L.F.S.F.; funding acquisition, M.S.d.M.M., T.C.T.P. and L.F.S.F. All authors have read and agreed to the published version of the manuscript.

Funding: The present study was carried out within the framework of the Post Graduation Research Program of 'Coordenação de Aperfeiçoamento de Pessoal de Nível Superior' (CAPES); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Agência do Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC); and Land Use Policy Brazilian Group (PolUS). For the author integrated in the CITAB Research Centre, the research was further financed by the FEDER/COMPETE/POCI—Operational Competitiveness and Internationalization Program, under Project POCI-01-0145-FEDER-006958, and by the National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UIDB/AGR/04033/2020. For the author integrated in the CQVR, the research was further financed by National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UIDB/QUI/00616/2020.

Institutional Review Board Statement: Not applicable. The study was conducted not involving humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank: the Coordination of Improvement of Higher Education Personnel (CAPES) for the scholarship; the National Council for Scientific and Technological Development (CNPq) for Research funds; the Agronomy (Soil Science) Post-Graduation Program from School of Agricultural and Veterinary Sciences, São Paulo State University (UNESP); The Land Use Policy Research Group—PolUS; the Federal Institute of Education, Science and Technology of 'Triângulo Mineiro' region (IFTM).

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

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A New Approach to Use Load Duration Curves to Evaluate Water Quality: A Study in the Doce River Basin, Brazil

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Received: 19 February 2020; Accepted: 10 March 2020; Published: 14 March 2020

Abstract: Although water availability depends both on qualitative and quantitative aspects, most studies focus only on one of these. Therefore, the goal here is to relate water quality and quantity with the construction of Load Duration Curves (LDC) and to estimate *E. coli* load patterns in different flow conditions, seasons, and positions of two sub-basins of the Doce watershed (Brazil): Piracicaba and Piranga. A novel methodology is proposed in which the Burr XII distribution is adjusted to the LDC to compare all observed loads to their respective Total Maximum Daily Load (TMDL), allowing the estimation of the relative difference (RD) between these. Higher values of RD were observed for low flows for the Piracicaba basin, more urbanized, where point sources of pollution are the primary concern, reaching up to 99% of needed load reduction. In the Piranga basin, more agricultural, there was a broader RD variation, from 9% to 97% load reduction needed, which is an evidence of point sources of pollution combined with non-point sources. The new methodology can be used to estimate the load reduction of any pollutant and can be used by environmental agencies to identify effective practices to minimize and control pollution in different locations of the basins.

Keywords: water quality; water quality management; TMDL; *E. coli*

1. Introduction

Water availability depends on the quantitative and qualitative assessments of this resource. Therefore, to ensure a sustainable future, these evaluations must be taken altogether. Nevertheless, in spite of this pre-requisite, most studies only cover the quantification and/or prevision of streamflow [1,2] or the characterization and/or modeling of water quality [3–5].

Watershed models consist of tools that can be used to assess water quantity and quality simultaneously. However, these approaches often require a diversity of input data and information to run, which can be viewed as a limitation for their use in the developing countries where data is fragmented, uncertain, and barely available [6–9]. The limited portability of watershed models can be overcome by simpler quantity-quality methods, which are less dependent on flow and transport equations and their adjustment parameters, such as Load Duration Curves (LDC).

An LDC is a graphical representation of water quality, namely observed and total maximum daily loads. The TMDL is an upper threshold of a predefined water quality criterion. For example, the TMDL for *Escherichia coli* (*E. coli*) can be computed considering a concentration of 1000 MPN dL^{-1} (Most Probable Number) for most Brazilian rivers, according to the Environment National Council

(CONAMA), which is multiplied by the Flow Duration Curve (FDC) of any given gauge. The setup of LDCs for observed and total maximum daily loads requires the existence of streamflow gauges close or in the same location of water quality gauges because it depends on the generation of the FDC. Thus, when observed loads are plotted with their respective TMDL curve, it is possible to understand the water quality standard, being in conformity when the observations are plotted below the TMDL curve.

The advantage of using LDCs instead of watershed models relies on their capability to make evident the links between streamflow conditions and the expected water quality. In the sequel, the use of LDCs can help to implement more successful efforts to improve water quality in the catchment, especially in the cases where flow regimes are typically characterized by recurrent pollution [10–12]. Although the analysis of concentrations can be used to describe water quality in a river, the analysis of loads allows a direct comparison between concentration and streamflow. Thus, the analysis of loads can improve watershed planning through the provision of a better description of water quality concerns [13]. For instance, the LDCs can easily portray the streamflow classes in disagreement with the regulations, and therefore, shed light on best management practices to improve water quality [14,15]. In that context, pollution events related to shorter permanence (i.e., high flows) are usually associated with diffuse pollution sources, whereas events related to higher permanence (i.e., low flows) are commonly linked to point source pollution [11,13,16].

In Brazil, there have been some attempts to use LDCs, but the frequent non-synchronous streamflow and water quality sampling represented a limitation [17–20]. For instance, FDCs were developed for rivers in the state of São Paulo, Minas Gerais and Paraná (SP) but considered the monthly average of streamflow in the estimation of the load [18,20]. The monthly average makes the day-to-day flow variation smoother, thereby, hampering the comparison between the loading capacity and the observed pollutant load into the river.

A relevant application of LDCs refers to the quantification of a potential load reduction per hydrological regime. The United States Environmental Protection Agency (USEPA) set up conventional ranges for streamflow regimes, namely 0–10% for the high flows, 10–40% for moist conditions, 60%–90% for mid-range conditions, 60%–90% for dry conditions and 90%–100% for low flows. To obtain the needed load reduction, i.e., for *E. coli* contamination, the middle flow exceedance percentile (from the LDC) is multiplied by the 90th percentile of sampled observations in each flow regime [21,22]. This approach is inherently a setback because the load variation represented in the observations is not well-captured by this technique and will be lost. The extreme hydrological conditions, i.e., high (0–10%) and low flows (90%–100%), are also not accounted as critical conditions for load reduction. It is worth noting that the exclusion of these marginal fringes can compromise the analysis when the observed data is limited, which is a common situation in developing countries.

These limitations inspired the quantification of a potential load reduction per hydrological regime based on a new approach. This would become the purpose of this study, detailed in the forthcoming sentences. With the new approach, a trend line of observed loads is estimated using the LOESS smoothing technique [23], while the calculated TMDLs are fitted to a non-linear line using the Burr XII distribution [24,25]. Having defined these two tendencies, they can be visually compared to identify impaired pollutant loads in a straightforward manner. They can also be used to quantify load reductions as relative differences between the two curves. While using this new method, the percent of load reduction for each streamflow regime would be a summary of all samples collected in that regime, instead of standing on the 90th percentile concentration or on a single load value.

The new method was tested in two watersheds from the Brazilian state of Minas Gerais, namely the Piracicaba and Piranga River basins. In these catchments, many water bodies are highly concentrated in *E. coli*, which is evidence of fecal contamination and the potential presence of pathogens. This fact has motivated the selection of *E. coli* as the pollutant in this load assessment study. The proposed methodology allows the comparison of each observed load to the maximum allowable load for the same exceedance permanence of flow, unlike the existing methodology used by the USEPA, thus providing a more representative evaluation of water quality. Thus, besides the presentation of a new method to quantify a required load reduction, the aim here was to increase our understanding of *E. coli* load variation and thus optimize resource allocation and selection of appropriate best management practices to reduce the percentage of impairment in the basins of study.

2. Materials and Methods

2.1. Study Area

The study was developed in two neighbor watersheds, the Piranga and Piracicaba basins, within the Doce river basin (MG), illustrated in Figure 1. This basin received worldwide attention when a tailing dam collapsed in 2015, destroying a small city and compromising the water quality from the basin headwaters towards the sea [26].

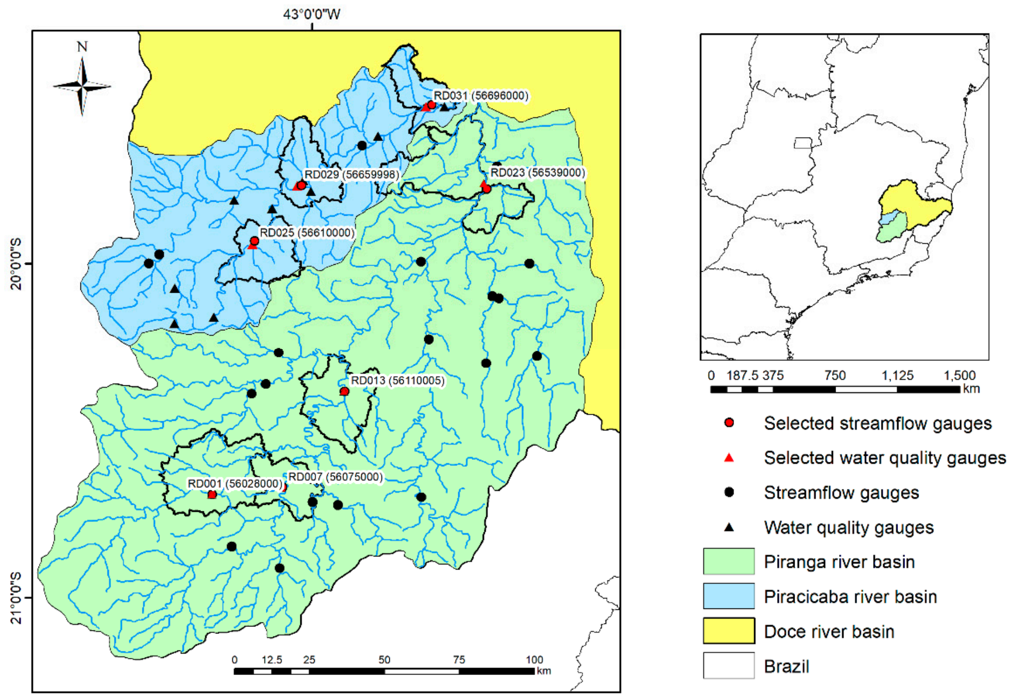

Figure 1. Identification and location of the studied basins, with the plot of streamflow and water quality gauges selected for this study.

Figure 1 displays the location of the basins, the gauges, and also the boundaries of cities where the gauges are located. The position of the gauges and the different drainage areas throughout the basin allow the assessment of the water quality patterns. These areas, as well as the names of the cities and their population, are depicted in Table 1.

Table 1. List of water quality and streamflow gauges used in the study, with the upstream drainage area. Information is also provided for the cities where the gauges are located, namely city name and their population.

Basin	Quality Gauge	Streamflow Gauge	Drainage Area (km^2)	City	Population
Piracicaba	RD025	56610000	1160	Rio Piracicaba	11,614
	RD029	56659998	3060	Nova Era	15,837
	RD031	56696000	5270	Timóteo/Cel. Fabriciano	85,888 and 106,945
Piranga	RD001	56028000	1400	Piranga	6,156
	RD007	56075000	4260	Porto Firme	5,081
	RD013	56110005	6230	Ponte Nova	53,169
	RD023	56539000	15,900	Córrego Novo/Marliéria	2,020 and 2,924

The basins are mostly occupied by not too populous cities. Thus, given the lack of resources from these cities, most of them lack wastewater treatment plants, which causes most of their generated sewage to be loaded into the rivers without treatment. This situation, associated with pasture and swine activities in the basins, has caused *E.coli* contamination to be one of their core water quality problems [27].

Regarding the loading capacities, CONAMA establishes that the loadings must respect the natural capacity of the river, which means that, after receiving the load, the water quality parameters of the river must meet its class of use. There is no maximum concentration of *E. coli* established in the loading legislation. Industries or cities that intend to load pollutants into rivers must apply for licenses in the responsible environmental agency and respect a list of minimum requirements, which must be fulfilled unless an unusual situation is experienced. However, given the lack of monitoring agents, situations in which this legislation is not met are frequent, compromising the water quality in many Brazilian water bodies [28].

2.2. Data Used in the Study

To understand the nexus between *E.coli* contamination and the hydrological patterns in the basins, the maximum allowed *E. coli* load was compared to the observed *E.coli* load in various water quality gauges. The maximum allowed load combines the water quality criteria set up by the CONAMA, which is 1000 MPN dL^{-1}, with the flow rate at the streamflow gauge, obtained with the development of an FDC. By multiplying the FDC with the water quality criteria, it is then possible to obtain the LDC, which relates the maximum allowed load to the percentage that can be observed in time (and flow permanence), the Total Maximum Daily Load (TMDL) [29,30]. Larger allowable loads are associated with a shorter permanence, since these are associated with higher flows when the dilution capacity of the river is more elevated. On the other hand, smaller allowable loads are associated with smaller streamflows.

Because it is necessary to measure water quality and quantity at the same location in order to estimate the TMDL, streamflow, and water quality gauges approximated from each other were selected for the study. Three and four pairs of stations were selected for Piracicaba and Piranga basins, respectfully, with data from 1997 to 2018. The MG state holds four water quality campaigns throughout the year to account for three different periods: Wet, dry, and intermediary. The wet season goes from January to March, the dry season from July to September, and the intermediary seasons from April to June and October to December. During the wet and dry seasons, 51 water quality parameters are sampled, whereas 19 parameters are sampled in the intermediary seasons. *E. coli* concentrations are measured in all campaigns.

In this state, the assessment of water availability and water quality occur separately. Therefore, the gauges are not installed in a way to minimize the distance between then. As a consequence, there are limited locations in which it is possible to apply an LDC-like methodology, and the amount of data is frequently limited.

First, the normalized 7-day, 10-year low flow (q7,10), in $m^3\ s^{-1}\ km^{-2}$, at the selected gauges was calculated per month. This analysis improves the understanding of the hydrological dynamics in the gauges and their potential relationship with water quality. The q7,10 was selected because it is the low flow used by the state of Minas Gerais for water resources management and planning, and it was normalized by the catchment's upstream drainage area to estimate water production, and therefore, allow their comparison [31].

For the scope of this study, extreme outliers were evaluated and eliminated from the dataset. Inferior and superior extreme samples can be identified using box-plots in combination with Equations (1), and (2) [32], respectively:

$$LE_{inf} = Q_1 - 3(Q_3 - Q_1) \quad (1)$$

$$LE_{sup} = Q_3 + 3(Q_3 - Q_1) \quad (2)$$

where LE_{inf} and LE_{sup} are the inferior and superior limits of the box-plot for the identification of extreme outliers.

The seven time-series used in this study, which represent stream flows in the main watercourses of their respective basins, were obtained from the HidroWeb, which is operated by the Brazilian Water Agency (ANA). The FDCs were generated with the Hydrology Plus software [33].

2.3. Load Estimation

The TMDL was calculated for all gauges ($Load_{TMDL}$), to understand their water quality dynamics, and then compared with the observed *E. coli* load monitored in the water quality gauges ($Load_{OBS}$). When plotted together, a water quality violation is characterized when $Load_{OBS}$ is higher than $Load_{TMDL}$. $Load_{TMDL}$ and $Load_{OBS}$ were calculated according to Equations (3) and (4), respectively:

$$Load_{TMDL} = C_{MAX} Q_{FDC} \mathrm{CF} \quad (3)$$

$$Load_{OBS} = C_{OBS} Q_{OBS} \mathrm{CF} \quad (4)$$

where C_{MAX} is the maximum allowable concentration of *E. coli*, determined according to Class 2 of the CONAMA regulation, which gives 1000 MPN dL^{-1}; Q_{FDC} is the streamflow obtained with the flow duration curve of the gauge; C_{OBS} is the observed concentration of *E. coli* sampled in the water quality gauges; Q_{OBS} is the streamflow observed in the day in which the water quality was sampled, and CF is a conversion factor used to estimate the load in MPN day^{-1} ($864{,}000 \times 10^3$).

The Loess smoothing technique [23] was applied to estimate the tendency of $Load_{OBS}$ samples in relation to the $Load_{TMDL}$ estimated with the LDC. This technique highlights the tendency of observed data in relation to the maximum observed load in all gauges. Thus, it is possible to understand the expected water quality for different flow permanences. The Loess method consists of a locally weighted regression that, for each value in the x-axis, a fitted value in the y-axis is generated, the so-called x_k. According to this method, the fitted values consider all values in the x-axis, but their weight varies according to the proximity of x_k. The result of the smoothing technique is that it generates curves with different parameters for each value in the x-axis.

The smoothing analysis helps the visual perception of observed loads in the basin in comparison to the water quality criteria, instead of comparing the sampled points with the $Load_{TMDL}$. Thus, in areas where the smoothing curve is above the TMDL, it is likely that the water quality will be impaired for the flows related to that permanence.

2.4. Burr XII Curve

The main novelty of the proposed methodology consists in the identification of the needed load reduction. To quantify the pollutant reduction for each observation and then for all classes of flow, the LDC representing the TMDL was fitted to the Burr XII distribution [24,25]. In this case, it is possible to predict the observed load for all the x-values in which the observed *E. coli* was sampled, unlike the LDC method proposed by USEPA, whereas the observed load is computed based on a single concentration and the middle permanence flow of each flow regime. The Burr XII is a flexible double-powered distribution and was selected because it has a precise fit for empirical data, thus representing with accuracy the extremes of an FDC, and consequently an LDC, for the scope of this study. The Burr XII distribution can also be adjusted to different streamflow regimes, such as for perennial, intermittent and ephemeral rivers. Equation (5) describes the Burr XII equation,

$$Load_p = \lambda \left[\left\{ 1 - (p/\tau)^{\beta} \right\} / \beta \right]^{\alpha} \quad (5)$$

where $Load_p$ is the observed load arranged in descending order; p is the percentage of exceedance, τ is the cease-to-flow percentile, which is the ratio between the days in which the flow was larger than zero to the total number of observations of the series. In this study, τ = 100 because all rivers are perennial; λ is the scale parameter and β and α are related to the shape of the curve.

If the curve is not adjusted, the quantification of the difference between observed and the maximum allowed *E. coli* load is computed through approximation, i.e, the method proposed by the USEPA, in which the observed load is set as the multiplication of the median streamflow for each flow range by the 90th percentile concentration of a given flow regime, whereas the maximum allowable is the medium load of that regime. This allowable load is compared to the existing load, in order to identify the ranges by which the pollutant contamination is more expressive [22].

In the present study, the R software was used to fit the permanence values which the observed *E. coli* was sampled. The equation parameters were determined by an iteration process. The fitted equations allowed to estimate the load related to each percentage in which there were sampled observations. In turn, this allowed the estimation of total *E. coli* contamination and its percentage observed in each flow regime: High, mid-range and low, corresponding to a percentile of 0%–30%, 30%–70%, and 70%–100%, respectively [34]. The r-squared statistics was used to evaluate the goodness-of-fit of the fitted distribution.

2.5. Estimation of the Needed E. coli Load Reduction

There are different methods to estimate pollutant reduction according to the flow regimes. Here, the reduction, or Relative Difference (RD), is calculated for all observations and compares the observed load with the maximum load, which is obtained with the adjusted curve of the FDC. The RD between the actual sampled load and the fitted load was calculated according to Equation (6),

$$\mathrm{RD} = \left(\frac{Load_{OBS} - Load_{MAX}}{Load_{OBS}}\right)100 \tag{6}$$

where $Load_{OBS}$ corresponds to the observed load of the water quality gauges, while the $Load_{MAX}$ represents the maximum allowed load estimated from the fitted TMDL curve.

The Relative Difference (RD) that represents the difference between the observed load and the maximum accepted load considering Class 2 of the CONAMA 357/2005 legislation [35] was calculated for all observed samples. The positive values indicate that there is a need for *E. coli* load reduction, whereas negative values indicate that the load in the section is not causing the river section to be impaired. In the format of Equation (6), positive values range from 0% to 100%, indicating the percentage of reduction required to meet the water quality criteria. Negative values, on the other hand, can be smaller than negative 100%, depending on the magnitude of $Load_{OBS}$ in relation to the $Load_{MAX}$. Nevertheless, these are always classified as "no-load reduction needed".

To facilitate the interpretation, the RD was also divided into three groups, representing three classes of flow regime: High (HF), mid-range (MRF), and low flows (LF). For each class, the number of impaired observations was quantified, and then it was possible to estimate the magnitude of the needed reduction for each flow regime with the use of box-plots where the load variation in each class of flow was represented. The RD observations were also divided into seasons, which represent the frequency in which the water quality samples are collected, in order to identify when the pollution is more expressive during the year, and if it matches the expected flow (high, medium or low).

The main limitation of this approach, however, is that the goodness-of-fit of the Burr XII curve to the FDC will determine the validity of the RD estimates, and hence the magnitude of the needed reduction. Additionally, the margin of safety (MOS) and allocation of loads that characterize the final aspects of the LDC methodology proposed by the USEPA were not covered here.

3. Results

3.1. Water Quality and Streamflow Patterns

Prior to the estimation of the *E. coli* load, the pollutant concentration and streamflow patterns throughout the studied basins were investigated to increase the knowledge about their relationship with the existing load. Figure 2 illustrates the box-plots of the stations involved in the study for the Piracicaba and Piranga basins (Figure 2a,b), as well as the normalized 7-day, 10-year low flow (q7,10) of the selected gauges per month for the Piracicaba and Piranga basins (Figure 2c,d).

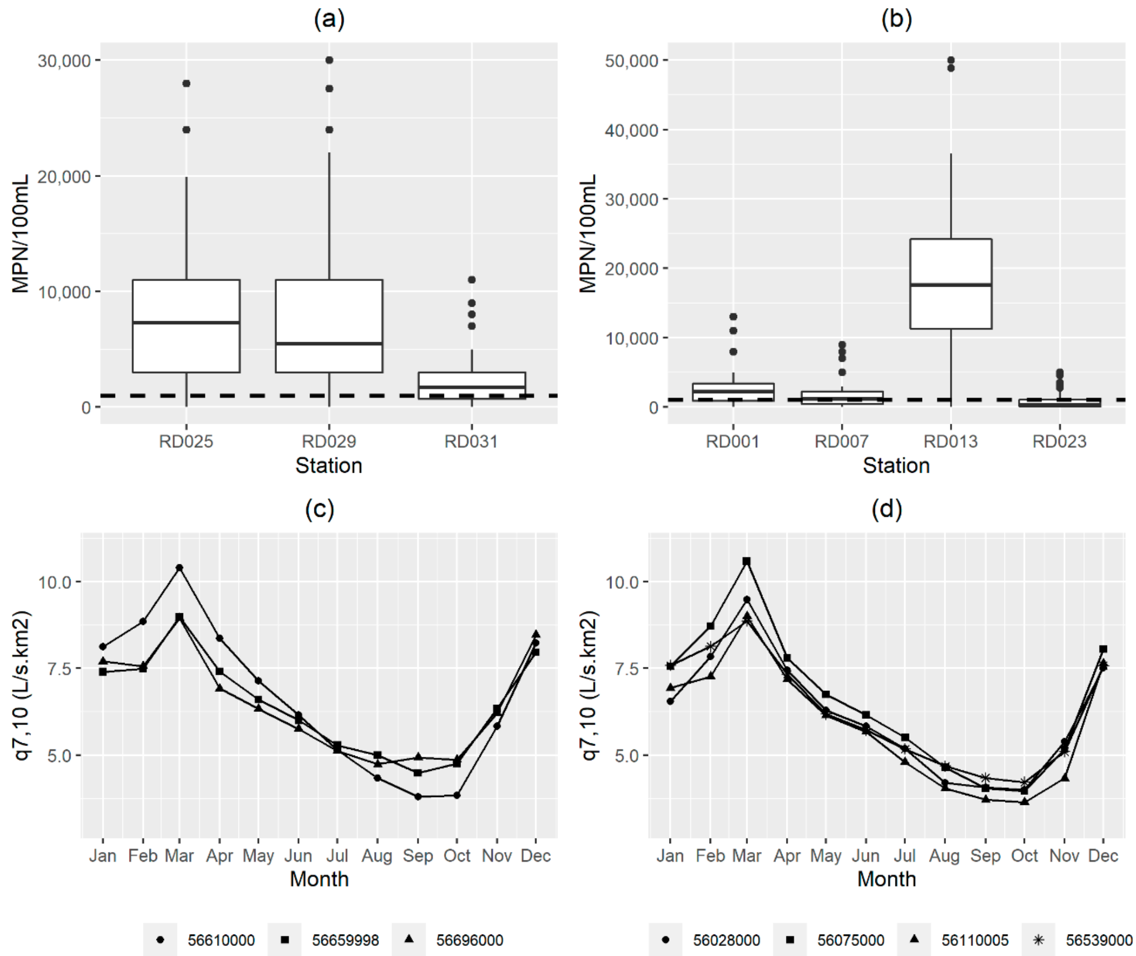

Figure 2. *E. coli* concentrations in the (**a**) Piracicaba, and (**b**) Piranga basins (the dashed line represents the maximum allowed concentration in Class 2 rivers), and monthly streamflow variation in (**c**) Piracicaba and (**d**) Piranga basins.

In Figure 2, the dashed line represents the maximum pollutant concentration allowed in Class 2 rivers, 1000 MPN dL^{-1}. After the outlier is removed, according to Equations (1) and (2), the number of *E. coli* samples in the Piracicaba basin was 80, 81 and 79 for gauges RD025 (56610000), RD029 (56659998), and RD031 (56696000), respectively. For the Piranga basin, the number of samples was 72, 73, 114, and 108 for gauges RD001 (56028000), RD007 (56075000), RD013 (56110005), and RD023 (56539000), respectively.

In most stations, the water quality was impaired for more than half of the samples, in particular stations RD025 and RD029 in the Piracicaba basin and station RD013 in the Piranga basin, in which cases more than 75 percent of the data were above the maximum allowed concentration established by the legislation.

With regards to the hydrological patterns, which summarize the historical flowrates from 1989 to 2018, it is clear that these are similar: Streamflow increases from November to March and decreases from March to October. In a study developed in the Piranga basin, streamflow regionalization techniques were applied to estimate the water availability variation throughout the network, and it was observed that, in some points of the hydrography, the difference between dry and wet seasons reaches almost 120% [31].

Given the nature of *E. coli* data, characterized by a wide range of values, smaller observations commonly get overwhelmed with larger ones. Therefore, log10 transformation was used in the analysis of the data patterns and generation of graphs, whereas the Burr XII was adjusted to untransformed data, and so was performed the RD computation.

3.2. Piracicaba Basin

Figure 3 illustrates the sampled *E. coli* load, in comparison with the maximum allowable *E. coli* load (TMDL) for the stations RD025, RD029, and RD031, generated with the development of LDC (Equation (3)). The Loess curve was also represented in the map to indicate the tendency of the sampled *E. coli* load in comparison to the points representing the TMDL, whereas the grey area surrounding the curve represents the 95% confidence interval for the smoothing curve. The Loess covers all frequencies of permanence for which *E. coli* data were sampled. Thus, considering that, for some gauges, sample collection could not cover the entire frequency range (0–100%), the Loess may also not cover all the range.

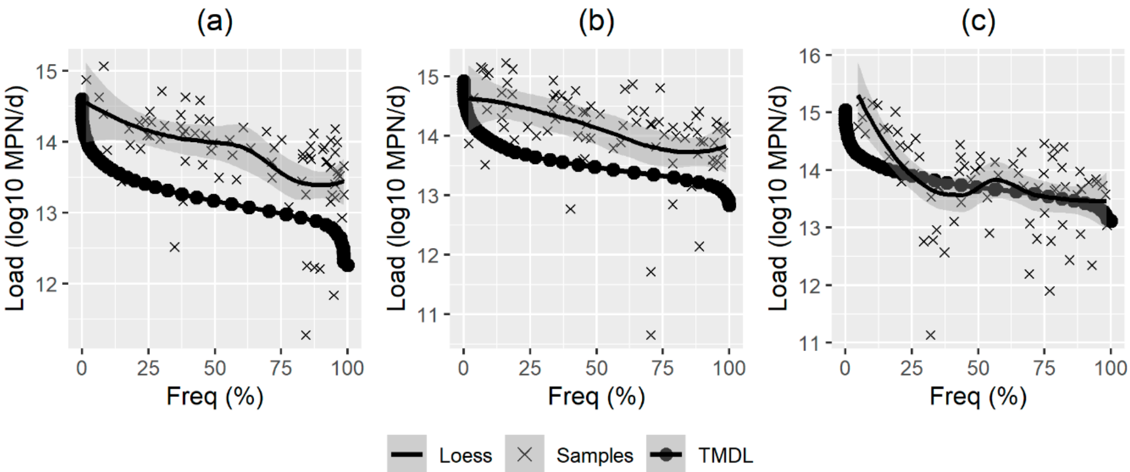

Figure 3. Comparison between load duration curves (TMDL) and Loess curve (representing the tendency of *E. coli* samples) in the Piracicaba river basin for gauges: (**a**) RD025/56610000, (**b**) RD029/56659998 and (**c**) RD031/56696000.

In the Piracicaba basin, there is an impairment for *E. coli* for all gauges, at some flow range, and *E. coli* contamination is higher as the drainage area decreases once there is a larger distance between the Loess and the TMDL curves in upstream regions. For gauges RD025 and RD029, a similar pattern is recognized: the tendency line is distant from the TMDL and the percentage of impairment in these gauges is also higher, 90% for both RD025 and RD029 in comparison to 68.8% in gauge RD031.

Figure 4 illustrates the adjusted TMDL curve according to the Burr XII distribution considering the flow duration points that represent the maximum loading capacity, as presented in Figure 3 for the gauges in the Piracicaba basin. It also illustrates a summary of the samples (a box-plot of the observed *E. coli*) in comparison to the TMDL curve for the high (HF), mid-range (MRF) and low flows (LF).

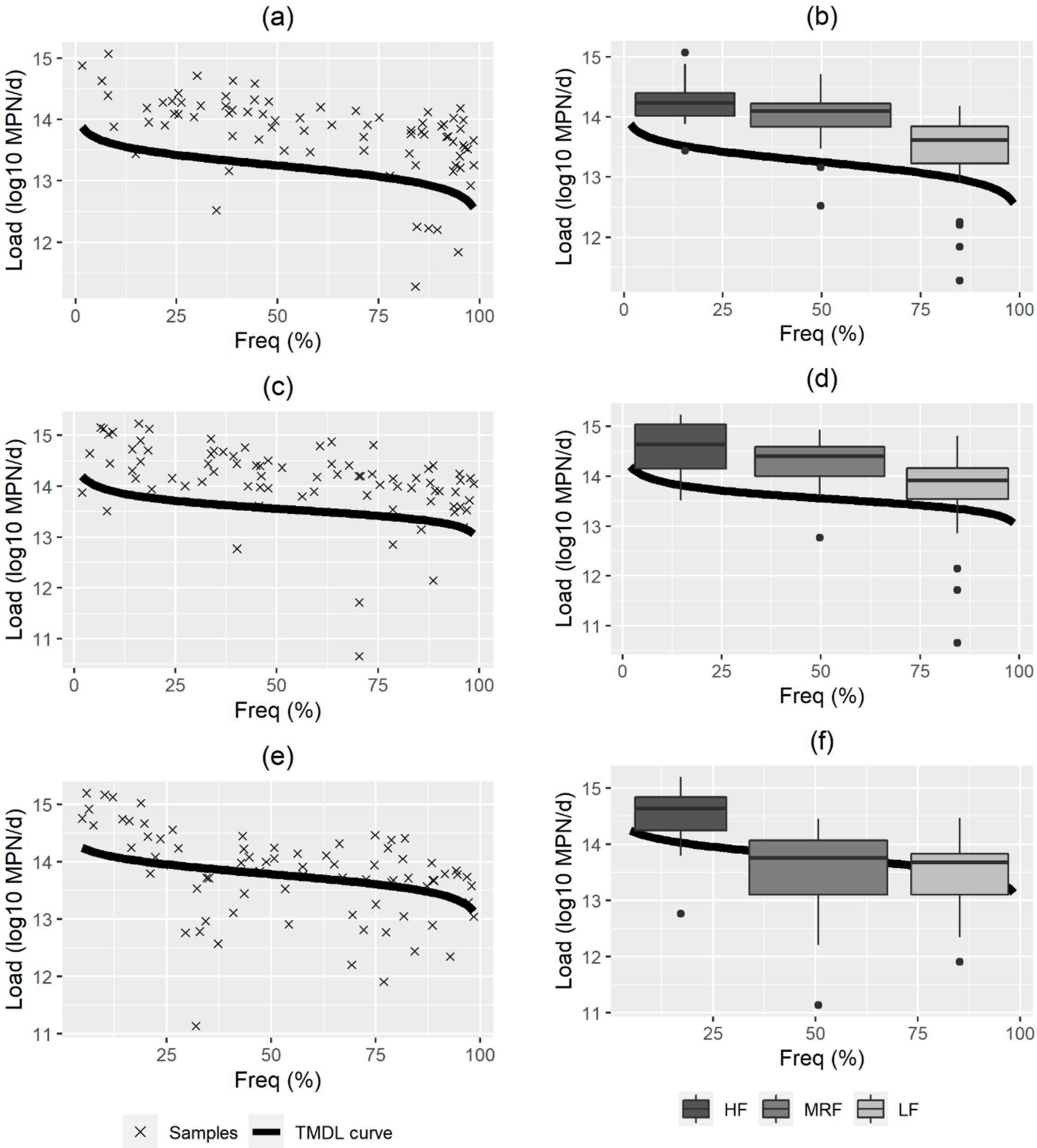

Figure 4. *E. coli* samples and box-plot per class of flow in relation to the TMDL curve for gauges: (**a**,**b**) RD025/56610000, (**c**,**d**) RD029/56659998 and (**e**,**f**) RD031/56696000. HF, high flows, MRF, Mid-range flows, LF, low-flows.

The box-plots allow recognizing how extensive the impairment of each flow regime is in relation to the TMDL curve. In contrast to Figure 3, Figure 4 allows the pattern of each flow regime to be interpreted and understood. For example, as observed from the tendency curves, gauges RD025 and RD029 have similar *E. coli* contamination patterns throughout the three regimes of flow (Figure 4a,c). Gauge RD031, on the other hand, have higher *E.coli* impairment for high flows, decreasing to almost none for mid-range flows (considering the median), and increasing for low flows but in a smaller magnitude, compared to the observed for high flows.

Overall, fewer observations were collected in high flow regimes, which is expected given the smaller permanence in time [36]. In gauges RD025 and RD029, the higher percentage of impairment is observed in mid-range conditions, while for gauge RD031 a smaller impairment was observed for this regime. Equations (7)–(9) illustrate the best-fit TMDL equations for gauges RD025, RD029, and RD031, respectively, as were illustrated in Figure 4.

$$Load_{RD025} = 1.11 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{1.03\times10^{-1}}\right\}/1.03\times10^{-1}\right]^{1.89}\left(R^2 = 0.995\right) \quad (7)$$

$$Load_{RD029} = 2.16 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{2.34\times10^{-2}}\right\}/2.34\times10^{-2}\right]^{1.75}\left(R^2 = 0.995\right) \quad (8)$$

$$Load_{RD031} = 1.19 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{2.06\times10^{-1}}\right\}/2.06\times10^{-1}\right]^{3.14}\left(R^2 = 0.994\right) \quad (9)$$

Figure 5 illustrates the RD between observed *E. coli* samples and the adjusted TMDL curve for each flow regime. When this information is combined with Figure 4, it is possible to assess the magnitude of the impairment in each flow class, and therefore an estimate for the needed *E. coli* load reduction.

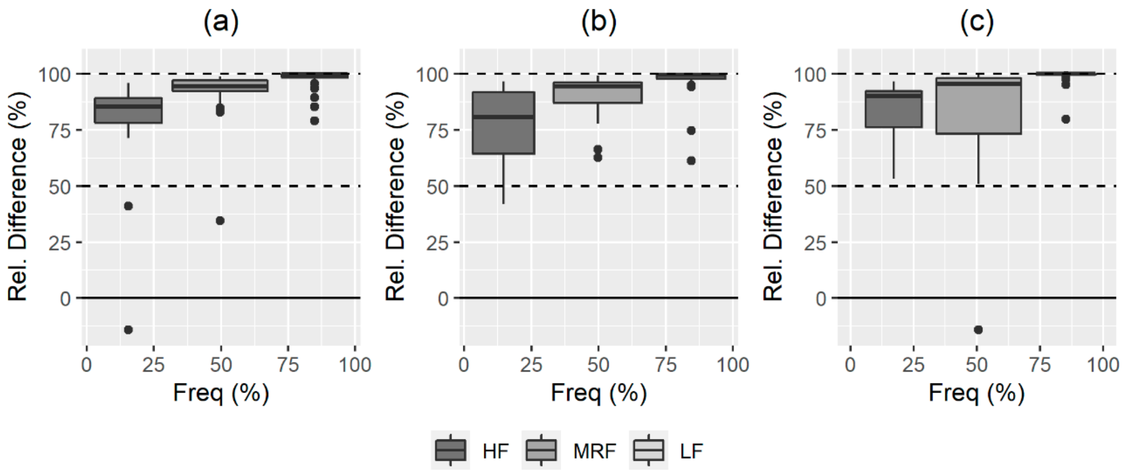

Figure 5. Percentage of reduction per class of flow for gauges (**a**) RD025/56610000, (**b**) RD029/56659998, and (**c**) RD031/56696000. HF, high flows, MRF, Mid-range flows, LF, low-flows.

In all gauges in the Piracicaba basin, the RD, estimated by the median, was between 50% and 100%, indicating the need to reduce this pollutant in all flow regimes. Additionally, it was observed in gauges RD025 and RD029 that there was a higher range between the first and the third quantile for HFs, decreasing for MRFs and again increasing for LFs. It can have been caused by the constant sewage load into the rivers, which have a higher impact on the LF. The variation of RD in HF is probably due to the variability of diffuse sources of pollution.

Figure 6 represents the RD divided into the seasons: January to March (JFM), April to June (AMJ), July to September (JAS) and October to December (OND). Although, the samples were divided into groups of three months, most samples were mainly collected in the first month within the season: January, April, July, and October, whereas fewer were collected in the second (February, May, August and November), and none during the last (March, June, September and December).

As observed in Figure 5, the higher *E. coli* load reduction in the Piracicaba basin is necessary for the LF. For gauge RD031, although the Loess indicated that the *E. coli* observations were similar to the TMDL, the needed reduction is still high for all flow regimes. It indicates that, although there is a higher variation within the samples, also observed in Figure 5c, there are more observations that do not match the water quality criteria.

In Figure 6, a smaller median is observed in the first semester of the year that represents mainly wet conditions. In all gauges, a higher RD was observed for the months with lower flows, July and October, where the RD almost reached 100% of reduction.

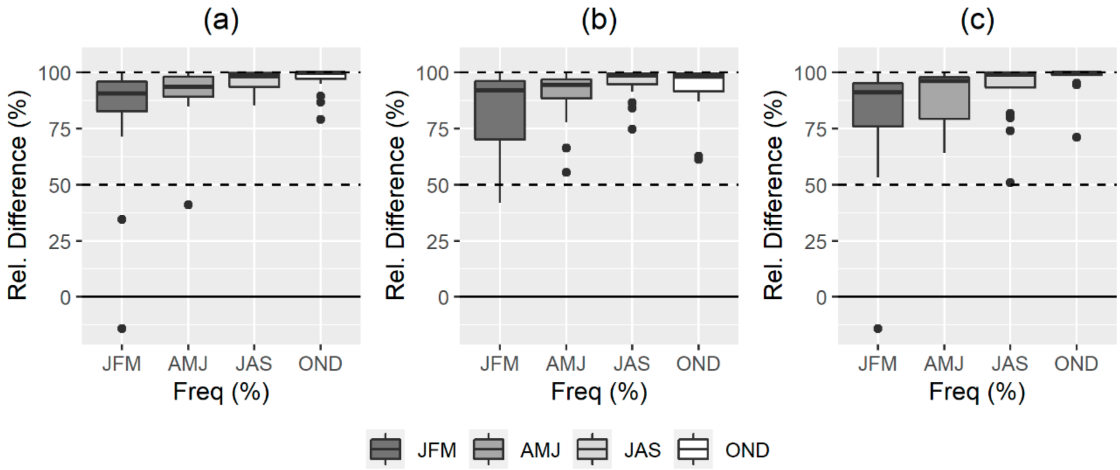

Figure 6. Percentage of reduction per season of flow for gauges (**a**) RD025/56610000, (**b**) RD029/56659998, and (**c**) RD031/56696000. JFM, January to March; AMJ, April to June; JAS, July to September; OND, October to December.

In RD031, although higher values of reduction are needed, the Loess curve was closer to the TMDL curve than for gauges RD025 and RD029. This happens because the reduction is measured by the median, considering the non-parametric distribution of the *E. coli* samples. Although there are many samples below the TMDL curve, the samples above it are many more, leading the needed reduction to higher levels. Table 2 illustrates the RD in the Piracicaba basin, according to the different flow regimes and seasons.

Table 2. Needed *E. coli* reduction (RD) per regime of flow and per season in the Piracicaba basin.

Gauge	HF (%)		MRF (%)	LF (%)
56610000/RD025	85.3		94.4	99.7
56659998/RD029	80.7		94.4	99.4
56696000/RD031	90.0		95.3	99.9
	JFM (%)	**AMJ (%)**	**JAS (%)**	**OND (%)**
56610000/RD025	90.5	93.85	98.3	99.6
56659998/RD029	86.6	94.4	98.1	97.9
56696000/RD031	91.1	96.1	98.9	99.8

Note: HF, high flows, MRF, Mid-range flows, LF, low-flows, JFM, January to March; AMJ, April to June; JAS, July to September; OND, October to December.

3.3. Piranga Basin

Figure 7 illustrates the sampled *E. coli* load in relation to the points representing the maximum allowable *E. coli* load (TMDL) in the stations RD001, RD007, RD013, and RD023, generated with the development of LDCs. The Loess curve indicates the tendency of sampled *E. coli* loads in comparison to the points representing the TMDL in the Piranga basin, within the 95% confidence interval.

In the Piranga basin, a similar pattern is observed for gauges RD001 and RD007 (Figure 7a,b). The impairment is more frequent in streamflow classes of higher flows, and it decreases for mid-flows. The main difference between these gauges is that the tendency line of the observed data is constant for low flows for the RD001 gauge, whereas it continues to decrease for the RD007 gauge. Nevertheless, within the 95% confidence interval (the gray area surrounding the smoothing curve) the TMDL and the Loess curve of the observed data are only different for high flows, from 0–25%.

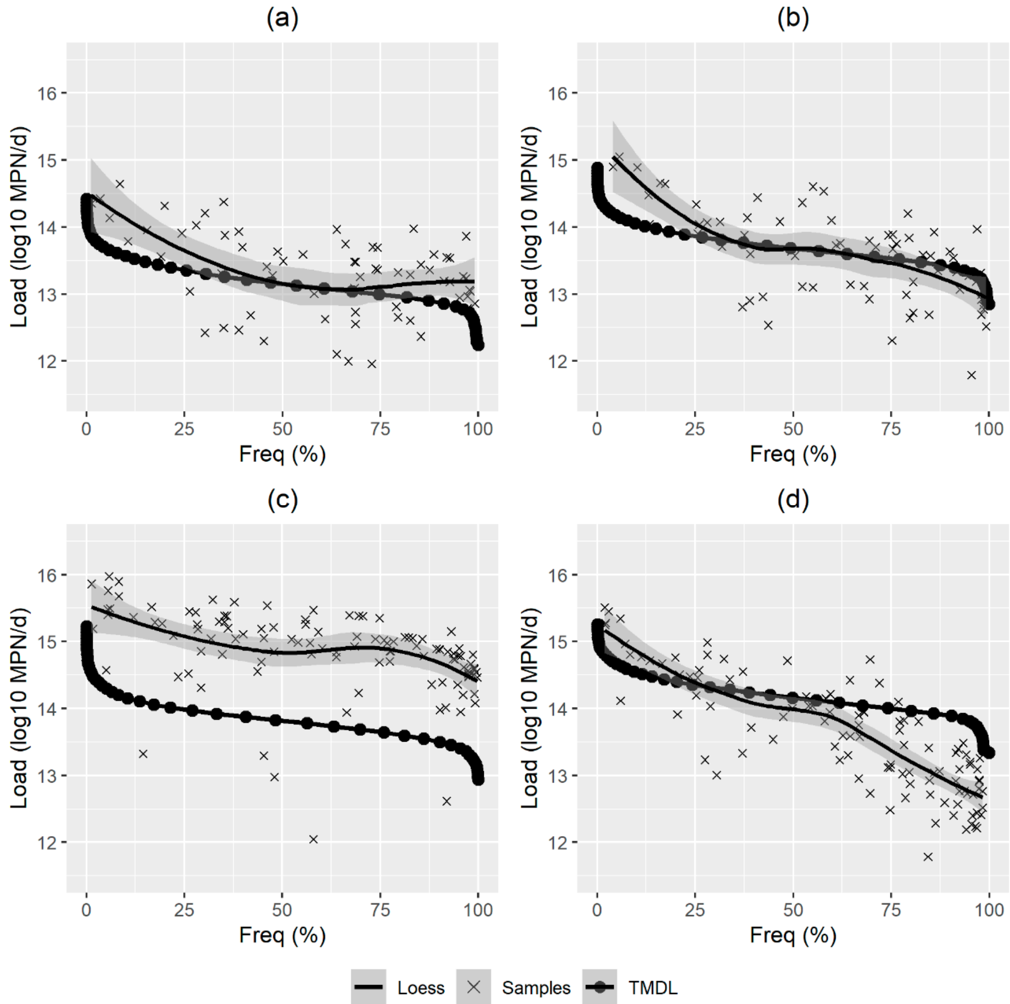

Figure 7. Comparison between load duration curves (TMDL) and Loess curve (representing the tendency of *E. coli* samples) in the Piranga river basin: Gauge (**a**) 56028000/RD001, (**b**) 56075000/RD007, (**c**) 56110005/RD013 and (**d**) 56539000/RD023.

The RD023 gauge, which is located near the mouth of the basin, is associated with the larger drainage area when compared to the other gauges and is inside a protected area. Unlike the other gauges, where the most sampled points were above the TMDL curve, in RD023 the impairment with the water quality standards is more expected from the high flow conditions to the mid-flow conditions. This situation might have happened because the constant load, generated from cities, is smaller than the loading capacity of the river in low flow conditions. In this condition, it is also expected that the *E. coli* load from upland locations in the basin has decayed before reaching this gauge. On the other hand, during high flows, the streamflow is higher, resulting in a higher velocity of the contaminant from bigger cities, as Ponte Nova, which caused the *E. coli* to reach gauge RD023.

Figure 8 illustrated the adjusted TMDL curve according to the Burr XII distribution considering the flow duration points that represent the maximum loading capacity for the Piranga basin, as well as box-plots of the observed *E. coli*, sampled points and the TMDL curve for the assessed flow regimes.

Considering the median of all observations collected in each flow regime, the pattern observed in Figure 7 persists in Figure 8. The loads for high and mid-flow conditions are similar for gauges RD001 and RD007, but for low flows they tend to maintain the same pattern of mid-flow conditions just for gauge RD001 and decrease for gauge RD007. For gauge RD013, a reduction in *E. coli* contamination is observed as the flow decreases. Finally, for gauge RD023 the main contamination is observed when flow conditions are high, whereas 75% of all observations are below the TMDL curve for mid-range and low flows.

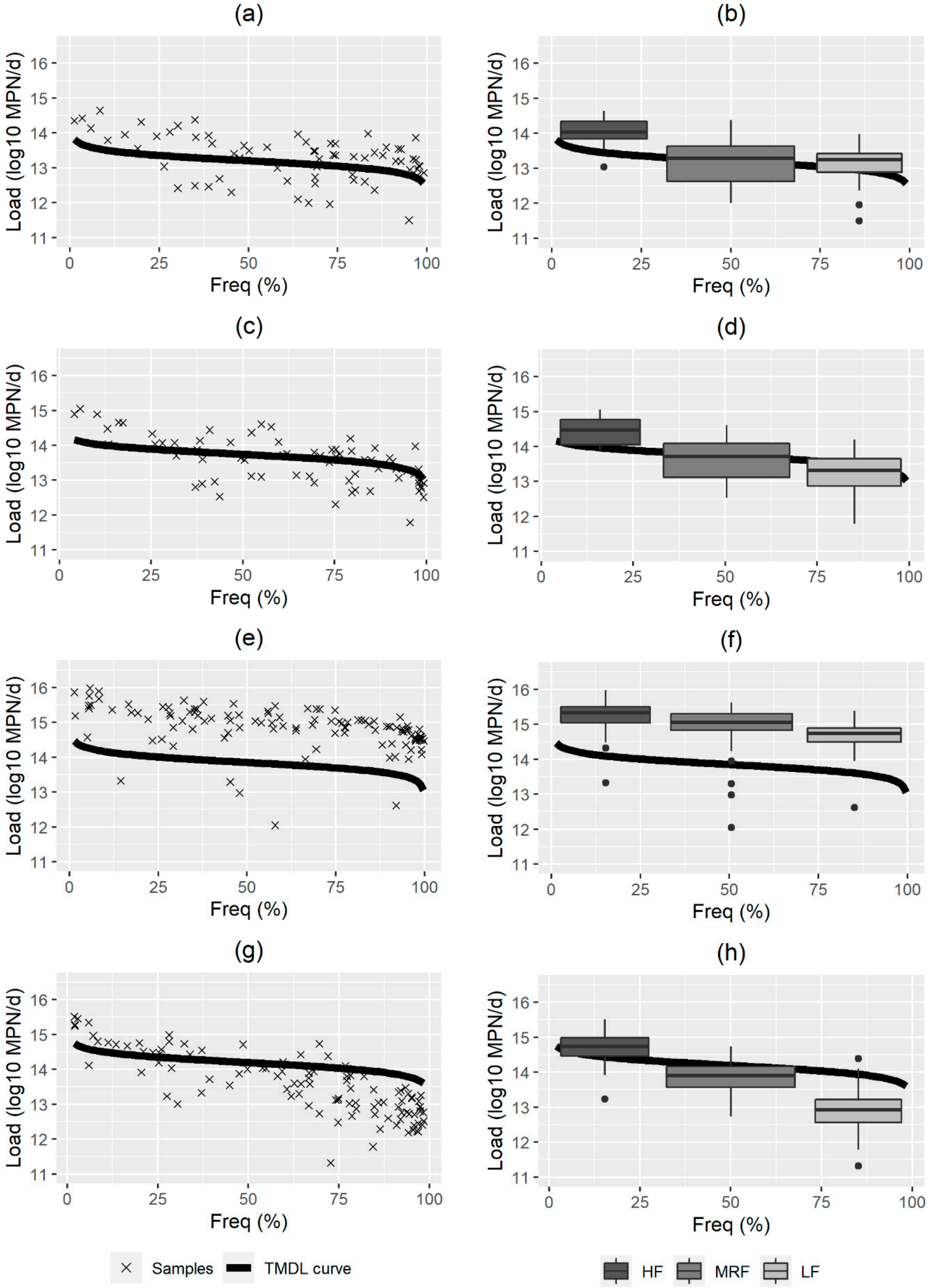

Figure 8. *E. coli* samples and box-plots per class of flow in relation to the TMDL curve for gauge (**a**,**b**) 56028000/RD001, (**c**,**d**) 56075000/RD007, (**e**,**f**) 56110005/RD013 and (**g**,**h**) 56539000/RD023. HF, high flows, MRF, Mid-range flows, LF, low-flows.

Equations (10)–(13) illustrate the best-fit TMDL equation for gauges RD001, RD007, RD013, and RD023, respectively.

$$Load_{RD001} = 1.36 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{-7.74\times10^{-2}}\right\}/-7.74\times10^{-2}\right]^{1.09} \left(R^2 = 0.993\right) \quad (10)$$

$$Load_{RD007} = 5.26 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{-2.23\times10^{-1}}\right\}/-2.23\times10^{-1}\right]^{7.37} \left(R^2 = 0.996\right) \quad (11)$$

$$Load_{RD013} = 7.07 \times 10^{13}\left[\left\{1-\left(\frac{p}{100}\right)^{-4.75\times10^{-1}}\right\}/-4.75\times10^{-1}\right]^{5.82} \left(R^2 = 0.996\right) \quad (12)$$

$$Load_{RD023} = 1.55 \times 10^{14}\left[\left\{1-\left(\frac{p}{100}\right)^{-1.38\times10^{-1}}\right\}/-1.38\times10^{-1}\right]^{8.81\times10^{-1}} \left(R^2 = 0.989\right) \quad (13)$$

Figure 9 depicts the relative difference (RD) between observed *E. coli* samples and the adjusted TMDL curve for each flow regime in the Piranga basin. As with Figures 5 and 6, the combined use of Figures 9 and 10 allows the magnitude of impairment to be assessed that is in each flow class and in each gauge, giving an idea of the need for *E. coli* load reduction.

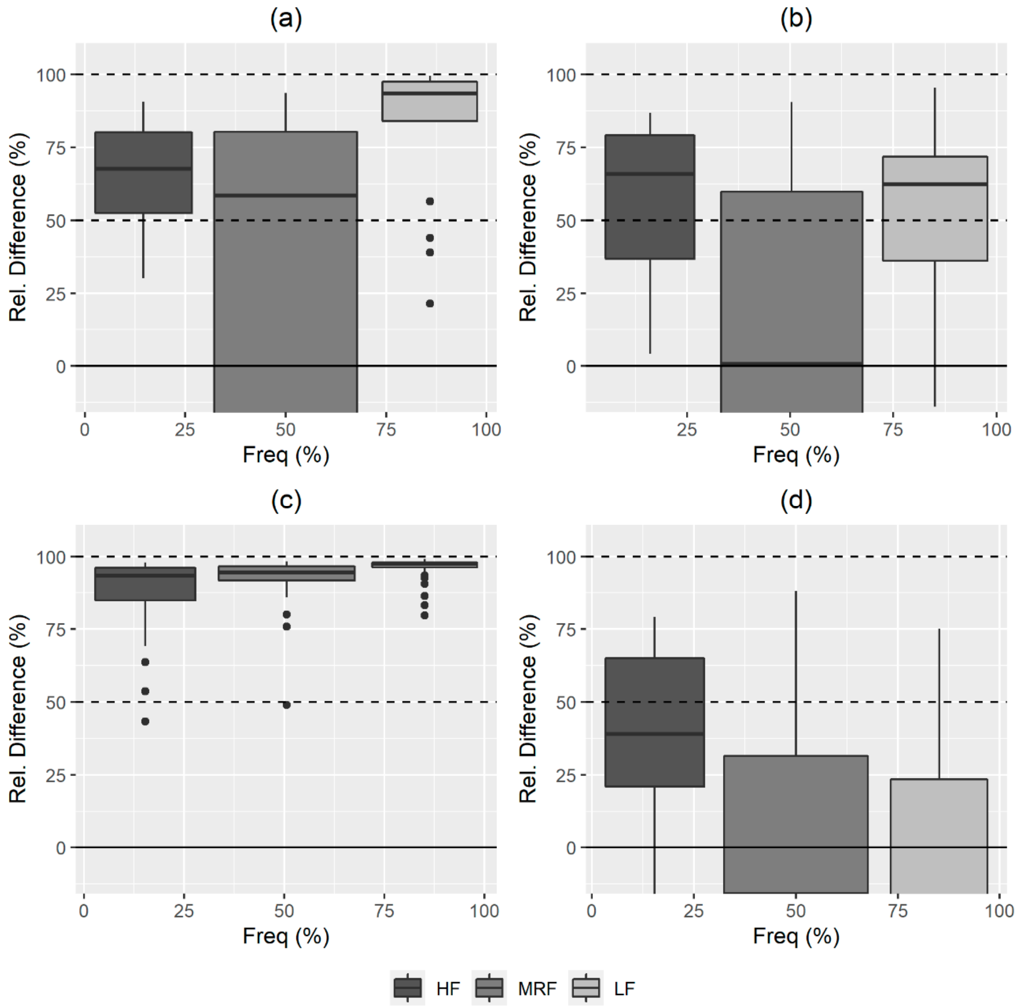

Figure 9. Percentage of reduction per class of flow for gauge (**a**) 56028000/RD001, (**b**) 56075000/RD007, (**c**) 56110005/RD013 and, (**d**) 56539000/RD023. HF, high flows, MRF, Mid-range flows, LF, low-flows.

In gauge RD001, there is a higher need for reduction in the LFs, whereas in gauge RD007 the reduction needed in the LFs and HFs is similar. The RD is consistently high in gauge RD013. This is a consequence of sewage load from Ponte Nova. In gauge RD023, a higher reduction is needed in the HFs. The variance in the gauges is a consequence of a smaller influence of point sources of pollution, meaning the sewage load in the rivers, as was observed for the Piracicaba basin. The negative values are obtained when the observed load is smaller than the TMDL, and higher negative magnitudes indicate a smaller $Load_{OBS}$ (Equation (6)), which explains why, for some gauges, the box-plot is not entirely on the plot (i.e., Figure 9d). Thus, it is possible to affirm that lower values of *E. coli* load (in relation to the TMDL curve) were observed in gauge RD023, followed by gauge RD007 and then RD001. Gauge RD013 presented only positive values.

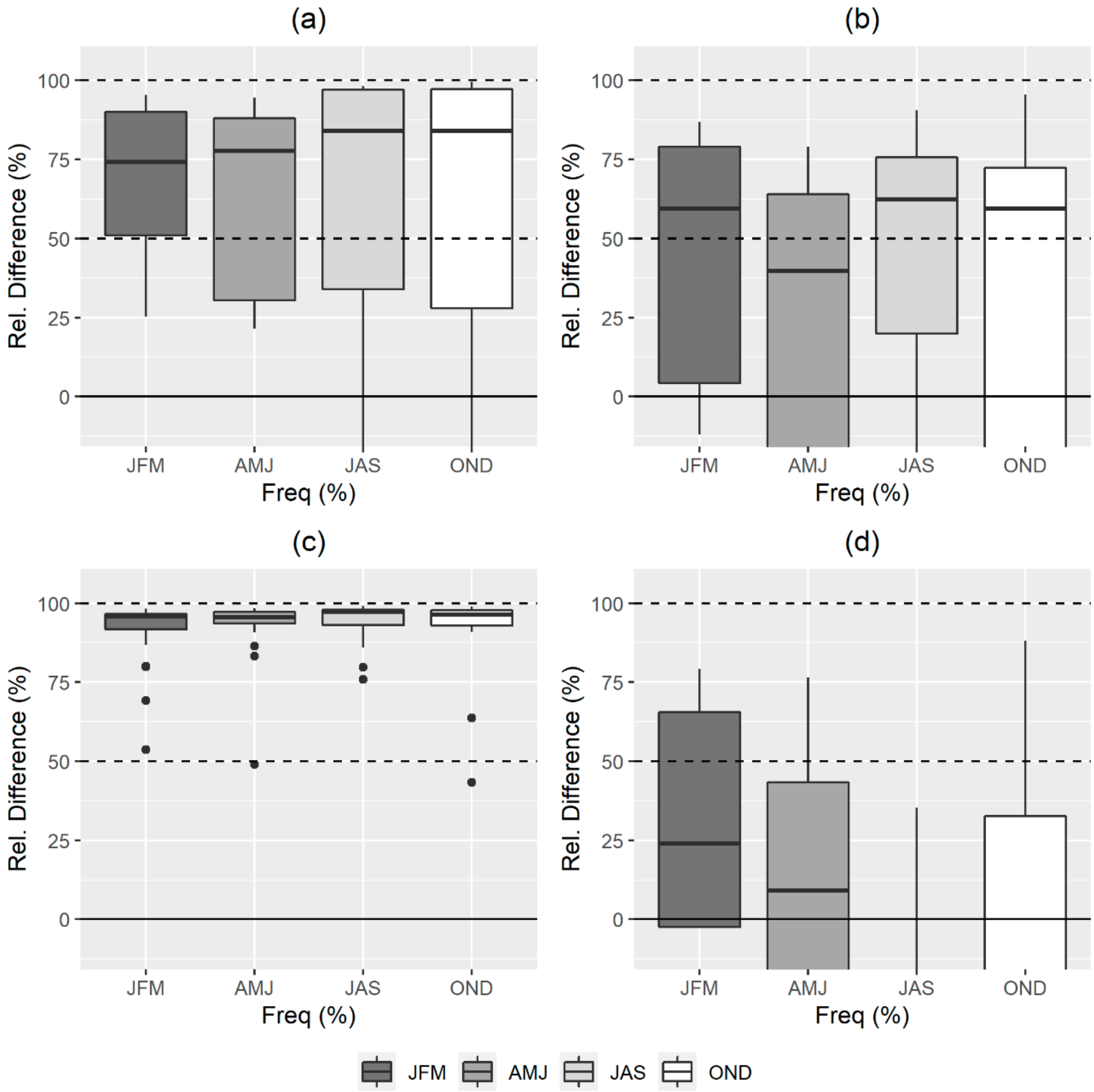

Figure 10. Percentage of reduction per season for gauge (**a**) 56028000/RD001, (**b**) 56075000/RD007, (**c**) 56110005/RD013 and, (**d**) 56539000/RD023. JFM, January to March; AMJ, April to June; JAS, July to September; OND, October to December.

Figure 10 illustrates the RD variation in the Piranga basin throughout the seasons. This figure shows higher load variances, with larger differences between the first and third quantiles, unlike the situation observed in the Piracicaba basin. As perceived from previous results, a higher pollutant reduction is needed in gauge RD013, which showed higher RD for all classes of flow throughout the year. It also shows that a higher *E. coli* reduction is needed in dry months (July and October) in comparison to wet months (January and April). In gauge RD023, the RD is positive only in wet months, indicating a need for load reduction in diffuse sources of pollution. Table 3 illustrates the RD in the Piranga basin, according to the different flow regimes and different seasons.

Table 3. Needed *E. coli* reduction (RD) per regime of flow and per season in the Piranga basin.

Gauge	HF (%)		MRF (%)	LF (%)
56028000/RD001	67.5		58.5	93.5
56075000/RD007	65.9		-	62.4
56110005/RD013	93.5		94.4	97.4
56539000/RD023	39.1		-	-
	JFM (%)	**AMJ (%)**	**JAS (%)**	**OND (%)**
56028000/RD001	74.2	77.7	84.2	84.0
56075000/RD007	59.4	39.8	62.4	59.4
56110005/RD013	95.7	95.6	97.3	96.4
56539000/RD023	23.9	9.1	-	-

Note: HF, high flows, MRF, Mid-range flows, LF, low-flows, JFM, January to March; AMJ, April to June; JAS, July to September; OND, October to December.

In general, the variation is more significant in this basin than in the Piracicaba basin. Besides, no-load reduction is needed in gauge RD023 during the dry season, but this observation is not valid for the other gauges.

4. Discussion

4.1. E. coli Concentration and Streamflow Patterns

The *E. coli* concentration in the gauges is directly related to the proximity of urban centers, where the population is mostly concentrated [37]. In the Piracicaba basin, the stations RD025 and RD029 were installed in city surroundings, whereas the gauge RD031 is within the extent of Cel. Fabriciano city, but was installed upstream of its urban center. In the latter case, the station did not receive the raw (untreated) sewage generated in one of the most populated cities in the basin. This fact explains the larger *E. coli* concentration upstream of the Piracicaba basin in relation to downstream.

Additionally, although the impairment at gauge RD031 is greater than 50% (Figure 2a), if the confidence interval of the Loess curve is considered in relation to the TMDL curve, these overlap, resulting in an impairment percentage of about 20%, mainly observed in high flows. In this gauge, the *E. coli* contamination is probably attributed to runoff, cattle grazing, or/and the sewage from upstream cities that arrive faster in the gauge during events of high flows, not allowing the process of bacterial decay.

For the Piranga basin, the stations RD001 and RD007 are located close to the urban center of the cities, while station RD013 is located downstream from the city center. For the first stations, most sewage generated by the city is likely loaded after their location, which would result in sampled *E. coli* values that do not reflect the water quality in the cities. For station RD013, most sewage load generated by the city likely reaches the gauge, although some of the loaded *E. coli* can decay from the moment the sewage reaches the river. This affirmation is supported by the fact that in this gauge the smoothing curve of the observed samples of *E. coli* is distant from the TMDL curve for all permanences of streamflow. This situation is probably a consequence of the untreated sewage load from Ponte Nova, one of the most populated cities of this basin, with over 53,000 inhabitants.

The station RD023, on the other hand, is located in a preserved state park, the Doce State Park, away from the urban centers of both cities where it is located. Although a higher *E. coli* concentration is observed near the cities, it cannot be ruled out that this region is a pole of swine farming activities, which also contribute to a high concentration of pathogens, due to high percentages of waste deposition that are not respecting the environmental regulations [27].

Apart from station RD013, the tendency of the median is to reduce as the drainage area increase. The same pattern was observed in other basins, in which higher *E. coli* loading was observed to be higher in watersheds with smaller drainage areas and with a higher population density [38]. It is suggested that this situation probably arises because, in smaller basins, the pollutant source is likely to be closer to the streams, resulting in a faster transport rate, thus reducing the impact of *E. coli* decay. Similarly, in the surroundings of Chinese counties and evidenced that the arrangements of the cities play an important role in water quality. Thus, government initiatives, such as structural reforms and environmental regulations, impact water quality [37]. An example of the importance of government actions in order to improve water quality happened in the USA when a detergent ban and a total P discharge was imposed in order to reduce algal blooms [39].

4.2. E. coli Load Patterns in the Piracicaba Basin

As expected, a higher RD was observed for the seasons with lower flows, which can receive closer attention in the establishment of measurements to reduce the pollution load. In a study developed in urban catchments in Florida (USA), higher *E. coli* contamination was observed during the summer, with wet and hot conditions [38]. This difference in relation to the results presented for this basin is probably due to the difference in scale, which is higher here, resulting in a delay in the transport velocity, lessening the effect of the diffuse pollution.

In a different study, the dynamics of fecal indicators were analyzed according to different conditions of land use, season and water chemistry. It was observed that sometimes the indicators had different patterns throughout the basin [40]. *E. coli*, in agricultural basins, maintained high concentrations throughout the year, whereas, in urban cities, it tended to increase during the summer season and is smaller during the winter.

The combination of these analyses can improve the current water quality assessment method where only the pollutant concentration is monitored. For instance, it is possible to estimate the pollution pattern, i.e., the regime where it is more recurrent and when there are more samples away from water quality criteria. In gauge RD025, for instance, the percentage of impairment is higher for greater flows (almost 94% of impairment during HF). However, as it is observed in Figure 5a, the magnitude of pollution is higher for low flows, as the median RD of low flows in this class is more distant to x-axis (RD equivalent to zero). As a whole, *E. coli* contamination in the basin is a concern and is the reason why all classes of flow and sources of pollution (point and non-point) should be addressed.

4.3. E. coli Load Patterns in the Piranga Basin

In the Piranga basin, the total impairment is ampler than in the Piracicaba basin, varying from over 95% in gauge RD013 to below 10% in gauge RD023. The impairment is larger in RD001 than in RD007, while this was not possible to detect in the smoothing curve. In a study developed in different scales in Texas: Field, small watershed and river basin, *E. coli* concentrations were evaluated with different agricultural management and land use [41]. In this study, the authors also observed that the primary *E. coli* sources in rural basins are wildlife, streamflow resuspension, failing wastewater treatment plants and animal feeding operations. Additionally, in the river courses evaluated, *E. coli* contamination tends to be higher upstream and decreases downstream. Throughout the Piranga basin, the main sources of pollution are likely caused by cultivated and grazed lands and swine production [27], except by gauge RD013, in which contamination is caused by failing and non-existing wastewater treatment plants.

In the Piranga basin, there is a need for *E. coli* load reduction in the HFs in all gauges. However, in gauges RD001 and RD013, the magnitude of reduction is higher for the LFs (Table 3). This can be used as evidence to address these flows first when summed with the fact that low flows can represent critical conditions in the context of water supply.

In gauge RD001, *E. coli* load reduction is also needed in all seasons, but unlike in gauge RD013, a higher variation throughout the seasons is observed.

With the information of the flow regimes with the must recurrence of impairment and the months in which the problems are more aggravated, it is easier for the statewide environmental agencies to identify potential sources of pollution and thus impose regulations to minimize this load.

4.4. *E. coli* Load Variation in Piracicaba and Piranga Basins

In order to understand the dynamics of the observed *E. coli* load throughout the Doce river basin, the smoothing curves of the gauges within the Piracicaba and Piranga sub-basins were plotted together in Figure 11.

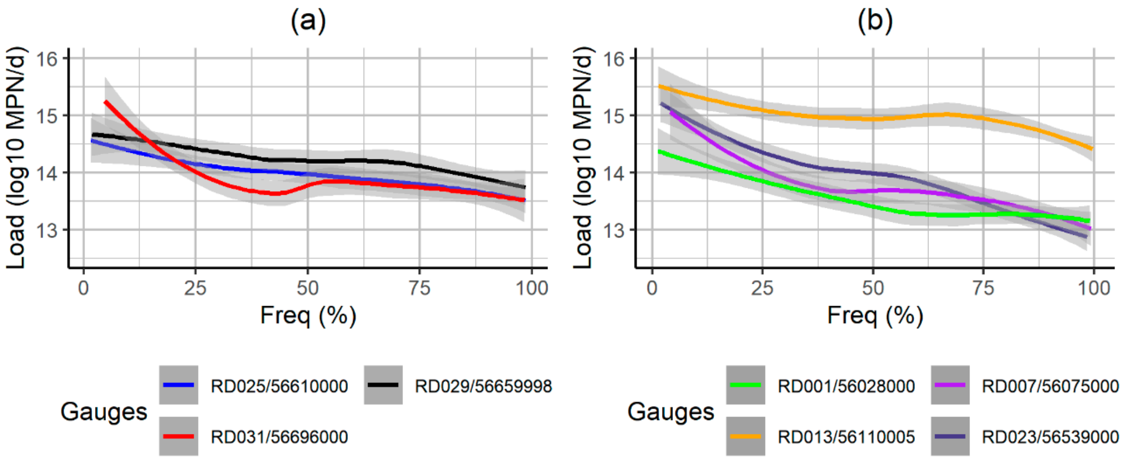

Figure 11. Tendency curves (Loess) of observed points in the gauges within the (**a**) Piracicaba and (**b**) Piranga basins.

Given the smaller size of the Piracicaba basin in comparison to the Piranga, there is not a significant load variation throughout the former basin (Figure 11a). For instance, with 95% confidence, the load in gauge RD029 is equivalent to the *E. coli* loads in gauges RD025 and RD031 at some flow permanence. In this basin, it is also possible to observe a steeper decrease in the *E. coli* load in the gauge RD031 as the permanence increases in relation to the other gauges in the basin.

In the Piranga basin (Figure 11b), a broader load variation is observed. The load in gauge RD013 is higher in all permanences of flow, as observed in other studies, where the agricultural basin presented higher and constant *E. coli* concentrations, in relation to the urban [40]. In gauge RD001, the load in low flow conditions is higher than the loads in the gauges RD007 and RD023 for higher permanences, even considering its smaller drainage area. The difference in the load of gauge RD013, with respect to the other gauges throughout the permanences of streamflow, can be attributed to the fact that it is located in the city with a higher amount of inhabitants, over 53,000, in relation to the others, in which the population is under 7,000 inhabitants.

The Loess curve does not present a continuum decrease in its load magnitude, as expected for the TMDL curve, because it was generated for the sampled observations, which reflected the water quality of these gauges. Therefore, the decrease in permanence does not imply in the reduction of the load, once it will follow the water quality observed in each permanence of flow and, for this reason, the Loess curve can have positive and negative slopes throughout the streamflows.

On that basis, the source control actions to be taken in order to improve water quality in the studied basins should prioritize regions where it could have more impact in the basin. In the Piracicaba basin, the gauges upstream (RD025 and RD029) are likely good candidates given the smaller drainage area and a probable high percentage of point sources. In the Piranga basin, on the other hand, the gauge where the adoption of pollution control practices would have a higher impact is the RD013. In the listed gauges, the main advantage is the existence of point sources of pollution, which are more feasible to identify and further control.

5. Conclusions

This study presents an alternative method to estimate *E. coli* load reduction in different locations of Piranga and Piracicaba basins, considering different flow regimes and seasons, using the concept of Load Duration Curves (LDC) and Total Maxim Daily Loads (TMDL). The results made evident that the loading of raw sewage in the rivers is one of the leading causes of *E. coli* contamination in all flow regimes for both basins. Thus, the first practice in the basins to control *E. coli* pollution should be the installation of wastewater treatment plants.

In the Piracicaba basin, the tendency is that the observed load is higher than the TMDL curve for all flow regimes, with a higher need for load reduction in low flows, in upstream gauges. On gauge RD031, on the other hand, located downstream of the basin, although there is an impairment of almost 70%, the TMDL load is equal to the observed load for about 80% of the streamflow permanence, considering the smoothing (Loess) curve.

For the Piranga basin, there is a higher variation in the *E. coli* contamination. Nevertheless, more efforts should focus on controlling the contamination in the higher flows (HF), because the RD was positive for all gauges under this condition, and the minimum percentage of impairment was over 65%.

The study proposes a different way to monitor water quality in Brazilian waters. Nowadays, the primary method used to measure water quality is through the measurement of pollutant concentration, not considering the streamflow related to that concentration. However, in order to improve water quality, it is essential to monitor both aspects, namely water quality and quantity, to propose techniques that are appropriate for the watershed and will control pollution.

The study brought different analyses that can be explored to improve water quality in the studied and other basins. For instance, with this methodology, it is possible to assess water quality and propose periodical goals in order to achieve a certain water standard. The method can also help define the needed efficiency in wastewater treatment plants, and thus, the definition of proper technology. Also, the identification of potential pollution sources can be facilitated with the seasonality approach. This type of approach can aid in the understanding of fate, transport, and survival of *E. coli*, which is a pollutant of many basins. Nevertheless, the methodology proposed can be applied to different contaminants.

Author Contributions: L.d.O.S., A.C.B. and F.F.P. conceived and designed the study. L.d.O.S. collected the data, performed the computations, analyzed the results and wrote the original draft of the manuscript. A.C.B. supervised the research work and contributed to the interpretation of the results and manuscript revision. M.C.d.M. and F.F.P. also contributed with the result interpretation and elaboration of the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Council for Scientific and Technological Development (CNPq) grant number 165565/2017-9, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), finance code: 001, and Minas Gerais Research Foundation (FAPEMIG) grant number PPM-00911-15.

Acknowledgments: We are thankful to Fernando Pacheco for his constructive and critical comments on this manuscript.

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

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Article

Water Security Assessment of Groundwater Quality in an Anthropized Rural Area from the Atlantic Forest Biome in Brazil

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Received: 13 December 2019; Accepted: 20 February 2020; Published: 25 February 2020

Abstract: The exploitation of natural resources has grown mainly due to the high rate of population growth that changed over time around the planet. Water is one of the most needed resources essential for survival. Despite all the efforts made to improve water security, an environmental impact related to anthropogenic influence remains of great concern, which is the alteration of surface and groundwater quality. In many regions around the world, there is limited or no access to rural and urban water supply while there is a need to improve sanitation facilities. This work evaluated the spatial distribution of groundwater and surface water quality as well as their changes in wet and dry seasons of the tropical climate in the Atlantic Forest Biome. The study area is under anthropogenic influence, which is in the municipality of Igarassú, Pernambuco State, Brazil. The analysis of the raw water was based on Standard Methods for Examination of Water and Wastewater, as referenced in the Brazilian Ministry of Health Consolidation Ordinance that sets standards for drinking water. The temporal analyses indicated a variation on water quality from the wet to the dry seasons, whereas the spatial results revealed deviations from the Brazilian's Water Supply Standards for some physicochemical parameters. There was an increase in the values of some parameters during the wet season in some hydrological compartments. The anthropized rural area from the Atlantic Forest Biome is affecting the water quality. It is, therefore, necessary to develop environmental policies and put them into practice by implementing engineering projects that guarantee proper treatment for raw water in order to bring the water quality back to a good status in this region.

Keywords: environmental monitoring; water quality; surface water; groundwater; drinking water

1. Introduction

The management of water resources as well as the sustainability of groundwater and surface water systems are topics of great concern [1–3]. Water covers 71% of the Earth's surface, but only 0.3% is available for drinking water [4]. The access to an adequate, reliable, and resilient quantity and quality of water for safe drinking is the main global water security issue related to aquatic ecosystems and human health [5–7] as well as to economic values. The understanding of natural processes and anthropogenic factors [8–10] and their roles for management and sustainability of water security resources require a better comprehension of changes that occur in groundwater and stream water quality [7,11], mainly to develop a governance and an implementation of water and land use policies [12].

Water governance is an excellent alternative for understanding and developing ways for water security [3,13] as well as seeking sustainable ways to exploit the groundwater resource to ensure human development [14] and integrated management [15]. Thus, environmental laws and guidelines are responsible for ensuring groundwater quality standards for consumption [16]. The Brazilian legislation and recommendations related to groundwater and stream quality list the parameters that must meet a certain potability standard directed to human consumption on drinking water [17].

Most of the water in the world goes to irrigation and agriculture, which is estimated at 70%, while industry uses 22%, and domestic use is at 8% [4]. In Brazil, the National Water Agency [18] through the Conjuncture of Water Resources in Brazil estimates that 72% of the country's water is destined for agriculture, 9% is destined for livestock, 6% is meant for industry, and, lastly, 10% is meant for domestic use. Land degradation is also a major source of water pollution related to erosion processes [11,12,19], contamination by heavy metals [20,21], eutrophication [22], and others, which, if unmanaged, can lead to significant economic and environmental costs.

Water quality is influenced by agricultural activities [23,24] and other land uses [11]. However, the consequences for water quality of some activities such as sand extraction or drilling of clandestine wells are still inconclusive or ambiguous. The extraction of sand through dredging is an important activity in the studied area with a need to supply the construction sector. Sand extraction can be an environmental stressor of surface and groundwater quality because the municipality of Igarassu explores a significant number of wells for the supply to local communities [25]. Therefore, the ecosystem integrity is vulnerable to physicochemical, erosive, suspended solid disturbances among others [26].

The Brazilian Northeast faces some inequalities in the access to water resources with certain population groups lacking a water supply system [25,26]. Extensive periods of drought can lead to irreversible socio-environmental impacts, which are related to soil water infiltration, increased runoff, and intensification of erosion. In the state of Pernambuco, the Pernambuco-Paraíba Basin is one of the largest underground water reserves. The Beberibe aquifer is one of the most important public water supplies, and the water company from the state of Pernambuco is responsible for distributing the drinking water to the municipalities of Recife and Igarassú. There are many socioeconomic activities that take advantage of water resources in the region. Additionally, the population in neighborhoods exploit groundwater [26,27].

Igarassú is a municipality of Pernambuco state, Brazil, with an area of 305,560 km^2, located 28 km away from the capital Recife. The climate is defined as Group As (Tropical savanna climate or tropical wet and dry climate), according to the Köppen climate classification. There are two well-defined dry and wet periods [27]: the wet season begins in the fall (May to October) and the dry season starts in the summer (November to April). The average annual rainfall is 1634 mm.

In a developing municipality such as Igarassú, there are densely populated areas with insufficient water supply, incomplete or inexistent sanitation, and ineffective environmental planning [28]. Under these conditions, water can transmit waterborne diseases and degrade environmental quality [28–30]. It is, therefore, important to systematically identify the factors that lead to water quality deterioration and propose solutions that are likely to secure the path of sustainable development [26,30,31].

This study was evaluated through field visits and laboratory analyses, the spatial distribution of groundwater, and surface water quality as well as the changes occurring from the wet to the dry season in the studied area, which aims to identify environmental issues that interfere within the quality of water consumed by rural communities as well as to propose solutions to impacts caused by human action within the framework of water security.

2. Materials and Methods

The study area is in an anthropized rural area from the Atlantic Forest Biome of Brazil, State of Pernambuco, located in the municipality of Igarassú, with central coordinates 7°51′09.5″ S and 34°53′05.4″ W (Figure 1).

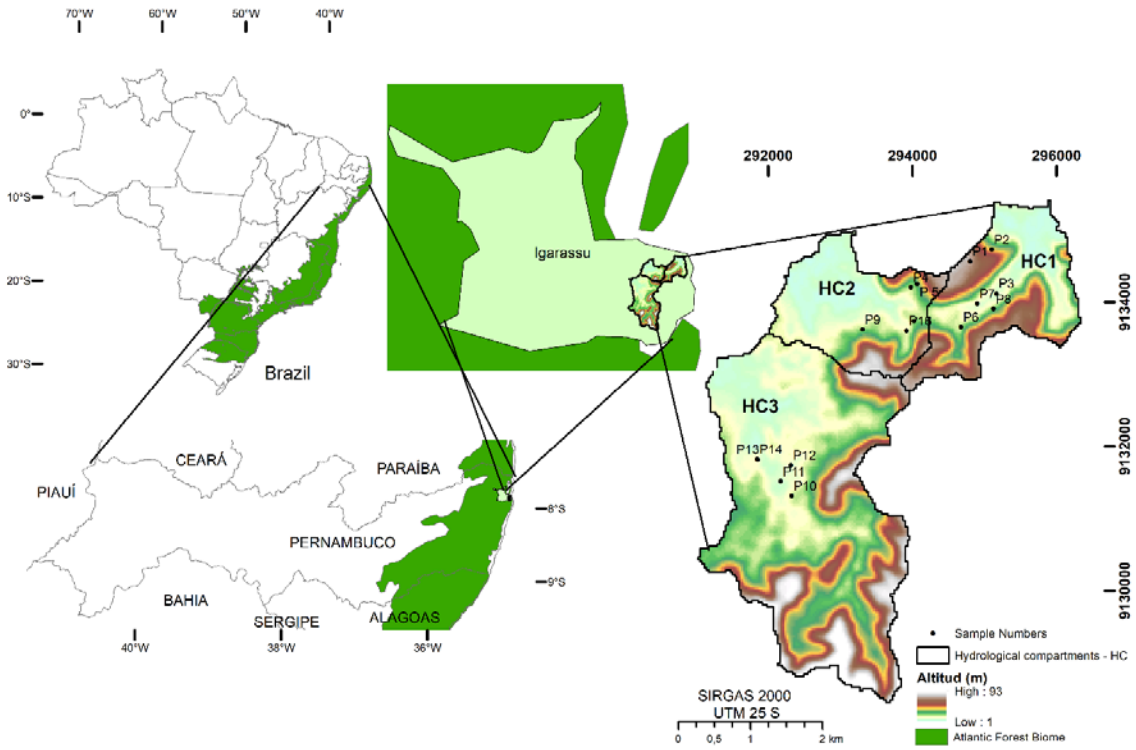

Figure 1. The location of the study area is an anthropized rural area from the Atlantic Forest Biome in Brazil, State of Pernambuco, Igarassú Municipality.

The study area covers approximately 16.1 km^2 with the anthropogenic pressures concentrated in the Northeast portion of the municipality. According to the geological map of the municipality of Igarassú (http://rigeo.cprm.gov.br/xmlui/handle/doc/16272), the area belongs to the Borborema Province where rocks from the Salgadinho Complex, sediments from the Beberibe and Gramame formations, and fluvio-marine and alluvial deposits crop out. Among others, the lithologic types include conglomerate and clay siltstone, sandstone with calcareous cement, and phosphorite interdigitated with calcarenites [29]. Topography is characterized by an undulated relief whereas soils are mostly represented by Yellow Latosols and Yellow Argisols with a sandy texture [27,29].

The water security assessment of groundwater quality was analyzed in three hydrological compartments (HC), as defined in Figure 1. Raw water samples were collected within the HCs and numbered from SN1 to SN16 and geo-referenced (Table 1). The sampling locations were strategically selected, considering the distribution of rural communities and their population. The samples, taken altogether, were representative of the different sources from which drinking water is obtained by the public rural community.

Table 1. Identification (number), source, and geographic coordinates of the water samples.

Sample Number (SN)	Water Source Types Depth (m)	Geographic Coordinate System UTM WGS 84 Longitude Latitude
1	Water well – 117 m	25M 294,802 9,134,568
2	Water well – 15 m	25M 295,100 9,134,730
3	Stream	25M 295,165 9,134,121
4	Cacimba – 8 m	25M 293,980 9,134,207
5	Water well – 128 m	25M 294,066 9,134,254
6	Cacimba – 2 m	25M 294,675 9,133,656
7	Cacimba – 4 m	25M 294,901 9,133,979
8	Cacimba – 4 m	25M 295,126 9,133,906
9	Cacimba – 8 m	25M 293,308 9,133,622
10	Cacimba – 8 m	25M 292,323 9,131,314
11	Water well – 30 m	25M 292,171 9,131,516
12	Dredging Pond – Sand pit	25M 292,313 9,131,739
13	Water well – 15 m	25M 291,853 9,131,820
14	Cacimba - 1.5 m	25M 291,847 9,131,823
15	Water well – 80 m	25M 294,024 9,133,740
16	Cacimba – 8 m	25M 293,919 9,133,606

The sampling of groundwater was conducted in drilled wells from the water table aquifer (SNs 1, 2, 5, 11, 13, and 15) in cacimbas that are small excavations dug near the streams to reach the water table with the purpose to remove water for domestic use or small plantations, which can be lined with a concrete pipe to prevent the collapse of their walls (SNs 4, 6, 7, 8, 9, 10, 14, 16) in the stream (SN 3) and from a dredging pond, which means an area where silt and sand are removed from the bottom of the water bodies (SN 12). The water well depths ranged from 15 m to 128 m, and the cacimbas depths ranged from 2 m to 8 m. The hydrological compartments (HCs) were drawn using a set of 1/10,000 scale contoured orthophoto cards by considering the water divides.

Campaigns for field data collection and raw water sampling in the study area were carried out during the rainy season between the months of March to July, called Wet Season Samples, and during the season without rain from August to February, which is called the Dry Season Samples. The sampling was done by collecting raw water in a 2-L bottle preserved under refrigeration for analysis, according to Standard Methods for the Examination of Water and Wastewater [32]. The samples were taken to the Minerals, Soils, and Water Analysis Laboratory (LAMSA), located at the Department of Chemical Engineering of the Federal University of Pernambuco (UFPE), for processing and conducting physicochemical and microbiological analyzes. The physicochemical analyses were based on specific protocols and assumed as pre-defined standards, described in PRC No. 5 - Annex XX, Chapter III, section V, Art. 22 of the Brazilian Ministry of Health [33] and in American Public Health Association (APHA) [32]. The samples were collected during the day between 6:00 to 18:00 h at the same hour for each sample number at a given site, by following the numbers from SN1 to SN16, during seven consecutive days in each season. The stream (surface water) was sampled at about 7:30 a.m.

Raw water temperature, turbidity, pH, total dissolved solids, dissolved oxygen, ox-redox potential, and electric conductivity were measured in the field during the sampling campaigns using a multiparameter probe called the HORIBA model U-50 (Table 2).

The heavy metal concentrations (lead, copper, total chromium, zinc, and cadmium) were measured by atomic absorption spectrophotometry. UV-VIS spectrometry determined sulfates, nitrate, and nitrite. Flame photometry was used to determine sodium and potassium. Analyses of total hardness and alkalinity (Mohr method) were performed by volumetric analysis. Total iron, aluminum, ammonia, and color were determined using Merck Millipore spectrophotometric analysis, using Merck Millipore PHARO 100 (VIS) and 300 (UV-VIS) spectrophotometers. The method was based on the use of Millipore filters with pores of 0.6 micron. Microbiological analyses of total and thermotolerant (fecal) coliforms and heterotrophic bacterial count were based on the methodology of the Standard Methods for the Examination of Water and Wastewater [32].

Table 2. Parameters measured by the Horiba U-50 model probe and their measurement units and precisions.

Parameter	Measurement Unit	Precision
Temperature	−5 to 55	±0.3 + 0.005
Turbidity	0 to 800 NTU	±1 NTU
pH	0 to 14	±0.1pH
Total dissolved solids	0 to 100 g/L	±5 g/L
Dissolved oxygen	0 to 50 mg/L	0 a 20 mg/L: ±0.2 mg/L 20 a 50 mg/L: ±0.5 mg/L
Oxi-redox potential	−2000 mV to + 2000 mV	±15 mV
Electric conductivity	0.0 µS/cm to 99.9 µS/m	±1%

The analyses were based on Directives 98/83/EC and (EU) 2015/1787, which are methods accepted by PRC No. 5 - Annex XX Chapter III, section V, Art. 22 [33] and by the APHA methodology [32].

Geospatial distribution maps were drawn for the pH, color, turbidity, and total iron parameters within the study area. The Nephelometric Turbidity Units (NTU) varies from 0 to 800 NTU. The Hutchinson's Topo to Raster [34] interpolation method was used. This method allowed the use of contours, basin boundaries, and georeferencing to interpolate data, which highlights the areas where the quality of water is not conforming with the legal standards [33]. The interpolation was performed using the weighted sum of squares in the residuals by the surface elevation data [34,35]. Thus, through this interpolation model, vector data were converted into hydrological land models [34–36].

Radar charts were drawn to display the multivariate water sample observations. Each spoke in the chart represents one variable. The length of a spoke is proportional for the magnitude of the variable. Radar charts were drawn for every data point (SN1 to SN16) and were represented in a multi-plot format.

3. Results and Discussion

3.1. Water Parameters' Interaction at the Sample Number and Hydrological Compartments

The specific studied area was divided in three hydrological compartments (HC) considering the altitude of land that drains the water downslope to the lowest point (HC1, HC2, and HC3) and the anthropized rural area from the Atlantic Forest Biome in Brazil.

Identification of seasonal trends (wet and dry) in raw water-quality constituents was especially important because high or low rates of each parameter have such a substantial effect on analyses of an anthropized rural area [9]. Surrogates monitored on a continuous basis provide resource managers with real-time information on sample number properties that showed different water characteristics and specific land uses as well as distinct reliefs [9,10]. The maximum, minimum, average, and stand deviation measured values at each compartment are shown in the Supplementary Material.

HC1 and HC2 stand out as areas of low dense community occupation within small planting areas, animal husbandry, drinking water, and multiple uses of water. HC3, in turn, represents an area where there are sand extraction sample numbers, a small aerodrome, and coconut processing industries for oil production.

The geospatial distribution of the physicochemical parameters showed that some of the SNs are not in line with the Brazilian Ministry of Health Consolidation Ordinance.

3.1.1. pH

The pH is a measure of the hydrogen concentration of the water, which is controlled by chemical reactions and the balance of ions present. According to the pH data, acidic waters are observed in the research sites. The raw water was measured in each Sample Number (SN) by the pH to show how acidic, neutral, or basic is the site. pHs of less than 7 indicate an acidic nature, whereas a pH of greater than 7 indicates an alkaline water, and it is a very important measurement concerning water quality. As the range moves from 0 to 14, with 7 being neutral, the PRC No. 5 recommends that the pH of water for the human supply stays around 6.0 to 9.0 [33].

As shown on sites, the raw water is changing chemically, and the measured sites (SNs) that showed relative acidic water (4.2 to 6.9) have a higher amount of free hydrogen. Yet, the sites where the raw water had more free hydroxyl ions were considered as basic samples (7.1 to 8.4) (Figure 2).

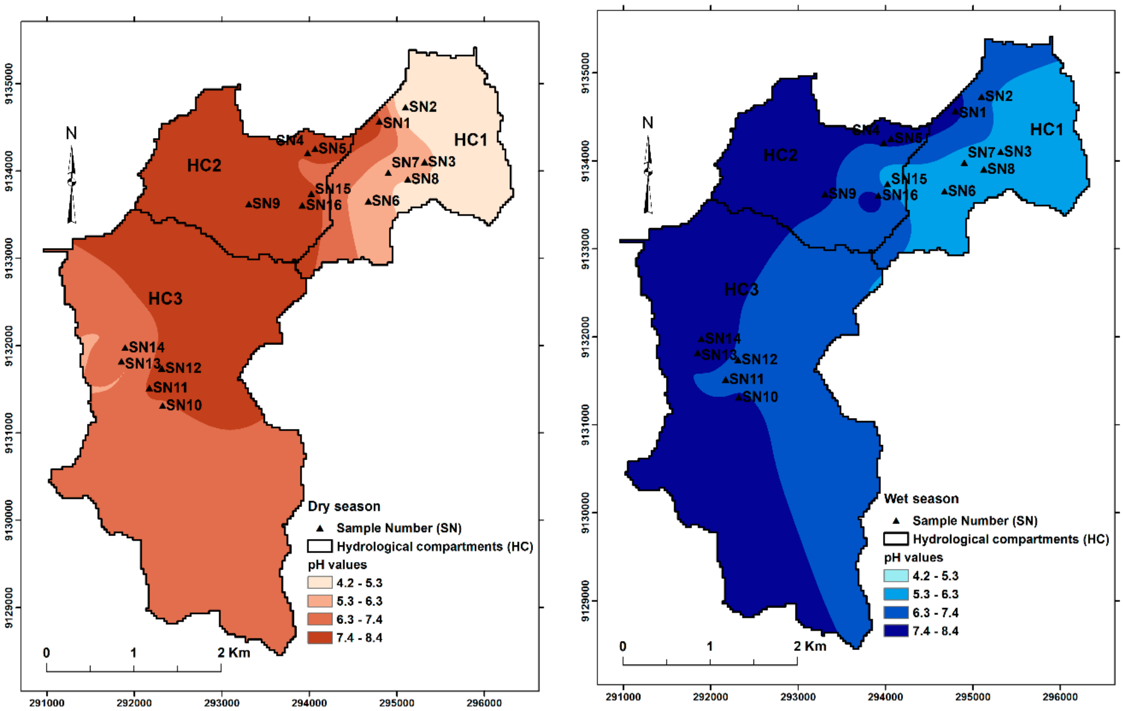

Figure 2. Spatial distribution of pH on the dry and wet seasons in the three hydrological compartments.

The pH represents a unit related to the activities of H + ions, which indicates in its expression's indices of neutrality, acidity or alkalinity. When comparing this parameter in the three hydrological compartments in the two climatic periods (wet and dry), there is a predominance of acidic pH in the hydrological compartment 1 (HC1), while the hydrological compartment 2 (HC2) presented an index of alkalinity in the studied period, which is similar to work conducted on groundwater as an alternative source to an irregular surface water in Namaqualand, South Africa [3].

The pH of groundwater is influenced by salts, acids, and bases present in the environment. In the studied area, the pH may result from natural geologic-soil-water interactions, or trace the environment's quality, which includes the water source, land degradation, or deforestation [2,3,6], among other factors that occur in the region. In the environment, aquatic systems showing low pH values may be related to weathering processes [3]. Some lithological structures, when weathered, contribute by releasing acid-forming elements [6].

The minimum values of pHs < 6 listed in the Supplementary Material were shown to be more prominent on sites SNs at HC1 during the dry season (Figure 2). In addition, one of the reasons for pH values stays less than 6 and is the higher concentration of clay minerals, which dissolve releasing silica and aluminum in the waters [6]. This parameter directly influences the distribution of elements and chemical compounds in their free and ionized forms, which gives water an ability to increase or reduce its potential solubility relative to substances, including those with a degree of toxicity [1]. One of the factors that also contribute to acidic pH indices in water is the concentration of organic acids from dissolution resulting from the decomposition of organic matter, which may be happening in the hydrological compartment 1 (HC1), where there is a stream with visible contribution of organic matter. Additionally, the pH of rain varies between 5.0 and 6.0, but also "acid rain" may reach pH values as low as 4.3 [1,33]. The highest pH values (e.g., <7.5) are most likely related to weathering of the carbonate rocks that are represented in the study area [29].

pH is a very sensitive component to changes and variations in water resources, and may oscillate, according to the dissolution of salts, decomposed organic matter, leaching processes, lithological soil types [29,37], and, above all, due to temperature [6,38].

3.1.2. Turbidity

The appearance of water with a turbidity less than 5 NTU is acceptable by the Brazilian Standards. The turbidity can be caused by particulate matter that may be present in the water source by resuspension of sediment along the flow path, or by the presence of inorganic particulate matter in groundwater [39,40]. Observing the turbidity in water (Figure 3) in both climatic periods (values in the Supplementary Material), there is an average value as a high turbidity during the dry season in SN 2, 7, 8 (HC1), 4, 9 (HC2), and 11, 13 (HC3) and on wet season in SN 10, 11, and 13 (HC3). The higher values of the parameter during the dry season may be related to the permanence of the suspended material that confers water turbidity through the lower rainfall of the dry season. Usually, clastic suspended sediments, such as sand and silt, give high turbidity in the waters [39–41], which are characteristic of the region where the study area is inserted.

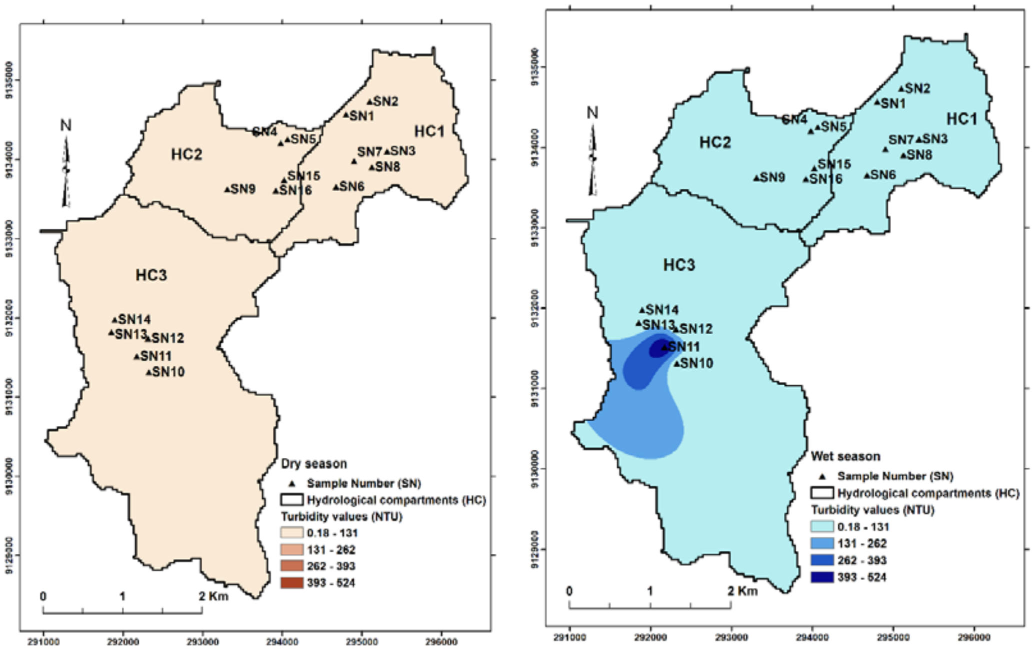

Figure 3. Spatial distribution of turbidity in the dry and wet seasons in the three hydrological compartments.

Considering the maximum values observed, the turbidity was higher than 5 NTU in almost all sites evaluated in both seasons except on SN 15 and SN 16 (HC2) during the dry season and SN9 (HC2) during the wet season (Supplementary Material). Anthropic actions have a direct relationship under high turbidity rates (SN11 and SN12) (Figure 3). Leaching and hauling of particles from soil exposed by mining activities, such as sand extraction, provoke upturning, which increases the availability of suspended particles. Environments where turbidity values are high are difficult for light to penetrate in water, which impairs the action of photosynthetic organisms. Some microorganisms are physically protected by the turbidity particles, which reduces the efficiency of water treatment [39–42]. Microbes and other colloidal particles can be physically removed from water by various processes. The sizes of the microbes are especially important for their removal by sedimentation and filtration. Such methods are described in report APHA methodology [32].

3.1.3. Color

The color in water can be caused by dissolved and/or suspended materials, and a brown shade often comes from rust in the water pipes. The physico-chemical characterization of color of sampling sites that exceeded the thresholds of PRC n°5, with color > 100 UH, were SN 3, SN 11, and SN 13 during the wet season and SN 3 and SN11 with color 67 UH and 80.9 UH, respectively, during the dry season. Studies refer that the presence of organic matter, metals, and other chemical and biological components can cause changes in color values in surface water and in groundwater [43]. To understand color, it is important to deepen the characterization of sampling sites where the anomalous values occurred.

The characteristics of site 3 are illustrated in Figure 4a. There is vegetation on the banks and a substantial amount of decomposing organic matter is suspended in the stream surface. The site number 11 (Figure 4b) is a lagoon where massive sand exploration occurs, and high turbidity occurred. Sample number 13 (Figure 4c) is a shallow cacimba without any fence and is situated in a contaminated area in a sanitation-free community surrounded by vegetation. Water is used for multiple uses and there is a makeshift toilet and laundry facility located within meters.

Figure 4. Sampling sites with anomalous color: (**a**) in the creek (SN3), (**b**) in the drainage pond of an area with sand exploration (SN 11), and (**c**) in an open cacimba (SN13).

According to Figure 5, the hydrological compartments HC1 and HC3 possibly presented the highest color indices, which is above what is allowed by the comparison norms (PRCn.5 threshold > B15UH). The results indicate that a probable source of color in these compartments is, as well as turbidity, responsible for the dissolution of organic substances that confer color and natural pigmentation.

Color as well as turbidity is a parameter influenced by natural factors such as decaying organic matter and substances dissolved in water. By analyzing the geospatial distribution of this parameter in the three hydrological compartments, it was shown that a similar profile in the two climatic periods occurred and was analyzed (Figure 5).

At the same sampling sites that showed color values outside the Brazilian Standards, turbidity was also out of the standard range. High turbidity was measured at the SN11 (> 100 UT), where sand extraction occurred for years. The emerging issue of sand extraction and solutions to address potential environmental impact is of great concern. Some authors discuss environmental stressors related to the exploitation of sand in which one of them is the alteration of the surface and groundwater quality since this activity is capable of dissolving, suspending, and transporting organic and inorganic substances, which changes several quality parameters [41–43]. Turbidity is one of the most affected parameters, and very little attention has been given to this parameter related to sand extraction.

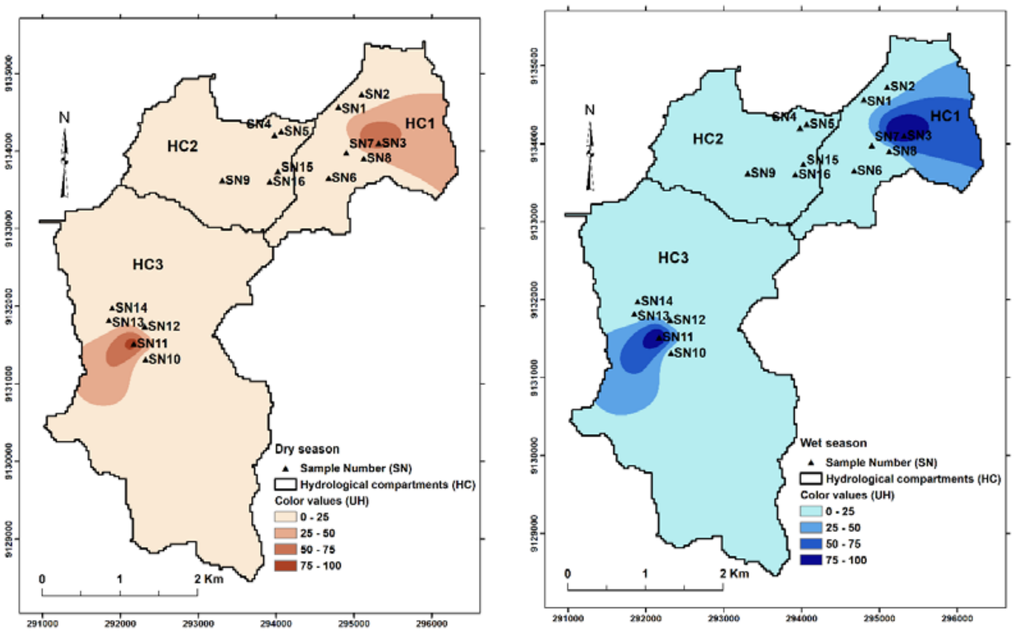

Figure 5. Spatial distribution of color on the dry and wet seasons in the three hydrological compartments.

3.1.4. Total Iron

Total iron was non-standard in four sampling sites. During the dry season, iron values were above the legal thresholds in sample numbers 1, 3, and 11 while, during the wet season, the affected sample numbers were SN3 and SN10. The SN1 presented relatively high values of iron where the soil and geology may be an influencing factor when considering the highest value of the well depth [6,43]. During the dry season, SN3 presented iron values of 4.5 mg/L and a pH of 5.41. It is common in waters that present this kind of pH values that the occurrence of Fe^{2}+ iron indicates that water with a certain acidity presents high iron concentrations [38,44,45]. Iron in groundwater may contain ferrous iron at concentrations up to several milligrams per liter without discoloration or turbidity in the water when directly pumped from a well [45]. On exposure to the atmosphere, however, the ferrous iron oxidizes to ferric iron, which gives a reddish-brown color to the water. At levels above 0.3 mg/liter (SN1, SN3, and SN11), iron stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations below 0.3 mg/l even though turbidity and color may develop [24].

The physico-chemical characterization of total iron of sampling sites that exceeded the thresholds of PRC n°5, > 0.3 mg/L were SN3 (0.6 mg/L) and SN 10 (0.53 mg/L) during the wet season, and SN1 (0.44 mg/L), SN3 (4.5 mg/L), and SN 11 (0.61 mg/L).

Observing the values of the total iron in both wet and dry seasons (Figure 6), an increase in concentration during the dry season is noticeable, especially in the SN 3, in hydrological compartments of HC1. In this compartment, sample number 10 showed values that did not comply with the compared norms. Hydrological compartments HC2 and HC3 did not show a significant change in iron concentrations in both climatic periods even though this element is not in accordance with the Brazilian Ministry of Health ordinance [33].

Iron can also arise from corrosion of ferrous pipework and chemicals used in treatment processes (coagulation). Iron suspensions cause aesthetic problems including metallic taste and discoloration of water fittings and laundry. The Brazilian drinking water quality regulations include national standards for iron (0.3 mg/L), which can be removed from water by filtration, oxidation, coagulation, and sedimentation [32,33].

Generally, in groundwater, iron levels derive from minerals and sediments that can be present in particulate or dissolved forms [1,38]. In surface waters, iron levels increase in the wet season as a result of soil runoff and erosion due to higher precipitation. Iron dissolved in water sets color, odor, and taste.

Iron concentrations in the dry season are higher than during the wet season, mainly in HC1. In both seasons, most of the area is higher than 0.3 mg/L (standard value for drinking water), but, during the dry season, much higher concentrations (up to 0.58 mg/L) can be encountered in groundwater from water wells, cacimbas, and surface water.

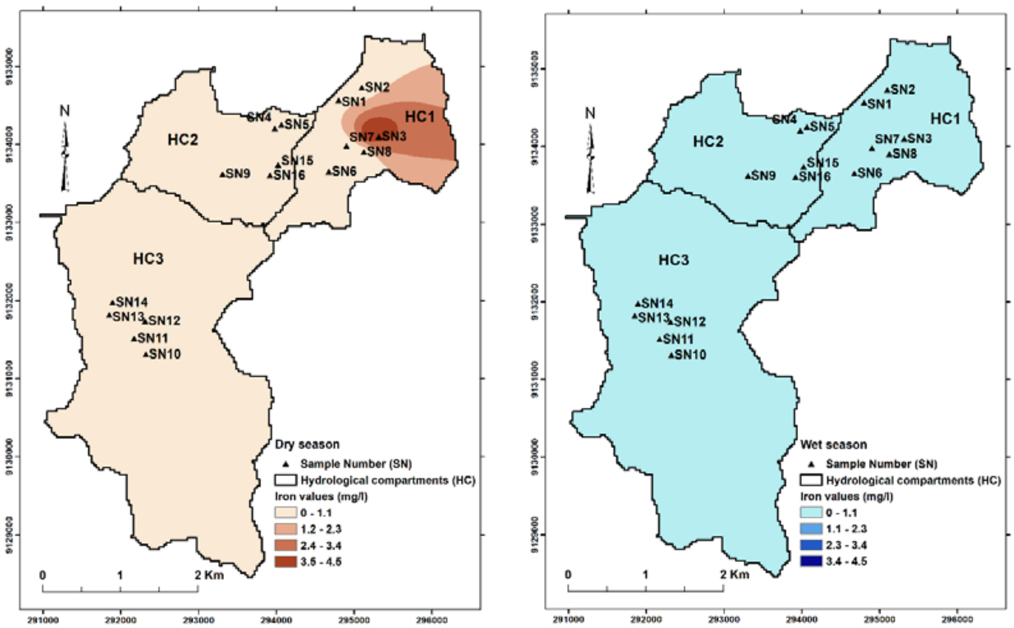

Figure 6. Spatial distribution of total iron during the dry and wet seasons in the three hydrological compartments.

The sample number SN3 during the wet season (0.6 mg/L) and the sample numbers SN3 (4.5 mg/L) and SN11 (0.61 mg/L) during the dry season showed a common phenomenon where high iron levels that occurred showed high color concentrations [38]. It is usually possible to find high levels of iron in groundwater whose pH has acidity, and, in surface water, that has organic matter [44,45].

With this distribution, a higher concentration of acidity pH in the hydrological compartment 1 (HC1) is present (Figure 2). This same compartment presented levels of turbidity, color, and total iron out of the PRC threshold [33] (Supplementary Material and Figures 3, 5 and 6).

3.1.5. Correlation Analysis

The chart on 7, 8, and 9 contains the star plots of seven water parameters. The variable list for the sample star plot is Total Dissolved Solids (TDS), Temperature (Temp), pH, Oxi-redox potential (ORP), Electric Conductivity (Cond), Turbidity (Turb), and Dissolved Oxygen (OD). The plots were analyzed individually to identify clusters of the water parameters with similar features. The star plot of the water quality parameters compares the variables during dry and wet seasons at the three hydrological compartments (HC1, HC2, and HC3). The star plot in Figure 7 predicts the concentration of the parameters in HC1 and their comparison with drinking water standards in each sample number. In the hydrological compartment 1 (HC1), there is a significant correlation in STD and Cond in SN1 and SN2. The SN3 was higher during the dry season than during the wet season.

The dissolved oxygen (OD) was higher on SN1, SN3, SN6, and SN8 during the wet season. This is likely a consequence of gas exchange with the atmosphere, agitation, rainwater recharge, and increased movement of the water stream, which improves the aeration capacity of this ecosystem. Dissolved oxygen concentration is one of the most important factors for maintaining biodiversity in surface waters [46] such as rivers and streams.

A constant relationship in HC1, regardless of the season, is Total Dissolved Solids (TDS) with Electrical Conductivity (Cond). There is a similar response of both parameters, and, when this does not occur, a significant reduction in turbidity is noted. This can be explained as described in water quality manuals where the dissolution of salts in water can result in electrolytes capable of conducting certain electrical current [23,46,47]. The temperature increase corresponds to a gradual increase in conductivity with a proportionality relationship [47]. All sample numbers (SN) show similar ecosystem performance, especially during the dry season. During the wet season, the correlation of the dissolved solids and conductivity became more evident.

In hydrological compartment HC2 (Figure 8), in general, the correlated comportment between dissolved solids and conductivity was similar for both wet and dry seasons. The parameters showed the similar concentration mainly during the wet season.

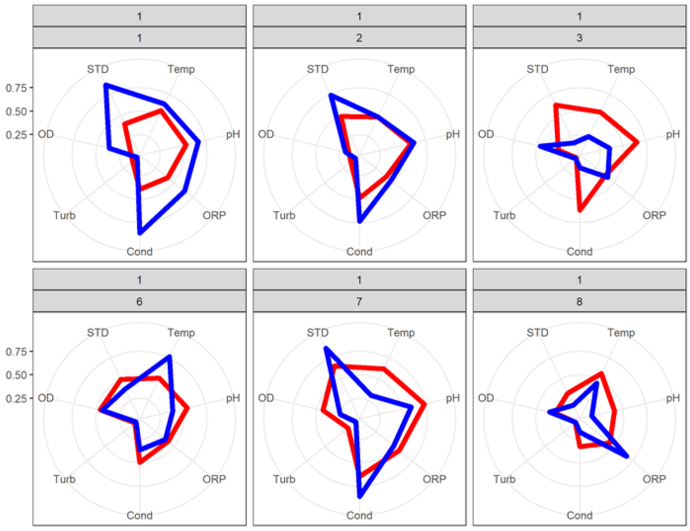

Figure 7. Correlation of water quality parameters during the wet and dry seasons in the hydrological compartment (HC) 1. Red line (dry season), blue line (wet season).

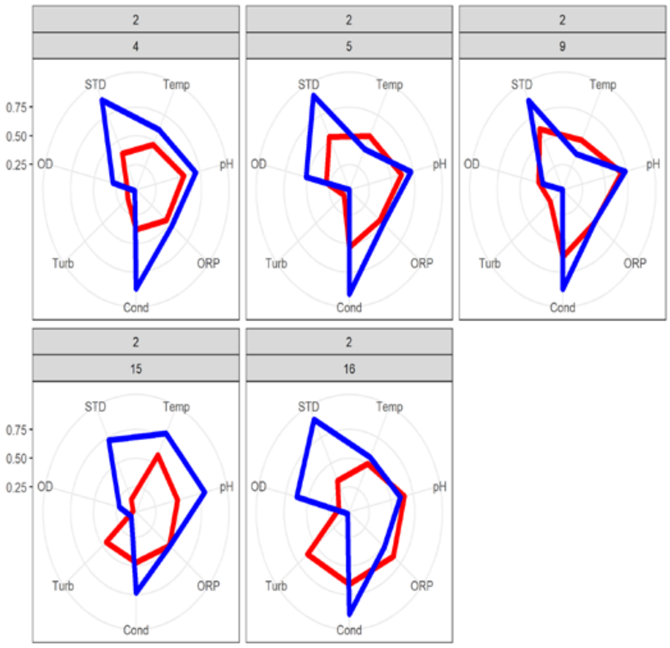

Figure 8. Correlation of water quality parameters during wet and dry seasons in a hydrological compartment (HC) 2. Red line (dry season), blue line (wet season).

The pH at all sample numbers from HC2 remained in the same ranges. However, the Oxi-Redox water Potential (ORP) had a different value when compared to HC1. The potential for oxir-reduction with the tendency of substances to receive electrons can be evaluated, and it is possible to determine the potential by the possibility of the microorganisms grown in the area by the values of the redox potential, as shown on research on ORP in environmental research [48]. The ORP values in this compartment were similar to the values studied [48], within this premise, in a sample of natural water at a pH of 7. Oxygen should be the main electron receptor when the measured redox potential is close to (and above) + 400 mV. When the ORP value is between +100 and +300 mV, all oxygen must have been consumed and the main electron receptors will be NO_3^- and Mn, respectively, with the most abundant products being nitrogen and ammonia in addition to solubilizing manganese in the form of Mn^{2+}. In more drastic anoxic conditions, ranging from 0 to –300 mV, the electron receptors will be Fe^{3+}, then SO_4, and, finally, organic matter and CO_2, which are generated as reduction products iron (II), sulfide, and methane, respectively. It can be characterized as stable for both seasons [44,48]. Where there is a greater availability of dissolved oxygen (OD), there is an increase of ORP, which is a clear correlation in both climatic periods in this compartment.

In hydrological compartment 3 (HC3) (Figure 9), there is a similar result of the correlations that occurred on HC1 and HC2. All sample numbers have a low correlation to turbidity except on sample number 11, which is a lagoon from which sand has been extracted for years. At this point, it is possible to notice what differs from all the sample points, with low correlation on turbidity (Turb) and high correlation during the wet season for STD and pH. Similar results were found in a natural water reservoir [49,50].

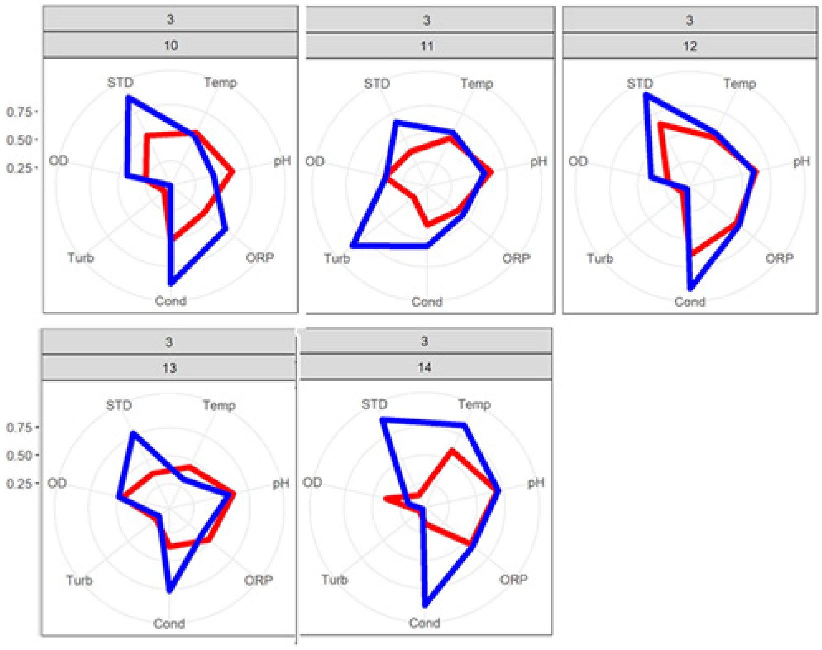

Figure 9. Correlation of water quality parameters during wet and dry seasons in the hydrological compartment (HC) 3. Red line (dry season) and blue line (wet season).

In all three hydrological compartments, there was a correlation between STD, pH, Cond and OD, mainly during the wet season. Similar results were verified in natural and anthropic influences on groundwater quality of public wells in São Paulo State, Brazil [28,47,50]. It was observed in all studied sample numbers an increase of the concentrations of the parameters evaluated, mainly during the wet season. In the summer, there is a shorter dwell time of water in the water table [50,51]. This is explained by the lower percolation of rainwater. Thus, it is understandable to increase the values of the physicochemical parameters evaluated during the wet season.

Considering all the parameters evaluated, the inequalities in access to water is verified and should aggregate contextual aspects of the ecosystem during dry and wet seasons and in the demographic perspectives, which reflect the intrinsic characteristics of the Atlantic Forest Biome dynamics and the relationships that are established daily in the water resource use and anthropized rural area. The view toward increasing inequalities in the access to water and the concentration of the deficit in certain rural communities corroborates the research in the Brazilian northeast area in underground flows of nutrients and trace metals [21,26,43].

The water supply system in the area must improve, mainly in treatment for drinking water, and from the aquifer [52]. Considering the inequalities in accessing better quality drinking water, the water security assessment is not present and significant progress is expected from the government to determine the vulnerability to water access [7,18,23]. Assessments involving the treatment of water or a better land use management [53,54] to ensure better water quality is necessary to include basic services such as the water supply for multiple uses.

The contributions of the paper results in (1) providing further evidence on similar investigations by water monitoring those rural communities and by an environmental education service, (2) the paper introduces the land use problems of the anthropized rural areas in the Atlantic Forest Biome, (3) the results show an improvement on the performance measurements of a set of water parameter results and should encourage the view that the subsequent water quality mapping that is necessary for a water security system.

For instance, the Pernambuco government must be alert of the boundaries between unconfined/confined aquifers that mark the interfaces for recharge and, thereby, contaminants that must be included in a study of hydro chemical investigation of the aquifers to determine the trace and minor element anomalies and possibly delineation of the interfaces and its vulnerability [52,53].

The anthropogenic activities from the rural area at the Atlantic Forest Biome in Pernambuco contribute significantly to groundwater contamination and to a water security assessment of groundwater quality. The government must investigate the influences from anthropogenic activities on deep groundwater (SN11) reflected in two possible scenarios: mixing with deep geological features and vertical leakage of shallow groundwater. Additionally, intensive groundwater contamination treatment must be done and controlled by water supply companies. The public drinking-water supply using groundwater should be tested prior to being used for general consumption.

3.2. Microbiological Analyses

3.2.1. Coliforms

Presence/absence tests were performed for total and thermotolerant (fecal) coliforms in all samples studied in the established climatic seasonal periods. Ministry of Health Consolidation Ordinance No. 5 establishes water as unfit for human consumption in the presence of coliforms, which requires a maximum permissible (MPN)/100 mL of thermotolerant coliforms [33]. All studied sample numbers (SN1–SN16) presented fecal coliforms in their waters, which make them unsuitable for direct human consumption. The waters studied in this region should only be used for drinking water after a previous disinfection water treatment.

Although water does not naturally provide conditions for the proliferation of pathogenic organisms, they survive long enough in the environment to occur in the water transmission [55]. Therefore, the presence of pathogenic microorganisms in water comes from the contamination by the anthropized area [55,56] from animal or human feces, which results from infiltration and wastewater among others [10].

The studied region does not have basic sanitation structures in the area of influence of this study. The study area receives impacts with the exploitation of sand. The population uses septic tanks as a sewage system including many without adopting the safe distances for the installation of such systems.

It is also emphasized that, in areas near the collection sampling sites, there is livestock breeding, and, in some of them, there is no proper sealing of the wells.

The contamination of water in an anthropized rural area from the Atlantic Forest Biome is not favorable since, in the studied area, risks of contamination can occur from the reservoirs or even in the distribution networks created by the residents since the urban supply system does not reach these areas [55–57]. Thus, it is common for distinct sources of contamination to occur [57].

Pathogenic agents have several properties that distinguish them from other drinking water contaminants. If infection is established, pathogens multiply in their host. Certain pathogenic bacteria are also able to multiply in food or beverages, and, thereby, perpetuate or even increase the chances of infection. The water studied must have a water quality verification that complements operational monitoring and assessments of contamination risks such as through auditing of treatment works and evaluating the process control and sanitary inspection. Water intended for human consumption should contain no indicator organisms. In most cases, monitoring for indicator bacteria provides a high degree of safety because of their large numbers in polluted waters [55–57].

3.2.2. Heterotrophic Bacterial Count

The Brazilian Ministry of Health Consolidation Ordinance No. 5 performed bacterial counting test analyses, which established a maximum permitted number of less than 500 CFU/mL [33]. From all sample numbers, six presented adequate values within the potability standards. They are the sample number 1, 6, 7, 8, 10, and 15. All other sample numbers presented inadequate values for human consumption. This is an important result because contaminants indicate a high probability of pathogenic microorganisms occurring in water [55]. Microorganisms responsible for gastroenteritis may occur, which are infections that have diarrhea as their main symptom.

3.3. Heavy Metals

Heavy metals are harmful for freshwater ecosystems such as fish communities, and, therefore, can also be harmful to humans if they enter the food chain through the fish [53,54]. The Brazilian Standards for drinking water are established in the maximum permissible physicochemical parameter's concentrations [33]. Based on those values of the analyzed sample numbers (SN 1 to SN16), the heavy metal (Lead (0.01 mg/L^{-1}), copper (2.00 mg/L), total chromium (0.05 mg/L), zinc (5.00 mg/L), cadmium (0.005 mg/L)), sulfates (250.00 mg/L), nitrate (10.00 mg/L), nitrite (1.00 mg/L), total hardness (500.0 mg/L), aluminum (0.20 mg/L), and ammonia (1.5 mg/L) had established an acceptable range for drinking water [21,33].

4. Conclusions

The water quality in all studied sample numbers and hydrological compartments was not according to drinking water standards related to the parameters established by the PRC n°5.

Drinking water sources in the rural area are contaminated, which can cause sickness and disease from pathogens. The presence of fecal coliforms is the most serious alteration in the quality of these waters since it configures contamination by pathogens that can lead to gastrointestinal diseases.

Drinking water sources are subject to contamination and require appropriate treatment to provide safe drinking water for their communities.

The color, pH, turbidity, and total iron parameters are the physicochemical parameters that classify, together with the microbiological ones, the waters studied as unfit for human consumption.

None of the collection sample numbers presented alterations for the analyzed heavy metals.

There was a significant change in water quality between the dry and wet seasons, which comes with a similar quality pattern throughout the year. There was an increase in the values of some of the specific physicochemical parameters during the wet season.

In all three hydrological compartments, there was a concentration of different chemicals of interest not suitable for drinking water. Assessing water quality must involve monitoring the chemical concentrations in a government baseline concentration in a guideline established to protect human health or ecological communities.

The anthropized rural area from the Atlantic Forest Biome affects water quality. The Pernambuco water supply system must implement a regional simplified water treatment, so that people in the rural area can have access to better quality water. This would solve many of the water quality changes assessed in this paper.

For a water security assessment of groundwater quality, practices can be adopted for effective improvement of water quality evaluated in this research regarding the development of environmental public policies that monitor the quality of water used by the population in the region or the increase of the water and sanitation distribution network. Environmental education and the regulation of wells and cacimbas used by communities in the area are also key practices to ensure water quality within the parameters.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/3/623/s1, Table S1: Raw water maximum, minimum, average, and stand deviation measured values at each compartment (HC).

Author Contributions: Conceptualization: I.F.B.V., F.C.R.N., R.d.B.V.P., A.M.C.; Methodology: I.F.B.V., F.C.R.N., M.N.C., K.S.d.S.; Software: I.F.B.V., R.C.A.C.; Validation: I.F.B.V., F.C.R.N., R.C.A.C.; Formal analysis: I.F.B.V., F.C.R.N., A.M.C., M.N.C., R.d.B.V.P., T.C.T.P.; Investigation: I.F.B.V., F.C.R.N., A.M.C., T.C.T.P., F.A.L.P., L.F.S.F.; Writing—original draft preparation: I.F.B.V., F.C.R.N., A.M.C., T.C.T.P.; Writing—review and editing: F.C.R.N., F.A.L.P., L.F.S.F., A.M.C., T.C.T.P.; Supervision: F.C.R.N., A.M.C.; Project administration: F.C.R.N., A.M.C.; Funding acquisition: F.C.R.N., F.L.P., L.F.S.F., T.C.T.P. All authors have read and agree to the published version of the manuscript.

Funding: The present study was carried out within the framework of the Post-Graduation Research Programme of Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). For the author integrated with the CITAB Research Centre, it was further financed by the FEDER/COMPETE/POCI—Operational Competitiveness and Internationalization Programme, under Project POCI-01-0145-FEDER-006958, and by the National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UIDB/AGR/04033/2020. For the author integrated in the CQVR, the National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UIDB/QUI/00616/2020, supported the research. Land Use Policy Research Group – PolUS/UNESP/CNPq/Brazil.

Acknowledgments: We acknowledge administrative and technical support for sampling and water analyses and materials used for experiments from the Universities Laboratories, and Polo Regional Centro Norte, Pindorama in name of the Antonio Lúcio Mello Martins for helping in field sampling.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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Influence of Small Hydroelectric Power Stations on River Water Quality

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Received: 29 November 2019; Accepted: 16 January 2020; Published: 21 January 2020

Abstract: Hydropower electricity generation is considered one of the cheapest technologies regarding electricity generation costs, and it is the most traditional, clean, renewable energy source. However, despite the environmental benefits offered by hydropower, they also can have negative impacts and consequences in the environment affecting water quality and disrupting river ecology. We investigated the environmental effects of four small hydropower plants (SPH) in north-west Spain by looking at the water quality of the four river stretches where the SPH plants are located. The physicochemical and biological characteristics of the water streams were analyzed, as well as the riparian ecological quality. Results showed that the presence of the hydropower plants did not significantly influence the physical and chemical characteristics of the water. There were no alterations of the benthic macroinvertebrate community at any of the plants except for one, and the riparian habitat was in general classified as good quality or close to natural conditions for all plants.

Keywords: hydroelectric power; physicochemical parameters; Iberian Bio-monitoring Working Party index; riparian forest quality

1. Introduction

Between 2010 and 2040 energy demand is expected to increase by 56% worldwide [1], particularly, oil demand which is estimated to increase in countries, such as Brazil, China and India [2]. This is mainly due to the world's population unprecedented growth rate. According to the United Nations, by 2050, the world population will reach nine billion [3]. Fossil fuel combustion is currently the main source of energy production.

Two-thirds of the world's greenhouse gas emissions are produced by burning coal, natural gas and oil [4]. Anthropogenic greenhouse gas emissions are linked to climate change and human health problems [5]. Each year, more than 30 billion tons of carbon dioxide (CO_2) are released into the atmosphere [6], and around 65% of the world's excess mortality—The number of deaths caused by a specific condition or exposure to harmful circumstances is directly associated with fossil fuel-related emissions [5]. According to The Lancet Commission on Pollution and Health [7], 9 million premature deaths were associated with pollution in 2015, representing 16% of all deaths worldwide. Environmental problems, such as ozone depletion, forest destruction and acid precipitation are direct consequences of the use of fossil fuels [8]. As suggested by the 2015 Paris Agreement, the average global temperature increase should be limited to 1.5–2 °C above pre-industrial levels [9] to avoid dangerous climate change. This will require measures, such as the phase-out of fossil fuels and geoengineering methods, such as CO_2 removal [10]. These options, however, raise issues, such as the costs involved, the environmental consequences and the process effectiveness [11,12]. In addition, Raftery et al. (2017) [13], estimated that global temperature increase would be between 2.0 and 4.9 °C by 2100, with a 5% chance that it will be less than 2 °C, and 1% chance that it will be less than 1.5 °C.

In the European Union, where electricity demand is growing, 40% of total energy consumption comes from the electricity sector [14,15]. In Europe, there are 450 GW of fossil-fuelled power plants, 200 GW each of coal and gas, and 50 GW of oil. These plants supply 40% of Europe's electricity, but release 1.4 GT of CO_2 emissions each year, which account for 30% of Europe's total emissions [15]. In Spain, 70% of the total energy consumption comes from abroad, and half of the energy generated in the country is supplied by imported combustible fuels [16]. This high energy dependency can cause problems of energy supply and affect wholesale electricity prices as these are linked to international combustible prices.

Renewable energy has been of interest since the oil crisis in the early 1970s [8]. Renewable energy technologies produce energy by converting natural resources into different types of energy. These technologies use the energy inherent in sunlight and its direct and indirect impacts on the Earth, such as wind, falling water, heating effects, and plant growth, gravitational forces, such as tides, and the heat of the Earth's core as the resources from which they produce energy [17]. Renewable energies have a positive impact in issues, such as the depletion of non-renewable energy sources, environmental problems (e.g., acid rain, ozone depletion) and the increase of energy use in developing countries [18]. They can supply-two thirds of global energy demands, and in combination with higher energy efficiency, could deliver 94% of the greenhouse emissions reduction that is necessary to comply with the Paris Agreement [19]. Moreover, the ability to access affordable energy at any time in the future is one of the main drivers for sustainable energy [20]. Because of this, renewable energies play an important role by contributing to mitigate climate change and is regarded as a potential solution to the environmental problems caused by the use of fossil fuels. In Europe, renewable energy development has been part of energy policy since 1986 when the Council of Europe established as one of its main targets to promote renewable energy sources direct [21]. The TERES II report, which aims to provide an update on renewable energy in Europe, estimated that by 2020 renewable energy could contribute as much as 14% of Europe's primary energy, creating around 500,000 jobs [22].

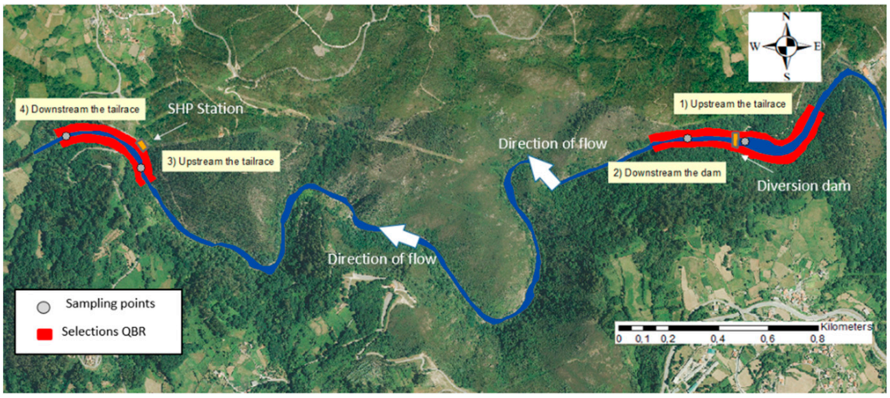
Hydroelectric power, known as hydropower, which is obtained by harnessing the power released when water passes through a vertical distance, has its origins in the pre-industrial revolution [23]. Hydropower electricity generation is considered one of the cheapest technologies regarding electricity generation costs [20], and it is the most traditional, clean, renewable energy source [24]. Hydropower plants have the capacity to respond to different energy demand fluctuations much faster than other systems, and they are able to convert direct mechanic work into electricity, making this technology highly efficient [20]. Hydropower is the leading source of renewable energy accounting for up to 70% of the world's supply [25]. However, despite the environmental benefits offered by hydropower, they also can have negative impacts and consequences in the environment, such as deforestation, aquatic and terrestrial biodiversity loss, affecting water quality and disrupting river ecology [26,27]. Yüksel [28] show that under the Renewables Scenario, 7250 MW of gas-fired capacity is substituted for 19,250 MW of wind and 1107 MW of small hydro over 2000–25. By 2025, all renewables combined (including large hydro) amount to more than 54 GW or 35% of installed capacity.

Although the energy industry in Galicia (Northwest of Spain) contributes to 8% of the region's gross domestic product (GDP) and is one of the main sources of employment, 77% of the region's primary energy is imported [29]. Due to its geographical location, Galicia has the potential to harness renewable energy through wind power, hydropower and biomass. In this work, we focus on hydropower and its effects in the ecosystem. Despite the environmental benefits of the small hydropower plants (SHP), they could negatively affect the ecosystem altering the natural hydrologic regime and the water quality, as well as the fish passage [24]. The aim of this study is, therefore, to investigate the environmental effects of four small hydropower plants (SHP) in north-west Spain by looking at the water quality of the four river stretches where the SHP plants are located. The physicochemical and biological (Iberian Bio-monitoring Working Party index) characteristics of the water streams of the SHP are analyzed, as well as the riparian ecological quality (QBR index). Based on the study of these two indices, it is intended to analyze how SPH affects the whole ecosystem in which they are found.

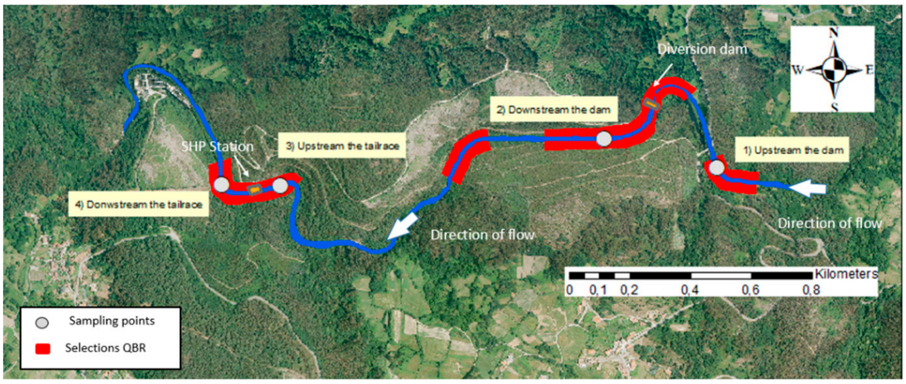
2. Materials and Methods

2.1. Study Areas and Parameters Studied

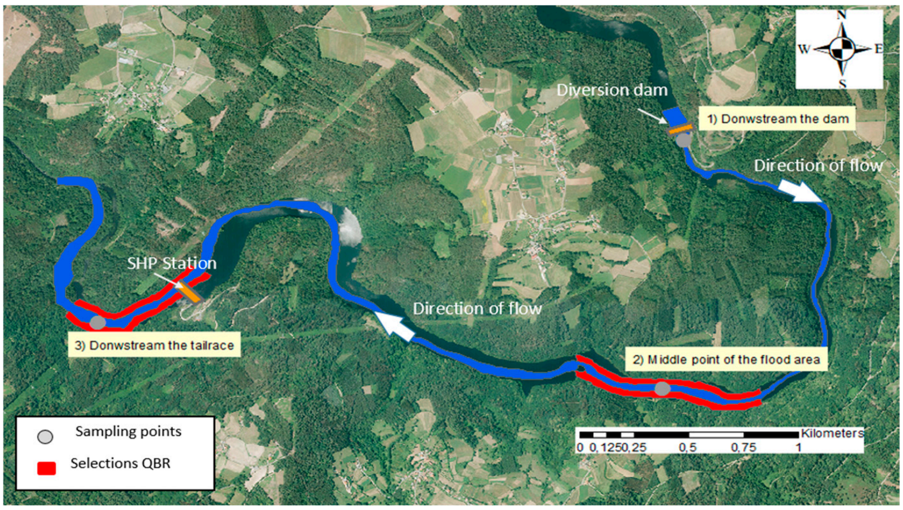
The SHP plants are located in the towns of San Xusto (UTM: 29T 539378.405; 4708387.927), Hermida (UTM: 29T 537226.719; 4716799.905), Touro (UTM: 29T 562005.977; 4742137.597), and Gomil (UTM: 29T 580284.87; 4786188.633), in the Lerez, Umia, Ulla and Mandeo rivers, respectively, all of them in Galicia (Figure 1).



(**a**)

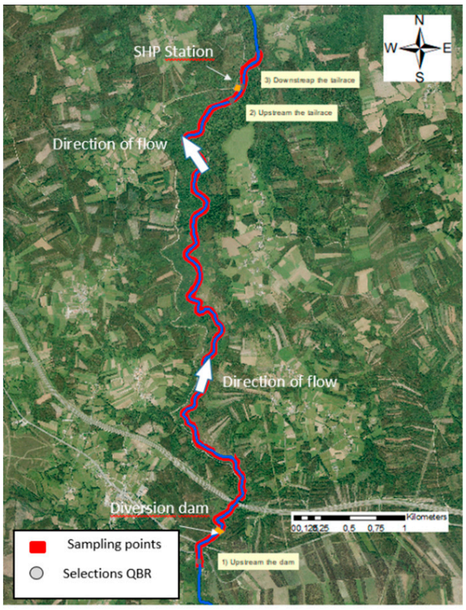


(**b**)



(**c**)

Figure 1. *Cont.*



(**d**)

Figure 1. Location of the sample points. (**a**) Lerez river (**b**) Umia river (**c**) Ulla river (**d**) Mandeo river. Environmental characteristics assessed, parameters and index used, and location of the sampling points (grey circles). Riparian habitat sections, where the QBR (riparian forest quality index) was calculated (red).

The SHP plants consist of a diversion dam that blocks the river and diverts the water, a pipeline that draws the water from a higher level to the powerhouse, a penstock and a powerhouse building. The total power production of the San Xusto, Hermida, Touro and Gomil plants is 11.81 MW, 2.916 MW, 12.81 MW and 9 MW, respectively. The total production of the San Xusto, Hermida, Touro and Gomil plants is 37.81 GWh/year, 9.14 GWh/year, 30.89 GWh/year and 22.82 GWh/year, respectively. The ecological status of the stream water around San Xusto was previously studied and analyzed in Valero [24], and it is included in this work for comparison with the other three SHP plants.

The Directive 2000/60/EC by The European Parliament [30], which establishes the framework in the field of water policy within the EU, was used in this work to assess the water status affected by the SHP plants. Thus, some of the water quality elements described in the directive were considered for this study. The physicochemical parameters taken into consideration were water temperature (T, °C), conductivity (mS/cm), dissolved oxygen (DO, mg/L) and pH (Figure 2).

The Iberian Biological Monitoring Working Party index (BMWP) score system was introduced in 1980 to provide an index of river water quality for England and Wales based on aquatic macroinvertebrates, was used to assess the biological quality of the water [31,32] (Figure 2). To do this, the taxa of macho-benthonic fauna found in the sampled areas were identified to the family level, a predefined score was allocated for each family, and the total BMWP score for a sample was the summation of the scores of all the families found. The scores of the BMWP (0–>100) were grouped in 5 quality classes [31]. In Ulla river, the Iberian Bio-monitoring Working Party index (IBMWP index) was applied in 1 and 3 sample sites because 2 and 4 were very deep waters, due to the embalming effect. The conditions are not suitable for collecting macroinvertebrates. IBMWP scores were then compared with conditions in Cantabric-Atlantic quality elements at high ecological status [33]. This index obtained optimal results in Thailand [34] United Kingdom [35], among others.

The Riparian Forest Quality index (QBR) was used to assess the ecological quality of the riparian habitats [36] (Figure 2). This index varies between 0 and 100, and it is based on four components of riparian habitat: Total riparian vegetation cover, cover structure, cover quality and channel alterations for the different geomorphology of the river from its headwaters to the lower reaches. After completing the analysis, the sum of scores for the four components gives the final QBR index. The QBR index, despite being developed for Mediterranean forests can be adapted to other types of riverside forests, as they have done in other studies [37–39].

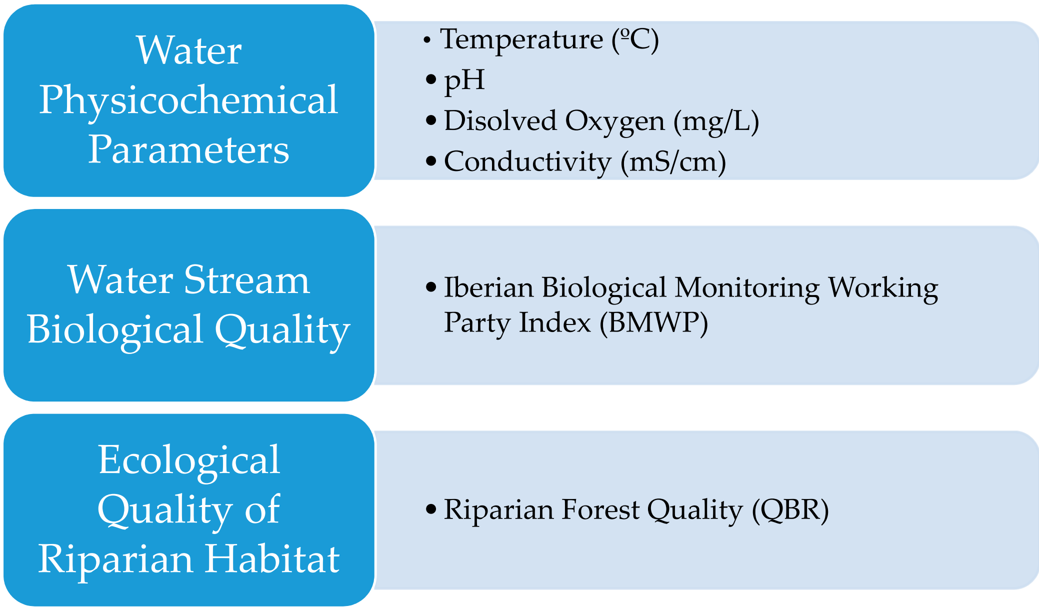


Figure 2. Schematic overview of the methodology.

2.2. Sampling

Four sample points each were selected at San Xusto and Hermida, and three sample points each were selected at Touro and Gomil. The points were selected in areas properly accessible and free of operational risks. A GPS GPSMAP 60CSx (Garmin, Olathe, KS, USA) was used to register the position of the sampling points.

The YSI 556 Handheld Multiparameter Instrument (YSI, Yellow Springs, OH, USA), was used to measure the water's physicochemical parameters in each sampling point. Different sensor types were used: The YSI Temperature Precision™ thermistor, the 4-electrode cell with auto-ranging, the steady-state polarographic, the platinum button, and the glass combination electrode. It was first submerged in the watercourse for twenty minutes for stabilization, and later left submerged (5 m deep) for another twenty minutes, while registering in order to obtain representative data. Measurements were made at the same time of the day.

To analyze the biological quality of the water using the IBMWP index, a 50 m radius from the points were sampled. Point 1 at San Xusto, and point 2 at Touro were not sampled, because it was not easy to obtain enough representative data. Pictures were taken of all the sampled areas and the locations were registered with a GPS. The different types of habitats were identified according to depth, flow velocity, substratum, and vegetation. Then, each habitat was sampled for benthic invertebrates, and captures were identified over a white tray on the field using an atlas and identification key. After the identification, specimens were released back into the river. Benthos which could not be identified in the field were kept in bottles with alcohol at 70% to be identified at the laboratory.

To calculate the QBR index, the Munné protocol [36] was followed, but with some modifications to be adapted to the tree species composition of our study area. A river stretch of 400 m around the dam, and another river stretch of 650 m around the SHP plant and tail race were selected. These reaches were divided into sections with similar characteristics, and the QBR was calculated for each one. Points between two sections with different QBR were located with GPS. We calculated one QBR index for each river bank. Based on the index, it is not necessary to apply it to all the banks, but it is recommended to choose strategic points according to their characteristics. In this study, the riparian vegetation was evaluated in the points where some direct affections were made (because of the construction phase). Intermediate points were considered in these cases where topographic conditions allow access to the river. In this last case, the embalming of the waters, due to the installation of the plants, will make the vegetation to change. However, it will be necessary for a considered period of time to evaluate these changes. The sampling period was carried out between December 2007 and November 2010. The physicochemical parameters and the biological quality of the water were sampled every three months, in March, June, September and December. Directed sampling has been performed—simple samples were collected in triplicate, and at the points already described. The samples were collected in amber borosilicate glass bottles previously washed with sample water. The QBR index was calculated every six months, in March and in September.

2.3. Analyses and Statistics

The software Ecowatch was used to download and process all the physicochemical data and mean, standard deviation, maximum and minimum were calculated. At the laboratory, the macroinvertebrates collected were identified using a glass Motic ST-37 20–80 × (Motic, Xiamen, China). Mean values of each physicochemical variable of the series registered in each sampling point, as well as the IBMWP index, were plotted over time to assess if their values stabilized themselves across time, as well as to observe differences between points. Differences between years and points, as well as differences between the four SHP plants, were analyzed using Kruskal-Wallis tests. Kruskal-Wallis is a nonparametric statistical test that assesses the differences among three or more independently sampled groups on a single, non-normally distributed continuous variable [40].

3. Results

The Kruskal-Wallis tests show no significant differences for the physicochemical parameters of pH, temperature, dissolved oxygen and conductivity between sampling points and years for any of the four plants, except for the temperature at the Touro plant (Table 1). No significant differences were obtained for the four water quality parameters, since the data do not present irregularities over time.

Table 1. Kruskal-Wallis results for each of the physicochemical parameters for each plant.

Plants	Temperature (n = 12)	pH (n = 12)	Dissolved Oxygen (n = 12)	Conductivity (n = 12)
San Xusto (Lerez)	0.249, $p = 0.969$	2.452, $p = 0.484$	3.557, $p = 0.313$	0.642, $p = 0.887$
Hermida (Umia)	2.176, $p = 0.537$	0.960, $p = 0.811$	0.281, $p = 0.964$	0, $p = 1$
Touro (Ulla)	2.573, $p = 0.276$	7.896, $p = 0.019$	0.412, $p = 0.814$	0.293, $p = 0.8634$
Gomil (Mandeo)	0.530, $p = 0.767$	1.794, $p = 0.408$	1.963, $p = 0.375$	0.0858, $p = 0.958$

This is in agreement with other studies, such as those from [41,42]. Jesus et al. evaluated the impact of an SHP plant over a period of two years on the water quality of the Ardena river in Portugal, and found the presence of the hydropower plant did not significantly influence the physical and chemical characteristic of the water. Santos et al. also studied the effects of SHP plants in central and north Portugal and found no significant difference between the physicochemical parameters at the different study sites.

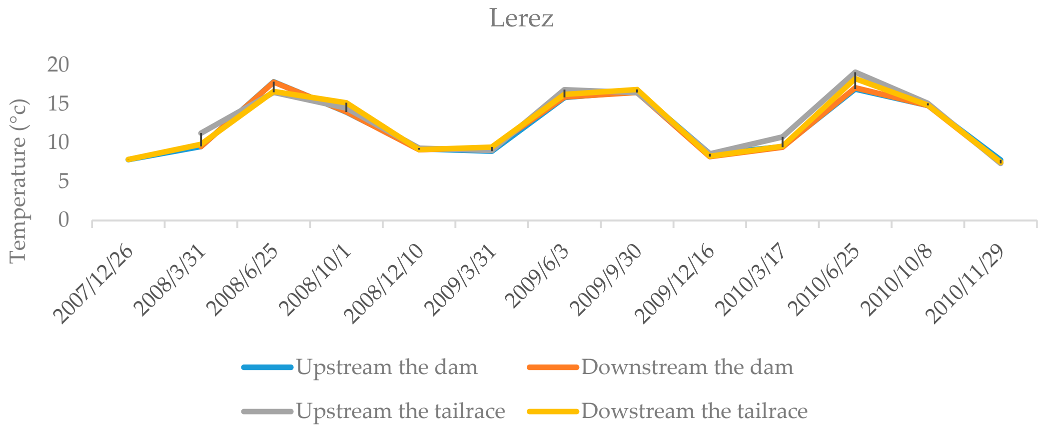
3.1. Temperature

Mean water temperature for the study period was 12.41 °C, 12.26 °C, 13.24 °C and 11.06 °C at San Xusto, Hermida, Touro and Gomil, respectively. Temperature values were in concordant with those from the Reference Condition in Cantabric-Atlantic siliceous rivers from IPH 2008 [43] (Table 2), where it is specified that the river's elements of this study belongs to the siliceous Cantabrian-Atlantic rivers.

Table 2. Reference Condition in Cantabric-Atlantic siliceous rivers.

Parameters	Reference Condition	Threshold Good/Moderate
Temperature (°C)	13.00	10.4–15.6
pH	7.00	6.0–8.4
Dissolved oxygen (mg/L)	9.00	6.7
Conductivity (mS/cm)	0.04	<0.03

These results also comply with the requirements of Directive 2006/44/EC [44] on the quality of freshwaters needing protection or improvement in order to support fish life, by which thermal discharges must not cause the temperature downstream of the point of thermal discharge to exceed 21.5 °C in salmonid waters. Temperature limits were not exceeded in any sampling point for any period in any of the plants (Figure 3). Directive 2006/44/EC also states that thermal discharges must not cause the temperature downstream of the point of thermal discharge to exceed 10 °C during breeding periods of salmonid species, which need cold water for reproduction and only to waters that contain such species. In Galician waters, the period when salmon breed extends from November to January [45]. Temperatures registered for all sampling points between November and January was below 10 °C at San Xusto, Hermida, and Gomil. The temperature at the Touro plant was above 10 °C in all points for two of the sampling periods. However, the Kruskal-Wallis test showed no significant difference between the temperatures recorded for all the points during the study period.



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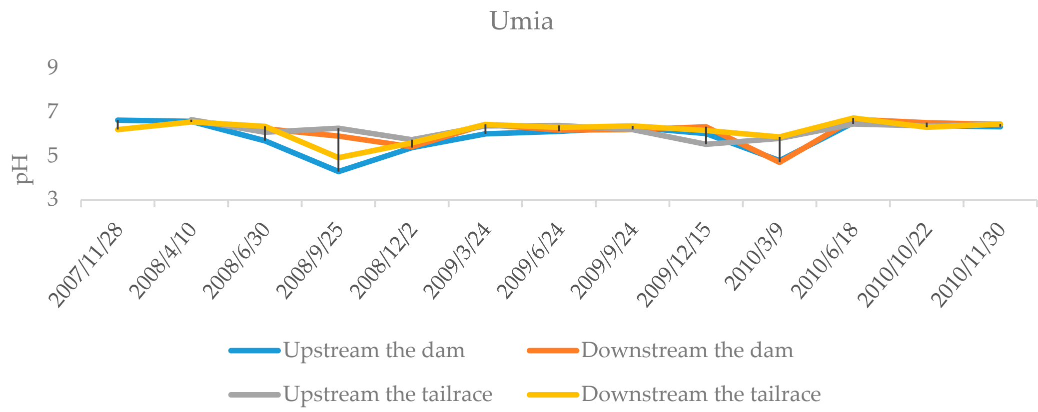

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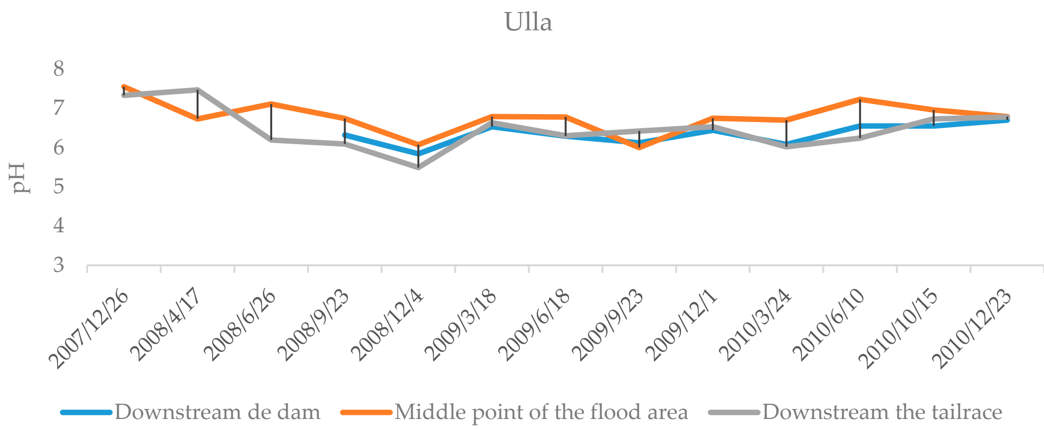

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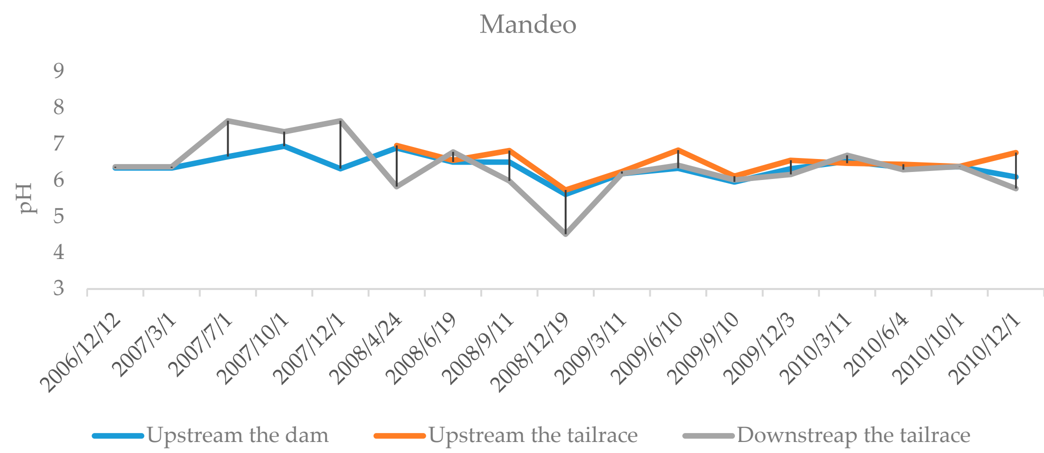

(**d**)

Figure 3. Temperature values measured during the survey period at (**a**) Lerez (San Xusto plant), (**b**) Umia (Hermida plant), (**c**) Ulla (Touro plant) and (**d**) Mandeo (Gomil plant).

3.2. pH

According to the Directive 2006/44/EC, artificial pH variations with respect to the unaffected values shall not exceed ±0.5 of a pH unit within the limits falling between 6.0 and 9.0 provided that these variations do not increase the harmfulness of other substances present in the water. At San Xusto and Hermida, low pH values were recorded in all four points close to the lower limit allowed for salmonid waters (Figure 4). However, mean pH values for all points for the sampling period was 6.02 and 6.09 at San Xusto and Hermida, respectively, which is within the limits established by the directive. In addition, there were no significant differences between all observations recorded in any of the two plants. Mean pH values for all points at Touro was 6.55, falling within the limits established by the Directive 2006/44/EC. There were only two observations at Touro, in points 1 and 3 recorded during the same period, where the pH value was below 6. Kruskal-Wallis test showed a significant difference between the sampled points. At Gomil, mean pH values for all points was 6.40, and there was no significant difference between the sampled points. However, some observations showed values below 6, but these were close to the limit allowed. According to Reference Condition (Table 2), the quality of the water for the four river starches can be classified as good/moderate.

The low pH values obtained for some of the points could be explained by the natural characteristics of the waters in Galicia, which are generally acidic [46].

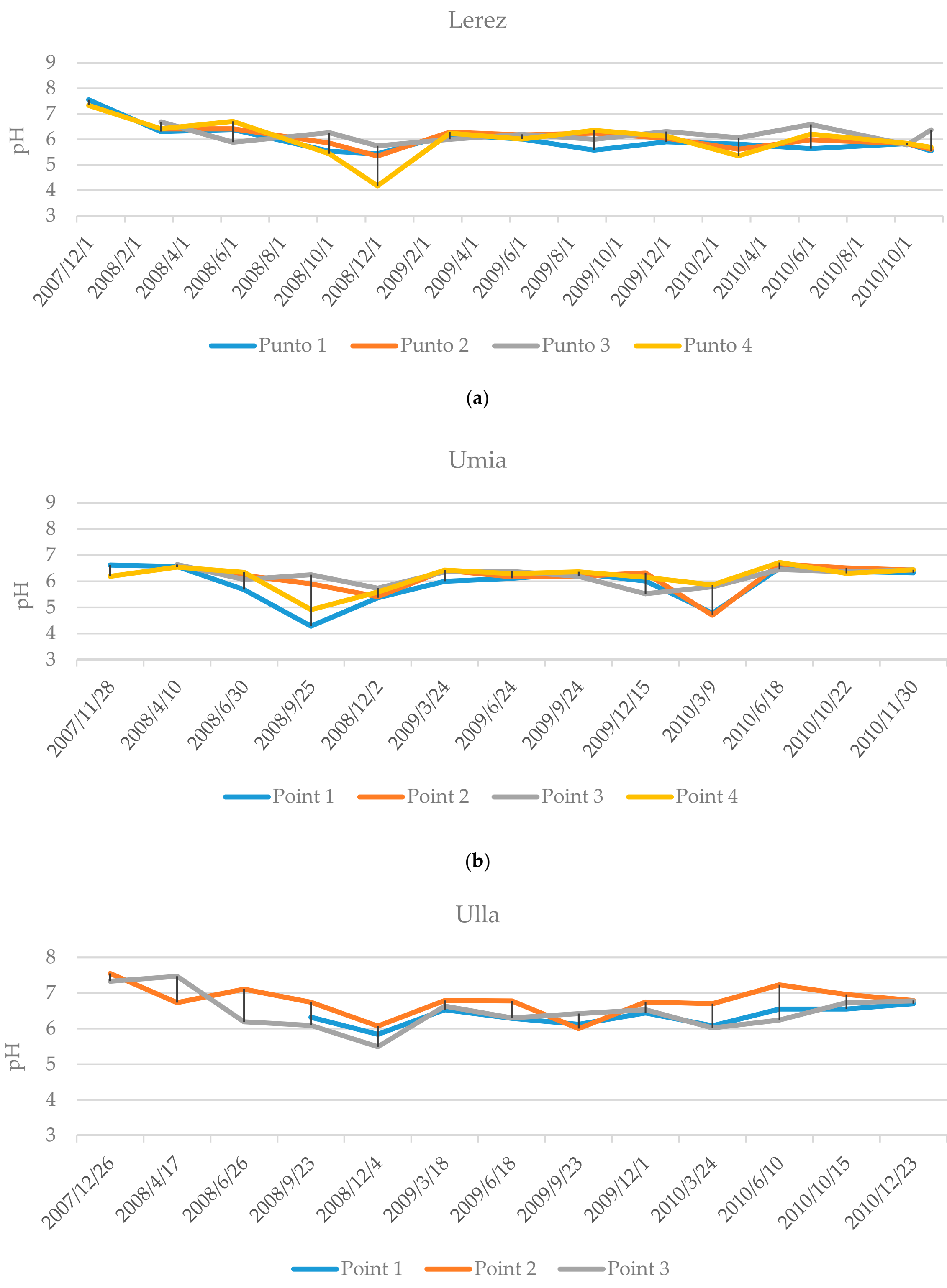

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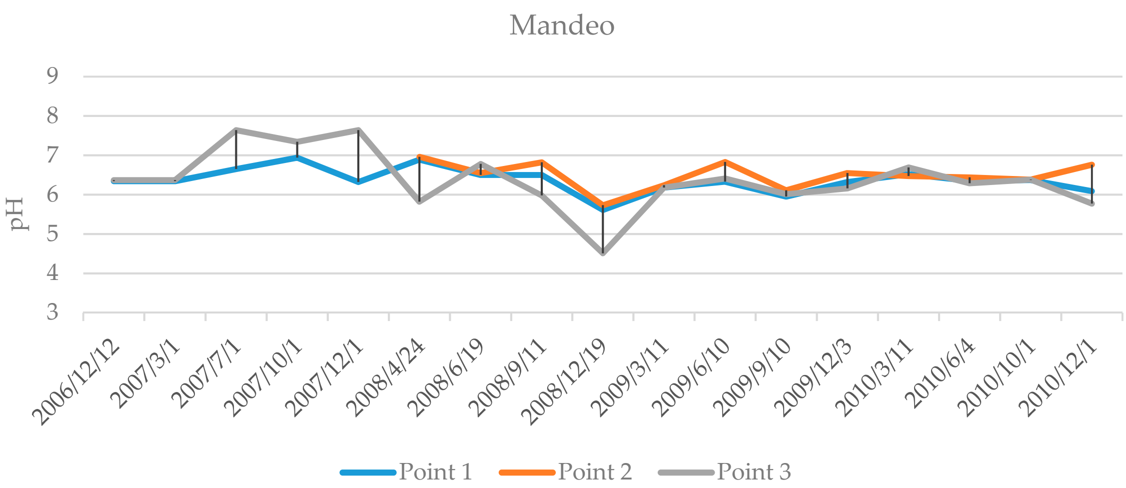
Figure 4. *Cont.*

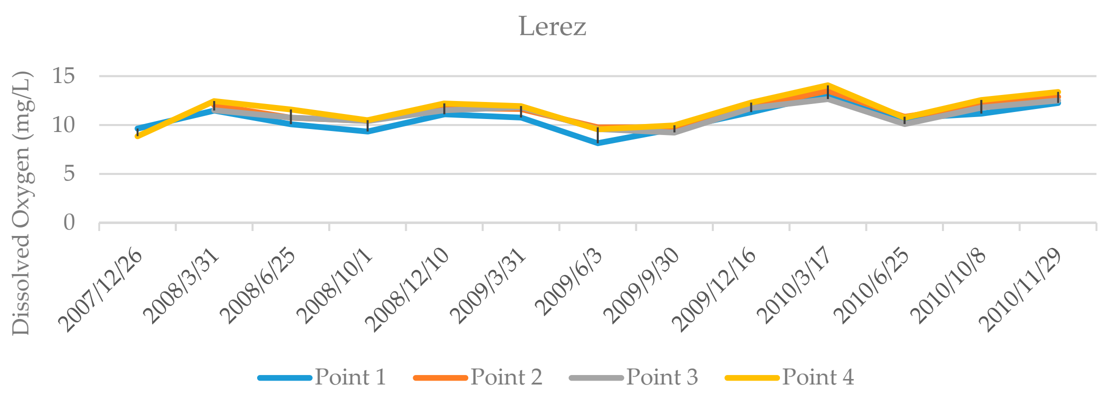


(**d**)

Figure 4. pH values measured during the survey period at (**a**) Lerez (San Xusto plant), (**b**) Umia (Hermida plant), (**c**) Ulla (Touro plant) and (**d**) Mandeo (Gomil plant).

3.3. Dissolved Oxygen

Mean dissolved oxygen values for the study period was 11.19 mg/L, 11.17 mg/L, 9.60 mg/L and 11.03 mg/L at San Xusto, Hermida, Touro and Gomil, respectively. These values were higher than the Reference Condition (Table 2). The results are in agreement with Directive 2006/44/EC, which states that the dissolved oxygen of 50% of the samples recorded must be equal or above to 9 mg/L. San Xusto plant had 96% of values above 9 mg/L, Hermida plant had 94% of values above 9 mg/L, Touro plant had 55% of values above 9 mg/L, and Gomil plant had 97.82% of values 9 mg/L (Figure 5). Results for the Kruskal-Wallis test show no significant difference between points during the study period for any of the plants. Dissolved oxygen concentration was inversely linked to temperature, which matches results from [41].



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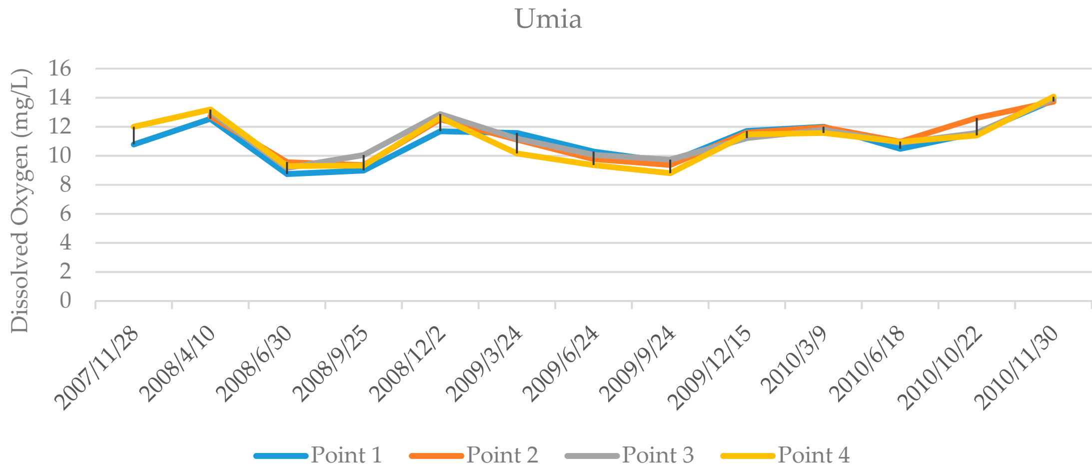

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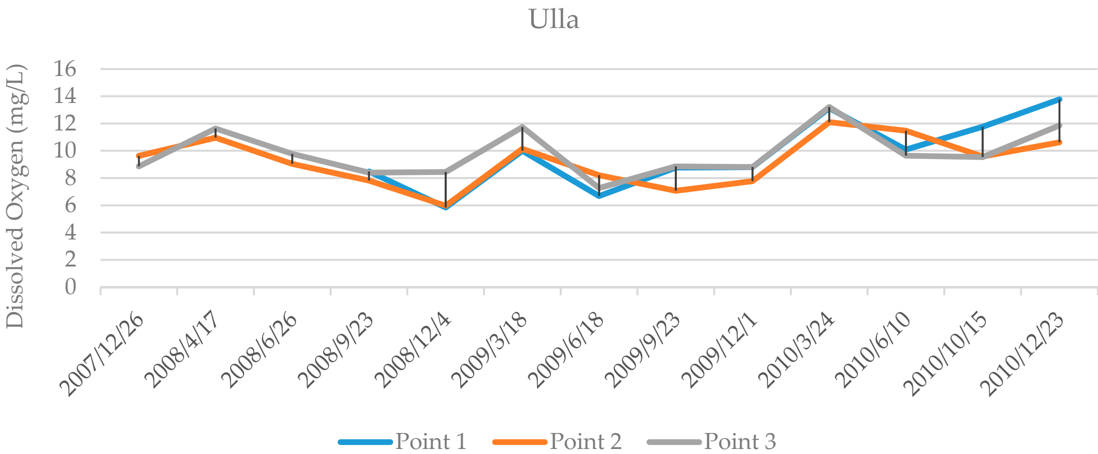

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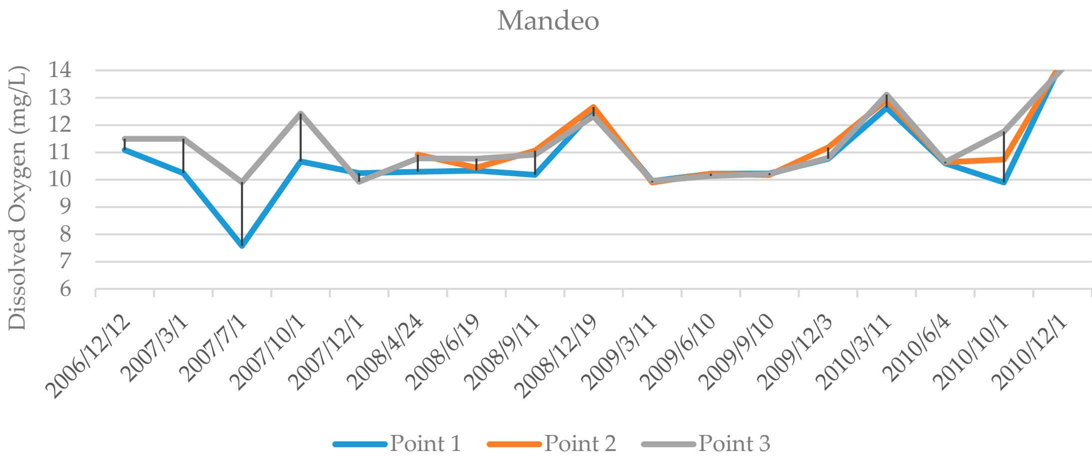


(**d**)

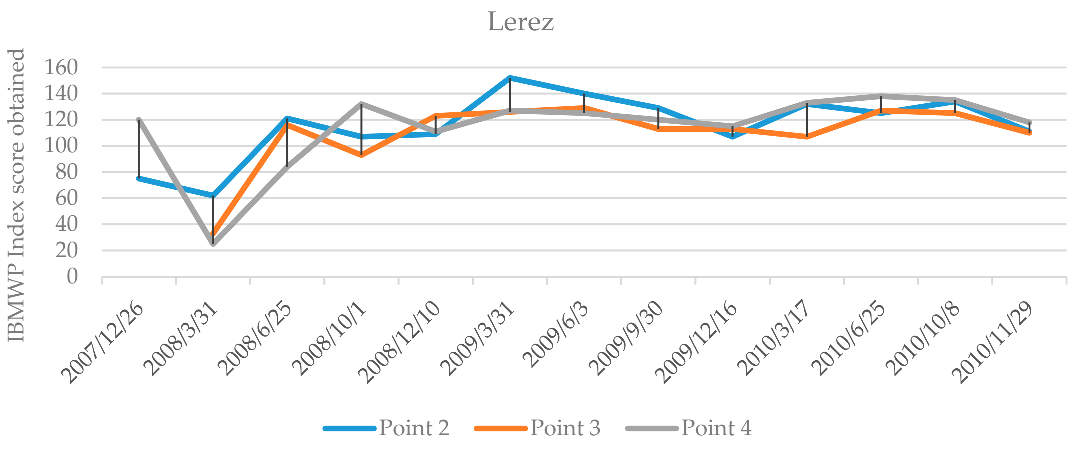
Figure 5. Dissolved oxygen values measured during the survey period at (**a**) Lerez (San Xusto plant), (**b**) Umia (Hermida plant), (**c**) Ulla (Touro plant) and (**d**) Mandeo (Gomil plant).

3.4. Conductivity

Mean conductivity values were 0.04 mS/cm at San Xusto and Hermida, 0.09 mS/cm at Touro and 0.07 mS/cm at Gomil. There were no significant differences between the points for any of the plants from the Kruskal-Wallis test. Our results are in compliance with the requirement from Reference Condition (Table 2) for San Xusto and Hermida, and are very close for Touro and Gomil. These results are also in agreement with previous studies from Costas et al. (2009) [47] and Ansemil and Membiela (1992) [46].

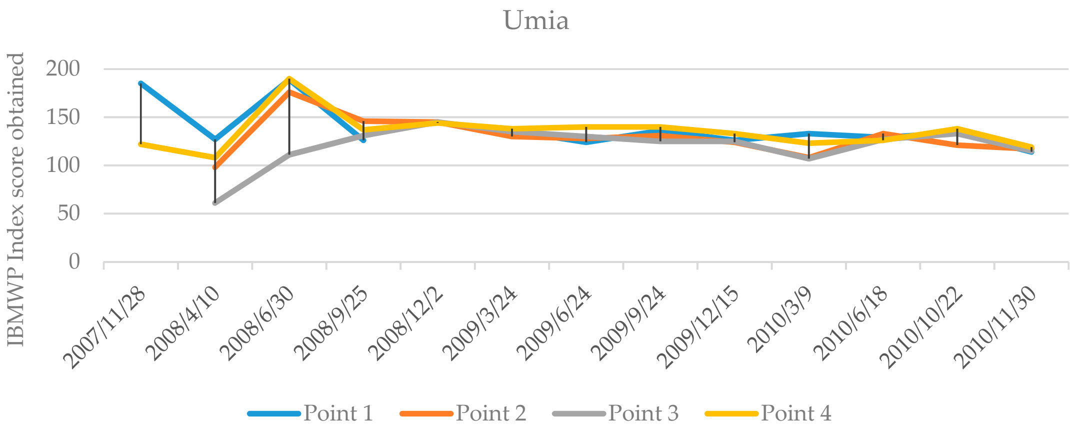
3.5. Biological Status of the Water

A total of 12 samples were collected for each river. At San Xusto, IBMPW index had a lower score at point 3, located upstream the power plant, than at points 2 and 4, although the Kruskal-Wallis test showed no significant differences between points (Kruskal–Wallis test = 1.756; df = 2; p = 0.416), and 86.84% of the scores fell within Quality I category (unpolluted or not consider altered water). At Hermida, Kruskall-Wallis test showed no significant differences between points (Kruskal-Wallis chi-squared = 3.800, df = 3, p-value = 0.283), and 95.91% of the scores fell within Quality I category. At Gomil, Kruskal-Wallis test showed no significant differences between points (Kruskal-Wallis chi-squared = 0.286, df = 2, p-value = 0.866), and 86.95% of the scores fell in the Quality I category. These results (Figure 6) are in agreement with some authors, such as Copeman (1997) and Almodóvar and Nicola (1999), [48,49], who found there were no alterations of the benthic macroinvertebrate community, due to small hydropower plants. At Touro, on the other hand, scores were very low, only 8.69% of them falling within Quality I category. Mann-Whitney test showed a significant difference between points ($p < 0.05$). In Point 1, all scores fell within Quality V category (waters highly contaminated), whereas, in point 3 most of the scores fell within Quality III category (evidence of some contamination). It is important to point out that the low scores obtained in point 1 are probably not, due to the low biological quality of the water, but rather to the lack of representative areas when the sampling was done.



(a)

Figure 6. *Cont.*



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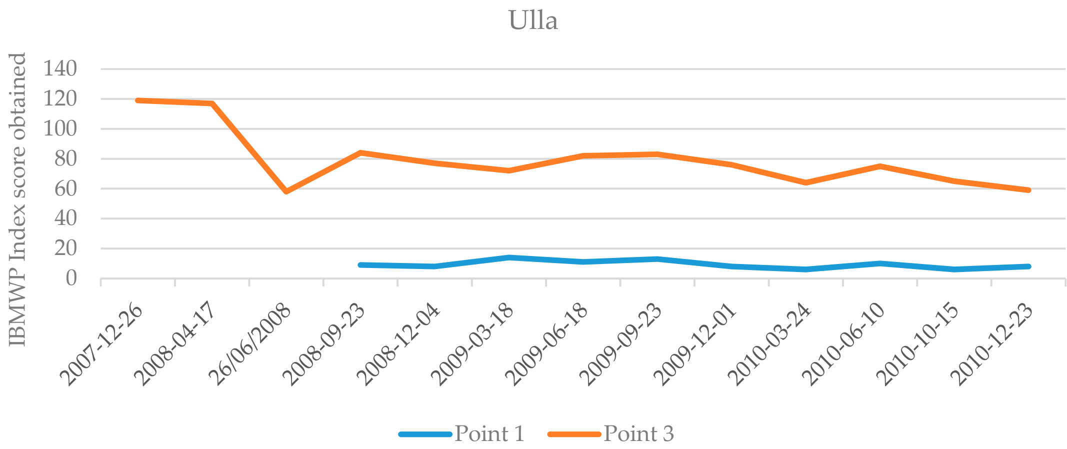

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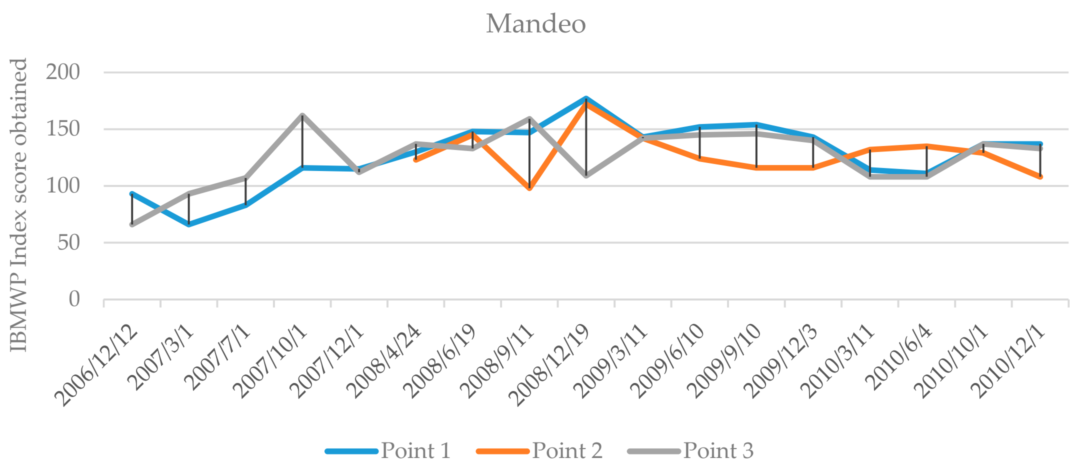

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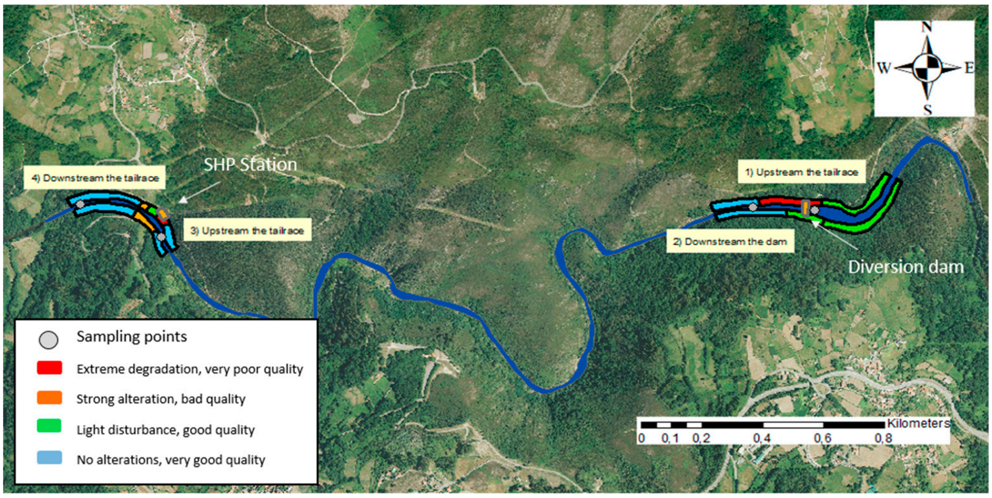
Figure 6. Evolution of the water biological quality index IBMWP during the period of study: I (>120) very clean waters; I (101–120) unpolluted or not considerably altered water; II (61–100) moderate effects of pollution are evident; III (36–60) polluted water; IV (16–35) very polluted water; V (<15) heavily polluted water, at (**a**) Lerez (San Xusto plant), (**b**) Umia (Hermida plant), (**c**) Ulla (Touro plant) and (**d**) Mandeo (Gomil plant).

3.6. Ecological Status of the Riparian Zones

A total of 7 samples were collected for each river. At San Xusto, the evaluation of the habitat according to the QBR index showed two river bank sections with extreme degradation and two with strong alteration, while in the remaining sections, the riparian habitat was classified as good quality or natural conditions (Figure 7). At Hermida, QBR index showed one section with extreme degradation, one section with strong alteration, while in the remaining sections, the riparian habitat was classified fair to good quality or even as having natural conditions (Figure 7). At Touro, the QBR index showed three sections with extreme degradation, while in the remaining sections, the riparian habitat was classified fair to good quality (Figure 7). At Gomil, the QBR index showed two sections with extreme degradation and four with strong alteration, while in the remaining sections, the riparian habitat was classified fair to good quality or even natural conditions (Figure 7).



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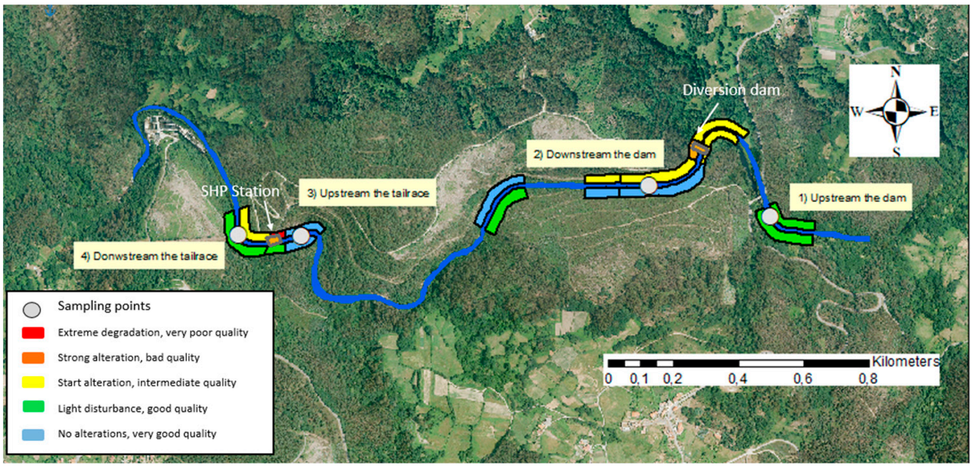

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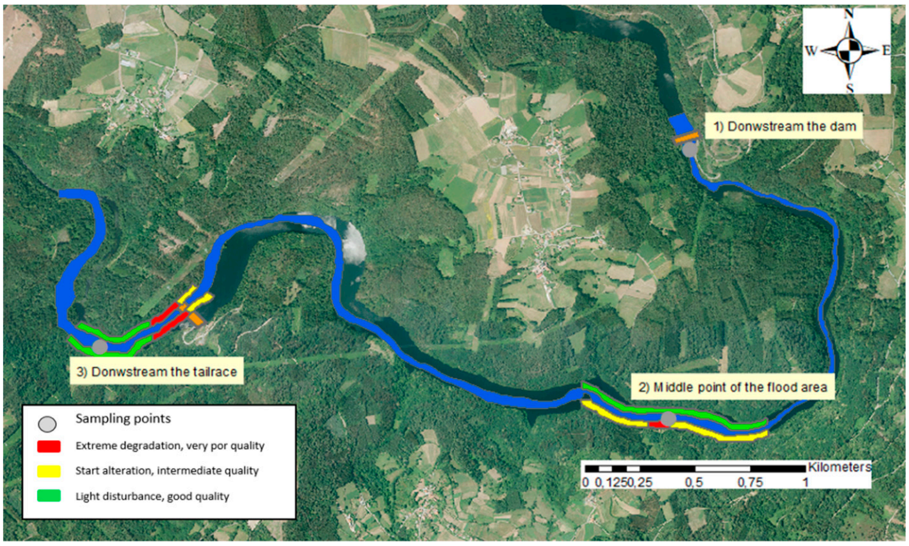

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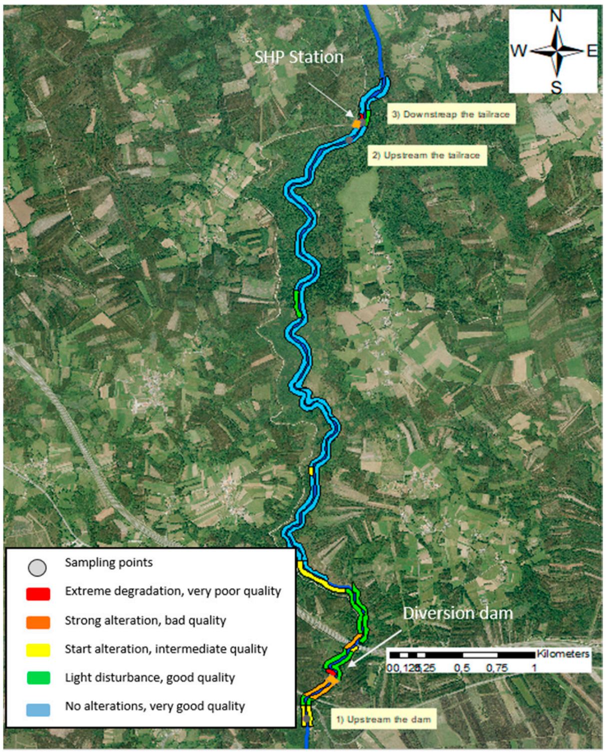

(d)

Figure 7. Riparian habitat quality index QBR in the reaches of the rivers (**a**) Lerez, (**b**) Umia, (**c**) Ulla and (**d**) Mandeo.

3.7. General Discussion

Renewable energies, such as the one provided by SPH are a clean source of energy. Regarding the four plants studied in the present work, it must be taken into account that their installation in the last decades was done without prior planning, and without any specific studies and analyses on the ecological quality of the river environment. Therefore, without these previous studies, it is very difficult to predict and know what impacts these SPHs have on the ecosystem.

For better planning, the idea would have been to carry out studies prior to the construction, and also during the different construction stages to have a better understanding of the final impacts.

These studies should have been planned in four distinct phases corresponding to: Phase 0 (prior to construction), construction phase, exploitation phase, and abandonment or dismantling phase.

In this way, we would have had information on how the ecosystem would change from its original state (on a small scale and on a global scale). We would also be able to know what impacts the construction works generate. The construction can generate environmental problems, such as spills and reduction of flows, which can have specific effects on some species. Finally, we could have made an evaluation of the evolution of the ecosystem once the plant began to work, so the impact of the operation of the plant itself (water diversion, heating of the water, etc.) would have been known. In the case of the long-term impacts that SPHs can cause, analyses over several years would be recommended.

Small impacts have been detected with this study, but they are short term since the sampling data are from 2007 to 2010. This study focuses on the impacts that the SPHs operation may have on the ecological quality of water and riverbank vegetation in the short term. What we want to highlight is that there are impacts that occur in the aquatic ecosystem, therefore, it is important to know to what extent they occur. In this way, preventive measures would be taken from the knowledge that these analyses can generate. On the other hand, to know the extent of these impacts, it is very important to have a large-scale data collection. In this way, water managers, energy companies and users., can make changes in their trends, consumption and models.

4. Conclusions

Results showed uniformity of the data obtained. Temperature limits were not exceeded at any point in any of the plants. Temperatures registered during the salmon breeding period was below 10 °C for all the plants with the exception of Touro. San Xusto and Hermida plants showed low pH values. However, mean pH at all the plants fell within the limits established. The low pH values obtained for some of the points could be explained by the natural characteristics of the waters in Galicia, which are generally acidic [50]. Mean dissolved oxygen values for the study period were in agreement with Directive 2006/44/EC, which states that 50% of the samples must be equal to or greater than 9 mg/L. Mean conductivity samples were in compliance with requirements outlined in Reference Condition for San Xusto and Hermida, and were very close for Touro and Gomil. The IBMPW results showed no alterations of the benthic macroinvertebrate community at any of the plants except for Touro, where scores were very low, although this could be explained, due to the lack of representative areas when the sampling was done. The riparian habitat (QBR index) was in general classified as good quality or close to natural conditions for all plants. The lack of data prior to the construction of the power plants is, in many cases, a limitation when determining their effects. It would be adequate to do the analyses with this information to have a complete picture.

Author Contributions: Conceptualization, X.Á. and E.V.; Data curation, C.A.-A.; Formal analysis, N.d.l.T.-R. and C.A.-A.; Funding acquisition, E.V.; Investigation, X.Á. and E.V.; Methodology, X.Á. and N.d.l.T.-R.; Project administration, X.Á.; Software, N.d.l.T.-R. and C.A.-A.; Supervision, X.Á.; Validation, X.Á. and E.V.; Writing—original draft, N.T.-R. and C.A.-A.; Writing—review and editing, X.Á. and E.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by TASGA. This work was possible thanks to the projects developed by the group AF4 for the company TASGA Renovables. Roberto Pérez Lodos and Juan Jesus Berzosa Aránguez from TASGA facilitated the work.

Acknowledgments: The authors are grateful to all the technicians participating in the samplings, as well as to Paula Rivas for her help.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Evaluation of the Stability and Suitable Scale of an Oasis Irrigation District in Northwest China

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Received: 28 August 2020; Accepted: 5 October 2020; Published: 13 October 2020

Abstract: Oases support human activities in arid and semiarid regions, and their stability is important for regional sustainable development and water resource management. Water consumption is the major factor affecting the stability of oases. On the basis of remote sensing images, evaporation and socioeconomic data, this study first evaluates the stability of the Dunhuang Oasis against the expansion of an oasis irrigation district and planting structure changes from 1987 to 2015. Next, it calculates a suitable area of the oasis irrigation district using water–energy balance theory. The results are as follows: (1) During the 1987–2015 period, with the expansion in the oasis irrigation area, the planting structure underwent a marked transformation from food crops to cash crops to orchards. Water consumption pattern likewise changed considerably. (2) The stability of the Dunhuang Oasis continued to weaken from 0.54 in 1987 until it reached a dangerously unstable level of 0.17 in 2010. With the implementation of water-saving measures and a water-transfer project, the stability of the Dunhuang Oasis irrigation district increased to a metastable level of 0.22 in 2015. (3) Setting the stability are 0.5 of a stable level and 0.75 of an extremely stable level, and the oasis irrigation district should be impractical and reduced by 168 and 241 km^2 to attain a suitable oasis ecosystem scale. Hence, at present, the water-transfer project is the most practical way to increase allocated water resource to the oasis irrigation district for improving its stability.

Keywords: oasis irrigation district; stability evaluation; suitable scale

1. Introduction

The mountain–oasis–desert unit is the main topographic feature of inland river watersheds in China [1]. For watersheds in this arid region, water from melted snow and glacier in the mountain flows through an oasis similar to a water tower, thereby providing fresh water to people and nature before disappearing into the desert. Through this morphotectonic pattern, as an important landscape, oases support human activities and economic development in arid regions [2] but are generally water deficient [3]. Its stability is directly related to the sustainable development of regional economy and ecological security [2].

In recent decades, the expansion of the irrigation district, population growth, and economic development in the middle-stream oasis of the inland river basin has considerably modified hydrological cycles and reduced surface runoffs to downstream reaches. Consequently, this situation has led to dried-up rivers, reduced outflows to terminal lakes, and the deterioration of the ecosystem in downstream areas [4–7]. These effects have manifested in dried-up inland lakes, such as the Aral Sea in Central Asia [8,9], Lake Urmia in Iran [10,11], and the Shiyang River in Northwestern China [12]. Thus, assessing whether an oasis is stable under the present development pattern is important in the pursuit of sustainable development. Moreover, evaluating a suitable oasis scale is crucial to the government development plan.

Several studies on stability evaluation and suitable oasis scales have focused on the Endorheic Basin in Northwest of China, specifically, the Keriya River Basin [13], the Manas River Basin [2], the Tarim River Basin [14], the Weigan River [15], and the Heihe River Basin [16]. Research methods in stability evaluation and suitable scales have continuously progressed owing to the rapid development of ecological hydrology. In the past, suitable oasis cropland areas were calculated by establishing a regression equation using the total amount of runoff water resources and the cropland area of the oasis [17]. Wang et al. [18] applied contrastive analysis to different oasis landscapes and their homologous water–energy balance relationship and proposed the concept of the "green degree" to assess stability evaluation and suitable oasis scales. In addition, a suitable farmland scale model had been established from the perspective of crop water footprint and water resources available in an oasis city [19]. Recently, Hao et al. [16] developed an approach for calculating oasis and cultivated land scales by combining water–energy balance and wind–sand dynamic theories with ecological health assessments in the Heihe River Basin.

Agricultural irrigation consumes the largest proportion of the water supply of an oasis, and the suitability of a cropland scale can directly affect the stability of an oasis. Previous research on stability evaluation and suitable oasis scales has generally neglected the impact of changes in planting structure and agricultural water consumption. Additionally, no relevant studies have been conducted on the Shule River Basin, which is adjacent to the Heihe River Basin. The Dunhuang Oasis, which is the study area of this research, is located west of the Shule River Basin and an important region along the Silk Road.

Similar to the case of the middle reaches of the Heihe River Basin, the Dunhuang Oasis also has a sharp contradiction of the water resource issue between the economy and the ecosystem. In the past decade, planting structures constantly changed with the expansion in oasis irrigation areas. Moreover, water exploitation and utilization rates reached nearly 100% in the oasis, in which agricultural water consumption accounted for nearly 90% of total available resources [20]. Hence, natural oasis ecosystems are unable to receive necessary water resources. Dunhuang City has proposed a water resource plan, namely, the "Comprehensive Planning of the Rational Use of Water Resource and Protection of Ecosystem Services in the Dunhuang Basin" [21] to improve the ecological environment of its natural oasis. The main purpose of this plan is to allocate large amounts of water resources to the natural oasis in the lower reaches of the Dunhuang Basin and leave only a limited amount of water for the irrigation district of the Dunhuang Oasis.

The objective of this study is to propose a novel research idea to evaluate the stability of the oasis and calculate the suitable oasis scale by combining water–energy balance with altered planting structures. First, this study evaluates stability during the long-term expansion process of the Dunhuang Oasis from 1987 to 2015. Next, it calculates a suitable oasis scale to a certain stability degree. Finally, it discusses to what extent the current water plan can improve the stability of the oasis and provides a scientific reference for the sustainable development of the oasis.

2. Materials and Methods

2.1. Study Area

The Dunhuang Oasis irrigation district is located east of Dunhuang City (92°13′–95°30′ N, 39°40′–41°40′ E) in Northwest China, with a total area less than 5% of that of the entire city (Figure 1). The Dunhuang Oasis irrigation district lies between the Mingsha Mountain (Echoing-sand Mountain) and the Sanwei Mountain in the southeast and the Mazong Mountain in the north and spreads into the

Gobi Desert in the west, thereby earning the name the "Gobi Desert Oasis". The world famous Mogao Grottoes are located southwest of the Dunhuang Oasis. The elevation of the oasis ranges from 800 to 1500 m and is high in the south and low in the north. The oasis experiences the strong sunshine with the annual solar radiation reaches to 6418.4 MJ/m^2, and mean maximum and minimum temperatures are −28.6–43.6 °C. The oasis also experiences high evaporation, with the annual potential evaporation reaches 2486.0 mm, but the annual precipitation is only 39.2 mm. The Danghe River, which originates from the Qilian Mountain, provides the water resources for the oasis, and the Danghe River alluvial fan developed the oasis. The oasis consists mainly of gray brown desert, alkali saline, and irrigation desert soil (China soil science database, http://vdb3.soil.csdb.cn). According to the Dunhuang City National Economic Statistics Yearbook (1987–2015), spring wheat, melon, cotton, and grapes are the main crops planted in this area [22].

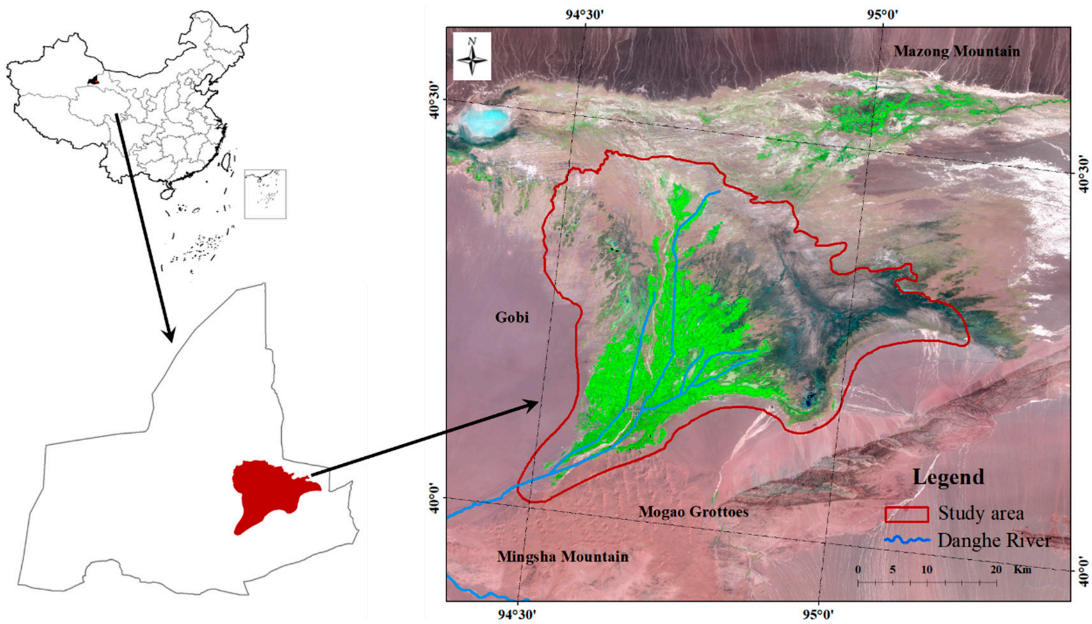

Figure 1. Study area derived by Landsat TM imagery (Bands 5-4-3).

2.2. Remote Sensing Image Data Processing

The high-quality remote images with a 30 m spatial resolution from Landsat TM (Thematic Mapper) were taken in low cloud covers during high biomass season, and all mage data were acquired from http://glovis.usgs.gov/ and http://www.radi.ac.cn/. We selected 1987, 1990, 1996, 2001, 2007, 2010, and 2015 to identify the actual irrigation district of the oasis using the software of ERDAS 9.1 and ArcGIS 10.3. Based on a 1:250,000 topographic map of the Dunhuang Oasis, all images were processed under the common universal transverse mercator coordinate system. A total of 50 uniformly distributed ground control points (e.g., roads and rivers) were used for geometric correction and georeferencing, and we used the quadratic polynomial transformation and nearest-neighbor resampling methods to identify ground control points in image-to-map rectification, the root mean square error of the geometrical rectification was less than one pixel. When the images were all ready, we divided the land use types into eight classes according to visual interpretation, namely, cropland, water, high-density grassland, medium-density grassland, low-density grassland, shrub land, urban construction land, and barren land. For verifying the result of visual interpretation, the field investigation points and corresponding interpretation results were compared, and the overall interpretation accuracy of land use classification in the 1987, 1990, 1996, 2001, 2007, 2010, and 2015 images was 80.91%, 84.96%, 79.85%, 79.69%, 84.98%, 85.79%, and 89.45%, respectively, which met the minimum accuracy requirement of 70% [23]. In this study, we used only the results of the cropland in the interpretation, as the scale of the oasis was mainly affected by the changes in the cropland. On the basis of the interpreted cropland data, we calculated the actual crop areas of crop food, cash food, and orchards by multiplying the crop food, cash food, and orchard area ratios in the Dunhuang City statistical yearbook [22] to determine the water consumption of each crop and orchard.

2.3. Water Consumption Data Analyses

In this study, water consumption denoted crop, domestic, and industrial water consumption.

2.3.1. Crop Water Consumption

The Food and Agricultural Organization (FAO)–Penman–Monteith methods were used to estimate reference crop evapotranspiration (ET_0), and multiplying by the crop coefficient (Kc) can get actual evapotranspiration (ET) as crop water consumption [24]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_{2(e_s - e_a)}}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

R_n is the net radiation at the canopy surface (MJ/m^2. day);
G is the soil heat flux density (MJ/m^2. day);
T is the mean daily air temperature at 2 m above the ground (°C);
U_2 is the wind speed at 2 m above the ground (m/s);
e_s is the saturation vapor pressure (kPa);
e_a is the actual vapor pressure (kPa);
$e_s - e_a$ is the saturation vapor pressure deficit (kPa);
Δ is the slope of the vapor pressure temperature relationship (kPa/°C);
γ is the psychometric constant (kPa /°C).

Based on the above principle, ET_0 is computed using the CropWat 8.0 [25] tool after the monthly averages of minimum temperature, maximum temperature, humidity, wind speed, and sunshine hours are inputted.

The values of Kc vary with the crop development stages, and values of monthly Kc were adopted from FAO-56 [24] for spring wheat, cotton and grape. Adjustments to Kc mid in climates where RH_{min} differs from 45% or wher U_2 is larger or smaller than 2.0 m/s, were made by following the guidelines of Allen et al. [24]:

$$K_{cmid} = K_{cmid(Tab)} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{2}$$

$$K_{cend} = K_{cend(Tab)} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{3}$$

$K_{cmid(Tab)}$ is the tabulated Kc values in the mid-seasonof Table VI-12 of Allen et al. [24];
$K_{cend(Tab)}$ is the tabulated Kc values in the late-season of Table VI-12 of Allen et al. [24];
U_2 is wind speed at 2 m height over grass, the range is 1 m/ s ≤ U_2 ≤ 6 m m/s;
RH_{min} is daily minimum relative humidity, the range is 20% ≤ RH_{min} ≤ 80%;
H is mean plant height, the range is 0.1 m ≤ h ≤ 10 m.

This research considered the water consumption of vines. Figure 2 shows the adjusted K_C of wheat, cotton and grape. Compared with wheat and cotton, the K_C of grape is more complicated, and the values of the germination, growing season with shoots, flowering, and berry growing periods as well as berry and tendril maturation were 0.80, 1.09, 1.13, 1.07, 1.03, and 0.82, respectively.

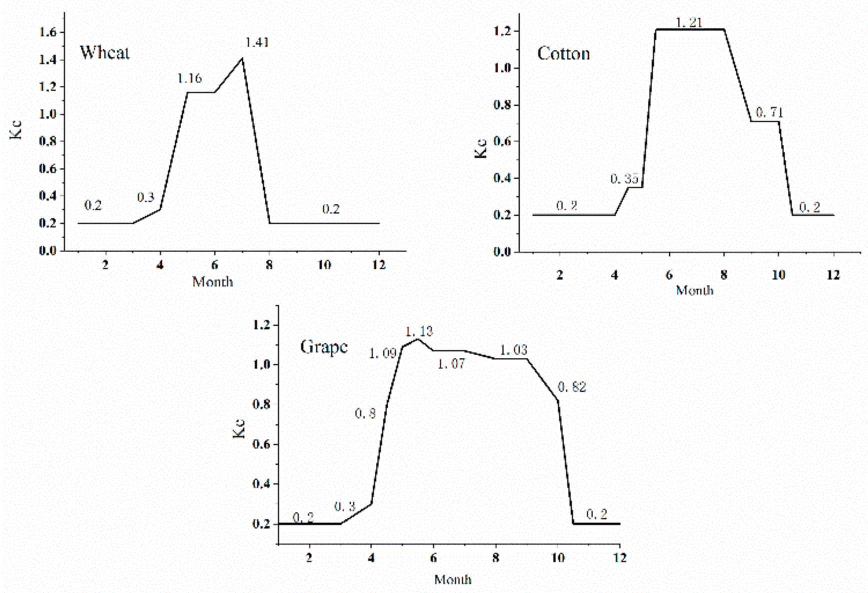

Figure 2. Crop evapotranspiration coefficients.

Actual ET rates of food crops and cash crops are estimated by Allen et al. [24]

$$ET = ET_0 \times K_C \tag{4}$$

2.3.2. Domestic Water Consumption

Domestic water consumption represented the water consumption of urban and rural populations, tourists, and livestock, which was positively correlated with living standards. It is defined as follows:

$$D = (P_1 \times C_1 + P_2 \times C_2 + P_3 \times C_3 + P_4 \times C_4) \times 365 \times 10^{-8} \tag{5}$$

D is the total domestic water consumption (10^8 m^3);
P_1 is the amount urban population (10^8 m^3);
P_2 is the amount rural population (10^8 m^3);
P_3 is the amount tourists population (10^8 m^3);
P_4 is the amount livestock number (10^8 m^3, sheep unit);
C_1 is the average per capital water use coefficient of urban (L/day);
C_2 is the average per capital water use coefficient of rural (L/day);
C_3 is the average per capital water use coefficient of tourist (L/day);
C_4 is the average per capital water use coefficient of livestock (L/day);

The values for C_1, C_2, C_3 and C_4 (Table 1) are obtained from the literature for the four periods with different living standards: 1987–1990, 1991–2000, 2001–2007, and 2008–2015 [26].

Table 1. Water use coefficient.

Item	Coefficient				Unit
	1987–1990	1991–2000	2001–2007	2008–2015	
Urban resident water-use coefficient (C_1)	80	95	110	120	L/day
Rural resident water-use coefficient (C_2)	25	45	60	80	L/day
Tourist water-use coefficient (C_3)	100	250	400	400	L/day
Livestock water-use coefficient (C_4)	15	15	20	20	L/day
Industrial water-use coefficient (C_5)	215	205	185	180	$m^3/10^4$ RMB

2.3.3. Industrial Water Consumption

Industrial water consumption was affected by industrial output, technology, processes, and the amount of water used to create RMB 10,000 (Chinese currency) worth of industrial output. It is defined as follows:

$$P = \text{Indo} \times C_5 \times 10^{-8} \tag{6}$$

P is the industry water use (10^8 m^3);
Indo is the industrial output (RMB);
C_5 is the amount of water used to create 10,000 RMB worth of industrial output ($m^3/10^4$ RMB).

The value for C_5 (Table 1) was also determined separately for the four periods with different living standards for the period of 1987–1990, 1991–2000, 2001–2007, and 2008–2015, respectively [26].

2.4. Oasis Stability and Suitable Oasis Scale Model

In this study, a stability index (H_0), which is based on the theory of ecological water–energy balance, was used to estimate the stability degree of the oasis under certain water resource conditions [18]. H_0 is the relative equilibrium analysis between water and energy conditions of the oasis, which can not only reflect ecological evolution and degradation from the internal perspective of the oasis but also the "green degree" or "stability degree" from the overall regional view point. The greater the H_0, the less affected the water stress and the higher the oasis stability, and vice versa. The formula is as follows:

$$H_0 = \frac{W_1 - W_2 + P \times \sum A_i}{ET_0 \times \sum A_i} \tag{7}$$

where A_i is the area of the land type (I = food crops, cash crops, and grapes; km^2), W_1 is the total available water volume of the river basin (10^8 m^3), W_2 is the annual average agricultural, industrial, and domestic water consumption, ET_0 is the reference crop evapotranspiration, and P is the annual average precipitation. The H_0 of the oasis was classified on the basis of the characteristics of the natural environment (Table 2).

Table 2. Classification of oasis stability.

H_0	Type	Evaluation of Exploration and Utilization
>0.75	Extremely stable	Has potential
0.50–0.75	Stable	Safeguarded; the oasis has limited developmental potential
0.20–0.50	Metastable	Does not have developmental potential
<0.20	Unstable	Reduced oasis scale

Based on the previous section, the calculation model of the suitable oasis scale (A) is

$$A = \frac{W_1 - W_2}{(ET_0 - P) \times k_p \times H_0^*} \tag{8}$$

where k_p is the comprehensive coefficient of plants in the oasis, which includes planting crops, trees, and grass. H_0^* is used to estimate the suitable oasis scale.

3. Results

3.1. Land Use/Land Cover Changes between 1987 and 2015

Figures 3 and 4 show changes in land use/land cover between 1987 and 2015. From Figure 3, we can deduce that the cropland area exhibited an expanding pattern, and the interpretation results demonstrate the total cropland area in the oasis was 272.69, 276.41, 295.33, 327.08, 371.40, 380.47, and

389.41 km^2 in 1987, 1990, 1996, 2000, 2007, 2010, and 2015, respectively. In terms of the temporal characteristics of land use/land cover changes, incremental rates from 1996 to 2007 more than doubled from 1987 to 1996 and from 2007 to 2015. With regard to spatial pattern, the cropland increased by 116.72 km^2. Growth is mainly attributed to its transformation from a grassland and a barren land in the fringe of the oasis [27] and to the continuously expanding urban construction land within the oasis.

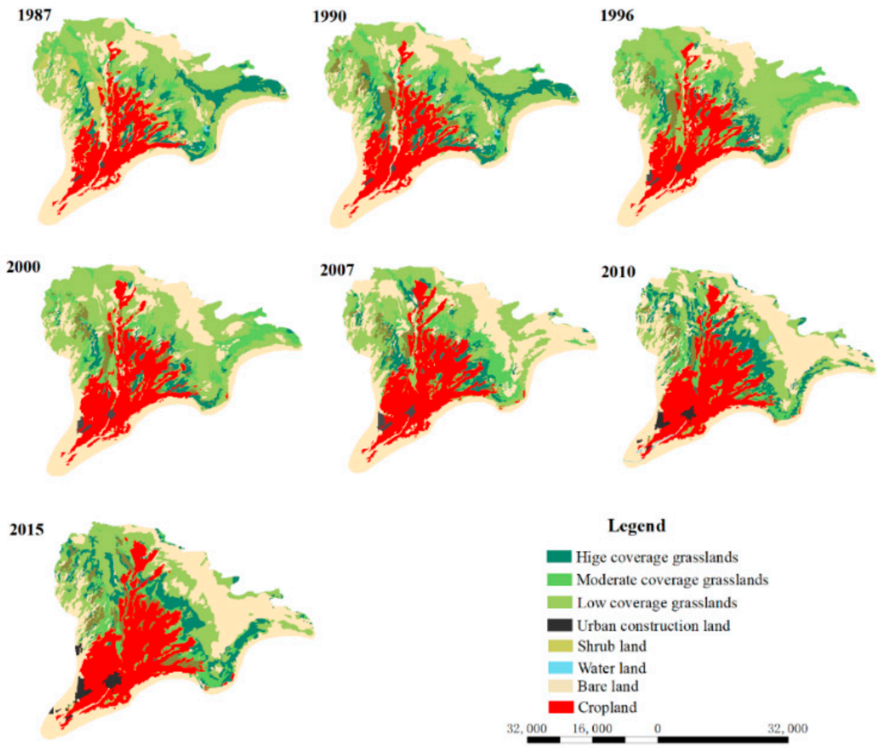

Figure 3. Land use/land cover spatial pattern from 1987 to 2015 in the Dunhuang Oasis.

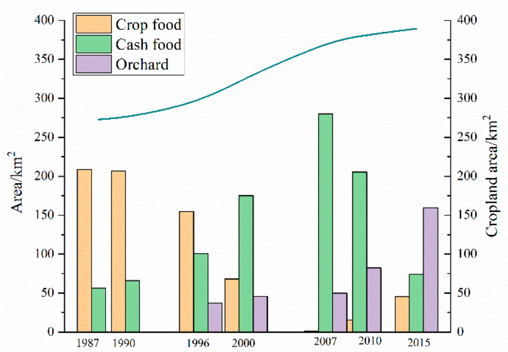

Figure 4. Planting structure changes in the Dunhuang Oasis.

The three different-colored bar charts in Figure 4 represent the crop areas of crop food, cash food, and orchards. The planting structure exhibited marked changes and even transformed during the 1987–2015 period. Specifically, (1) the crop food area decreased continuously from 1987 to 2007, and the crop food area in 2007 was only 1.61km^2, making it too small to display. Meanwhile, cotton was the main cash crop, which experienced a substantial increase owing to its high value. A distinct transformation in the food and cash crops from 1996 to 2000 can be observed, as the crop area of the cash crops gradually became larger than that of the food crops. In addition, the trial planting of grapes in the sandy soil region began in 1996. (2) In 2010, cotton areas gradually decreased, and grape orchards increasingly involved large-scale cultivation.

3.2. Water Consumption

3.2.1. Agricultural Water Consumption

Agricultural water consumption comprises the core section of the suitability evaluation of the oasis. In the Dunhuang Oasis, agricultural water consumption includes food crops, cash crops, and orchards. From 1987 to 2015, total water consumption increased initially from 2.293 × 10^8 m^3 in 1987 to 3.513 × 10^8 m^3 in 2007, then decreased to 2.902 × 10^8 m^3 in 2015 (Table 3). Listed individually in Table 3, food crop water consumption decreased sharply by 1.334 × 10^8 m^3 from 1987 to 2015. Meanwhile the water consumption of cash crops with high economic benefits progressively increased by 2.374 × 10^8 m^3 from 1987 to 2007 then began to decrease to 2.207 × 10^8 m^3 in 2010 and eventually decrease to a very low value of 0.774 × 10^8 m^3 in 2015. This trend in cash crop water consumption is closely related to that of grapes, which increased slowly before 2010 before rising rapidly.

Table 3. Agricultural water consumption in 1987–2015 (10^8 m^3).

Year	Food Crop	Cash Crop	Grape/Orchard	Sum
1987	1.727	0.566	0	2.293
1990	1.754	0.668	0	2.422
1996	1.300	0.984	0.389	2.673
2000	0.585	1.780	0.489	2.854
2007	0.015	2.940	0.558	3.513
2010	0.139	2.207	0.915	3.261
2015	0.393	0.774	1.735	2.902

3.2.2. Domestic and Industrial Water Consumption

Domestic and industrial water consumption should not be neglected in the suitability evaluation of the oasis. During the 1987–2015 period, the total population of the Dunhuang Oasis increased from 108,373 to 142,558, in which the rural population accounted for nearly 70% to 80%. Rural livestock increased from 349,820 sheep units in 1987 to 486,816 in 2015. In addition, the number of tourists increased from less than 100,000 in 1987 to 6,603,914 in 2015. Furthermore, industrial output increased by 84.6 × 10^8 RMB [22]. Thus, we can calculate overall domestic and industrial water consumption under increasing populations and the booming tourism industry. Table 4 shows that overall domestic and industrial water consumption rapidly increased from 0.038 × 10^8 to 0.219 × 10^8 m^3. The percentage of domestic and industrial water consumption in overall water consumption is very small.

Table 4. Domestic and industrial water consumption in 1987–2015 (10^8 m^3).

Year	Domestic	Industrial	Sum
1987	0.034	0.004	0.038
1990	0.036	0.007	0.043
1996	0.050	0.026	0.076
2000	0.045	0.045	0.09
2007	0.064	0.117	0.181
2010	0.075	0.116	0.192
2015	0.102	0.117	0.219

3.3. Oasis Stability Evaluation

In this study, the total available water volume originates from the Danghe River; thus, we use its perennial mean runoff, that is, 4.13 × 10^8 m^3, as W_1. From the above data, total available water quantity for the oasis in 1987, 1990, 1996, 2000, 2007, 2010, and 2015 was 1.79 × 10^8, 1.66 × 10^8, 1.37 × 10^8, 1.78 × 10^8, 0.43 × 10^8, 0.67 × 10^8, and 1.00 × 10^8 m^3, respectively. From the oasis stability evaluation, as shown in Equation (7), the H_0 of the Dunhuang Oasis were 0.54, 0.51, 0.41, 0.39, 0.15, 0.19, and 0.22 from 1987 to 2015 (Table 5).

Table 5. Stability of Dunhuang Oasis.

Year	P/(mm)	ET_0/(mm)	W_1-W_2 (10^8 m^3)	H_0
1987	43.80	1300	1.79	0.54
1990	45.60	1279	1.66	0.51
1996	40.20	1288	1.37	0.41
2000	36.70	1357	1.78	0.39
2007	87.40	1355	0.43	0.15
2010	50.90	1322	0.67	0.17
2015	31.40	1299	1.00	0.22

3.4. Suitable Oasis Irrigation District Scale

We take 2015 as an example and use Equation (8) to derive a suitable oasis irrigation district scale. Crops and natural vegetation are considered as having a common effect on kp, which is 0.72 [18], and the H_0^* is set as two values, namely, 0.5 for the stable level and 0.75 for the extremely stable level.

Table 6 shows that the suitable oasis irrigation district scale was smaller than the actual area in 2015. According to the water–energy balance model, the current oasis irrigation district scale should be reduced by 168 and 241 km^2 to attain stable to extremely stable levels, respectively.

Table 6. Suitable oasis irrigation district scales/km^2.

Year	H_0^* (0.5–0.75)	Status Quo 2015	Suitable Scale(A)/Km^2
2015	0.5 0.75	389	221 148

4. Discussion

The planting structure exhibited two marked changes. The first planting structure change happens between crop food and cotton. Except for cotton's high value and cultivation suitability, the rapidly increasing cotton lands, which were mainly attributed to farmers, had autonomy in terms of land use activities since the early 1980s under China's economic reform policy. Against this background, farmers envisioned market economy ideas, and production activities were closely associated with market demands. In addition, the trial planting of grapes in the sandy soil region began in 1996. The second planting structure change happens between cotton and grape; this is because of successful grape trial experiments in the sandy soil region, and from then on, a large number of farmers began to install grape trellises in fields previously planted with cotton or wheat. Hence, the planting structure of the oasis changed once again.

Although the total cropland area increased by 18.01 km^2 from 2007 to 2015, agricultural water consumption decreased by 0.611×10^8 m^3. This result may be beneficial to the transformation of crop patterns and water-saving irrigation measures. Traditional field canal irrigation was the primary irrigation pattern used in the past, but, from the beginning of 2010, advanced water-saving irrigation models, such as micro, pipe, and greenhouse micro irrigation, were implemented in the entire oasis.

Table 5 shows that stability was in a stable level in 1987 and 1990 owing to low agricultural, domestic, and industrial water consumption. During this period, though each industry was gradually developing, stability was not extremely stable, which may have been due to limited water resources. Farmers' enthusiasm for production and cropland areas increased under reform and opening-up policies, but irrigation measures were difficult. At the same time, tourism in the Dunhuang Oasis began to flourish. When the national economy improved, the stability of the oasis fell to a metastable level from 1996 to 2000 and reached a dangerously unstable level from 2007 to 2010. Water resource exploitation and utilization rates nearly reached 100% in the oasis, in which agricultural water consumption accounted for nearly 90% of overall available resources [27]. Serious ecological problems, such as accelerated desertification and salinization, shrunken terminal lake and declining groundwater level, accompany rapid economic development [27]. Water has become the primary restricting and bottleneck factor in the socioeconomic development of the Dunhuang Oasis.

In this case, a series of water resource plans was implemented to address this issue, in which the most important program "Comprehensive Planning of the Rational Use of Water Resource and Protection of Ecosystem Services in the Dunhuang Basin" was proposed. This program aims to reduce the croplands of state farms, implement agricultural water-saving measures, and carry out a water diversion project from the Sugan Lank Basin to the Danghe River. Approximately 0.835×10^8 m^3 of water allocated from the water diversion project is intended for the improvement of the ecological environment, which plays a crucial role in alleviating the water crisis by increasing groundwater levels and recovering the vegetation in marginal areas of the oasis [20]. The system dynamic model simulated the agricultural water consumption under different scenarios in the Dunhuang Oasis and shows that the proportion of agricultural water consumption in overall water consumption can be reduced from 92.50% in 2010 to 86.30% in 2025 [20], but, if reduced by 168 km^2, to attain a stable level, the agricultural water consumption should be decreased to at least half of what it is now. In this study, the suitable oasis area is far less than the actual area, which is a common issue in the Endorheic watershed oasis in Northwest China [2,16,28]. Reducing cropland in the oasis is the most direct and effective means, which is difficult to achieve. Specifically, individual croplands in the Dunhuang Oasis should be reduced to preserve the ecological environment. However, several reasons highlight the difficulty of this solution. (1) The reduction of croplands will harm the economic interests of farmers and subsequently decrease their quality of life. Thus, the possibility of criminal problems due to poverty should be considered. (2) The reduction of croplands is not in line with the Chinese policy of farmland protection. Hence, only on the basis of maintaining water-saving irrigation, reducing domestic water consumption, improving industrial water consumption efficiency, forbidding sprawl inside and outside the oasis, and increasing the amount of water allocated to the oasis from the water-transfer project, can the stability of the oasis be improved and the sustainable development of the regional economy and ecology be maintained.

5. Conclusions

This study analyzed the stability of the Dunhuang Oasis against the background of planting structure changes during the 1987–2015 period. Our main findings and recommendation are as follows:

1. From 1987 to 2015, the oasis irrigation district area expanded internally and externally, and, at the same time, the planting structure underwent a marked transformation, from food crops to cash crops to orchards. In the Dunhuang Oasis, the structure of croplands might be quickly and flexibly changed according to economic perspective and visions and policy reforms
2. In the Dunhuang Oasis, agricultural water consumption is mainly for food crops, cash crops, and orchards. From 1987 to 2015, food crop water consumption decreased sharply by 1.334×10^8 m^3, cash crop water consumption (cotton) first increased by 2.374×10^8 m^3 and then decreased substantially, and grape water consumption was closely related to that of cotton, which increased slowly in 2010 before rising rapidly.
3. The Dunhuang Oasis was at a stable level in 1987 and 1990 but gradually declined until it reached a dangerously unstable level in 2010. Meanwhile, serious ecological problems emerged one after the other. Against the background of water-saving measures and the water-transfer project, the stable level of the oasis increased to a metastable level of 0.22 in 2015.
4. The oasis irrigation district should be reduced by at least 168 km^2 to reach a suitable scale. However, this goal does not facilitate the improvement of the living standards of farmers and is not in line with the Chinese policy of farmland protection. Hence, the most practical way at present is to increase allocated water resources from the water-transfer project to the oasis irrigation district.

Author Contributions: X.Z. and Q.W. conceived and designed the experiments. X.Z. and Y.Z. performed the experiments and analyzed the data. J.Q. provided remote sensing image of 2010 and 2015. X.Z. and Q.W. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation of China, grant number: 41701321 and No. 41661105.

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

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water

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Article

Spatial Variability of Water Resources State of Regions around the "Belt and Road"

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Abstract: Water resource has become a key constraint for implementing the "Belt and Road" initiative which was raised by the Chinese government. Besides the study of spatial and temporal variability of precipitation, this study created a water hazard risk map along the "Belt and Road" zone through combined flood and drought data from 1985. Our results showed that South-Eastern Asia, southern China and eastern Southern Asia are areas with the most abundant precipitations, while floods in these areas are also the most serious. Northwest China, Western Asia, Northern Africa and Southern Asia are areas highly vulnerable to drought. Furthermore, the potential influence of flood and drought were also analyzed by associating with population distribution and corridor map. It reveals that China, South-Eastern Asia, Southern Asia, Western Asia and Northern Africa have the largest population number facing potential high water hazard risk. China–India–Burma Corridor and China–Indo-China Peninsula Corridor have the largest areas facing potential high water hazard risk.

Keywords: water security; precipitation; drought; flood; transport planning

Citation: Huang, Y.; Li, Z.; Chen, M.; Song, X.; Kang, P. Spatial Variability of Water Resources State of Regions around the "Belt and Road". *Water* **2021**, *13*, 2102. https://doi.org/10.3390/w13152102

Academic Editors: Fernando António Leal Pacheco and Luís Filipe Sanches Fernandes

Received: 5 June 2021
Accepted: 27 July 2021
Published: 31 July 2021

1. Introduction

In 2013, China proposed the "Silk Road Economic Belt" and the "21st-Century Maritime Silk Road" initiatives, which are collectively referred to as the "Belt and Road" [1]. The "Vision and Action for Promoting the Construction of the Silk Road Economic Belt and the 21st Century Maritime Silk Road" ("Vision and Action") was issued subsequently in 2015, which marks the formal implementation of the "Belt and Road" [2]. "Vision and Action" proposes that infrastructure interconnection is a priority mission for the "Belt and Road", due to improving the accessibility of roads not only facilitating the lives of local individuals but also promoting the sustainable development of the local economy and society [3]. Strengthening the ecological cooperation of the countries and regions along the corridor to avoid potential ecological risks and establish a green silk road is another important recommendation of the "Vision and Action" [2]. It is foreseeable that the implementation of the "Belt and Road" will have a significant impact on the transportation, urbanization and water resources in the countries and regions along the corridor. However, water scarce, flood and drought have posed a huge potential threat to the implement of the "Belt and Road" and sustainable development of society, especially in arid and semi-arid areas [4–7]. Therefore, understanding the temporal and spatial variability of water resources and water-caused natural hazards along the corridor can not only ensure the smooth construction of transportation infrastructure but also promote the sustainable development of countries and regions along the "Belt and Road" zone [8].

The "Belt and Road" zone traverses Eurasia and spans subtropical, temperate, cold temperate and frigid zones, with complex terrain and geological conditions. It is a high-risk zone for natural hazards such as flood, drought and extreme precipitation [9]. In Central and Western Asia, the construction of transportation, oil and gas pipelines is threatened by high temperatures, droughts and extreme precipitation. Frequent floods in Southern and South-Eastern Asia have also brought tremendous security risks to the operation of transportation facilities. According to the EM-DAT hazard database, there were more than 7200 natural hazards that happened in the world from 1990 to 2010 and more than 3003 times in the "Belt and Road" area, including 1131 floods and 94 droughts respectively which caused serious casualties and property damage [10]. At the same time, most countries and regions along the "Belt and Road" corridor are economically underdeveloped and agricultural dependent with relatively weak ability to withstand water stress [11]. Impacted by global warming, the risks of encounter extreme precipitation, drought and flooding are increasing [12–15], which brings tremendous potential risk to local human life, property, agriculture, economy and society along the "Belt and Road" corridor [16–19]. The fifth assessment report of Intergovernmental Panel on Climate Change (IPCC) indicated that the Lancang-Mekong River Basin has an increased precipitation during the monsoons of the past 30–50 years, while the precipitation during the dry season has dropped sharply, and with the accelerated thaw of the Himalayan glaciers and the Pamirs glaciers, the supply of glaciers to the rivers will be significantly decreased, and in a few years the billions of people living in South and Central Asia may confront the risk of losing fresh water [20]. Xia et al. found that there will probably be an increase in extreme floods and droughts in the Eastern Monsoon of China and irrigation water in the North China Plain will increase by 4% with the impact of global warming [21]. Reza et al. analyzed the data observed by more than 400 river monitoring stations distributed throughout Iran and discovered that floods caused by extreme precipitation in most parts of Iran have an obvious growth [22]. Other studies have shown that Belt and Road countries or regions, such as the Philippines, and Vietnam, Pakistan, the North-South Road Corridor and East-West Road Corridor of Myanmar, South Asia and South-Eastern Asia, also faced serious risk of floods and droughts [23–25]. However, spatial variability of water resources' condition and its related risk at a macro scale is more significant to the sustainability of Belt and Road Initiative.

Since water resources is a major constraint to the execution of "Belt and Road" initiative, it is necessary to figure out the spatio-temporal pattern of water resources on a macro scale. In this paper, we first analyzed the spatial distribution of mean precipitation in more than 60 countries of the "Belt and Road" zone. Then we used the flood data and drought data in the same period to make the water hazard risk map and graded the map with five levels based on potential water-caused risk. In addition, based on the flood and drought frequency map, we assessed the potential impact population, the corridor along the "Belt and Road" zone. We hope this paper will provide some support of water resources' state for the Belt and Road initiative to some extent.

2. Materials and Methods

2.1. Study Area

The "Belt and Road" zone stretches across the continent of Asia, Europe and Africa from the Pacific in the East to the Atlantic Ocean in the west and from Indonesia in the South to the Arctic Ocean in the north (Figure 1). Over 60% of areas of the "Belt and Road" zone is arid and semi-arid grassland, desert and high-altitude ecologically fragile areas with dry climate and low precipitation caused by effect of the Himalayas and global weather patterns [4]. Central Asia, Western Asia and Northern Africa are the driest areas in the world where serious water shortage and severe land desertification pose serious threats to social and economic sustainable development. South-Eastern Asia and Southern Asia are strongly affected by monsoon, with frequent natural disasters including droughts, torrential rains and floods [26]. "Belt and Road" countries have a population amounting to more than 70% of the world's population. However, the amount of water resources is only 36% that of the global total. It poses higher pressure in water security compared with the world average level [27]. In the initial vision for "Belt and Road Initiative" in 2015, there are 6 land economic and transportation corridors, which are a global economic connectivity program led by China. The 6 land corridors are China–Mongolia–Russia Corridor, New Eurasian Continental Bridge, China-Central Asia-West Asia Corridor, China–Pakistan Corridor, Bangladesh–China–India–Burma Corridor and China-Indochina Peninsula Corridor (Figure 1). Herewith, we zoned the study area of "Belt and Road" to 6 major zones of the Mongolia-Russia and Central Asia zone (MRCA), the South-Eastern Asia zone, the Southern Asia zone, the Western Asia and Northern Africa zone (WANA), the Central and Eastern Europe zone (CE Europe) and China [28] according to the 6 corridors.

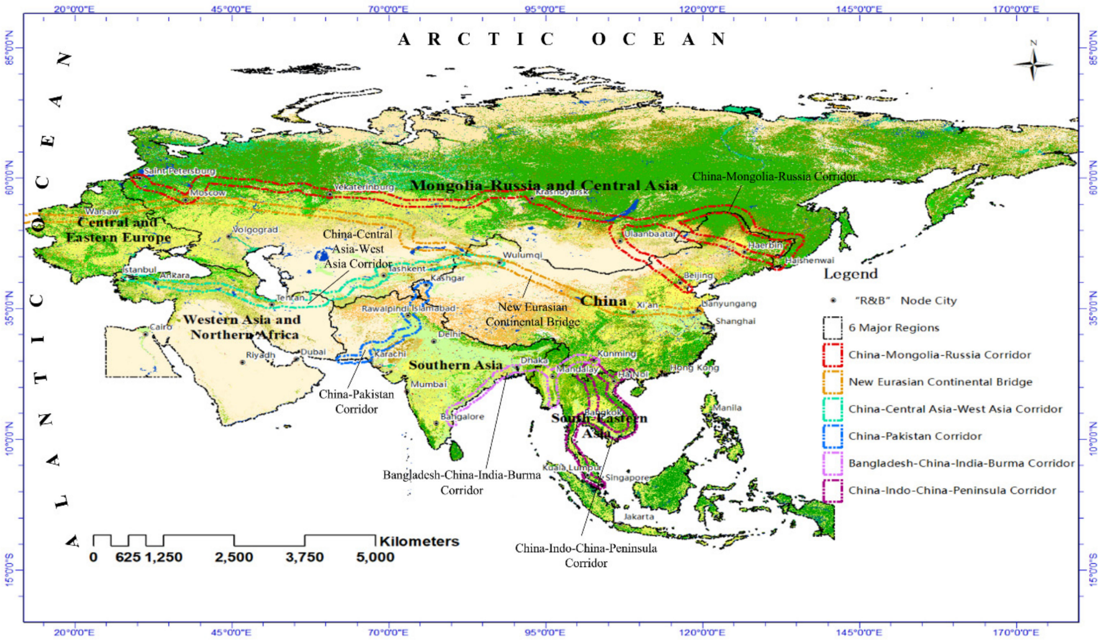

Figure 1. "Belt and Road" monitoring area and corridor map.

2.2. Data Source

The data used in this paper mainly include precipitation, drought, flood, population, cropland, highway and railway. The specific data sources and formats are shown in the following table (Table 1).

Table 1. Data specification.

Item	Spatial Resolution	Temporal Resolution	Format	Time	Source
Precipitation	0.5° × 0.5°	1 day	tif	1985–2016	National Oceanic and Atmospheric Administration
Drought	0.5° × 0.5°	1 month	tif	1985–2016	National Oceanic and Atmospheric Administration
Flood	0.5° × 0.5°	1 year	tif	1985–2016	Dartmouth Flood Observatory, University of Colorado
Population	30″ × 30″	/	tif	2015	Socioeconomic Data and Applications Center, NASA
Cropland	30 m × 30 m	/	tif	2015	U.S. Geological Survey
Railway	/	/	shp	2016	Resource and Environment Data Cloud Platform
Highway	/	/	shp	2016	Environment Data Cloud Platform

(1) Precipitation

Global daily precipitation data of 1985-2016 is derived from the NOAA Climate Prediction Center (CPC) Unified Precipitation Products dataset. It is created on a 0.5° lat/lon over the global land by interpolating gauge observations from 30,000 stations by considering orographic effects in precipitation.

(2) Drought

The Global SPEI (Standardized Precipitation Evapotranspiration Index) drought dataset of 1985–2016 is made available by Consejo Superior de Investigaciones Científicas (CSIC), with a 0.5 degrees spatial resolution and a monthly time resolution. SPEI is one of the most widely used drought indices in monitoring and quantifying droughts, which is developed by Vicente-Serrano et al. [29] based on the standardized precipitation index (SPI). The specific procedures for calculating SPEI can be found in the studies of Mahmoudi et al. [30] and Pei et al. [31] Positive values of SPEI indicate wet conditions, while negative values indicate dry conditions. SPEI classification rules are as follows: SPEI > -0.5 no drought; $-1.0 <$ SPEI ≤ -0.5 light drought; $-1.5 <$ SPEI ≤ -1.0 moderate drought; $-2.0 <$ SPEI ≤ -1.5 severe drought; SPEI ≤ -2.0 especially severe drought. In this paper, the droughts severity of no drought, light drought, moderate drought, severe drought and especially severe drought is assigned to values of 0, 1, 2, 3, and 4, respectively. Then, the drought frequency was classified into 5 classes of approximately equal number of grid cells based on the accumulated 32 years of datasets of drought severity from 1985 to 2016.

(3) Flood

The flood dataset of 1985–2016 is derived from Dartmouth Flood Observatory, University of Colorado, with a 0.5 degrees spatial resolution and a yearly time resolution, which is mainly retrieved based on official reports and remote sensing sources (http://floodobservatory.colorado.edu/index.html, accessed on 30 July 2021). The original data of floods is divided into three classes of severity based on 1–2 scale. Class 1 (large flood events): significant damage to structures or agriculture; fatalities; and/or 1–2 decades-long reported interval since the last similar event. Class 2 (very large events): with a greater than 2 decades but less than 100 year estimated recurrence interval and/or a local recurrence interval of at 1–2 decades and affecting a large geographic region (> 5000 km^2). Class 3 (Extreme events): with an estimated recurrence interval greater than 100 years. In this paper, we assigned the Class 1, Class 2 and Class 3 to values of 1, 2 and 3, respectively, and generated the 5-classes flood frequency map similar to drought frequency map mentioned above.

(4) Population

The population data of 2015 is obtained from Socioeconomic Data and Applications Center of NASA with spatial resolution is $30'' \times 30''$. Population input data are collected at the most detailed spatial resolution available from the results of the 2010 round of Population and Housing Censuses, which occurred between 2005 and 2015. The raster datasets are constructed from national or subnational input administrative units to which the estimates have been matched.

(5) Cropland

The Global Food Security-support Analysis Data 30 meter (GFSAD30) Cropland Extent data product provides cropland extent data across the globe, divided and distributed into 7 separate regional datasets, for nominal year 2015 at 30 meter resolution which was released by Department of the Interior, U.S. Geological Survey. Additionally, the validation dataset used to conduct an independent accuracy assessment of global cropland extent is available.

(6) Railway and Highway

The railway and highway data of 2016 was downloaded from the Environment Data Cloud Platform of Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences. The data format is ARCGIS shapefile.

3. Analysis of Spatio-Temporal Heterogeneity of Water Security

3.1. Precipitation

Changes in precipitation is the primary driving forces of flash floods [32,33]. Similar to previous studies of precipitation in the regions of the Belt and Road [34–37], our analysis of mean precipitation along the "Belt and Road" zone from 1985 to 2016 shows that the spatial distribution of precipitation is extremely uneven. The Western Asia and Northern Africa zone has the least annual precipitation of 142 mm among all regions; the areas with the most abundant precipitation are mainly concentrated in South-Eastern Asia, eastern Southern Asia and southern China. In particular, South-Eastern Asia has the highest average precipitation of 1867 mm, much higher than the average level of "Belt and Road" zone (Figure 2, Table 2). Spatial distribution of precipitation within China is also extremely uneven. While there is abundant precipitation in the southeast coast, precipitation in Northwest China is scarce. Southern Asia and South-Eastern Asia are faced with similar situations as China. Precipitation in the Mongolia-Russia and Central Asia and the Central and Eastern Europe are both at moderate level along the "Belt and Road" zone. Areas starting from Northwest China to Western Asia and Northern Africa are faced with severe water shortages, which is consistent with the fact that this area has extensive deserts with rare precipitation and intensive evaporation. This area has the most fragile ecological systems, which means special attention should be paid to local water resources' condition and ecological environment before carrying out urban and transport planning in this area.

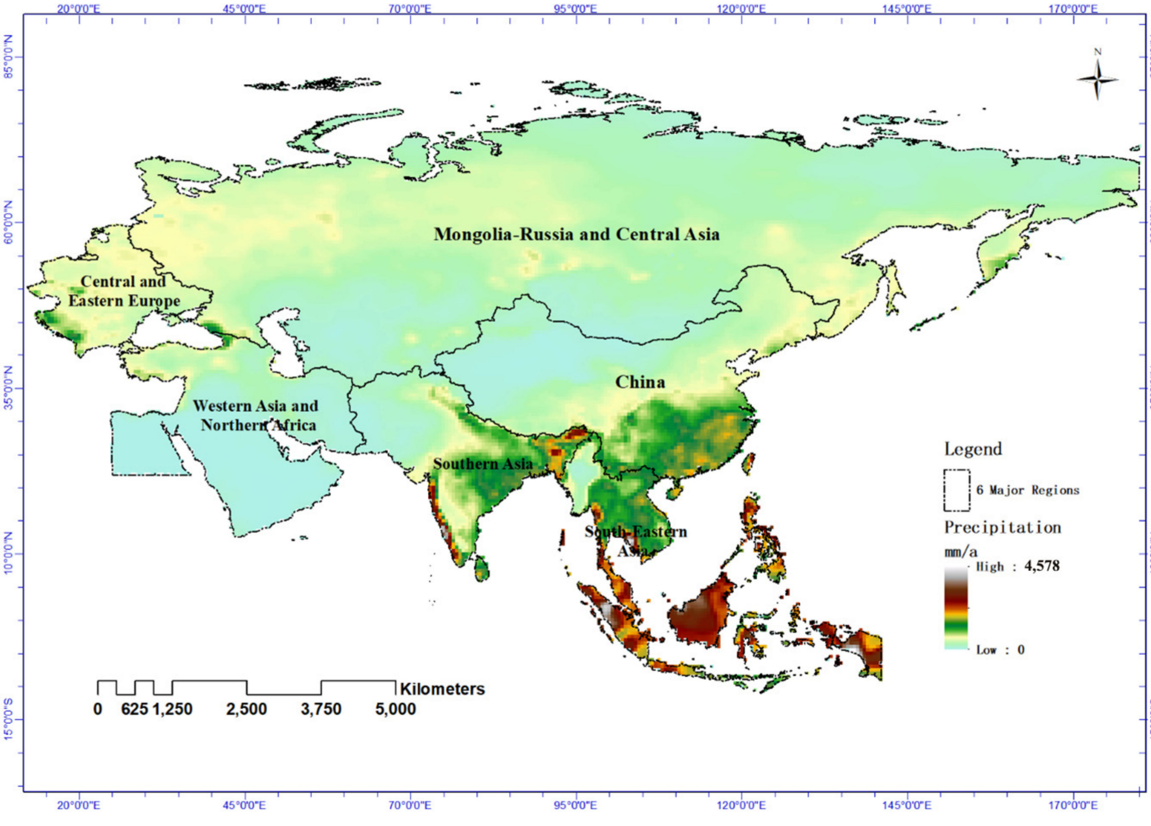

Figure 2. The spatial distribution of mean precipitation along the "Belt and Road" zone from 1985 to 2016.

Table 2. "Belt and Road" regional precipitation statistics table.

Zone	Minimum (mm)	Maximum (mm)	Mean (mm)	Std. Dev.
China	0	2573	549	466
South-Eastern Asia	0	4578	1867	900
MRCA	0	1396	351	156
Southern Asia	0	4059	778	618
WANA	0	1552	142	190
CE Europe	0	1448	603	146
Belt and Road	0	4578	497	531

Furthermore, we also analyzed the inter-annual variation trend of precipitation during 24 h with at least 50 mm according to the Chinese national standard of "grade of precipitation (GB/T 28592-2012)". Figure 3 shows an increasing trend with extreme precipitation in most areas of South-Eastern Asia, South-Eastern China and eastern Southern Asia, while the change trend in other areas is not obvious.

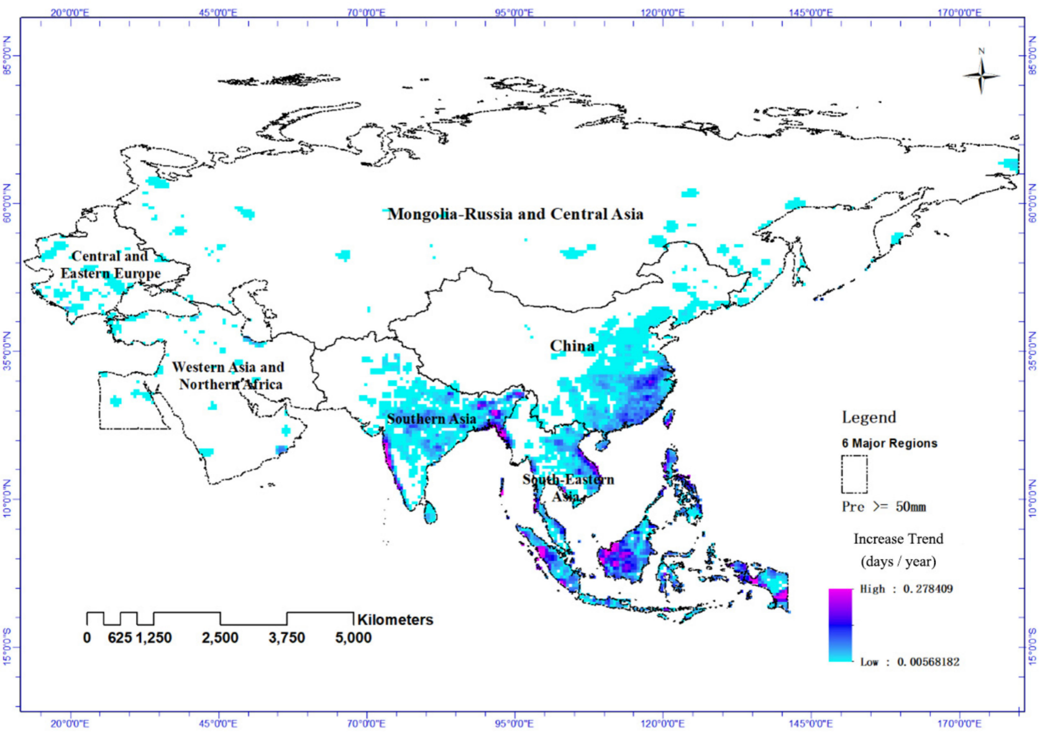

Figure 3. Inter-annual variation trend of precipitation during 24 h with at least 50 mm from 1985 to 2016.

3.2. Droughts

Drought is a natural disaster that has high occurrence frequency, long duration and a wide range of impacts. Drought can be regarded as regional and time-series water deficit processes, resulting in diminished water resource availability and ecosystem carrying capacity [38,39]. As shown in Figure 4a, Central Asia, Southern Asia, Western Asia and Northern Africa along the "Belt and Road" zone are all threatened by desertification and drought to varying degrees [40]. As can be seen, the drought in most areas of Western Asia and Northern Africa and Northwestern China are the most severe and the impact of drought in Mongolia-Russia and Central Asia is the most moderate. The severity of drought in eastern China, Southern Asia, South-Eastern Asia and Central and Eastern Europe is the slightest.

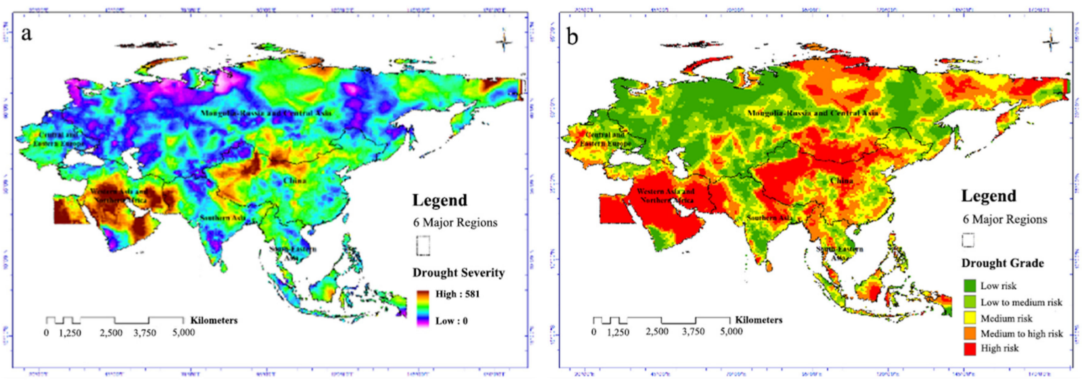

Figure 4. (**a**) drought frequency map along the "Belt and Road" zone; (**b**) drought frequency hierarchical map.

Then the drought frequency map was classified into five classes of approximately equal number of grid cells (Figure 4b). The greater the grid cell value in the final dataset, the higher the relative frequency of drought occurrence. The five drought frequency grades are low drought risk, low to medium drought risk, medium drought risk, medium to high drought risk and high drought risk respectively.

As shown in the table (Table 3), droughts in Western Asia and Northern Africa are the most serious, with high drought risk area covering 67% of the region, far exceeding the average level of "Belt and Road" zone. Droughts in China and Southern Asia are slightly better than Western Asia and Northern Africa but still not optimistic. The shares of the areas that suffer with medium drought risk and medium to high drought risk in South-Eastern Asia are both higher than the average level of "Belt and Road" zone. Central and Eastern Europe and Mongolia-Russia and Central Asia are the least affected areas by drought along the "Belt and Road" zone.

Table 3. "Belt and Road" drought impact area and proportion statistics table.

Zone	Low Drought Risk		Low to Medium Drought Risk		Medium Drought Risk		Medium to High Drought Risk		High Drought Risk	
	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage
China	50	5%	130	13%	248	26%	257	27%	276	29%
South-Eastern Asia	35	8%	98	22%	137	30%	140	31%	38	9%
Southern Asia	70	14%	111	22%	111	22%	103	21%	105	21%
MRCA	662	29%	522	23%	414	19%	412	18%	246	11%
WANA	30	4%	55	7%	66	9%	98	13%	509	67%
CE Europe	39	18%	68	31%	65	30%	41	18%	6	3%
Belt and Road	886	17%	984	19%	1041	20%	1051	20%	1180	23%

3.3. Flood

Flood is the most common natural hazard in the world which causes tremendous losses to human life and property every year [41–43]. Based on the analysis of the distribution of floods that happened along the "Belt and Road" zone from 1985 to 2016, the flood frequency map was obtained (Figure 5a); it revealed that southern China, South-Eastern Asia and the north of Southern Asia are the regions with the most serious floods, while floods in Mongolia-Russia and Central Asia, Central and Eastern Europe and Western Asia and Northern Africa are relatively rare.

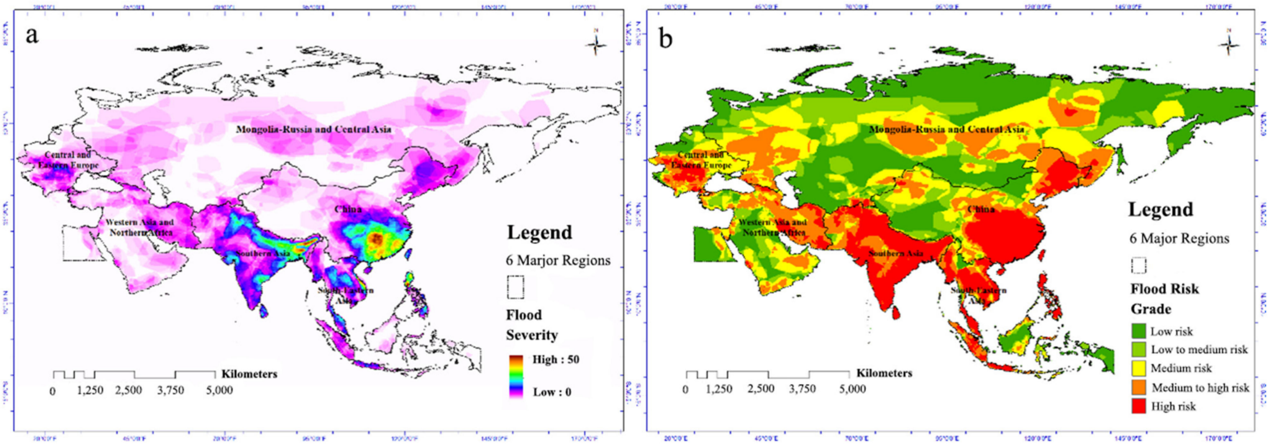

Figure 5. (**a**) flood frequency map along the "Belt and Road" zone; (**b**) flood frequency hierarchical map.

Then the flood frequency map was classified into five classes of approximately equal number of grid cells (Figure 5b). The greater the grid cell value in the final dataset, the higher the relative frequency of flood occurrence. The five flood frequency grades are low flood risk, low to medium flood risk, medium flood risk, medium to high flood risk and high flood risk respectively.

As shown in the table (Table 4), floods in Southern Asia are the most serious, with high flood risk area covering 67% of the region, far exceeding the average level of the "Belt and Road" zone. Floods in China and South-Eastern Asia are slightly better than Southern Asia but it is still not optimistic. The shares of the areas that suffer with medium flood risk and medium to high flood risk in Western Asia and Northern Africa and Central and Eastern Europe are both higher than the average level of "Belt and Road" zone. Mongolia-Russia and Central Asia is the least affected area by flood along the "Belt and Road" zone. There are especially few floods in Central Asia.

Table 4. "Belt and Road" flood impact area and proportion statistics table.

Zone	Low Flood Risk		Low to Medium Flood Risk		Medium Flood Risk		Medium to High Flood Risk		High Flood Risk	
	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage
China	138	14%	133	14%	182	19%	188	20%	319	33%
South-Eastern Asia	106	24%	31	7%	52	12%	87	19%	171	38%
Southern Asia	5	1%	5	1%	22	5%	131	26%	336	67%
MRCA	977	43%	417	18%	515	23%	336	15%	11	1%
WANA	179	24%	124	16%	182	24%	218	29%	56	7%
CE Europe	30	14%	23	11%	71	32%	59	27%	34	16%
Belt and Road	1435	28%	733	14%	1024	20%	1019	20%	927	18%

In addition, the distribution of flood in 2016 and potential affected cropland, railway and highway was analyzed. The most serious floods occurred in South-Eastern China. Southern Asia was affected by floods the most extensively. Total area affected by flood is the largest in Mongolia-Russia and Central Asia, while no floods occurred in Central Asia. Floods and disasters not only cause fatal blows to infrastructure of cities and industries, they also have serious consequences on agriculture and transportation [44]. Statistics on regions along the "Belt and Road" zone affected by floods are made based on spatial distribution of cropland, highways and railways. The results are shown below (Figure 6, Table 5).

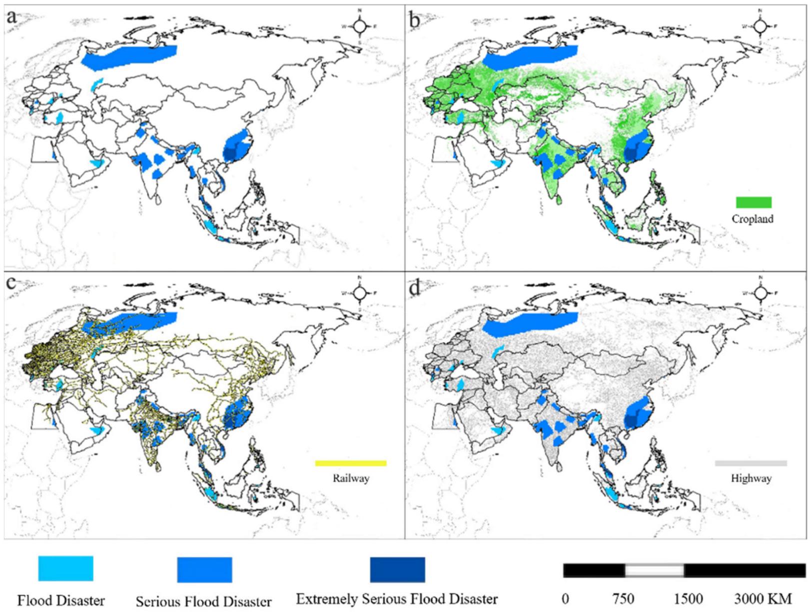

Figure 6. (**a**) spatial distribution of floods in 2016 along the "Belt and Road" zone; (**b**) potential affected cropland by floods in 2016 along the "Belt and Road" zone; (**c**) potential affected railway by floods in 2016 along the "Belt and Road" zone; (**d**) potential affected highway by floods in 2016 along the "Belt and Road" zone.

Table 5. Potential affected cropland/railway/highway by floods in 2016 along the "Belt and Road" zone.

Zone	Flood Area (10^4 km^2)	Cropland (10^4 km^2)	Highway (10^4 km)	Railway (10^3 km)
China	105	92	7	10
South-Eastern Asia	76	46	3	8
Southern Asia	117	93	9	22
MRCA	195	21	7	30
WANA	28	7	2	2
CE Europe	10	9	1	4
Belt and Road	531	268	29	76

In 2016, Mongolia-Russia and Central Asia had the largest area affected by flood disasters, reaching as high as 2 million km^2. However, since flood areas are mainly located in sparsely populated old-growth forest areas, the area of cropland affected is not large. China and Southern Asia have the largest areas of cropland affected by floods, both exceeding 1 million km^2. With respect to highways and railways, China, Southern Asia and the Mongolia-Russia Central Asia are the most heavily affected areas. Central and Eastern Europe and Western Asia and Northern Africa are the least affected areas in cropland, highways and railways (Figure 7a,b).

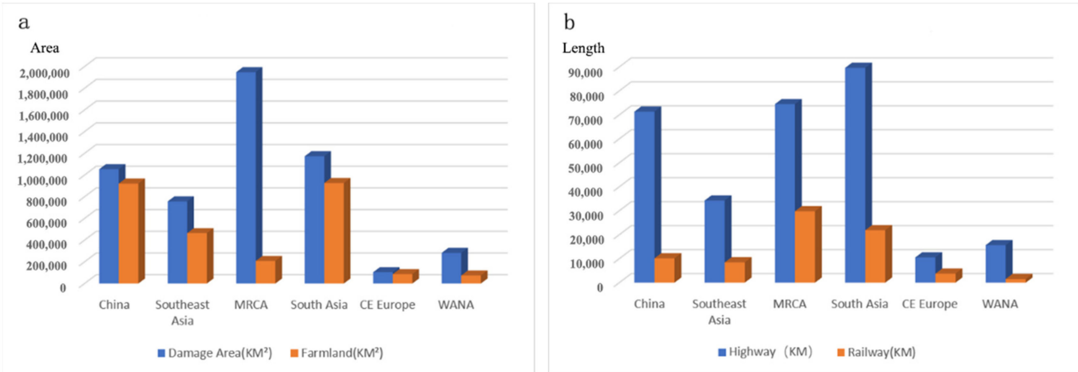

Figure 7. (**a**) Statistic of floods potential affected land and cropland along the "Belt and Road" zone in 2016; (**b**) Statistic of floods potential affected railway and highway along the "Belt and Road" zone in 2016.

4. Hydrological Disaster Impact Analysis

4.1. Water Hazard Risk Analysis

Water security is a key element to national and social development and regional stability, and many scholars have studied the vulnerability framework which combines natural and human-related risks [45–48]. In this paper we drew the water hazard risk map by combining flood data (Figure 5b) and drought data (Figure 4b) during 1985–2016 by accumulating the assigned values of drought severity and flood severity (Figure 8). Then the severity of the water hazard risk map was classified into five classes of approximately equal number of grid cells: low risk, low to medium risk, medium risk, medium to high risk and high risk respectively.

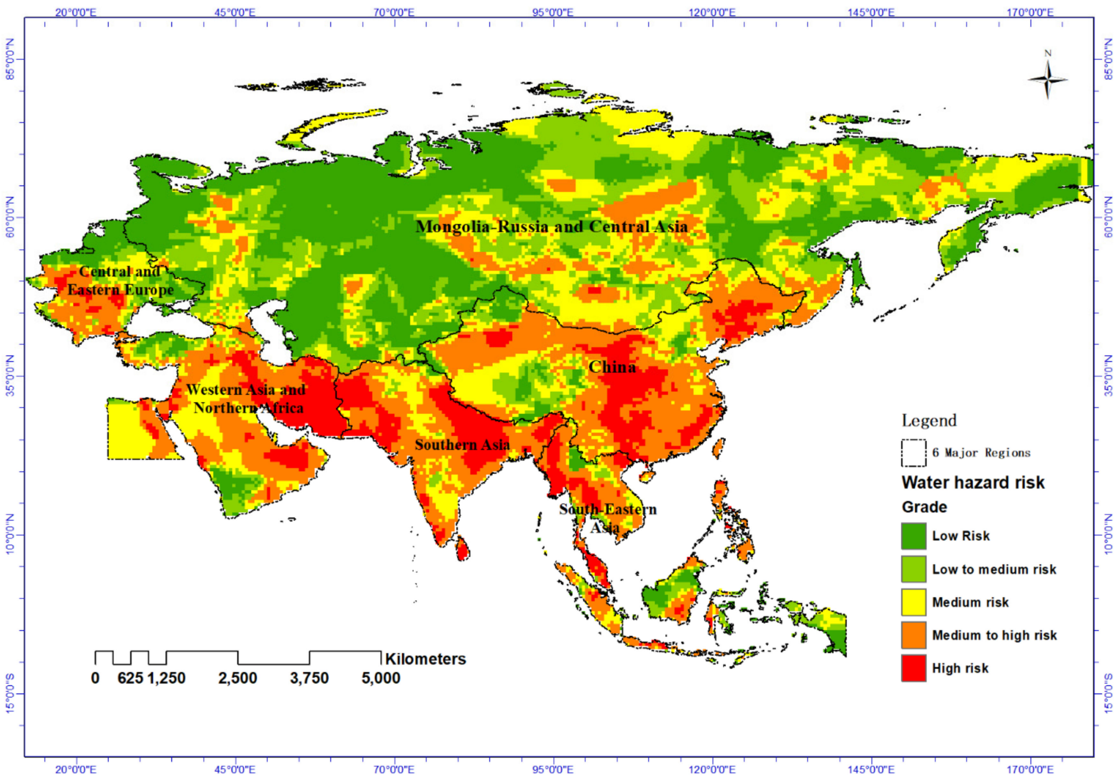

Figure 8. Water hazard risk map.

According to the statistics data from water hazard risk map (Table 6), 80% of the lands in Southern Asia are threatened by high and medium to high water hazard risk, which is much higher than the average level of the "Belt and Road" zone. The areas face high and medium to high water hazard risk in China, Western Asia and Northern Africa and South-Eastern Asia have also reached 65%, 62% and 56% respectively; the security of water resource is also not optimistic. The best areas with respect to water resources condition along the "Belt and Road" zone is Mongolia-Russia and Central Asia, where the areas facing high hazard risk in water resources are basically zero. The water security condition in Central and Eastern Europe is at a moderate level.

Table 6. "Belt and Road" regional water hazard risk statistics table.

Region	Low Risk		Low to Medium Risk		Medium Risk		Medium to High Risk		High Risk	
	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage
China	57	6%	94	10%	185	19%	445	46%	178	19%
South-Eastern Asia	63	14%	62	14%	71	16%	175	39%	77	17%
Southern Asia	5	1%	12	2%	86	17%	228	46%	168	34%
MRCA	927	41%	652	30%	486	21%	190	8%	2	0%
WANA	42	6%	48	6%	198	26%	303	40%	167	22%
CE Europe	60	27%	41	19%	37	17%	66	30%	15	7%
Belt and Road	1154	22%	909	17%	1063	20%	1407	27%	607	12%

As shown in the Figure 9, Southern Asia faces much higher water risk than other regions, followed by China and South-Eastern Asia, Mongolia-Russia and Central Asia; Central and Eastern Europe have the best water security condition.

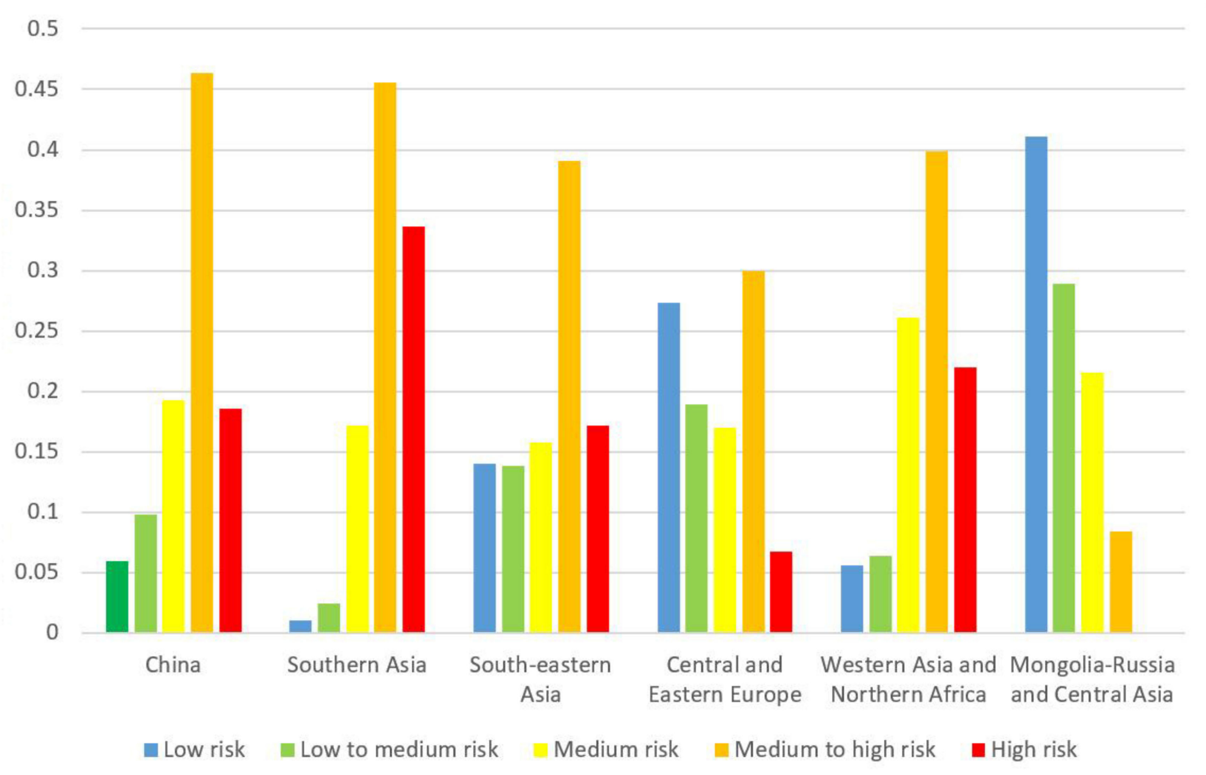

Figure 9. "Belt and Road" regional water hazard risk histogram.

4.2. Potential Impact Population Analysis

The "Belt and Road" zone passes through three continents—Asia, Europe and Africa, covering a wide range of areas, with complex and diverse natural environments and highly fluctuating population density (Figure 10). Spatial distribution of population has been recognized as a fundamental indicator of various studies including ecosystem assessment [49].

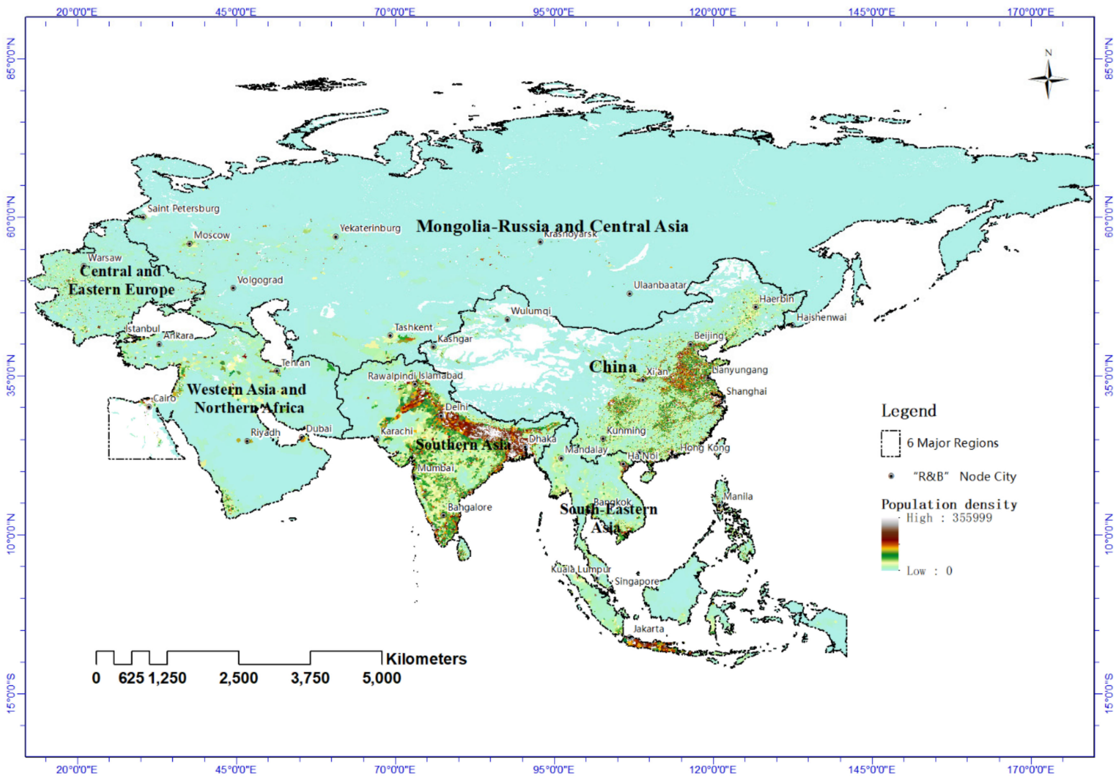

Figure 10. "Belt and Road" zone population density map.

By integrating the population density map of areas along the "Belt and Road" zone with the map of water hazard risk (Figure 8), the results are shown as the following table (Table 7). This means that 84%, 82%, 79% and 77% of the population of China, South-Eastern Asia, Southern Asia, Western Asia and Northern Africa are facing potential high water hazard risk, which is the most severe along the "Belt and Road" zone. The population facing potential water hazard risk in Mongolia-Russia and Central Asia is the least, followed by Central and Eastern Europe.

Table 7. Potential impact population along the "Belt and Road" zone by water hazard.

Region	Low Risk		Low to Medium Risk		Medium Risk		Medium to High Risk		High Risk	
	Popu (million)	Percentage	Popu (million)	Percentage	Popu (million)	Percentage	Popu (million)	Percentage	Popu (million)	Percentage
China	29	2%	47	3%	152	11%	838	59%	361	25%
South-Eastern Asia	22	4%	35	6%	66	11%	327	56%	132	23%
Southern Asia	0	0%	17	1%	278	17%	742	45%	609	37%
MRCA	80	43%	63	34%	26	14%	14	8%	1	1%
WANA	22	4%	32	6%	64	13%	245	50%	135	27%
CE Europe	38	21%	34	18%	27	15%	70	38%	15	8%
Belt and Road	191	4%	228	5%	613	14%	2236	50%	1253	28%

4.3. Potential Impact Corridor Analysis

The key areas of "Belt and Road" initiative mainly include six corridors, which are China–Mongolia–Russia Corridor (CMRC), New Eurasian Continental Bridge (NECB), China-Central Asia-West Asia Corridor (CCAWAC), China–Pakistan Corridor (CPC), Bangladesh–China–India–Burma Corridor (BCIBC) and China–Indo-China Peninsula Corridor (CICPC). Take NECB as an example, it runs through China and Central Asia with possible plans for expansion into South and West Asia. The Eurasian Land Bridge system is important as an overland rail link between China and Europe, with transit between the two via Central Asia and Russia. By integrating the corridors map (Figure 1) along the "Belt and Road" zone with the map of water hazard risk (Figure 8), the results are shown as the following table (Table 8). This means that 85%, 72% and 57% of the area of the China–India–Burma Corridor, China–Indo-China Peninsula Corridor and China–Pakistan Corridor are facing potential high water hazard risk, which are the most severe along the "Belt and Road" zone. China–Mongolia–Russia Corridor and New Eurasian Continental Bridge have the least area facing potential water hazard risk, followed by China-Central Asia-West Asia Corridor.

Table 8. Potential impact corridor area along the "Belt and Road" zone by water hazard.

Corridor	Low Risk		Low to Medium Risk		Medium Risk		Medium to High Risk		High Risk	
	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage	Area (10^4 km^2)	Percentage
CMRC	66	27%	53	21%	72	30%	48	20%	6	2%
NECB	61	35%	37	21%	28	16%	35	20%	15	8%
CCAWAC	27	28%	26	27%	11	11%	23	24%	10	10%
CPC	5	12%	2	5%	10	26%	14	34%	9	23%
BCIBC	1	1%	1	1%	7	13%	31	60%	13	25%
CICPC	1	1%	5	7%	16	20%	36	46%	20	26%

5. Discussion

Water hazard risk of regions around the "Belt and Road" have increased in response to continued global warming and rapid urbanization. Understanding the spatial variability of water resources state of regions is necessary to the "Belt and Road" initiative. In nations of Western Asia and Northern Africa (WANA), the major water problem is the high drought risk (67% in Table 3), which leads to a decrease in food production, forest ecosystems degradation, expansion of desert and so on. Herewith, to WANA, the steps of afforestation, forest care and management, tree species improvement, domestic water saving, water use and irrigation efficiency improvement, utilization of sewage and rainwater, industrial water recycling and sewage treatment should be included in the "Belt and Road" initiative. Whereas, in Southern Asia, South-Eastern Asia and China, the main threat of water is the high risk of flood (Table 4), which also leads to vast economic loss and damage. Herewith, various methods such as enhancing flood prevention research, strengthening hydrologic infrastructure, emphasizing the role of flood early-warning systems, raising the standard of flood control and utilizing the resources of flood water, will be helpful to these regions in the "Belt and Road" initiative.

According to the experience of China, drought can be solved by the thought of harmony between human and water, construction of water-saving society, management of water resources and strategy of connecting river and lake systems. To the flood outside the city, a large number of water projects are necessary. While loosening waterlogging in the city needs cooperation from several departments of government, including water resources, municipal administration, transportation, land and so on. Of course, many countries around the "Belt and Road" are very concerned about water problems. However, under the conditions of frequent extreme climate, lack of water resources, fragile ecological environment and complex transboundary water resources issues, water resources security and its corresponding ecological security are significant to the "Belt and Road" initiative.

In this paper, we focused on floods and droughts to represent water security, which is mainly retrieved from surface water. Whereas groundwater is important to floods and droughts for providing nearly half of the water used for irrigated agriculture and it supplies drinking water for billions of people. Groundwater levels declining will exacerbate the risk of droughts in countries around the "Belt and Road". Furthermore, the hydrological interaction between ground water and surface water will loosen the risk of floods. So, when considering the water security around the "Belt and Road", groundwater resources and their availability for exploitation should be taken into account in the future. Furthermore, apart from the quantitative aspect, water quality both of surface and ground water is also a significant issue to water security. It is the same for droughts and floods; water quality deterioration has been classified as an important water hazard. Although water quality data is scarce around the "Belt and Road", the utility value of surface and groundwater should also be analyzed in terms of its quality in future study.

6. Conclusions

Analysis of water security along the "Belt and Road" zone from 1985 to 2016 shows that, (1) The areas with the most precipitation are mainly distributed in the southeast, including South-Eastern Asia, southern China and eastern Southern Asia. Precipitation is scarce from Northwestern China to Western Asia and Northern Africa, with annual precipitation being less than 100 mm in most areas. (2) To the impact of floods, Southern Asia is most serious impacted, followed by China and South-Eastern Asia; Mongolia-Russia and Central Asia are the least affected area by flood along the "Belt and Road" zone. (3) To the impact of droughts, Western Asia and Northern Africa are the most serious, followed by China and Southern Asia. Central and Eastern Europe and Mongolia-Russia and Central Asia are the least affected areas by drought along the "Belt and Road" zone. (4) To the potential water hazard risk, China, South-Eastern Asia, Southern Asia, Western Asia and Northern Africa have the largest population number facing potential high water hazard risk. China–India–Burma Corridor and China–Indo-China Peninsula Corridor have the largest areas facing potential high water hazard risk.

Water security has become a key constraint to the sustainable economic and social development of countries along the "Belt and Road" zone. Rapid urbanization has exacerbated the contradiction between water shortage and water demand and has also caused the increasingly serious floods and droughts in urban areas. Therefore, bearing capacity of water resources and the environment should be carefully considered before formulating urban and transport planning. All these considerations will contribute to the smooth implementation of the "Belt and Road" Initiative. Of course, there are still many shortcomings in this study. For example, all the countries along the "Belt and Road" zone are not included in the analysis. Only the precipitation, drought and flood in the region are analyzed. The data such as groundwater and soil moisture are not taken into consideration. The utility value of surface and groundwater should also be analyzed in terms of its quality. All of the above shortcomings will be the emphasis in our future research.

Author Contributions: Data curation, Z.L. and X.S.; Investigation—Methodology, M.C.; Resources, P.K.; Supervision, Y.H.; Writing—original draft, Z.L. and M.C.; Writing—review and editing, Y.H. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by National Natural Science Foundation of China (Grant NO. 41822104), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19040402), the National Key Research and Development Program of China (Grant No. 2017YFB0503005 and 2016YFC0401404) and China high-resolution earth observation system (21-Y20B01-9001-19/22).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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Machine Learning to Evaluate Impacts of Flood Protection in Bangladesh, 1983–2014

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Received: 22 December 2019; Accepted: 1 February 2020; Published: 11 February 2020

Abstract: Impacts of climate change adaptation strategies need to be evaluated using principled methods spanning sectors and longer time frames. We propose machine-learning approaches to study the long-term impacts of flood protection in Bangladesh. Available data include socio-economic survey and events data (death, migration, etc.) from 1983–2014. These multidecadal data, rare in their extent and quality, provide a basis for using machine-learning approaches even though the data were not collected or designed to assess the impact of the flood control investments. We test whether the embankment has affected the welfare of people over time, benefiting those living inside more than those living outside. Machine-learning approaches enable learning patterns in data to help discriminate between two groups: here households living inside vs. outside. They also help identify the most informative indicators of discrimination and provide robust metrics to evaluate the quality of the model. Overall, we find no significant difference between inside/outside populations based on welfare, migration, or mortality indicators. However, we note a significant difference in inward/outward movement with respect to the embankment. While certain data gaps and spatial heterogeneity in sampled populations suggest caution in any conclusive interpretation of the flood protection infrastructure, we do not see higher benefits accruing to those living with higher levels of protection. This has implications for Bangladesh's planning for future and more extreme climate futures, including the national Delta Plan, and global investments in climate resilient infrastructure to create positive social impacts.

Keywords: Bangladesh; climate resilience; flood protection; machine learning; socio-environmental impacts

1. Introduction

Climate change is expected to increase the frequency and extent of extreme flood events, which will directly impact the environment and the livelihoods of people in the affected areas [1,2]. Low-lying coastal regions of the world are particularly vulnerable to these flood events and sea level rise [3,4]. The issue is compounded in countries such as Bangladesh, where about 60% of the country is lower than 6 m above the sea level [5] while more than 70% of land is used for agriculture, the country's primary economic source [6]. Although there have been global investments on climate change adaptation, these adaptation measures can have both beneficial and unintended detrimental consequences when wider issues or longer time frames are considered [7,8]. Integration of adaptation actions and policies across sectors at different spatio-temporal and societal scales remains a key challenge to achieve effective adaptation in practice [9]. Another major challenge is the lack of consistent empirical methods linking climate change to the impacts on the environment and the livelihoods of people [10]. Although success of these interventions relies on developing principled methods to monitor and evaluate the impacts across different environmental and socio-economic factors [11], currently there is a lack of such methods in the literature. This work aims to bridge a key gap in knowledge by proposing rigorous analytical methods to evaluate the impacts of adaptation measures.

Bangladesh has had five decades of political and policy attention focused on implementing flood mitigation strategies, whose evaluation has been documented in the past literature on Bangladesh flood protection infrastructure. The total flood protection coverage area currently stands at 5.37 million ha, more than one third of the country [12,13]. Primarily aimed to protect monsoon crops and prevent damage to homesteads, these interventions have often not considered the social, economic, and environmental dimensions of water resource management [13]. While the interventions led to several positive impacts, they also resulted in considerable medium to long-term negative consequences in many places. The flood secure environment facilitated enhanced economic activities in the protected areas, e.g., increased agricultural output [14]. But when embankments failed to provide protection during moderate to extreme floods, the resulting damage was higher owing to the accelerated economic activities compared to areas outside embankment [13,15]. Floodplains were deprived of several environmental and ecological functions, including improvement of soil fertility from silt-laden inundation water, groundwater recharge, and biodiversity. The disruption in hydraulic connection between river and floodplain led to substantial damage to fisheries and local boat transports [14–18], compromising the livelihood activities of people, especially the marginalized.

Previous evaluations of flood protection investments in Bangladesh have widely suggested that it has been difficult to attain the stated objectives of the interventions based on only technical and economic viability, but without giving due consideration to the hydromorphological features of the floodplain and the socio-economic condition of its inhabitants. Despite the negative consequences of embankments, the popular demand for flood protection by people has been high. Hence, the priority of the Government started to shift from traditional flood control to flood management towards the later stages of the Flood Action Plan (FAP) in late 1980s. Here, flood control refers to the conventional method of constructing an embankment and drainage regulator whereas flood management refers to mitigating flood damage without causing degradation of the floodplain environment, which might involve implementing floodplain land use regulation that identifies floodplain zones and enforces appropriate planning and design during construction of infrastructures in these floodplain zones to account for flood and preservation of floodplain resources and environment. There was a real paradigm shift to integrated flood management, i.e., covering issues relevant to not only flood but also drainage, irrigation, navigation, environment and socio-economic development, which was subsequently reflected in the National Water Policy (NWP) in 1999 [19] and the National Water Management Plan (NWMP) [12]. A combination of structural and non-structural measures was envisioned, with full structural protection against floods in regions of economic importance (such as metropolitan areas), a reasonable degree of protection in other critical areas (such as district towns), and flood proofing measures in the rural areas. However, translating integrated management into action, particularly at the program and project levels, has remained a major challenge [20].

The Bangladesh Delta Plan 2100 also gives more emphasis to restoration, redesign and modification of existing embankments and associated structures, and a high importance to the urgency of maintenance [21]. New developments are envisioned only for protecting economic strongholds and critical infrastructure. Most are already in place but requires improvement; additional developments will be required in some areas. In order to properly evaluate the impacts of these investments, this work strongly recommends adoption of principled analytical methods early on, considering socio-economy and environment across longer time frames, so that appropriate studies are conducted at the outset, e.g., baseline and periodic survey and monitoring to assess the impact of interventions.

The changes in Bangladesh Delta are affected by many factors, upstream interventions being one of them. In this work, we evaluate the impact of flood infrastructure on a large project in Bangladesh. We took advantage of an existing data set of this project to further clarify evaluation outcomes in Bangladesh flood management using machine learning approaches. We chose the site also because it had robust historic continuous data to trial machine learning that enabled the type of analysis that other sites could not. Machine learning, generally considered a subset of artificial intelligence, is a field of study that uses algorithms and statistical models to learn patterns from data so that useful inference may be made about new data. Machine-learning approaches are useful in the context of this study because they provide robust metrics to evaluate the impacts of interventions as well as identifying the most informative indicators.

Context and Related Works

The Meghna–Dhonagoda Irrigation Project (MDIP) is one of the largest flood control, drainage and irrigation projects in Bangladesh, implemented in 1988 with the objective to protect the area in Matlab North from river flooding and drainage congestion during the monsoon via embankment and regulators. The primary aim was to improve agricultural conditions in monsoon, with special reference to encouraging introduction to high yielding variety (HYV) monsoon rice (Aman), and also to provide irrigation from surface water in the Rabi (dry) season and early monsoon seasons. Located 55 km south-east of the capital city Dhaka, the study area is 184.4 km^2 with a population of 230,185 as of 30 June 2014 [22]. The Dhonagoda river bisects the area into Matlab North and Matlab South. The embankment protects the Matlab North area from flooding from Meghna river on the north and west and Dhonagoda River on the east and south (Figure 1).

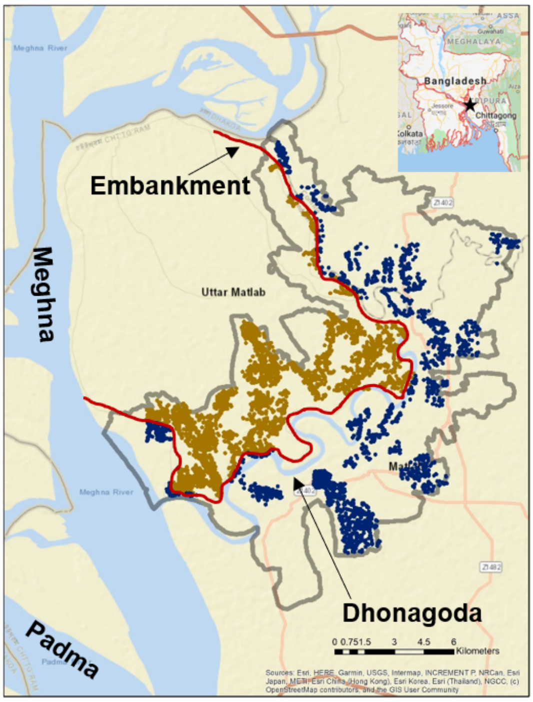


Figure 1. Baris (cluster of households) are colored based on whether they are located inside (brown) or outside (blue) the embankment (red).

This study area provides a unique setting to evaluate the long-term impacts of an embankment on households living on both sides of the embankment by using an unrelated but population-wide Health and Demographic Surveillance System (HDSS) [22,23] managed by the International Centre on Diarrheal Disease Research, Bangladesh (icddr,b). The research site was created in 1963, over 25 years before the embankment's construction, to provide field-based research on cholera vaccines and treatments. The site maintains a primary research focus on studying public health interventions and demographic changes. The study site evolved around two sets of comparison zones. The primary division is a quasi-experimental maternal and child health and family planning program where half the population received reproductive health interventions and home visits from community health workers, while the other half received the government's public health services [22].

The other key division across the study area is between those within and those outside the embankment. The embankment-led agricultural and related economic variables are not rigorously tracked through the icddr,b data systems and health-focused research agenda [24]. Discussion of the embankment's impact did not appear in the icddr,b annual reports until the 2014 analysis of the socio-economic survey and is not a feature of these reports which serve as a core site output [23]. However, the embankment provided a clear division of the population between people living inside vs. outside the embankment [22,25]. The HDSS data, spanning pre–post-embankment periods provide a unique opportunity to study the long-term impact of embankment.

Multiple studies have used the HDSS data to advance analysis around the indirect impacts of embankment [25–30]. Earlier studies of child mortality in Matlab in 1981 identified the socio-economic factors as indicators of severe malnourishment, impacting child mortality, which was a basis for socio-economic survey focus on household assets, education and occupation [26]. A later study during 1983–1992 showed that child mortality was higher outside than inside the embankment, with the differences particularly significant for deaths caused by infectious diseases [27]. The study recommended comparison of long-term mortality data with migration patterns and other factors (e.g., proximity to main rivers). Another study of the embankment's impact on cholera during 1983–2003 showed that after controlling all other environmental variables, living inside the embankment area does not appear to affect whether the household experiences cholera. Counter-intuitively, among households where cholera is reported, living inside the embankment area significantly increases the number of cholera cases, possibly due to a combination of environmental factors and behavioral change [29]. In particular, a joint study by Bangladesh Rural Advancement Committee (BRAC) and International Centre for Diarrheal Diseases Research, Bangladesh (icddr,b) analyzed the impact of embankment on both environment and people [28]. Based on both quantitative and qualitative surveys conducted in 1992 and 1996 respectively, the study revealed both positive and negative impacts. The positive impacts were associated with a higher level of agricultural yields and economic prosperity, particularly for a subset of farmers, while the negative impacts were associated with lower fish catch and intake of fruit and vegetables, displacement of poorer households, and complaints about ill health due to greater demand for agricultural labor [28]. However, the core findings around welfare differences were inconclusive. The study recommended doing a follow-up study using longer-term data to analyze how these impacts would evolve over time. Another study found that the embankment resulted in a net welfare loss, which had been an outcome of higher than anticipated construction costs, lower benefits to agriculture due to loss of soil fertility over time, higher waterlogging damages and the highly negative impact on capture fisheries [30]. The embankment also caused negative distributional outcome, with big landowners benefiting from increased agricultural production, reduced property damage, and increased livestock and aquaculture production. In contrast, the traditional fishermen and the river transport workers, belonging to the poor sections of the community, suffered significantly negative impact. However, the variables related to these impacts were not monitored consistently over time, limiting ability to include in longer-term impact assessments.

Most studies occurred within a decade of the embankment completion, showing only the short-term impacts. There is a limited body of literature exploring long-term impacts outside agricultural productivity, providing a core motivation of this paper to re-purpose multi-decadal HDSS data. Using this data, machine-learning approaches can be used to empirically evaluate the impact of embankment and identify the most informative socio-economic indicators. Besides, these approaches provide robust metrics to evaluate the model's accuracy and generalizability to future examples. We explore the extent to which machine learning can provide analytical insights from detailed historical data on long-term impacts from climate resilient infrastructure to help guide future policy and investments.

2. Methods

2.1. Machine-Learning Approaches

Machine-learning approaches have found useful applications in a wide variety of fields, including text processing, computer vision, healthcare, finance, and robotics [31–36]. Recently, these approaches have also been applied to socio-economic [37–40] and environmental [41–45] studies.

We implement machine learning on two types of data to answer two specific questions:

1. Based on multidecadal socio-economic survey data, are there any significant differences in socio-economic status of households living inside vs. outside embankment over time, and which variables are most informative of the differences?
2. Based on multidecadal events data, are there significant differences in mortality and migration patterns of households living inside vs. outside embankment over time?

To answer the first question, socio-economic variables corresponding to a household (inputs) are mapped to a binary label (output). The responses provided by households during a socio-economic survey are used to determine whether the households live inside or outside embankment. By comparing classification outputs over time, we can infer whether the embankment has caused differences in welfare inside vs. outside embankment over time. To answer the second question, a regression model is used to map time (input) to event rate (output), e.g., mortality rate per year. After learning two independent regression models for two event rates corresponding to inside vs. outside embankment, we can analyze whether the embankment has caused differences in the event rates over time. An array of approaches exists to perform classification and regression. The ones adopted in this work are motivated by their suitability to model the available data in answering the aforementioned questions.

2.1.1. Classification Approaches

For each household, its label y_n (output), indicating whether it lies inside or outside embankment, is defined in terms of its responses to D survey questions $\mathbf{x_n} = [x_{n1}, ..., x_{nD}]^T$ (inputs) as follows:

$$y_n = f(\mathbf{x_n}) + \epsilon_n, \tag{1}$$

where ϵ_n is the residual or noise, and $f()$ is the mapping function specific to the type of classifier. The mapping function and its parameters can be learned using a collection of household survey responses and their corresponding labels (termed "training" examples). Once a mapping function is learned, it can be used to predict labels for new previously unseen (termed "test") examples. By evaluating whether the labels are correctly predicted for test examples, we can determine the ability of a classifier in discriminating two classes. The simplest mapping function is a linear function of the inputs as follows

$$y_n = w_0 + w_1 x_{n1} + ... + w_D x_{nD}, \tag{2}$$

where the weights $\mathbf{w} = [w_0, ..., w_D]^T$ are known as the parameters of the mapping function. However, this simple linear discriminant function [31] cannot model interactions between variables or other complex phenomena. Generally, classification techniques learn a non-trivial mapping function, capable of performing nonlinear classification, which are more relevant to model real-world examples.

Some standard classification approaches are Logistic Regression (LR) [31], kernel-based methods, e.g., Support Vector Machines (SVMs) [46], decision trees, e.g., Random Forest (RF) [47], and Neural Networks (NN), e.g., Stacked Auto-Encoders (SAE) [36]. Logistic Regression (LR) is one of the most popular classification approaches, which uses a logistic sigmoid function to perform probabilistic binary classification. However, without using kernels, LR is often only suitable to classify linearly separable examples. In general, we expect other above-mentioned approaches to perform as well as or better than LR.

Random Forest (RF) is a type of ensemble-based method that performs an average over an ensemble of many estimates obtained over bootstrapped subsets of data, where the ensemble of estimators can be thought of as leaves of a tree [47]. An added advantage of RF is that it also ranks the input variables by their importance to discriminate the two classes. In the context of this study, the variable importance ranking helps identify which survey questions are most informative of households living inside vs. outside embankment. When using RF, it is important to choose an appropriate number of estimators, and optimize other parameters.

Stacked Auto-Encoders (SAE) is a type of deep learning methods that first learns the lower-dimensional representation of data by constraining the hidden layers to capture the most relevant aspects of the data. Then the whole network is discriminatively fine-tuned like a feedforward neural network to perform classification [36]. Similar to Principal Component Analysis (PCA) [34], which is the most common dimension reduction technique, SAE can be used to learn useful lower-dimensional representations of data to uncover patterns in data, e.g., identify clusters of households with similar features. Unlike PCA, SAE is not limited by the Gaussian distribution assumptions of the input space, it is more flexible to model mixed data types (binary, categorical, and continuous), and being a deep learning approach, it is capable of handling large amounts of data. These are all favorable properties for analysis of socio-economic survey data. It is important to optimize SAE's parameters such as learning rate, batch size, number of epochs, number of hidden nodes, number of hidden layers, etc.

We do not go into details regarding the specifics of these approaches other than provide a general intuition for the ones that are implemented. Having experimented with a variety of these approaches, we report majority of our results based on RF, while comparing RF to LR and SAE on one specific example for reference.

2.1.2. Regression Approaches

Shifting from discrete to continuous output labels, for each year x_n (input), the event rate for that year, i.e., its label y_n (output), can be defined with (1), where y_n is now a continuous variable. Different regression approaches exist, e.g., Relevance Vector Machines (RVMs) [48], Gaussian Processes (GPs) [49]. Gaussian Processes (GPs) are probabilistic methods (i.e., capable of giving uncertainty of model's predictions) that can be used to model time-series data as a distribution over function [49]. We use GPs because in addition to modeling event rates as time-series, they are also useful to compare differences in the resulting time-series models. In a Bayesian framework, the event rates $\mathbf{y} = [y_1, ..., y_N]$ for N years $\mathbf{x} = [x_1, ..., x_N]$ can be defined by a GP prior as follows

$$f(\mathbf{x}) \sim GP(m(\mathbf{x}), k(x, x^T)), \tag{3}$$

where $\mathbf{y} = f(\mathbf{x}) + \epsilon$, ϵ is the noise, $m(\mathbf{x})$ is the mean function and $k(x, x^T)$ is the kernel or covariance function. This allows the posterior distribution of the function evaluated at a finite set of points $\mathbf{x}_*$ to be a multivariate Gaussian distribution as follows

$$p(\mathbf{f}_*|\mathbf{x}_*, \mathbf{x}, \mathbf{y}) = N(\mathbf{f}_*|\mu_*, \mathbf{\Sigma}_*), \tag{4}$$

where μ_* and $\mathbf{\Sigma}_*$ are the posterior mean and covariance, respectively. This posterior formulation allows us to compare the differences in two event rates in a principled manner, which is described in the next section. When using GPs, it is important to choose an appropriate kernel function and optimize its parameters.

2.2. Evaluation Metric

We evaluate inside/outside embankment classification using Receiver Operating Characteristics (ROC) curve based on k-fold (k=3) cross-validation [31], which prevents a classifier from overfitting to training examples, thus ensuring the results are generalizable. Intuitively, a diagonal ROC curve means the predictors (socio-economic survey variables) are not indicative of inside/outside class discrimination. On the other hand, the more the curve pushes towards the top-left corner, the more discriminatory are the predictors. A statistical significance test can be performed to compare the area under ROC curves (AUCs) of the later three years with the AUC of 1982 [50]. Whenever a comparison is statistically significantly different with p-value less than 0.01, the corresponding p-value is highlighted with a $*$ symbol.

In line with the previous studies [25,29], to compare differences in events data pre- vs. post-embankment, we divided the 32-year study duration into pre (1983–1989) vs. post (1990–2014) embankment periods. Within each of these two periods, we can compare the temporal differences in these events using a Gaussian Process-based Bayesian statistical significance test [51]. The posterior formulation in (4) allows us to model the differences in event rates, $\Delta\mathbf{f}_* = \mathbf{f_1}_* - \mathbf{f_2}_*$, as another multivariate Gaussian with mean $\Delta\mu_* = \mu_{1*} - \mu_{2*}$, and covariance $\Delta\mathbf{\Sigma}_* = \mathbf{\Sigma_1}_* + \mathbf{\Sigma_2}_*$. Then, we say the two event rates are equal with posterior probability $1 - \alpha$ if the credible region for $\Delta\mathbf{f}_*$ includes the zero vector or, in other words, if

$$(\Delta\mu_*)^T(\Delta\mathbf{\Sigma}_*)^{-1}\Delta\mu_* \leq \chi^2_\nu(1-\alpha), \qquad (5)$$

where $\chi^2_\nu(1-\alpha)$ is the $1 - \alpha$-quantile of a Chi-squared distribution with ν degrees of freedoms and ν is the number of positive eigenvalues of $\Delta\mathbf{\Sigma}_*$ [51]. This test can be used to compare two event rates within each (pre or post) embankment period.

3. Data

Part of the HDSS dataset is available for this study, covering roughly one third of the study area geographically.

3.1. Socio-Economic Survey Data

Socio-economic survey data are available for four years, roughly a decade apart. The number of questions in surveys increased over the years from 21, 40, 62, to 146 in 1982, 1996, 2005, and 2014, covering 14791, 19448, 22799, and 25840 households, respectively. Considering 1982 as a baseline pre-embankment period resulted in only four variables equivalent across all four years. Those variables were agricultural land ownership, primary drinking water source, number of cow/buffaloes/goats owned, and boat ownership. Considering only the later three years (1996, 2005, and 2014) resulted in slightly more (12) variables equivalent across all three years. Those variables were agricultural land ownership, homestead land ownership, primary drinking water source, number of cow/buffaloes/goats owned, boat ownership, household assets—sofa, chair/table, showcase, radio, TV, bike/bicycle, primary rood structure, and sanitation facility type. For a consistent comparison, we only consider households that are common across all years, i.e., 10563 and 14276 households common across all four and the later three years, respectively. We note that the results are similar when all households per year are used. For a separate analysis specific to socio-economic survey data from 2014, whose aim was not to compare with prior years, we use all available variables and households.

3.2. Events Data

Events data, collected monthly to bi-monthly, correspond to birth, marriage, divorce, death, inside/outside migration, and inward/outward movement [23]. Here, *migration* refers to the migration from anywhere outside the study area into either the embanked part or the outside part of the study area; whereas *movement* refers to the movement of the study area inhabitants either into or out of the embanked area. We hypothesize that if the flood-protected area were to provide increased socio-economic benefits and stability, people would more likely move to inside the flood-protected area. Although experiments were performed with all data, we only provide results from analyzing death, internal movement, and migration data, which are presumed to be the most informative of the effect of embankment. The event counts in each group (inside/outside) are normalized by the inside/outside annual mid-year population. Since the mid-year population was unavailable for one particular year, we only use data from the remaining 31 years.

4. Results

4.1. Socio-Economic Survey Data Analysis

ROC comparison across four years in Figure 2a seems to suggest there are differences in inside/outside discrimination over time based on socio-economic variables. However, one of these variables, the ownership of a boat, is mostly a consequence of differences in habitat due to embankment rather than an indication of welfare. Indeed, when we remove the ownership of boat variable, Figure 2b shows that the discrimination does not change much over time except for 1996. To understand the increased discrimination in 1996, we rank the three variables (agricultural land ownership, primary drinking water source, and number of cow/buffaloes/goats owned) by their importance in Figure 2c. We observe that agricultural land ownership is the most discriminative variable across all four years. When we classify households based on only agricultural land ownership (results not shown), we observe that although the discrimination increases temporarily during 1996, it falls back to pre-embankment period over time. The statistical significance test in Table 1 supports that only the 1996 AUC metric is significantly different compared to 1982. The results suggest that although there was a short-term increase in agricultural land ownership for inside residents, the difference seems to have evened out over time. Despite the statistical significance test, it should be noted that all AUCs, including 1996, have low values, implying that the equivalent variables are not very discriminative. The results also highlight the need for more data on agricultural productivity and markets to further investigate the differential impact over time.

Setting aside the temporal comparison for a moment, if we were to make use of more variables for a particular year, we could learn a better model and use the classifier's outputs to further investigate the most informative variables in details. Figure 2d shows that when 122 relevant out of 146 variables from year 2014 are used, the classifier performs strong inside/outside discrimination. Figure 2e shows the top 10 informative variables, ordered by their importance—homestead land size, number of households sharing drinking water source, number of chicken/ducks, agricultural land size, fuel source is wood/gas, primary income source, primary drinking water source is Arsenic-safe tubewell/pipe, and if zakat received. Each of these variables can be visualized by aggregating the corresponding household responses at bari-level and comparing each plot to inside/outside locations of baris in Figure 1 as a reference. Figure 3i,ii show that indeed households inside the embankment appear to own more homestead land and owning homestead land appears to be correlated with owning agricultural land. Consequently, land ownership is identified as the most important discriminative indicator. However, for several other variables, the difference appears to be a consequence of the households' proximity to significant infrastructures (e.g., hospital, gasline, pipeline, deep tubewells) instead of a direct consequence of the households living inside/outside embankment. Availability of gasline (Figure 3iv) in certain parts of the study area is complementary to those households not using the more ubiquitous wood as fuel source (Figure 3iii). Likewise, availability of pipeline (Figure 3vi) is complementary to those households not using the more ubiquitous tubewell as drinking water source (Figure 3v). Similarly, larger number of households sharing a drinking water source (Figure 3viii) appears to be complementary to those households using deep tubewells (Figure 3vii).

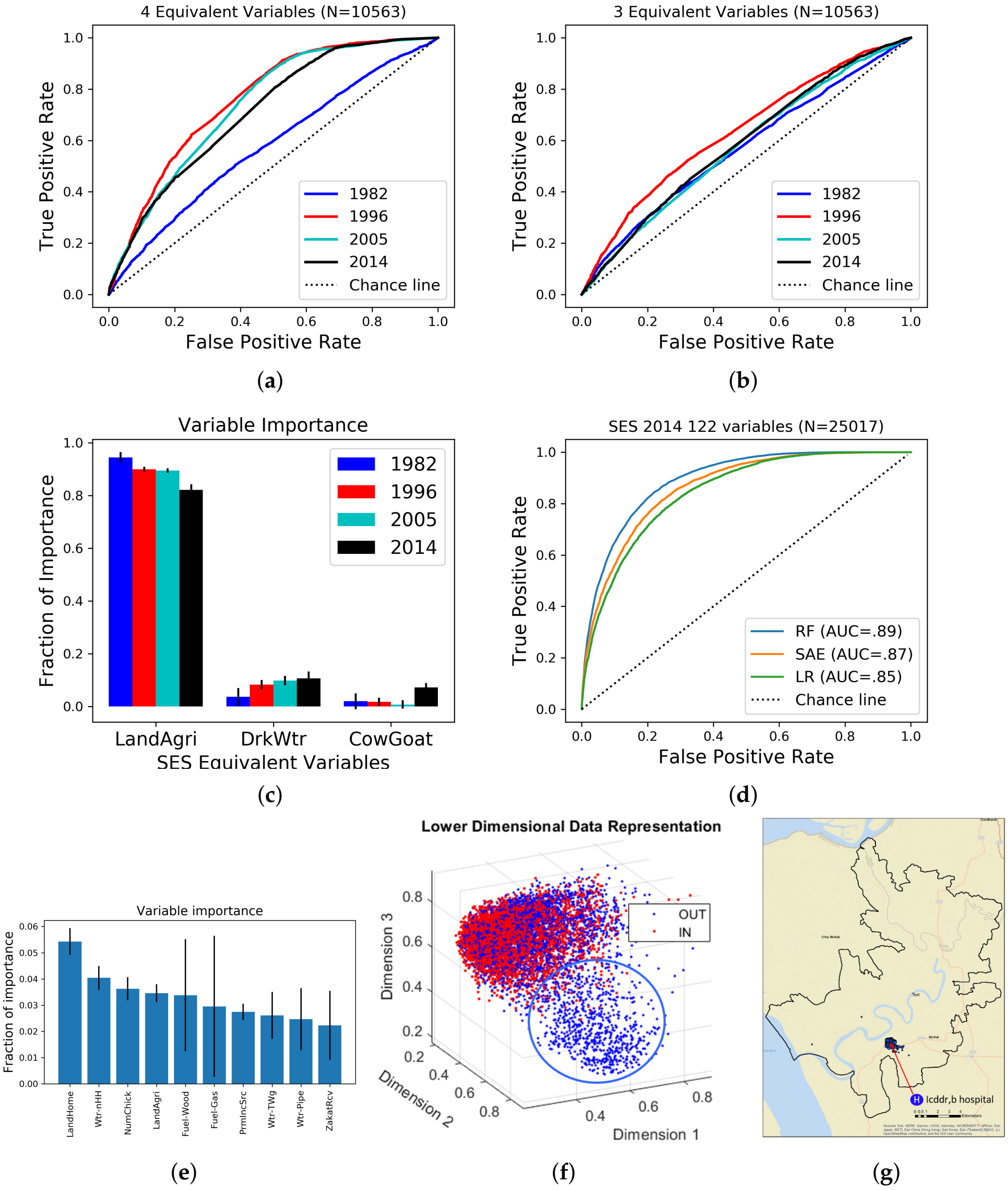


Figure 2. Inside vs. outside embankment classification outputs based on socio-economic survey data using (**a**) four equivalent variables across four years, (**b**) same as (**a**) excluding boat ownership variable, (**d**) 122 variables from 2014 survey, (**c**) top three, and (**e**) top ten discriminating variables identified by Random Forest classifier in respectively (**b**) and (**d**). (**f**) lower-dimensional representation of SES 2014 data, and (**g**) the location of households, corresponding to the cluster inside the blue circle, in the study area.

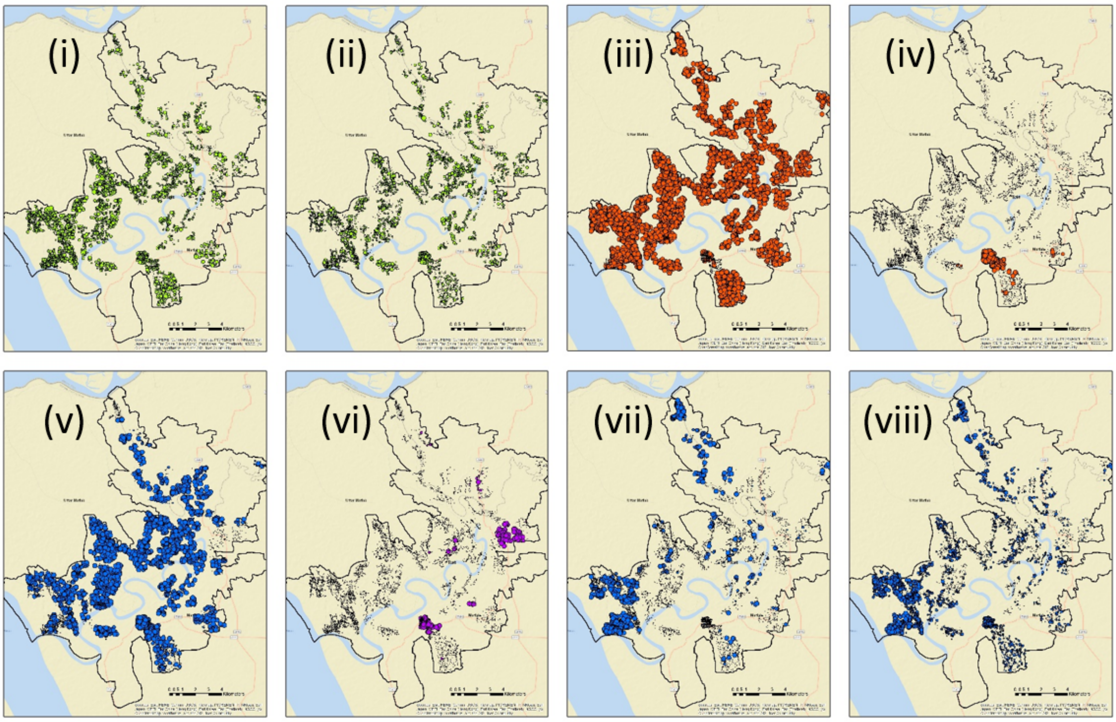


Figure 3. Selected variables from socio-economic survey data. Responses aggregated over bari. (**i,ii**) Homestead vs. agricultural land owned, (**iii,iv**) primary fuel source is wood/wood dust/paddy husk vs. gasline, (**v–vii**) primary drinking water source is green shallow tubewell, pipeline, vs. deep tubewell, and (**viii**) number of households sharing drinking water source.

Table 1. Comparison of AUCs across four years based on Wilcoxon statistic. The ∗ symbol denotes the AUCs are significantly different with *p*-value less than 0.01.

Year	AUC	SE	|Year−1982|	SE of Diff	Z Score	*p* Value
1982	0.564	0.0056				
1996	0.616	0.0055	0.052	0.0078	−6.6611	$< 0.01^*$
2005	0.567	0.0056	0.003	0.0079	−0.3803	0.7
2014	0.557	0.0056	0.007	0.0079	0.8862	0.38

Referring back to Figure 2d, we note that we expect Stacked Auto-Encoders to perform as well or better than Random Forest when Stacked Auto-Encoders' parameters are exhaustively optimized. Rather than obtaining the best discrimination, the primary goal of using Stacked Auto-Encoders was to show its value in learning useful lower-dimensional representation of data. Figure 2f shows a 3-dimensional representation of 122 survey questions, which identifies a cluster of outside residents who are very different from inside residents based on their responses to the survey questions. A geospatial plot (Figure 2g) reveals that this cluster of outside households, in fact, are all located close to the icddr,b hospital, which incidentally, is associated with factors such as availability of gasline. These results suggest that although there was a significant relationship between introduction of embankment and change in land ownership patterns, recent development progress is linked to other variables (e.g., electricity/energy and proximity to services). Spatial analysis of these variables might provide useful insight to track differential progress in the study area.

4.2. Events Data Analysis

Figure 4 summarizes the results of events data analysis for three cases—inward/outward movement, inside/outside in-migration, and inside/outside mortality over time. The first column shows the individual event rate data modeled by independent Gaussian Processes. For each of these plots, the dots represent the normalized event rates per year, the solid lines represent the estimated means, and the shaded regions represent the 99% confidence interval. For each of these three cases, the second column shows the estimated differences in two event rates. The more the two event rates differ, the more the curve deviates from the zero-line, represented by the dotted black line. Finally, the dashed red line marks the pre- vs. post-embankment periods. For each of the second-row plots, within each embankment period, the confidence interval region helps us visually determine if the difference in event rates is statistically significant. If the confidence interval excludes the zero-line, the difference in event rates in this period is statistically significant. These test results are also summarized in Table 2.

Figure 4a,b show that the inward movement rate increased leading up to the embankment's construction, peaking at 1988, and continued to remain significantly higher than the outward movement rate. In recent years, the difference seems to have evened out. Figure 4c,d show that after embankment's construction, the in-migration rate to the area outside of embankment has been increasing compared to inside. However, the difference in in-migration rates is not statistically significant. Based on available data, it is unclear if the decreasing inward movement and the increasing in-migration inside the embankment area are due to growing competition for land inside the embankment or due to falling motivation to move inside. In contrast, Figure 4f shows that the embankment has not caused differences in mortality inside vs. outside over time. The mortality data was disaggregated into vulnerable (under 5-year-olds or over 70-year-olds) vs. non-vulnerable population, and male vs. female. The results (not shown) are similar to Figure 4e,f. Similar analysis done using out-migration data (not shown) shows no difference inside vs. outside. These results suggest that apart from internal movement within the study area, significant differences are not observed in migration and mortality patterns inside vs outside over time.

4.3. Hydro-Climatic Data Analysis

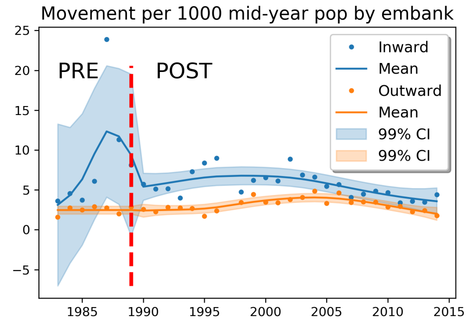
To fully understand the impact of embankment, it is important to link the socio-economic impacts with the hydro-climatic events. With about 47% of the land being low lying, the Meghna–Dhonagoda project area within Matlab North used to be regularly flooded in the monsoon up to a depth of 2–3 m in the pre-project condition [52] (Saleh et al. 2000) (Figure 5b). In contrast, there is a lower proportion of low-lying land area in Matlab South (Figure 5b). While the low-lying areas get inundated during an average annual flood, the relatively higher lands are inundated only during moderate to extreme floods. Since Matlab South is only exposed to the Dhonagoda river, the area is relatively less vulnerable compared to other areas which are directly affected by floodwater from the large Meghna River.

Figures 5c,d show the inundated areas in Matlab in two major flood years, delineated from LANDSAT 4-5 TM images using Normalized Difference Water Index (NDWI) [53]. Although designed based on 1 in 100-year flood level, the embankment, suffering major breaches, could not protect the project area during the 1988 flood (corresponding to a 30-year flood). After repairs, the embankment successfully withstood floods during subsequent years, but frequently suffered many problems. Although the river water level was higher than the design 100-year flood level during the 1998 flood, the severest in recent history both in terms of magnitude and duration, the embankment was able to protect the project area from inundation (Figure 5d) (Saleh et al. 2002; [52]). The flood did; however, cause substantial damages to the embankment. No inundation due to riverine flood inside the embankment has been reported in later years. However, some areas inside the embankment are subject to waterlogging induced by rainfall [30,54]. Two pumping stations inside the project area are operated during the monsoon to drain out the accumulated rainwater.

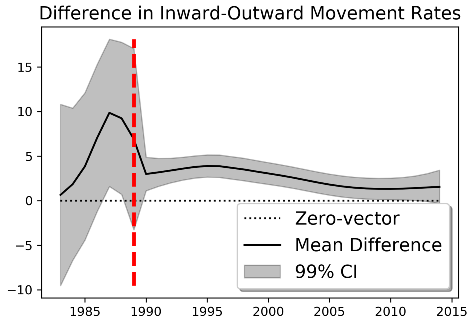
Figure 5b shows that the inward movement rate behaves like an impulse function during the embankment's construction, propelling a substantial inward movement. However, subsequent spikes in the inward movement rates and the overall trend do not appear to be correlated with the monthly tidal data observed at a monitoring site. Further analysis of relevant data (e.g., financial loss due to floods) may allow us to study the relationship between hydro-climatic events and socio-economic behavior.

Table 2. Comparison of event rates within each (pre/post) embankment period based on GP-based. Here, $\chi^2(\nu = 7, \text{p} = 0.01) = 1.24$, and $\chi^2(\nu = 24, \text{p} = 0.01) = 10.86$. The $*$ symbol denotes the event rates are significantly different with *p*-value less than 0.01.

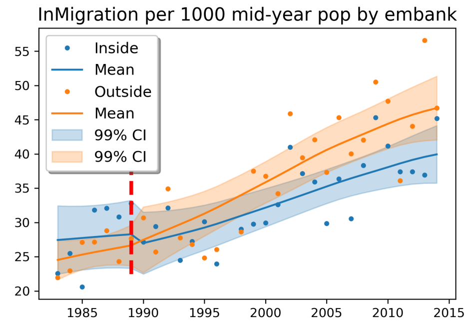
Event	**Pre-Embankment** $\chi^2(x, \nu = 7)$	***p* Value**	**Post-Embankment** $\chi^2(x, \nu = 24)$	***p* Value**
Internal Movement	10.63	0.31	102.57	<0.01 *
In-Migration	1.82	1.94	14.19	1.88
Mortality	2.88	1.79	17.43	1.66



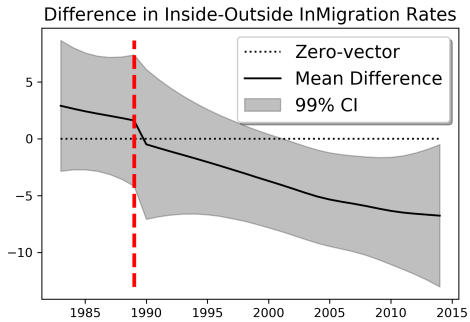
(**a**) Movement rates



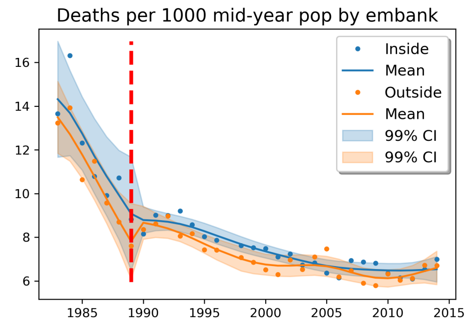
(**b**) Difference in movement rates



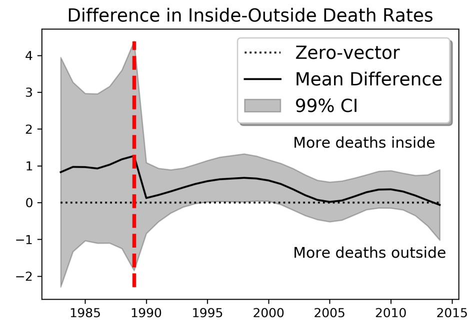
(**c**) In-migration rates



(**d**) Difference in in-migration rates



(**e**) Mortality rates



(**f**) Difference in mortality rates

Figure 4. Analysis of temporal difference for three specific events— (**a**,**b**) inward/outward movement, (**c**,**d**) inside/outside in-migration, and (**e**,**f**) inside/outside mortality during 1983–2014. For each case, the left column shows the individual time-series modeled by GP, and the right column shows the estimated differences in two time-series. The red dashed line marks the pre- and post-embankment periods.

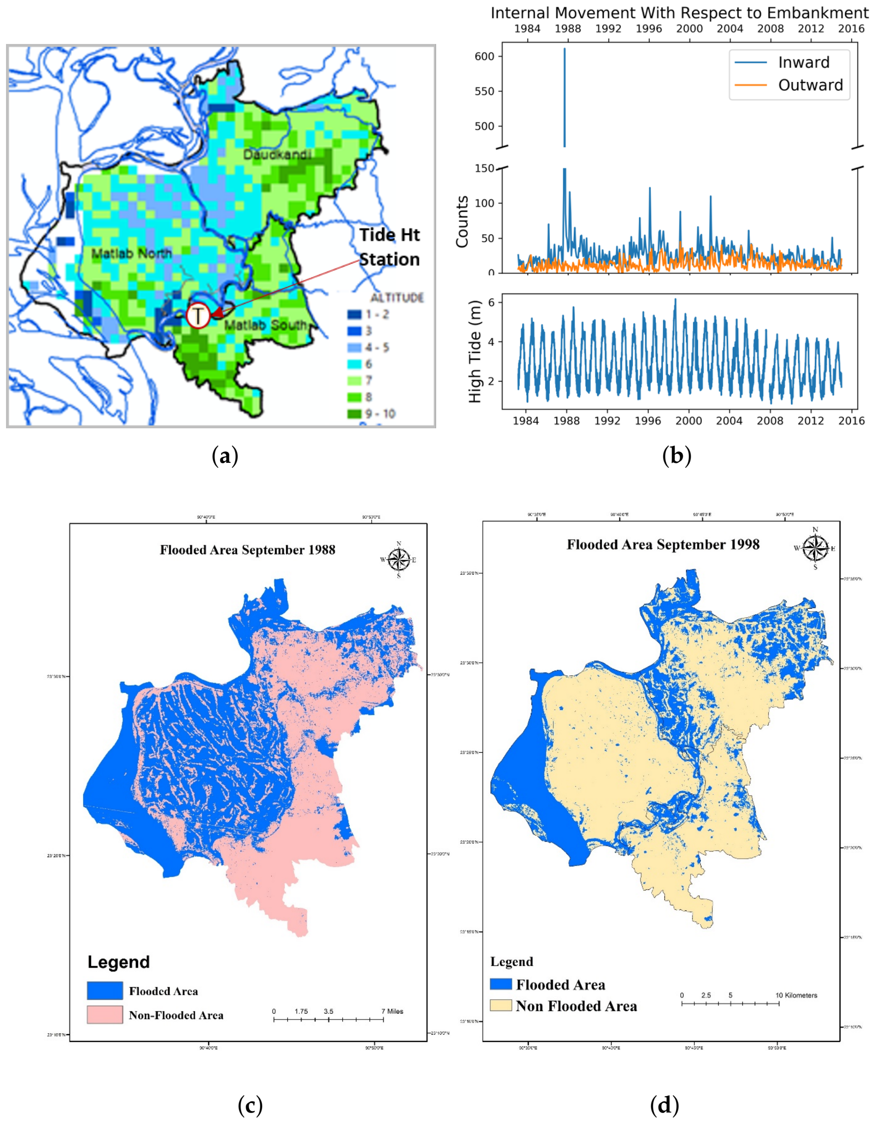


Figure 5. (**a**) Land elevation map of Matlab North, Matlab South and Daudkandi Upazilas based on 20 m × 200 m National DEM data (Source of data: WARPO), (**b**,**c**) inundated area in Matlab North, Matlab South and Daudkandi Upazilas in two major flood years [delineated from LANDSAT 4-5 TM images using Normalized Difference Water Index (NDWI)], and (**d**) (top) monthly inward/outward movement of households within Matlab, and (bottom) monthly high-tide observed at station located in (**a**).

5. Discussion

The study has limitations that are largely due to either unavailability of relevant data or some inconsistency in the data collected over multiple decades. Data from only one third (geographically) of the study area were available for analysis. The study may not generalize due to small study size and differences in hydroclimatic conditions. The results based on the classification approaches should be accepted with caution due to lack of enough common indicators across different years, especially the pre-embankment baseline year. We acknowledge other infrastructures (health, roads, electricity, education, etc.) have impacts in relation to the embankment. The spatial plots of a selection of socio-economic variables suggest recent social developments may be tied to these and other interventions. Similarly, data on agricultural yields, fishing, and other water-dependent economic activities would provide vital information. The limitations in data highlight the challenges of evaluating long-term impacts of interventions such as the embankment, where relevant indicators may not be identified during the baseline study (if performed), and may not be consistently monitored over time.

Although other health event outcome related data were collected as part of HDSS, such data were unavailable for this study. The available data only has ICD-9 (until 2001) and ICD-10 (post 2001) codes, but otherwise no specific details on identifying water-borne disease morbidity data. A medical expert's help was sought to use the ICD codes to narrow the causes potentially related to water-borne diseases. Based on this indirect method of obtaining water-borne disease morbidity data, similar analysis was performed as was done using all-cause mortality data in Figure 4e,f. The results were similar and showed no significant difference in inside/outside population. However, we note that this indirect method of obtaining water-borne disease morbidity data has its own limitation in addition to inconsistent coding schemes before and after 2001. If further health-outcome specific data were available in future, including records related to water-borne diseases or nutrition in children, we could perform a focused comparison of morbidity rates corresponding to water-borne diseases or malnutrition.

Machine-learning approaches provide further opportunities to integrate socio-economic data with other types of ancillary data, e.g., investment in public/private water infrastructure, data on fishing and farming productivity, data on loan amounts and types, hydro-climatic data, etc. Inclusion of these datasets combined with spatio-temporal analysis would constitute an interesting work to further study the embankment's impact on the environment and people. By reformulating the problem and restructuring the data, the machine-learning approaches and the framework implemented in this study can be used to answer questions relevant to related studies, e.g., identify the most informative variables indicative of owning a deep tubewell, using solar panels for electricity, contracting certain water-borne diseases, etc., which can provide valuable information to future developmental interventions.

6. Conclusions

Overall, the available socio-economic indicators and mortality, migration data do not provide a strong predictive value of the location of inside vs. outside residents. The study reinforces findings in the past literature around the immediate impacts of the embankment but does not find those are continued three decades later, with certain well-being indicators evening out across the two defined areas. The proposed approaches are particularly suitable in the face of large numbers of variables and samples. These methods are applicable to evaluate the environmental and socio-economic impacts of human interventions in general beyond the context of Bangladesh.

Moreover, the proposed approaches provide a new framework to identify indicators that are relevant to evaluate the impacts of interventions. Results show households inside the embankment owned a larger proportion of agricultural land within a decade of the embankment's construction. Similarly, the embankment is associated with the differential movement of people, with more people moving inward vs. outward within the study area. However, the difference appears to be evening out in recent years.

This work performs a quantitative analysis of the impacts of embankment using machine-learning approaches. By providing rigorous analytical tools, these approaches may be relevant to tackle the global challenges of flood risks. Such principled analysis is key towards evaluating both short-term and long-term as well as intended and unintended consequences of interventions, providing evidence to support future actions and policies related to combating climate change.

Author Contributions: Conceptualization, A.M., A.F., D.J.B., R.H.; methodology, A.M., A.F., D.J.B., R.H., D.A.C.; software, A.M.; validation, A.M., A.F., D.J.B., D.A.C.; formal analysis, A.M., A.F., D.J.B., R.H.; investigation, A.M., A.F., D.J.B., M.S., R.H.; resources, M.S.I., R.H., D.A.C.; data curation, A.M., A.F.; writing–original draft preparation, A.M., A.F., M.S.; writing–review and editing, A.M., A.F., D.J.B., M.S., M.S.I., R.H.,D.A.C.; visualization, A.M., D.J.B., M.S.; supervision, D.J.B., R.H., D.A.C.; funding acquisition, R.H., D.A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This document is an output from the REACH program funded by UK Aid from the UK Department for International Development (DFID) for the benefit of developing countries (Aries Code 201880). However, the views expressed and information contained in it are not necessarily those of or endorsed by DFID, which can accept no responsibility for such views or information or for any reliance placed on them.

Acknowledgments: The HDSS data was kindly provided by icddr,b. icddr,b acknowledges its donors who provide unrestricted support to icddr,b for its operation and research. Current donors include the Government of the People's Republic of Bangladesh, Global Affairs Canada(GAC), The Swedish International Development Cooperative Agency (Sida), and the Department of International Development (UK Aid).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

FAP	Flood Action Plan
NWP	National Water Policy
NWMP	National Water Management Plan
MDIP	Meghna–Dhonagoda Irrigation Project
HYV	High Yielding Variety
HDSS	Health and Demographic Surveillance System
SES	Socio-Economic Survey
icddr,b	International Centre for Diarrheal Disease Research, Bangladesh
LR	Logistic Regression
RF	Random Forest
SAE	Stacked Auto-Encoders
PCA	Principal Component Analysis
GP	Gaussian Processes
ROC	Receiver Operating Characteristics
AUC	Area Under ROC Curve

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Combination of Ecological Engineering Procedures Applied to Morphological Stabilization of Estuarine Banks after Dredging

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Received: 27 November 2019; Accepted: 28 January 2020; Published: 1 February 2020

Abstract: Gravel extraction and upstream damming caused profound effects on the estuary of the Lima river (NW Portugal) which was reflected by the collapse of banks, leading further to the destruction of riparian vegetation. This led to consequences such as a progressive negative impact on the preservation of salt marshes over several decades of this protected area, which continued even after the cessation of extraction activities. In this work, we present a restoration project combining civil engineering with soft soil engineering procedures and revegetation, along with two distinct segments, and follow the recovery process. The main intention of the study is to promote hydraulic roughness in order to dissipate energy from peak flows and tides, increasing accretion and indirectly the stimulation of plant succession and salt marsh recovery. We are able to observe that the built structures (an interconnected system of groynes, deflectors and rip-rap/gabion mattress) allowed the erosion process to be detained. However, they did not allow as much sediment as expected to be trapped. The colonization of species (plants) in brackish and tidal water was a difficulty posed by this project. A more extensive restoration of all estuarine areas and river mouths, namely to overcome the sediment deficit, will require proper land-use management at the catchment scale instead of local actions.

Keywords: riverbank erosion; restoration; bank stabilisation; vegetation revetment

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1. Introduction

Coastal salt marshes are ecosystems of great ecological and economic value since they provide habitats and breeding areas for many animal species. They play a crucial role in the food chain, in the quality control of the environment and in the sedimentation dynamics in estuarine systems [1,2]. However, around the world, erosive processes related to dredging activity for navigation or gravel extraction represent essential factors for the loss of salt marshes through erosion under the living root zones caused by flowing drainage water. This leads to the overhang of marsh vegetation growing over the banks [3,4]. In addition to the positive benefits of accreting sediment, vegetated marshes effectively dissipate wave energy [5], decreasing the impact of turbulence, which can be crucial in entraining sediment, as shown in [6,7]. The eroding process resulting from the degradation of these ecosystems was described by Castillo's group [8] in other marshes of the Iberian Peninsula, leading to the formation of vertical slopes (usually concave in their lower part), the appearance of mass-movement phenomena and the detachment of blocks of the substrate. The horizontal erosion of these slopes typically begins with the undermining of the lower part, just below the zone of live roots. This is followed by the detachment of substrate blocks from the upper part of the slope, detaching the plants from their roots. Of course, navigational conditions in this estuary (mainly for tourism and fisheries) induce another disruptive factor in acceleration erosion because of wave energy [8,9], but also because channel incisions close to the banks are also observed in order to overcome unfavorable depths.

Ecological engineering has been increasingly used in order to stabilize river banks [10–16], but this is still very uncommon in estuarine areas in Portugal. Some other studies supported the use of hydrodynamic models to predict bank stability under flow conditions [17–20]; in addition, these are essential for the identification of adequate vegetation to improve restoration processes [21–24]. In Portugal, there has also been increasing attention paid to soil engineering techniques for the control of fluvial erosion and for the settlement of riparian galleries in physically disturbed streams [25–28].

The Lima Estuary is subject to many detrimental human impacts. It is the recipient of point pollution originating from the town of Viana do Castelo, an important pulp-mill factory and non-point pollution from agriculture. An input of persistent organic pollutants to the estuarine water and nutrients has led to eutrophication processes in the lower part of the estuary [29]. We also call for attention to be paid to the disturbance by boat navigation and the inherent introduction of fuel and paint residuals into the estuarine system. In spite of the multiple human impacts, the main purpose of this study is to stabilize the river banks along the estuary of the Lima river, as a result of decades of unregulated gravel extraction, causing profound effects on the bank morphology and the destruction of riparian vegetation, either due to tidal action or situations of peak flow. Over the past three decades, there has been a progressive bank cutting leading to substantial marsh losses, also affecting recreational activities. Moreover, the present work shows the implementation of a restoration project aimed at the natural reposition of salt marshes. This is an innovative procedure that has not been used before in Portugal and attempts to provide the necessary conditions that may drive the restoration of the lost wetlands (and the protection of the existing ones) by reverting and supporting river banks that surround previous salt marsh areas, which were washed away after the collapse of the protecting banks. The basis of this design was a combination of civil engineering with soil engineering procedures that not only secure river banks against further erosion but may also increase the patterns of sediment deposition. The biophysical recovery and protection processes were carried out along two distinct segments in the right bank (the nearby Cardielos and Portuzelo villages), both in the estuarine zone of the Lima river. We must emphasize that the downstream part of this river, including the estuary, is included in a protected area of Nature 2000, associated with the preservation of wetlands and riparian layers. Therefore, this work is crucial to defining the procedures for more extensive action. We hypothesize that, by increasing the hydraulic roughness along the banks, we may increase the sedimentation rate along the banks and aid the recolonization process.

2. Materials and Methods

2.1. Study Area

The Lima river catchment is shared between Portugal and Spain, and the run-off average flowing into the estuary is 3298 hm^3, whereas 1598 hm^3 corresponds to the Portuguese part (which includes a near 35 km length, with an average slope of 0.1%). The downstream part of this river represents a transition between a narrow and steep valley towards a progressive gentle slope (0.024%) along with a shallow-vee valley form and finally a large floodplain. The average annual precipitation in this hydrographic basin is high (1444 mm) but averages 2745 mm in some sub-basins. It has a very humid climate and is a hydrographic basin with an excess of water availability throughout the year, with water shortages in the summer months [30,31]. These conditions favor the occurrence of frequent floods in the downstream areas of the main catchment. Impacts on water quality are relatively low since we observe a dominant land use of forest stands (eucalyptus and pine trees) and, in the lower parts of the valley, extensive agriculture characterized by small patches of vineyards, orchards and grasslands with cattle breeding. The areas prioritized for the rehabilitation projects of Cardielos and Portuzelo, both on the right bank, were a consequence of the demands of the municipalities due to the loss of recreational grounds and the increasing pressure on multiple infrastructures (marginal roads, sports and leisure equipment, etc.), but also to protect a layer of marshes in the neighborhood.

2.2. Disturbance Factors

The intense dredging related to gravel extraction over nearly three decades in the lower segment of the Lima river has led to a complete change in the morphological character of the river mouth, with the main current flow and thalweg being relocated towards the right margin derived from the intense withdrawal of sediments. Moreover, the sedimentary supply dramatically decreased after 1992 due to river regulation (two tail-race dams were built upstream, Alto Lindoso and Touvedo; the former is the second-most important hydropower system in Portugal, with a dam of 110 m in height and a reservoir capacity with 347.8 hm^3, with a maximum area of 1072 ha, whereas the Touvedo dam, 7 km below Alto Lindoso, has a height of 43 m, and the reservoir covers 172 ha. Bank instability is the direct consequence of the deepening of the river channel and the exceedance of the critical height of the river banks, which led to its subsequent collapse. We can see in Figure 1 that the comparison of the studied area (upper part of the estuary) between 1965 and 2010 shows the intense sediment loss in this period and the transformation of a braided channel into a progressive linearization of the river banks, resulting in a river with a significantly higher stream power. Damming is known to affect the entire downstream segments by trapping sediments and reducing the sediment transport capacity because of the strong reduction of peak flows. The downstream geomorphic and ecological effects of dams are largely determined by the relative changes in the sediment transport regime, with consequences on channel incision and bank instability [32–34].

The detailed studies conducted by INAG (Portuguese water institute) [31] concerning the decision of whether or not to authorize the extraction activities allowed intense ecological impacts to be conclusively determined, demonstrating that the lowering of the estuary bed exceeded 7 m in depth in some points. Such studies also demonstrated that gravel mining, which ceased effectively in 1992, was environmentally unsustainable, and no further authorizations were processed, except for maintaining navigation conditions in the harbor. However, the morphological adjustments necessarily continued dramatically, which can also be explained by the fact that all 19 identified exploitation extractions exceeded the legal limits, driving estimated total values reaching 600,000 m^3/year [31]. In addition, the constant pressure on the marshes and on the banks of the lower segment of the river led to the loss of important habitats for conservation.

The survey carried out in situ and by aerial photography led us to consider that interventions with long-term purposes could not be limited to the consolidation of banks, but that they also should modify hydrodynamics because of the continued process of excavation of the lower layers of the bank. These display a complex structure, with a less cohesive layer at the base, affecting the stability of the entire bank. These aspects are similar, both in Cardielos (Figure 2, left) and Portuzelo (Figure 2, right), where the progressive erosion has led further to the collapse of the riparian layer.

This part of the estuary, downstream of the previous section, displays a higher vulnerable condition, which is due to the fact that the lowering of the estuarine bed caused by dredging reached a considerably higher depth close to the banks (the channel deepening reached here is 4–6 m).

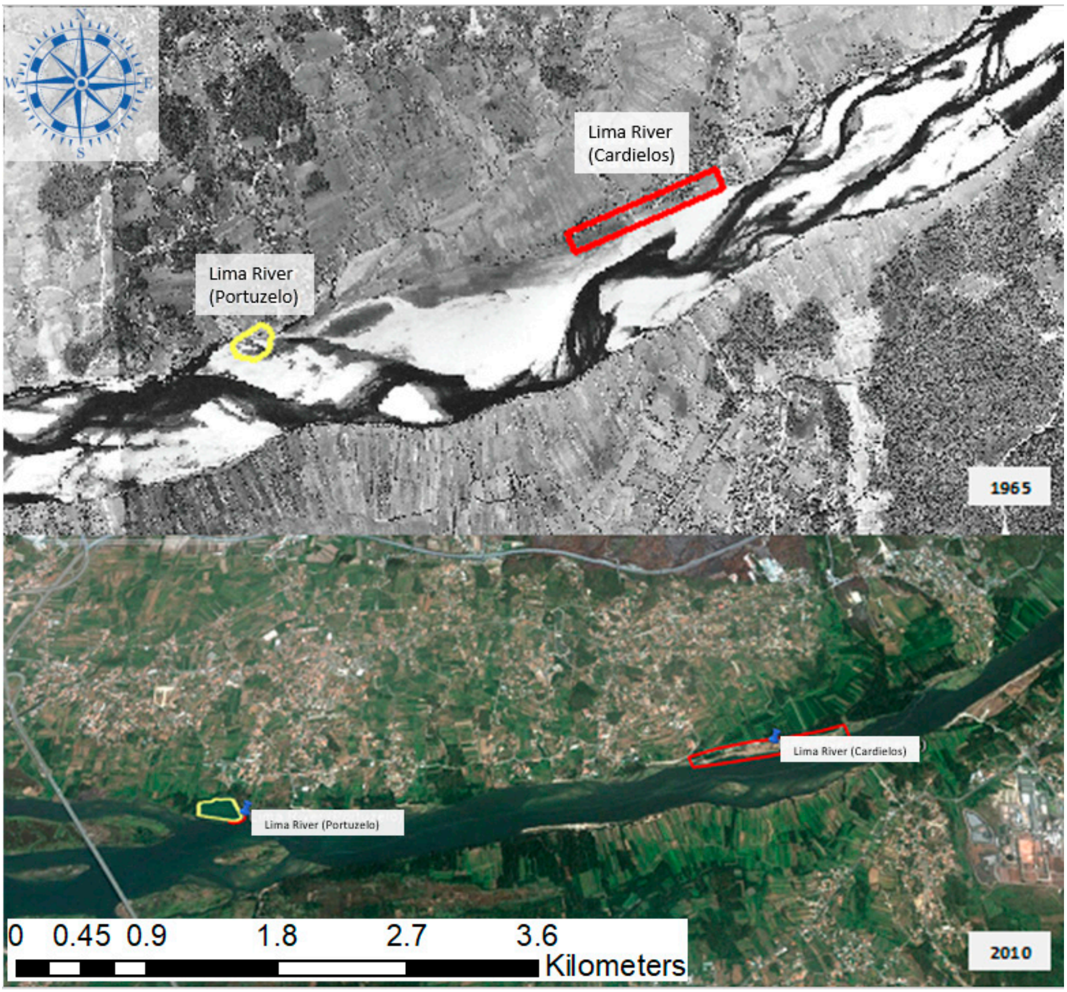

Figure 1. Aerial photographs of a part of the R. Lima estuary with the localization of the two considered priority segments for intervention: the comparison of the year 1965 with meander characteristics and the year 2010 without sediment in the river is shown. The yellow line intervention areas represent Portuzelo and red represents Cardielos.

Figure 2. Cardielos (left panel) and Portuzelo (right panel) sections in 2010, previous to the bank reinforcement, where an apparent bank collapse is visible.

3. Results

There were multiple purposes of this project besides bank protection. We are aware that some of the civil engineering techniques used may have negative aesthetic implications, so there was concern about visual mitigation; besides, the rehabilitation should improve the riverine habitats, allowing a revegetation process towards a riparian gallery. Therefore, in this rehabilitation, we integrated different concepts of bank protection and hydrodynamics processes through the selection of convenient engineering techniques, with the additional purpose of stopping the irretrievable loss of an area of high biodiversity (wetlands/marshes) and marginal leisure infrastructures. The promotion of hydraulic roughness to progressively increase accretion (and, indirectly, salt marsh recovery) was inherent to the conception of the project.

3.1. Cardielos Section

The project was developed along with two temporal phases carried out between 2011 and 2013. It was defined as the first set of six triangular groynes, which were located in the most eroded segment. Afterwards, we built a second layer of groynes, closer to the water level, with a smaller dimension, which was further disposed along the same segment to complement and strengthen the first layer. This field of two lines of groynes, implanted along approximately 1 km, then formed a group of structures that acted together with the objective of causing the water to flow some distance from the riverbank and to increase hydraulic roughness. A groyne increases the roughness of the bank on which it is constructed and, in doing so, creates a zone of lower flow velocity in which the tendency for erosion is less and the deposition greater. Typically, eddy currents form in the pools between groynes where the water flows upstream along the bank [35]. These are wall-like structures, perpendicular to the flow direction and pointed towards the edges where the nose of the groyne is gently sloping.

Both sets of layers were built with rip-rap material, whereas the second line removes their visual impact since it is below the waterline at high tide. This group of structures (Figures 3 and 4) include granite rocks of 0.5–0.8 m in diameter packed in a layer thickness between 1.5–1.9 m and creates structures ranging in length from 13–29 m, depending on the topographical conditions where they are implanted. The second set (closer to the water) was composed of material with similar diameters, but packed around an axis of material with a small grain size (20–30 cm) and placed over a synthetic mat.

Because this set was placed in a plane which was more exposed to tidal and river flow energy, it was planned that the foundation of the structure should be place at a level close to the depth of the expected scour; this level was indicated by a careful observation along this section of the river. The defined layout (straight in plan and perpendicular orientations) allows the set of groynes to trap a moderate amount of sediment upstream and downstream, keeping the current more or less parallel to the bank and offering a medium potential for scour at the head. Both sets of groynes were rooted successively in a set of structures, which are listed in order from water level as follows: a) rip-rap between 3–5 m long; b) gabion mattress (placed on a gravel layer after shaping the bank), which is characterized by a wire basket filled with rock (covered with 20 cm of soil for planting and a wire mesh to decrease tidal washing); c) vegetation roll and willow fascine; and d) a gravel layer with soil (40 cm) covered by tridimensional geomats after bank reprofiling (Figure 4).

Finally, the described structures were vegetated with autochthonous hygrophytic and salinity-resistant herbaceous and woody species, such as reeds and rushes, combined with semi-halophyl macrophytes and salinity-resistant shrubs (*Juncus maritimus*, *J. acutus* or *J. effusus*, *Typha angustifolia*, *Phalaris arundinacea*, *Agrostis stolonifera*, *Scirpus maritimus*, *Festuca arundinácea*, *Phragmites* spp., *Tamaryx tamaryx*, *Carex* sp. or *Najas* spp.). In the vegetation roll and willow fascine layer, over the severely eroded area, we also conducted hydroseeding since the area is a space which is intensely used by visitors. Table 1 shows the techniques involved at the Cardielos site, including the floristic composition associated with the specified structures.

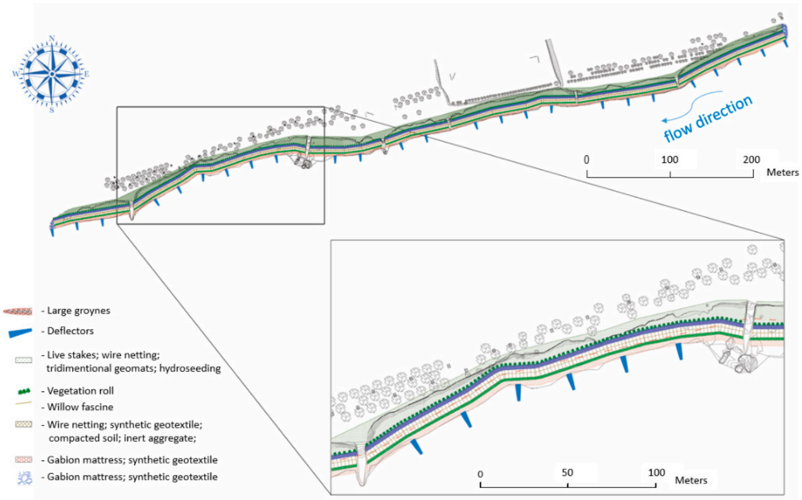

Figure 3. General view of the intervention area at the Cardielos site.

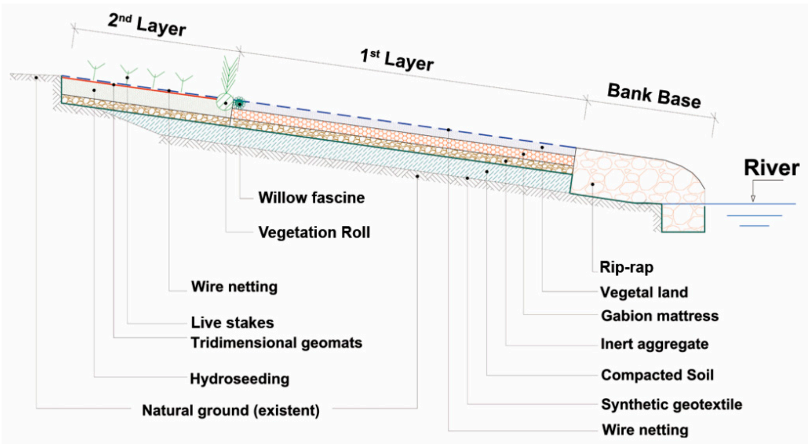

Figure 4. Planned techniques and vegetation species along the bank profile designed for the Cardielos site.

Table 1. Description of the planned techniques involved in each layer for the Cardielos section.

Bank Profile	Techniques	Species
Bank base	Small groynes	-
	Rip-rap (50/80 cm)	-
	Large groynes	-
First layer (close to the water)	Live stakes	Salinity-resistant shrubs (*Juncus* spp., *Typha angustifólia*, *Phalaris arundinácea*, *Agrostis stolonifera*, *Scirpus maritimus*, *Festuca arundinácea*, *Phragmites* spp., *Tamaryx tamaryx*)
	Gabion mattress	-
Second layer	Willow fascine	*Salix atrocinerea*
	Vegetation roll	Semi-halophyl macrophytes
	Tridimensional geomats	*Salix atrocinerea; Salix salvifolia*
	Hydroseeding	*Lolium perenne; Festuca pratensis; Poa pratensis; Lolium multiflorum; Lupinus luteus; Dactylis glomerata; Trifolium subterraneum*
	Live stakes	*Juncus* spp., *Salix atrocinerea; Salix salvifolia*

3.2. Portuzelo Section

The techniques designed and implemented for this area, with lengths of approximately 150 m, are schematized in the profile shown in Figure 5 and Table 2. Again, the objectives, besides bank stabilization, allowed for the settlement of vegetation and increased the roughness on the submerged bank in order to trap sediments and to dissipate the energy from river flow and tidal dynamics, contributing to long-term sustainability. Besides, this bank constitutes a barrier that protects a large salt marsh. Therefore, it is a crucial aspect of this defense system for the preservation of this sensitive environment. As Figure 5 shows, from the base to the top of the bank different layers, we successively used a) rip-rap with large boulders (0.6–0.8 m) in a foundation frame of wood piles, with stakes driven into the riverbed (since the river depth was higher when compared to the previous section) in order to promote roughness (groynes were not considered because of the water depth); b) bank reprofiling to smooth the slope, which was covered with a layer of geogrids, filled in the lower part with gravel (for adequate infiltration) followed by soil and further vegetated, where reeds were placed near the base and woody vegetation (mainly *Tamaryx* sp.) was planted in the upper layer, and finally a wire mesh was used to decrease the potential tidal washing; and c) top lining and plantation with willow species as well as a row with broadleaf trees to improve the landscape attractively for visitors and to increase the overall bank consolidation. Besides this, we installed drains to allow the water to flow between the estuary and marshland.

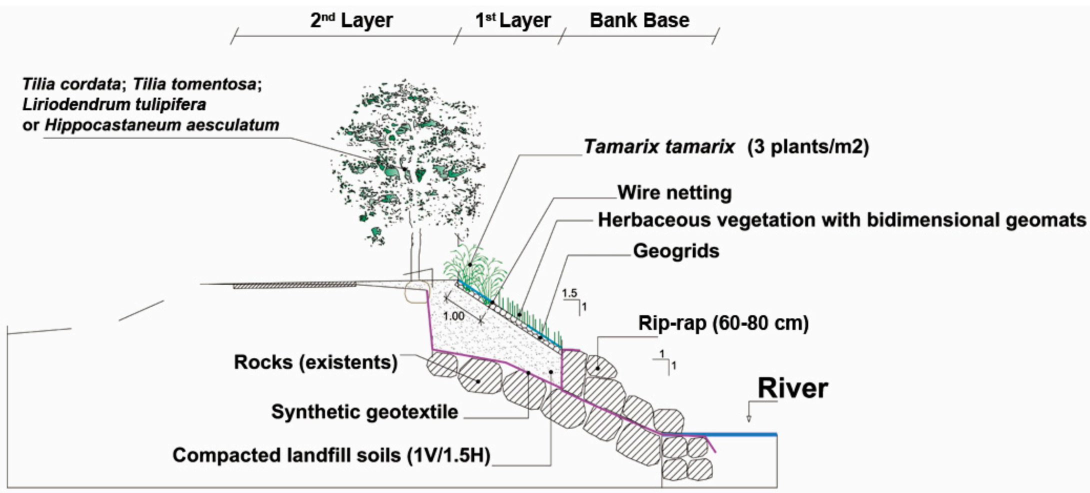

Figure 5. Planned techniques and vegetation species along the bank profile designed for the Portuzelo site.

Table 2. Planned techniques and vegetation species along the bank profile designed for the Portuzelo section.

Bank Profile	Techniques	Vegetation Species
Bank base	Rip-rap (60/80 cm)	-
First layer (close to the water)	Geocells	-
	Bidimensional geomats (synthetic and organic)	-
	Live stakes	*Tamarix tamarix*; *Juncus* spp.
Second layer	Planting	*Salix atrocinerea*; *Salix salviifolia*

Following this, a hydraulic study was conducted (using the HEC-RAS model) to compare the hydraulic conditions of the bank before and after the projected intervention, in order to estimate the energy dissipation of the flow energy. The hydraulic modelling enabled us to simulate various scenarios; in particular, the effect of increasing the hydraulic roughness to provide sedimentation and the inherent stabilization of the bank toes. Consequently, these actions contributed indirectly to creating the conditions for the natural colonization and resettlement of marginal vegetation.

4. Discussion

This study includes local mitigation actions which have been applied to solve the most dramatic erosion problems in specific estuarine area sections. Of course, it would be more convenient to adopt a global management plan for the restoration of the entire estuary considering the stressing agents. However, the design presented here in the two considered areas represents a process to defend the salt marshes in this protected area, which we assume that will act as a motivation for extension to the different impacted areas of this estuary. Besides this, the inherent value of salt marshes for biodiversity, in the R. Lima estuary is that they also act as filters trapping or accumulating heavy metals, especially in the more densely vegetated high marsh layers [36], which play a significant role in dealing with the industrial effluents discharged upstream. More holistic approaches take advantage of conceptual models such as the one presented by Bergh's team in [37], where the dysfunctional patterns in habitat and community structures were traced back to anthropogenic changes in the physical and chemical processes, with the identification of key parameters and distinct rehabilitation proposals.

In these specific areas, we adopted soft engineering solutions to coastal flooding, namely by incorporating the planting of marsh vegetation in the intertidal zone for the purpose of promoting sedimentation and dissipating wave energy. We also followed the principles of Morris [38], for whom a successful design would employ plant species with varying degrees of tolerance to flooding, maximum drag, broad vertical ranges within the intertidal zone and which form a successional series. However, each rehabilitation method has to be observed under its specific conditions: if we provided the conditions for accretion because of a sediment deficit, other situations may require an inverse approach. This was the case for Garcia-Novo's team [39], which projected a hydraulic scheme favoring sand deposition upriver, avoiding its transfer to the Donãna marshes (South Spain) in order to prevent the excess of silting during flood events, which caused an unstable substrate with a lack of vegetation.

Thus, to estimate the hydraulic differences in order to analyze the ability to dissipate the energy created by the introduced structures, we computed the shear stress and current velocity for different recurrence periods, between the initial situation and considering the disposed of sets of groynes (Table 3).

Table 3. Values obtained by simulation with the HEC-RAS model to compare hydraulic parameters before and after the intervention.

		Before		After	
Manning Roughness (n)		**0.030–0.050**		**0.023–0.036**	
Cross-Section	**Return Period (years)**	**Shear Stress (N/m^2)**	**Current Velocity (m/s)**	**Shear Stress (N/m^2)**	**Current Velocity (m/s)**
(Cardielos)	2.33	6.13	0.50	4.34	0.58
	5	7.56	0.57	5.45	0.66
	100	14.58	0.84	10.76	0.98
(Portuzelo)	2.33	10.66	0.68	3.93	0.61
	5	14.05	0.79	5.19	0.72
	100	25.51	1.10	10.39	1.1

The hydraulic simulation was conducted to evaluate the results of flow magnitudes corresponding to two frequent events (2.33 and 5 years) and one extreme event (100 years). The hydraulic model developed adopted a range of manning values, n (Table 3), in order to calibrate the model based on the reference data and the conditions observed in situ.

We may conclude that there was a significative reduction of shear stress, which reached about 65%, corresponding also to the estimated lower current velocities, as a consequence of increasing the resistance to flow (displayed by Manning coefficients), which may also act as a sediment trap, protecting the base of the bank. However, as a result of the type of solutions implemented in the Cardielos area, there was an increase in speed; nevertheless, there was no risk of bank collapse.

Following the appropriate post-appraisal of the implemented project in the target areas of Cardielos and Portuzelo, we may draw some conclusions and recommendations. In the first 2 years after the project's conclusion, we could observe that, in Cardielos, all the structures showed a convenient resistance to critical environmental conditions. This is the case for the two rows of groynes, as well as the rip-rap or the gabion mattress (Figure 6), representing, therefore, a convenient solution since the erosion impact also decreased substantially and created the required barrier for bank protection preserving the built leisure structures. Besides this, the subsequent field surveys allowed us to observe that no more obvious scour holes were formed around the groyne layers. However, we also must accept that not much sediment deposition was observed between these structures, in contrast to our expectations, which retarded the natural re-vegetation process. The less successful results were observed in the layer affected by to the tidal movement, where we noticed a low success of woody vegetation development as the stake rooting was deficient, probably because of the small size of this biological material (less than 30 cm in length). Another cause was the lack of protection in relation to trampling (people and animals). In the case of the layer in the upper bank, other than the influence of the tides, we could observe better results, with higher plant survival and floristic diversity. With regard to the area of Portuzelo, the robustness of the rock base protection was evident, as well as the stability of the plateau following the installation of the geogrid wall. However, the planting success was only relative, such as the natural colonization by macrophytes or herbs, but the viability rate was more intense with the plantations of shrubs based on tamarisk. At low tide, it was possible to check for the proper functioning of the installed drains which were integrated into the created protection structure, which allowed the water to flow into the marshland, keeping a constant water level in this ecosystem, which essentially contributes to the sustainability of this wetland (Figure 7).

Figure 6. Rip-rap (left) and first row of small groynes (right) in Cardielos, after the implementation of the project in Cardielos in 2014.

Figure 7. Rip-rap (left) and geogrid disposal (right) in the Portuzelo site (2014).

Of course, this action was focused in a specific part of an overall degraded estuarine environment. Immediately upstream and downstream of the rehabilitated sections, there is still a constant progression of the pressure on the banks and the consequent set-back of the bank line, which is reflected in Figure 8.

Figure 8. Two segments of the estuary banks, adjacent to the rehabilitation project in Cardielos (2014), showing that the severe erosion still progresses along the un-revetted banks, either in the upper section (left) or in the lower section (right), which requires an extension of the techniques already implemented.

Finally, we must stress that this is only a mitigation action, even if integrative; it will require a more complete study at a larger regional scale in the future, including proper actions in the entire estuary and even at the catchment level, in order to include the appropriate management actions that may contribute to overcoming the deficit of sediments in the estuarine area. For instance, Jacobs' workgroup [40], to restore tidal marshes on sites with low elevation, used a technique of controlled reduced tide (CRT), restricting the tidal regime with neap and spring tides by using high inlet culverts and low outlet valves, allowing the restoration of typical tidal freshwater vegetation. The choice between the advantages of intensive versus extensive ecological restoration should always be considered, and an interesting contribution to this subject was analyzed in terms of community biodiversity, successional changes, and costs by Gallego Fernandez and García Novo [41] in the restoration of a tidal marsh in SW Spain. Here, they compared high and low-intensity interventions, allowing us to conclude that the extra cost of building heterogeneous habitats in the intense intervention bore no relation to results. Ecological engineering is a very promising approach to maintaining intertidal marshes in equilibrium, but we believe that it has to incorporate a larger area of the estuary. This is also the concept of Danielsen's group [5] and Morris [38], who adopted the extensive planting of marsh vegetation in the intertidal zone to promote sedimentation and dissipate wave and river energy, with the additional positive benefits of accreting sediment.

Much research has focused on the importance of vegetation floodplains to create transient storage for channel sediments, becoming efficient traps—also for pollutants—and avoiding streambank retreat [42,43] (see Curran and Hession [44] for a compilation of the vegetative impacts on hydraulics and sediments). The sediment trapping ability of the vegetation allows for more growth and consequently further deposition; in [45], it was observed that plant succession could lead even to softwood forest establishment.

We must point out that if gravel extraction were to seriously impact the upper part of the estuary, reducing the salt marsh area—an activity that is now forbidden, in the most downstream part—a 3 km navigational channel would be maintained by regular dredging activities, which now will also cause the destruction of the wetlands and changes in sediment composition (the enrichment of fine sediments with high organic matter content), where typical floristic communities have been washed away [46]. We intend that the partial rehabilitation techniques presented here may constitute a stimulus to a more global management action aimed at the protection of salt marshes in this important hot-spot; however, more consistent restoration requires another scale and the coordination of different river authorities. This is indeed a critical overview of this project. For instance, the dredged material from the lower estuary (the mentioned channel for navigation) could be moved into the eroded river bank to mitigate incision, where the built groynes and deflectors (particularly at Cardielos) could promote the sedimentation and stability of the inserted gravel. The monitoring of this bedload transport, namely by particle tracking via radio telemetry [47], could allow us to obtain transport paths and increase the efficiency of this procedure.

5. Final Remarks

Finally, we share the opinion of González del Tanágo's team [32], arguing for a more holistic approach to water resources and land-use management at the catchment scale in order to understand the synergistic effects of dams, sediment supply and vegetation growth to implement the appropriate management and rehabilitation actions. The authors stress very different processes and geomorphic consequences in Iberian rivers, namely gravel-bed systems as in the case of the Lima river, in which sediment deficit downstream of the dams has triggered channel incision, and other Mediterranean streams where river regulation, in contrast, resulted in channel narrowing. Here, long-term photographic registrations allowed us to conclude that there was an increase of aggradation processes and vegetation encroachment, because of the reduction of the geomorphic discharges which are able to transport fine sediment downstream from the dams and the high sediment delivery of the catchment promoted by agricultural development. These aspects, finally, show the necessity of adopting specific rehabilitation processes adapted to each catchment, according to soil use patterns, flow changes and geological and physiographic features and the important of avoiding generic solutions.

Author Contributions: Conceptualization, L.F.S.F., A.A.S.P. and R.M.V.C.; Methodology, A.A.S.P.; L.F.S.F. and R.M.V.C.; Validation, L.F.S.F. and R.M.V.C.; Supervision, L.F.S.F. and R.M.V.C.; Project administration, R.M.V.C.; Funding acquisition L.F.S.F., F.A.L.P. and R.M.V.C.; Software implementation, A.A.S.P. Data curation and processing, A.A.S.P. and D.P.S.T.; Writing—original draft preparation, A.A.S.P.; Writing—review and editing, D.P.S.T. and F.A.L.P. All authors have read and agreed to the published version of the manuscript.

Funding: For authors integrated with the CITAB Research Centre, this work was further financed by the FEDER/COMPETE/POCI—Operational Competitiveness and Internationalization Program, under Project POCI-01-0145-FEDER-006958, and by the National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UID/AGR/04033/2019. For the author integrated in the CQVR, the research was additionally supported by the National Funds of FCT—Portuguese Foundation for Science and Technology, under the project UID/QUI/00616/2019.

Acknowledgments: The authors are grateful to the Viana do Castelo Council who supported the project's conception and implementation and the office "Formas & Conceitos" who collaborated in all the steps of the project appraisal, from baseline surveys to option evaluation and technical design and project documentation preparation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Review

Water-Saving Agricultural Technologies: Regional Hydrology Outcomes and Knowledge Gaps in the Eastern Gangetic Plains—A Review

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Abstract: Increasing food demand has exerted tremendous stress on agricultural water usages worldwide, often with a threat to sustainability in agricultural production and, hence, food security. Various resource-conservation technologies like conservation agriculture (CA) and water-saving measures are being increasingly adopted to overcome these problems. While these technologies provide some short- and long-term benefits of reduced labor costs, stabilized or increased crop yield, increased water productivity, and improved soil health at farm scale, their overall impacts on hydrology outcomes remain unclear at larger temporal and spatial scales. Although directly linked to the regional hydrological cycle, irrigation remains a less understood component. The ecological conditions arising from the hydrology outcomes of resource-conservation technologies are associated with sustainability in agricultural production. In this paper, the philosophies and benefits of resource-conservation technologies and expert perceptions on their impacts on temporal and spatial scales have been reviewed comprehensively focusing on regional hydrology outcomes in the Eastern Gangetic Plain (EGP). Due to data inadequacy and lack of knowledge-sharing among disciplines, little is yet known about actual water saving by these resource-conservation technologies and the level of their contribution in groundwater and surface water storage over large temporal and spatial scales. Inadequate knowledge of the hydrological effects of water applied in the agricultural field leads to the implementation of water management policy based on local perspectives only, often with the possibility of deteriorating the water-scarcity situation. Therefore, multidisciplinary future research should quantify regional hydrology outcomes by measuring the components of regional water balance in order to develop a proper water management policy for sustainable agricultural production.

Keywords: irrigation management; rice; percolation; scale effects; hydrologic cycle

Citation: Mojid, M.A.; Mainuddin, M. Water-Saving Agricultural Technologies: Regional Hydrology Outcomes and Knowledge Gaps in the Eastern Gangetic Plains—A Review. *Water* **2021**, *13*, 636. https://doi.org/10.3390/w13050636

Academic Editor: Fernando António Leal Pacheco

Received: 6 January 2021
Accepted: 19 February 2021
Published: 27 February 2021

1. Introduction

The global demand for food, energy and water by the ever-growing population has been forecasted to increase by 50%, 50% and 30%, respectively, in 2030 compared to 2012 [1]; in the same base period, food demand will increase by 70% to 100% by 2050 [2]. The Indo-Gangetic Plains (IGP) comprising more than 250 Mha of area across Bangladesh, India, Pakistan and southern Nepal have over 100 Mha of agricultural land and host over 750 million people [3]. The Lower Gangetic Plain, called the Eastern Gangetic Plain (EGP), comprises the adjoining states of Bihar and northern West Bengal in North-eastern India, the North-West of Bangladesh and the Terai plains of Nepal (Figure 1). The EGP is characterized by the world's highest density of rural poor, persistent yield gaps, low agricultural productivity, limited crop diversification, ample water resources [4,5], and highly fertile lands [6,7] of agricultural importance [8]. The region is therefore a global priority for sustainably increasing food production [9].

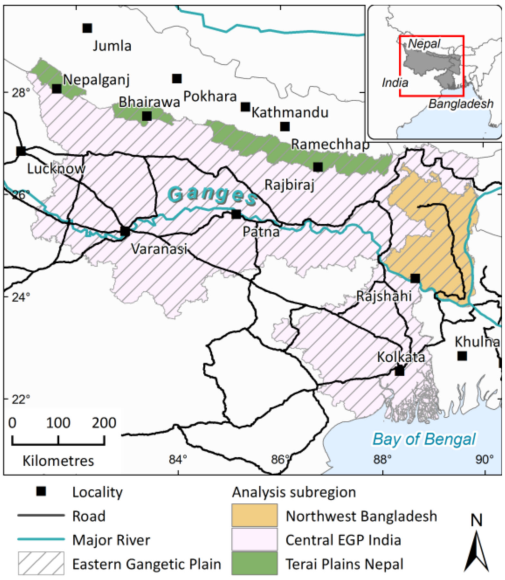

Figure 1. Location and area map of the Eastern Gangetic Plain (EGP) region.

Agricultural productivity is critically dependent on the availability of water. Adequate water supply significantly increases crop productivity [10,11] by introducing high yielding crop varieties, a better cropping pattern, and increasing cropping intensity [12]. Compared to rain-fed agriculture, irrigated agriculture produces two to four times more crop yields [13]. This contribution of irrigation increased global irrigated land by 76% between 1970 and 2012 [14]; the reliance of agricultural production on irrigation is expected to further increase in the future [15]. Farmers' capacity to access and use water is a major driving factor in obtaining the best yield and hence is an important variable for the food security index [16]. However, the growing competition for water by various sectors will affect farmers' ability to produce food [17,18]. So, making food production sustainable, while conserving diminishing water supplies, will be a great challenge in the future [19].

The Ganges basin has a tropical climate, with a distinct wet monsoon (June–September) and a dry winter (November–February); the summer is characteristically hot and humid. Except for the East and North-East hilly regions of the basin where annual rainfall often exceeds 4000 mm, the average annual rainfall in most other parts is 1500 mm. The rainfall is mostly concentrated in the monsoon season and the winter is almost rainless [20] but the main cropping season. In many parts of the IGP, agricultural drought and other climatic shocks severely affect crop production, thus, necessitating an adequate water supply to stabilize agricultural production [21,22]. Surface water is inadequate in the dry season, but groundwater plays a vital role in sustaining agricultural productivity. In India, 60% of the agricultural water requirement is satisfied from groundwater, covering over 50% of the irrigated area [23]; in Bangladesh, the corresponding quantities are 79% and 85% [24]. Of the many factors now threatening sustainability in agricultural productivity, water is the most crucial [25–33] since, without further improvement in water productivity, the amount of water needed for crop agriculture is predicted to increase by 70–90% by 2050 [34].

Several resource-conservation technologies like minimum tillage, no/zero-tillage, direct-seeding, bed-planting, laser land-leveling and residue retention [35–37], and water-saving technologies like alternate wetting and drying (AWD) and deficit irrigation methods have been developed over the past three decades and are being practiced in many parts of the world, including the EGP. In addition to the benefits from the conserved resources, these technologies can also change crop-water use and the regional water cycle [38] with negative impact on groundwater dynamics [39]. They save water by reducing water application in the fields, with resulting lower percolation and groundwater recharge. Large-scale adoption of these technologies can therefore lead to significant decline in groundwater levels [40–42], with possible degradation of soil quality and damage of vegetation [43]. In many parts of the EGP, groundwater level has declined significantly, and is now threatening sustainable water supply for irrigation and drinking [44–49] with resulting negative impacts on the economy, society and environment [50–53]. Although less than one-third of the IGP has experienced declining groundwater levels [54] the situations in high-population centers (e.g., Dhaka city) and other stressed areas (e.g., the Barind area) are potentially alarming [49].

Agriculture in the IGP is mostly dominated by irrigated rice–wheat systems, which cover 13.5 Mha and play a crucial role in the food security and livelihoods of millions of people [37,55,56]. In Bangladesh and West Bengal, rice is produced on 6.05 Mha and 5.5 Mha, respectively [57]. Both mechanized and tillage-based traditional agriculture and transplanted rice cultivation with flood irrigation requiring a huge quantity of water [58–60] are a major challenge in agriculture, in order to maintain or increase rice production. Shifting current agriculture to water-efficient ones [61–65] would conserve water from being wasted through unintended purposes and make considerable water savings [66–69] to face the challenge. Conversion of conventional agriculture to resource-conservation methods [70–72] using resource-conservation technologies and water-saving measures has been demonstrated as of particular interest in this regard [29,73–76].

When water is applied in a crop field, not all of it is consumed as illustrated in Figure 2. The local surface and sub-surface hydrological systems retain a considerable portion of the applied water, which might be reusable later by other users. Consequently, irrigation has a direct link to the regional hydrological cycle, especially in areas with shallow groundwater [54]. A large part of the applied irrigation water infiltrates below the root zone and is stored in the underlying aquifer [7,43] or in downstream surface water bodies. Figure 3 conceptualizes the flow paths of the components of water from a rice field under conventional flood irrigation with pumped groundwater. The percolated water is perceived as lost by the farmers and irrigation practitioners [77] but is a gain to the local surface and sub-surface hydrological systems. The efficiency of water usage at any separate component (e.g., crop fields, ponds) within the hydrological system may be low, but the overall efficiency of the entire system can be much higher than in the individual components. So, the general concept of water use efficiency undervalues the real efficiency of the whole hydrological system. Water recycling must be integrated into the concept of water-use efficiency to develop new realistic concepts [78]. The water flux exchanging between the aquifer and vadoze zone greatly controls the dynamics of the groundwater table [39] thus raising a valid question of how the currently advocated water-saving measures impact on the hydrological cycle of a groundwater basin. Do these water-saving measures assure proper utilization of groundwater reserves? In situations where downstream aquifers and surface water bodies are fed from upstream aquifers, what will be the effects of the water-saving measures on these downstream water resources (Figure 3)? These important issues have not yet been investigated critically on the system level; only some field-scale studies have investigated the possibilities, which are also contrasting in nature. A summary of the major previous studies assessing the impacts of various agricultural water-saving technologies on local and regional hydrology is presented in Table 1. In light of this short-coming, this paper comprehensively reviewed the available literature to evaluate the present state of knowledge and emerging knowledge-gaps on this subject so as to guide future research on this topic. Note that since rice-based cropping systems dominate the agricultural landscape of the EGP [56], this study focuses on the exchange of water flux between irrigated rice fields and the underlying aquifers. The paper is structured into five major sections in addition to an introduction and a concluding section. The benefits and impacts of conservation agriculture have been reviewed in the second section. The third section highlights the complementary and contemporary meanings of water saving while the fourth section addresses the impacts of agricultural water-saving methods on regional hydrology outcomes (i.e., links between various components of the regional hydrological cycle). The next section identifies current knowledge gaps in the key water-saving issues, including scale-effects and policy, before an overall summary and concluding section on water-saving measures and regional hydrology outcomes.

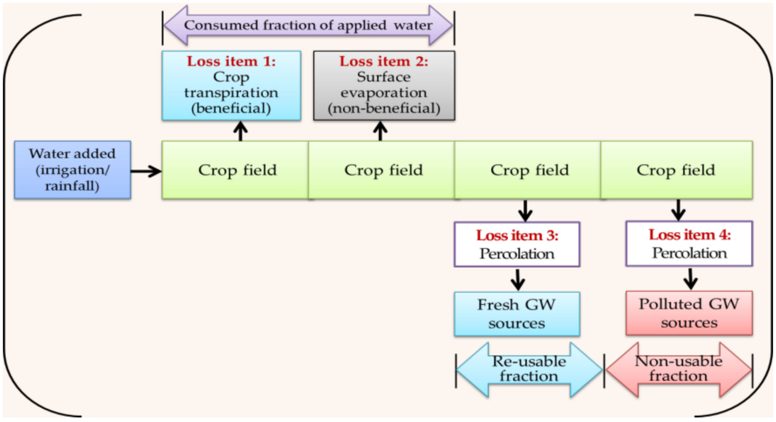

Figure 2. Utilization and fate of applied water to crop fields and hydrological links to groundwater resources.

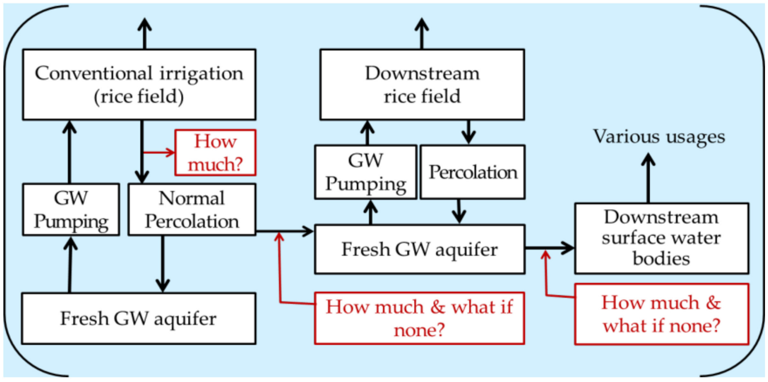

Figure 3. The pathways of the components of water from a rice field under conventional irrigation with groundwater.

2. Conservation Agriculture

2.1. Philosophies and Benefits

Conservation agriculture (CA) has been developed as a response to concerns about sustainability in agriculture [55,79–83] with basic principles of rebuilding soil, optimizing crop production inputs (resource and energy), enhancing food production and optimizing profits [84–87]. It comprises application of three inter-linked principles: (i) no or minimum mechanical soil disturbance through conservation tillage (e.g., minimum or zero-tillage), (ii) biomass mulch soil cover (e.g., crop residues), and (iii) crop diversification, as well as other practices of integrated crop management [88]. Under conservation tillage, approximately 30% of the soil surface is kept covered with crop residues, which reduces erosion of surface soil by overland flow [89,90]; a crop is planted directly into a seedbed without any tillage operation in the zero-tillage system. Cultivation of wheat under zero-tillage in the rice-wheat cropping system is an emerging CA-based technology in the IGP [91]. A CA-based sustainable intensification program was started in 2014–15 in two districts each of Nepal, Bangladesh, and Bihar and West Bengal in India [92]. Globally, the cropland under CA increased at 5.3 Mha annually since 1990 and reached 106 Mha in 2008/2009 [93] and 180 Mha in 2015/2016; 78 countries in the world have adopted CA practices.

Table 1. Summary of major previous studies assessing the impacts of agricultural water-saving technologies on local and regional hydrology. The studies are grouped by apparent and actual water saving, impacts of water-saving measures on water usage and regional water balance, gaps in current knowledge in certainty and scale-effect of water saving, and policy formulation for water resources management.

Main Findings	References
Apparent and actual water saving	
Water-saving technologies make only narrowly perceived local water saving without considering irrigation return flows.	[94,95]
Percolation from irrigated fields recharges the underlying aquifer in many groundwater basins, including the IGP basin, from where it is recoverable for reuse; so is not a loss.	[54,96–102]
Water-saving by one user may be a loss to another over large spatial scale. So, reducing percolation does not always save water.	[75,95,103,104]
Reduction in evaporation and water-flows to non-recoverable sinks (e.g., polluted water sources) makes actual water saving.	[105–107]
Impacts of water-saving measures on water usage	
Alternate wetting and drying (AWD) water management method saves between 15% and 60% of water compared to continuous standing water rice system.	[60,108–112]
Demand for water increases when technological intervention adds more value to it (e.g., reduced cost of water due to increased irrigation efficiency); this is the re-bound effect.	[75,113–116]
Re-bound effect is a potential hindrance in water resource management.	[117]
Impacts of water-saving measures on regional water balance	
Water-saving measures over regional scales cause decline in groundwater level by limiting recharge and exert stress on regional hydrology and ecology.	[38,40,77,118]
Most rivers and aquifer systems are hydraulically connected in Bangladesh and the Bengal Basin.	[119,120]
Separate management of surface and groundwater in the interconnected hydrologic systems hinders water resource allocation.	[121–123]
Knowledge gaps in certainty and scale-effect in water saving	
Impacts of water-saving technologies on the degree of actual water-savings and overall water usage in groundwater-based irrigation systems are poorly understood at larger spatial scales.	[75,95,115,116,124]
The components of water balance in the Eastern Gangetic Plain (EGP) basin have not been quantified yet.	[106,125]
Focusing on only local efficiency of water use and ignoring the return flows is a risky perception.	[126]
Knowledge gaps in formulating proper policy for water resources management	
Lack of attention, improper legislation and ineffective/less-effective institutions are the common problems in governing groundwater in many countries, especially in the face of re-bound effect.	[75,127–129]
Reliable detail information on water reserves, safe yield, water withdrawal patterns and water quality dynamics in the aquifers is lacking in most of the EGP basin.	[130]
Whether water-saving technologies can maintain sustainable development and what more need to be done for this in future remain uncertain.	[39]
Appropriate strategy for water management should be regionally suited and must establish strong regulation and policy. This is a topic of future research for the Indo-Gangetic Plains (IGP) basin.	[9,131–134]

Resource-conservation technologies have revealed some promising immediate [135–137] and long-term benefits [138–140]. They reduce field-scale irrigation, fertilizer applications, labor shortages, energy use, greenhouse gas emission, and erosion of field soil; while they increase soil organic matter and biotic activity, crop diversification, yields, and farm incomes by improving resource-use efficiency [36,37,55,75,83,91,141–146]. Tillage accelerates oxidation of soil organic matter to CO_2 and loss to the atmosphere, but CA reduces the oxidation rate [147,148]. Increased crop residues under CA and root exudation of carbon compounds into the soil cause a reversal of soil carbon from net loss to a net gain [86,149–151]. In spite of these multiple benefits [152–154] the farmers' prime interest in CA-based agriculture is mostly the monetary gain [155]. Nonetheless, CA is now emerging as a major component of farming systems for ensuring food security in South Asia [85,87].

2.2. Impacts on Soil and Water Use

The effects of conservation agriculture on soil properties vary depending on the type of chosen system, soil-type, climatic conditions, cropping history, etc. [156–158]. Soil becomes more stable and less susceptible to erosion under zero-tillage compared to conventional tillage [158,159] and provides more satisfactory physical properties for crop production [160]. Soil organic carbon increases [92,161,162] and pH decreases [163] under zero-tillage compared to a conventional tillage system over time [164,165]. Organic matter improves soil aggregation, alters pore-size distribution, reduces soil bulk density, and increases both total and effective porosities within 0–5 cm soil profile [166,167]. The increased number of 0.5–50 μm pores augments soil-water storage and 50–500 μm pores enhance water movement through the soil [92,168]. Conventional tillage creates a surface crust of high bulk density, while long-term (e.g., 8–10 years) zero-tillage helps in forming many continuous pores extending from the soil surface to the deeper layers causing significant increase in infiltration [161,166,169–171]. Zero-tillage thus increases the saturated and unsaturated hydraulic conductivity of soils [159,162,172,173]. Conservation tillage can increase the capture of rainfall and reduce runoff due to stable aggregates and increased porosity in the surface soil [174] and water-holding capacity due to increased organic matter [159] with resulting reduction in surface evaporation. The magnitudes of water-, labor- and energy-saving of some CA practices are listed in Table 2. However, generalization about such gains in water saving for all hydrological situations can provide a wrong message in many regions. In the dry season, there is not enough water on the soil surface to increase its capture in the soil within the EGP. There are only occasional relatively ample rainfall events in some areas of the EGP, in which cases CA can make more water available for plants' use and increase the precipitation-use efficiency of the production system [166]. However, water is almost always in excess of soil's saturation capacity in the wet season, thus leaving no scope for further capturing of rainfall into the soil. The important controlling factors in conserving water in the wet season are the infiltration capacity and hydraulic conductivity of the soil. However, this likelihood has not yet been investigated.

Table 2. Degree of benefits of conservation agricultural (CA) practices.

CA Practices	Benefits	Magnitude	References
Zero tillage/ laser land leveling/ bed and furrow planting	Water saving	23–45%	[175]
Zero tillage	Water saving	5–15%	[176]
Laser land leveling	Water saving	25%	[177]
Permanent bed	Water saving	10.6%	[178]
Zero-tillage	Water saving	21.8%	[178]
Direct-seeded rice	Labor saving	40–45%	[179]
Direct-seeded rice	Water saving	30–40%	[179]
Direct-seeded rice	Energy saving	60–70%	[179]

3. Agricultural Water–Saving

3.1. Water-Saving Measures

Water-saving irrigation, groundwater regulation, shifts to rain-fed agriculture, artificial recharge to groundwater, rainwater preservation, virtual water imports and indirect approaches like energy pricing and regulation are the currently available measures to reduce regional water use [134,180]. However, appropriate water-accounting is essential to identify the scope of these water-saving practices [181]. Based on the approach of reducing evaporation, runoff losses, and the extent of free water on the soil surface [182] irrigation strategies like shallow water depth associated with wetting and drying [183,184], alternate wetting and drying, AWD [108,124,185,186], semi-drying [187], aerobic rice cultivation [188,189], partial root-zone drying [190], and non-flooded mulching [191] are being practiced in different rice-growing regions. The AWD technique allows the soil to dry for a certain pre-determined number of days after depletion of the standing water in the field before the next irrigation [192]. The multiple-shallow irrigation method (1–3 cm irrigation applied frequently) can efficiently utilize rainfall and reduce percolation and surface runoff [94]. In the aerobic cultivation method, rice is grown in well-drained dry soils with supplementary irrigation, as with upland crops [188]. Furrow irrigation with raised beds, mulching, conservation tillage, deficit irrigation [193–195] and improved weed control can also achieve substantial water-saving.

3.2. Apparent and Actual Water-Saving

The impact of efficiency of water consumption and water productivity on water-saving has been investigated at field scale on several occasions e.g., [196–200]. Any effort toward improving irrigation efficiency is valuable [201], but the commonly used concepts of water-use efficiency underestimate the system-level's actual efficiency [78]. The actual fraction of the applied water that is used efficiently at a regional scale has not yet been quantified; current measurement methods are inadequate for such quantification.

All the water applied in the crop/rice fields ends up at any of, or a combination of, consumptive use, non-consumptive use, non-recoverable flow (Figure 2), and change in storage [95]. These water use-terms allow a clearer definition of various issues and options for water usage in irrigated agriculture. Water-saving through a resource-conservation technology refers to a narrow local perspective of water application by reducing percolation rates, as conceptualized in Figure 4. This water-saving does not account for return flows from the irrigated field that may be either non-recoverable outflow (e.g., to saline or otherwise polluted groundwater or surface water as schematized in Figure 5) or recoverable outflow, where it ends up in rivers or as useable groundwater source [94,95]. The return flow may be a significant contributor to groundwater recharge [131,202–204].

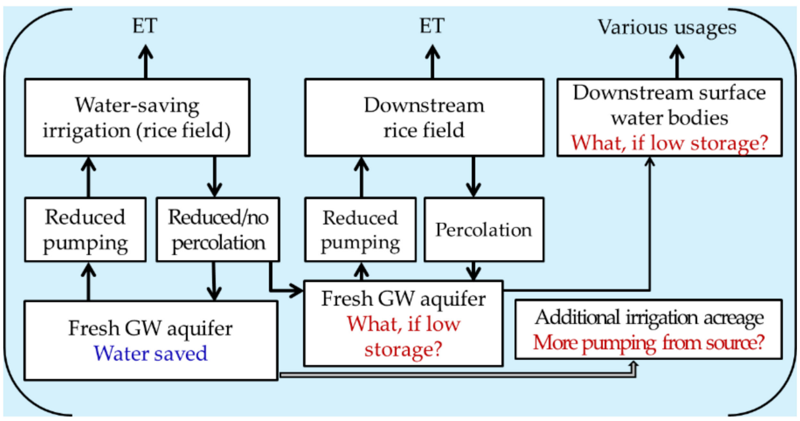

Figure 4. Conceptualizing of impacts of water-saving measures on regional surface and groundwater sources when irrigation uses groundwater.

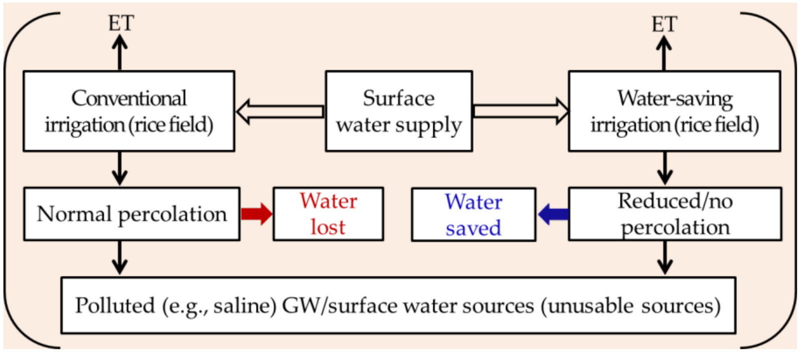

Figure 5. Water loss and water saving issues under conventional and water-saving irrigation from surface water sources when underground aquifer contains polluted water (e.g., saline).

Due to various natural calamities (e.g., seasonal storms, hailstorms, cyclonic storms, heavy rainfall and floods), dry season is the main and safe cropping season in the EGP, which has an annually renewable groundwater system. Here irrigation is predominantly done with groundwater; 79% of total irrigation in Bangladesh and more than 90% of irrigation in North-West India uses groundwater. An individual farmer considers the combined outflow of water by evapotranspiration, seepage and percolation as water usage by his/her rice field and hence actual water loss in the field. However, when considering a large spatial scale, achieving water-saving by one user may be a loss to another since the seepage and percolation from one's field enter the underlying aquifer or nearby surface water sources, from where others can reuse the water [75,103] causing no net loss to the system [205,206]. The real water-saving occurs only when the non-recoverable non-usable water losses (Figure 2) are eliminated or reduced. Avoidance of peak evaporative demand, use of short-duration varieties, cultivating less water-demanding crops, and changing from ponded to non-ponded rice culture are the potential technologies for reducing evapotranspiration [205–207]. The practicability and effects of technologies on crop yields must, however, be investigated before their large-scale field adoption.

Modifications of the water balance components by resource-conservation technologies, the fate of water saved through reduced application, and hydrologic interactions across spatial scales determine whether any reduction in water application leads to actual water-saving and reduces water usage [75]. Farmers always intend to achieve maximum output from the water resource, leading them to utilize as much water as they can have access to. Society, on the other hand, prefers utilizing scarce water to maximize profits by shifting water from agriculture to high-value economic sectors. The goals of the two entities in utilizing the scarce water are clearly opposing, and therefore appropriate terminology to describe real water-saving remains a central issue of debate [95].

Interactions between non-agricultural and agricultural water usages are scale-dependent and play a major role in water-saving [208]. At basin scale, the main interest is to reduce water usage in irrigated agriculture and transfer water to other higher-valued usages. This again implies that actual water-saving can be achieved only by reducing evaporation and water-flows to non-recoverable sinks [107]. The basin approach, instead of paying attention to individual water usage, assesses return flows, estimates water-use efficiencies at field- and basin-scales and differentiates consumptive water-saving from non-consumptive saving (Figure 2) while accounting for water and analyzing water-use efficiencies [209–213]. Despite many complexities in perceptions of water-saving, its ultimate objectives are clear and undisputable: to stop unsustainable exploitation of the available water resources and to increase the quantity of water for other essential and more beneficial usages. It is therefore essential to understand the scale-effects of water usage clearly to improve water-savings and water productivity [124,210,214–216].

3.3. Impacts on Water Use

AWD effect: Irrigation management through alternate wetting and drying is widely practiced in many countries/regions like the Philippines, Vietnam, China and EGP [217–220]. Under AWD, the percolation rate decreases leading to water-saving; the reduction in evapotranspiration plays only a minimal role [221]. Compared to the continuous standing water rice system, the levels of water-saving by the AWD method are listed in Table 3. Percolation from the crop fields controls the transport of nitrate [94], heavy metals [222], salts [223], nutrients [224], and pesticides [225] to groundwater. So, with reduced percolation the quality of groundwater remains under safeguard. The AWD method also reduces greenhouse gas emission [226,227], uptake of arsenic in rice grain [228,229], the cost of pumping water [230,231], and concentration of methyl mercury in field soil [232].

Table 3. Levels of water-saving by alternate wetting and drying (AWD) method compared to the continuous standing water rice system.

Type of Effect	Quantity	References
Water saving	23%	[108]
Water saving	15–40%	[109–111,221,233]
Water saving	30–60%	[112]
Percolation reduction	50–80%	[112]
Percolation reduction	19–28%	[60]

Bund effect: An unsaturated zone beneath standing water and a higher hydraulic conductivity zone beneath the bunds in rice fields are developed. This causes the applied irrigation water to move through the bunds and recharges the underlying aquifer [234]. The destinations of the applied irrigation in the rice fields were measured on several occasions e.g., [205,235–238] and a significant portion was reported to percolate through the field boundaries. This type of lateral seepage flow field is horizontal first and then vertical below the bunds [239]. Often rice fields of irregular shape are transformed into regular rice fields in order to improve irrigation efficiency, keeping part of the previously generated plow pan beneath the bunds of the reformed rice field [234]. Consequently, the dominant movement of water is in the horizontal direction through the bund. The seepage flux is, however, much less than the deep percolation rate [239–241] except when rice is cultivated on terraced fields, where the seepage water moves to the downstream plots through the bunds [239]. In flat rice fields, the infiltration rate below the bunds remains close to the average infiltration rate for the crop field with plow pan beneath the bunds, but may double or more without plow pan beneath the bunds [205,239]. [234] demonstrated 50% of water lost through the bunds, 25% through evapotranspiration, and 25% equally through infiltration providing an estimated annual water loss of 41 km^3 through percolation underneath the bunds of rice fields in Bangladesh. Based on this field scale estimate, sealing of bunds (e.g., by puddling) can reduce seasonal water use by 52 $\pm$ 17%. Much greater savings (~90%) can be achieved in fields with larger perimeter-to-area ratio.

Puddling effect: Puddling eliminates large pores and alters the field soils to stratified layers: a top puddled layer, muddy layer and plow pan overlying a lower layer [242,243]. A low-permeable layer, formed above the puddled layer, comprises a finer fraction of the soils in suspension [244,245]. Puddling creates a 5 to 10-cm layer of plow pan, of low hydraulic conductivity, 20–25 cm below the ground surface. The hydraulic properties of plow pan regulate the water regime in the irrigated field [236–247]. Water flow occurs under unsaturated conditions below the plow pan [243]. The percolation rate varies widely with soil texture, 3–17 mm/day for clay and 13–30 mm/day for sandy loam [245,248]. The intensity [249] and depth of puddling [250], soil-type and post-puddling time period [251], and ponding water depth [252] regulate reduction of the percolation rate in the puddled soils. The percolation rate is high during the early growth period but decreases by 35–45% with the advance of the growth stage [253–255].

Re-bound effect: The re-bound effect, a less-known proposition, suggests that when efficiency of using a resource increases, its consumption rate also increases simultaneously [113]. Jevon's contradiction/paradox in economics advocates that any technologies aimed at saving energy actually end up by achieving the contrary of what they were supposed to do. Although the re-bound effect is quite well-known in energy usage [256], it is less known in the irrigation literature. Any intervention to modernize irrigation systems will improve efficiency, reliability and flexibility of the system, with a consequent increase in demand and consumption of water, especially by progressive farmers. The re-bound effect is therefore a potential problem in water resource management as recognized by [117].

Water-saving technologies are promoted based on the supposition that a reduction in water inputs per unit of output makes a comparable water-saving. However, this assumption may not be factual for two reasons. First, whether the quantity of water spared by reducing input transforms into real water-saving depends on the destination of the saved water. A significant part of the applied irrigation water percolates to the underlying aquifer, which can be pumped by the same or other farmers for reuse (Figure 1) and hence is not lost or wasted [212]. So, there is a risk of focusing on local efficiency alone and ignoring the return flows [126]. Secondly, based on economic theory [257], water-saving technologies, by adding more value to water, may encourage farmers to use more water as observed by [114] in Pakistan and Yemen where the overall water usage increased significantly [127,258]. Contrasting evidence is also found in the central United States where new technologies reduced water usage [74].

It is crucial to quantify water extracted and water consumed separately in order to effectively investigate the re-bound effect in irrigation. The usage of extracted water can comprise a consumed part and a non-consumed part. The consumed part may comprise both beneficial and non-beneficial evapotranspiration and runoff or percolation loss that are not recoverable. The non-consumed part comprises parts of the runoff and percolation that are recoverable for further use [213,259]. So, efficiency improvements do not always reduce overall water use; these actually reduce the effective cost of net irrigation encouraging the farmers to achieve more benefit by increasing net irrigation [115,260–262].

4. Regional Hydrology Outcomes

Irrigation water is an important but as yet less characterized component of the hydrological cycle in regions with intensive agricultural irrigation, due to complexity in monitoring [263]. Appropriate differentiation of the natural inter-connection between the surface and groundwater resources is an impending problem [121]. In a highly connected hydrologic system (e.g., EGP), separate management of surface and groundwater will cause conflict in water resource allocation between various sectors (e.g., irrigation, households, industry and fisheries) and exert stress on groundwater-dependent ecosystems [121–123]. Groundwater is mostly a renewable resource in the IGP because of its recharge and depletion mechanisms associated with the regional hydrologic cycle. Water extracted from the aquifers can follow a number of pathways in the hydrologic cycle (Figures 3 and 4), with some travel only over a short distance, and may not join the aquifer [264,265]. Recharge to the aquifers occurs through rainfall, seepage and percolation from rivers and canals, and irrigation return flow [99], with rainfall and irrigation return flow remaining as the major contributors for many groundwater basins ([97,98,102]). So irrigation return flow that depends on soil hydraulic properties and irrigation management practices [266] is an important outcome of irrigated rice fields [96,100,267].

Abstraction of groundwater lowers the water table in aquifers with resulting reduction in groundwater pressure head that induces groundwater recharge by drawing down water from surface sources into aquifers [268,269]. Most rivers in the Bengal Basin, having direct hydraulic contact with aquifer systems [119,120] recharge the aquifers during March to November and receive water from the aquifers during December to February. These water exchange behaviors imply that groundwater tables can be deliberately lowered to more extent in the dry season to accommodate more recharge during the monsoon. This intervention, first put forward in the 1970s [270] and then re-examined occasionally [271], will increase groundwater reserve for irrigation during the dry season and also help control flooding during the monsoon.

Percolation from irrigated rice fields is important to the economy, environment and water resource conservation in irrigated rice-dominated South Asian countries like Bangladesh, India and Taiwan. Flooded rice fields are comparable to wetlands [101,272] and play an important role in raising groundwater level [273]. The recharge potential of rice fields is 69.2 cm for sandy loam and 37.2 cm for clay loam in India [274], between 1–2 mm/day and 7.5 mm/day in Bangladesh [275], and 21.2–23.4% of the applied irrigation water from the terraced rice fields in northern Taiwan [239]. The groundwater-dominated irrigation in Bangladesh has changed the nature of aquifer recharge and the flow patterns of groundwater with a resulting reduction in residence time of water in the aquifer, especially in the shallow aquifers [276]. Recharge from the irrigation fields can be significantly modified by changes in irrigation management practices [77,118].

Adoption of agricultural water-saving technologies at the farm level changes crop-water use and regional hydrology [38] by reducing groundwater recharge. In many groundwater irrigated areas of the EGP (e.g., the North-West region of Bangladesh) the aquifers are not currently recharged fully from other sources (e.g., rainfall and interflow from adjacent aquifers). Consequently, water-saving technologies cause decreased opportunities for groundwater irrigation. There are other factors (e.g., canal lining, reduced water diversion, leveling undulating lands) that also reduce recharge by restricting percolation with eventual decline of groundwater tables. Some countries (e.g., China) widely use mulched-drip irrigation system, which significantly modifies the dynamics of regional groundwater by changing water exchange flux between the irrigation fields and underlying aquifer [39]. The exchange flux at the groundwater table during drip irrigation period is downward and remarkably reduces after adoption of water-saving technologies [39]. Adoption of efficient water-saving measures at regional scales would significantly restrict groundwater recharge with a consequent decline in groundwater levels [40]. This will exert negative impacts on regional hydrology and ecology by degrading soil quality and deforesting, particularly in arid regions [43]. With decades of large-scale groundwater withdrawal and reduced recharge opportunity due to increasing urbanization and decreasing wetlands, water tables have already declined significantly and are continuously declining in many large urban areas (e.g., Dhaka city in Bangladesh) over time [3]. There is, however, evidence of induced groundwater recharge due to the creation of significant vertical head gradients by increasing pumping in areas with shallow water tables and permeable upper soil formation [277]. This implies that dry season abstraction of groundwater can create storage space in the aquifer that can be utilized for harvest in the monsoon. Such intervention would exert a positive contribution on overall water availability in the area [131]. The main threat in the IGP Basin is not considered to be the diminished quantity of groundwater, but the degraded water quality resulting from high arsenic and salt contents [54].

5. Gaps in Current Knowledge

5.1. Uncertainty in Water-Saving

The reported impacts of conservation agriculture on water-saving are yet to be ascertained and evaluated more rigorously [278–282]. Water moves through very complex pathways and the impacts of conservation agriculture are so far understandable only at field-scale, but not at the larger scale [75]. Puddling forms plow pan and also creates soil cracks in addition to preferential flow paths. Consequently, increasing percolation, instead of commonly reported decreasing percolation, has been also reported [283]. In groundwater-based irrigation systems, improved irrigation efficiency and consequent water-saving achieved by reducing irrigation applications with water-saving technologies are clearly understood at the field-scale [115,116]. However, due to the lack of measurement of the water balance components, these are poorly understood at a larger spatial scale [75,106,116,125]. When farmers in a region reduce percolation substantially, which would ultimately recharge a usable aquifer or join to a usable surface water body on the one hand but may also increase the irrigated area with the saved water on the other (Figure 4), the overall impact may be unintended. Instead of saving water, it can actually increase water consumption and reduce water availability for other users [95,116].

The growth period of rice with high evaporative demand can be avoided by shifting planting time. Adoption of short-duration varieties will also reduce evapotranspiration and percolation loss of water. The effects of these alternative crop technologies on water losses and crop yield have not been investigated adequately yet. If field-level estimates of water-saving are extrapolated to larger spatial scales in rice-based cropping systems that utilize recycled water or surface and groundwater conjunctively, there is a possibility of underestimating the real water-saving [284]. The concept of classical irrigation efficiency for an entire basin becomes erroneous and misleading when irrigation management is considered for the water resources of a region as a whole. The discrepancy arises since the water losses with respect to which the classical irrigation efficiency is calculated are not the actual water losses when considering the whole system. It is not possible to clearly know the extent of water-savings until the destination of the lost water is correctly known [95]. It is not yet clear how the water-saving technologies alter the dynamics of overall water balance. Whether application of water-saving technologies can maintain sustainable development and what else needs to be done for this in future are still major questions [39].

5.2. Limited Knowledge of Recharge–Discharge Interaction

Groundwater recharge occurs from several sources (e.g., rainfall, flood water, irrigation return flow, inter-basin transfer, etc.) through several processes, the complexity of which varies widely. In an inefficient surface water irrigation system, a large fraction of the applied irrigation water percolates to the underlying aquifer, causing a significant loss of water when considering irrigation efficiency. However, this irrigation system appears as one of the most efficient methods of recharging groundwater, as occurs in most parts of Bangladesh, India, Pakistan and elsewhere [54,99]. So, the common perception of more efficient irrigation systems that can reduce seepage and percolation losses must be thought about with great caution.

A reliable quantification of groundwater recharge from irrigation fields, although essential in order to know its impending impacts on the dynamics and quality of groundwater, is difficult and remains unresolved in regions with confined aquifers. The groundwater table is confounded with both recharge from irrigation fields and extraction by irrigation wells. Many factors like soil type and surface condition, vegetation, depth to groundwater level, and chemical quality of soil and irrigation water control groundwater recharge. Although groundwater flow and recharge from rice fields have been examined on many occasions e.g., [101,246,285–287], the effects of land use conditions on recharge and groundwater level are not yet clear [288]. When groundwater is abstracted from an aquifer, recharge from surface sources occurs under transient conditions. The knowledge of soil-water flux in the vadoze zone that can help understanding the transient recharge [289] is still limited [290]. Therefore, a major pre-requisite for sustainable groundwater management is to reduce the uncertainty in aquifer recharge from rice fields.

5.3. Uncertain Causes of Groundwater Decline

Large-scale withdrawal of groundwater, increased Boro rice cultivation, dry season reduction in river flow, reduction in wetland areas, declining annual rainfall, low recharge potentiality of soils, and lack of recharging of aquifers through artificial methods are regarded as the major barriers to sustainable groundwater use in the IGP basin [291]. These factors, in their various combinations, are causing decline in groundwater level in some regions in the EGP (e.g., North-West region of Bangladesh; [49]). In a groundwater irrigation system, reduced application of irrigation may be an effective way to check groundwater level depletion [292], although contrasting results were also reported [293–295]. These contrasting opinions and observations raise valid questions of how far irrigation return flow contributes to groundwater recharge.

Field-level water-savings can make water use more profitable by increasing crop-water productivity and may lead to greater total water use in the basin [75,116]. Mere adoption of resource-conservation technologies cannot guarantee overall water-saving unless the usage of saved water can be controlled by proper policies and regulations. However, regional-scale study is still scarce for the evaluation of impacts of water-saving on evaporation and groundwater levels [296]. A proper policy to achieve stabilized groundwater levels must not consider only the adoption of technology and management of users' demand; recharging the aquifer artificially and finding alternative water sources, i.e., supply side management, is also necessary in some situations [64]. To establish sustainable levels of groundwater usage and achieve maximum benefit therefrom, investigation of the feasibility of combination of demand management, recharge improvement and alternative water supplies are crucial [297].

5.4. Inadequate Understanding of Scale-Effects

Improved irrigation methods and conveyance systems are essential to increase efficiency of water use. However, water loss through deep percolation has the possibility of reuse in another region and the quality of percolated water may undergo changes during transmission through the hydrological units. It is therefore essential to account for the usages of surface water and groundwater, losses of water while being used, and interactions of various water components at the field scale and basin scale by adopting a system approach [67]. The common system approach of water accounting requires that, in closed basins, all lost water is presumed to be re-used somewhere downstream and hence any intervention to increase efficiency of water use would not make significant water-savings. So, there is hardly any scope for water-scarce regions to reduce water stress, especially through improvement in efficiency of water use. This approach has three major faults [298]. This disregards a major element of unproductive water use, values only new water without sufficiently considering water productivity in a broader aspect, and fails to account for several co-benefits arising from increasing efficiency of water use (e.g., upgraded water quality, increased reliability and less energy demand). Because of the complexity of the impacts of water-saving technologies at large scales, good approaches must integrate the conceivable spatial and temporal effects. Often a three-dimensional surface-groundwater interaction approach [299] is considered for this; but the problem remains as yet unexplored.

5.5. Weakness in Policy

In the past, agricultural water management generally concentrated attention on irrigation options and water withdrawals from rivers and aquifers. Now it dedicates more attention to managing rainwater, evapotranspiration and water reuse, and views land-use decisions as water-use decisions [103]. In current perceptions of water management, considerable water-savings can be realized if the water-saving options are assessed in terms of technical, economic and institutional aspects and selections are made based on their efficacy [67]. Although technologies play a vital role in reducing water applications per unit of crop production, the re-bound effect is always a problem. If the increase in cultivated area of a certain crop, or even the irrigated area due to the re-bound effect, can be adequately known, the regional impacts of water-saving measures could also be scientifically explainable. However, restricting the demand of water is a challenging issue [75,127] with weak institutional arrangements. In the IGP, instability in the market price of agricultural products often guides the farmers to choose crops irrespective of the set policy. The performances of water-saving technologies contrast, and their adoption is a widely debated issue. Nonetheless, promoting water-saving technologies is a popular policy for governing groundwater in many countries (e.g., Bangladesh, India, China, Spain, Mexico, and the USA). Lack of attention, proper legislation, and ineffective or less-effective institutions are the main difficulties in governing groundwater in many least-developed and developing countries [128]. In cases when aquifers extend across more than one independent country, groundwater governance becomes extremely complex [131].

When the groundwater table is very close to the surface (within capillary rise) the declining groundwater table can increase percolation rates by increasing the hydraulic gradient that would not have happened with a deeper groundwater table. It is speculated that this will offset the gains, at least to some extent, that the adopted water-saving technologies can offer. The recharge of shallow aquifers is therefore an important mechanism that needs to be well-understood for effective management of aquifers [300]. As the scale of water use extends, water loss increases, with resulting decrease in traditional irrigation efficiency. In contrast, water recycling increases with extending scale of water use, with eventual increase in net efficiency except when recycling is not feasible at the system level. This scenario of water usage suggests that the term 'irrigation efficiency' can lead policy planners to miscommunication and misunderstanding. While the problems of groundwater are clearly intuitive, the solutions are not. Enactment of wrong, flawed or misemployed concepts of efficiency in water-resource strategy and management can bring about many unexpected problems [78]. An example is the assumption that the rate of natural groundwater recharge is the safe yield of an aquifer [301]. This water budget myth ignores the factual possibility of increasing recharge and/or decreasing discharge from the aquifer due to groundwater extraction [199]. Our knowledge of the nature of interconnection between surface and groundwater systems over a large spatial scale is not yet adequate. Consequently, many water managers have been suffering in formulating strategy and establishments separately, rather than based on the linked inter-connection of surface water and groundwater. It is important that groundwater systems are treated as complex systems, which respond dynamically to abstraction-induced perturbation. A correct account of the vadoze zone in irrigation fields [302] can enable assessment of the impacts of change and of interventions to be prioritized [77].

Effective governance, although lacking in many countries, is a prerequisite for sound water resource management [129]. Because of existing political structures and systems, adopting a policy of restricting tube wells to reduce groundwater extraction in the IGP basin seems unrealistic. Several states in India have adopted regulations to prevent/minimize groundwater mining but could not implement these regulations totally [303,304]. In Bangladesh, reliable and detailed information on water reserves, safe yield, water withdrawal patterns and groundwater quality dynamics of aquifers is lacking [130]. These knowledge gaps have raised serious concerns about sustainable use of groundwater for irrigation, especially in the North-West region of the country [305]. Recently, emphasis has been placed on increasing dry season Boro rice production in the southern zone to reduce stress on groundwater use in the North-West region [306]. However, the viability of this approach remains to be cross-examined. The potential major restrictive factors are salinity problems of soil and water, weakness in synchronized water governance and the likely effects of climate change in the southern region [130,307,308]. In Bangladesh, there are specific problems in governing groundwater usage. The number of groundwater users is very large, most water users are resource-poor, and the institutional settings are mostly ineffective to ensure execution of laws and regulations. Under such a situation, enforcement of water rights and controlling access to groundwater by permit systems are probably not feasible options. A well-conceived rational and persistent strategy is appropriate for groundwater governance. Some prospective drivers of success may be engagement of users, refinements in water pricing structures, inspiring farmers to move from high to less water-demanding crops [53], in situ rainwater conservation, deficit irrigation, modifying rice–wheat areas [309], extensive investments in technology, and advancement of proactive policies and decision-making systems. Certainly, all these options will not be equally effective at all times and places since groundwater dynamics are localized; local countermeasures, such as managed aquifer recharge, can be implemented [9]. The best option(s) for governing groundwater at specific times and locations must be, however, identified through policy research [130].

Artificial recharge to aquifers through natural drains, canals and topographical depressions is a technically feasible and economically viable option [310] in the EGP. However, this option needs to be within a proper policy framework for its implementation. If groundwater-irrigated areas are not further increased, groundwater levels are expected either not to decline further or decline at much smaller rates than currently. With checked groundwater-irrigated areas, the other possibility is that groundwater levels will attain a new equilibrium that will be lower than at the current level. This proposition, yet to be considered in national policy, implies that the existing abstraction rates of groundwater can be continued and the presumed lower groundwater levels will not hamper the environment and economic and social developments [311]. However, these suggested potentials are only propositions and because of widely variable hydro-climatic, political and socio-economic conditions among the affected regions no single solution will be adequate for groundwater management. The most logical strategy would be to select, from among the available options, regionally-suited strategies and establish strong regulation and policy for management of regional water resources [131–133]. Therefore, sustainable long-term strategies that are appropriate and adaptable for individual regions need to be recognized and exchange of knowledge and actions between regions must be established. Thus, establishing region-specific strategy and communication systems [134] will be important topics for future research in the IGP basin.

6. Summary and Conclusions

Manifold attempts have been made in different regions of the world to increase food production for the rapidly growing population since the early 1960s. There has been great success in increasing food production globally but with a tremendous resulting pressure on the production-linked resources, specifically water and soil. The accelerating stress on these vital resources in the EGP raises sustainability concerns regarding agricultural production systems. Researchers and practitioners have been facing these challenges, both locally and regionally, over the last few decades. They have developed resource-conservation technologies as a response to concerns about agricultural sustainability, with basic principles of rebuilding the soil, optimizing inputs for crop production, increasing food production, and optimizing profits [84,86,87]. This review study has summarized the benefits of these technologies, and the scale-dependency and uncertainty of some of the benefits. Also identified are the gaps in current knowledge regarding the conceptual aspects of these technologies to make agriculture sustainable over a large regional scale so as to guide the future research in proper directions.

Of these resource-conservation technologies, conservation agriculture and water-saving measures are being practiced in many regions of the world, including the EGP [85,87]. Some benefits of these technologies, such as reduced energy and nutrients usage and reduced agrochemical leaching, are scale-invariant and intuitively clear [37,83]. However, the issue of water-saving remains uncertain at the system level since it is both a temporal and spatial scale-dependent element and linked to the regional hydrologic cycle [94,95]. Water saved at the farm level could otherwise join the groundwater or surface water systems to be used later by the same or other users [75,103]. Consequently, whether water-saving achieved at the farm level makes any real saving when considering the entire groundwater or river basin has not yet been adequately investigated. Furthermore, there is evidence of increasing demand for water after adding more value by technological interventions, such as increasing irrigation efficiency by adopting water-saving measures [114]; however, contrasting evidence has also been observed [74]. Whether or not the reduced extraction of groundwater, as well as reduced recharge, under resource-conservation technologies raise groundwater storage/groundwater level or reduce it remains unresolved [306]. Apparently, the reduced extraction of groundwater is expected to increase groundwater storage, but this likelihood is also uncertain since most aquifers in the Gangetic basin discharge to the rivers as base flow in the dry season. Thus, the current level of understanding of the complexity of the hydrological link to field-applied water is inadequate due to lack of measured data on the components of regional water balance. Lack of shared knowledge on the impacts of resource-conservation technologies on regional water balance among the pertinent disciplines, such as agricultural production practitioners (e.g., agronomists, economists, irrigation engineers) and hydrologists (e.g., groundwater hydrologists, surface water hydrologists), is another drawback in planning and implementing holistic approach to investigate regional hydrology outcomes. This inadequate knowledge of inter-linked water systems may lead to the implementation of wrong policy [121–123] merely based on local perspectives with eventual worsening of the water-scarcity situation. Therefore, all pertinent disciplines should adopt integrated research approaches to measure the components of local and regional water balance and quantify regional hydrology outcomes over a large temporal scale. Only then proper water management policy can be planned and implemented for sustainable agricultural production.

Author Contributions: Conceptualization, M.A.M.; funding acquisition, M.M.; writing—original draft, M.A.M.; writing—review and editing, M.A.M. Both authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by the Australian Centre for International Agricultural Research (ACIAR) under the project 'The regional hydrological impact of farm-scale water saving measures in the eastern Gangetic plains'.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the contributions of the authorities of Bangladesh Agricultural University (BAU) in Bangladesh and Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia in conducting this study. The BAU authority granted a 2-week leave to the principal author to visit CSIRO, which provided access to their electronic academic resources to facilitate conducting this study.

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

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Review

Responsible Water Reuse Needs an Interdisciplinary Approach to Balance Risks and Benefits

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Received: 20 March 2020; Accepted: 24 April 2020; Published: 29 April 2020

Abstract: Freshwater is a precious resource, and shortages can lead to water stress, impacting agriculture, industry, and other sectors. Wastewater reuse is increasingly considered as an opportunity to meet the freshwater demand. Legislative frameworks are under development to support the responsible reuse of wastewater, i.e., to balance benefits and risks. In an evaluation of the proposed European regulation for water reuse, we concluded that the proposed regulation is not practically feasible, as the water provider alone is responsible for the risk assessment and management, even beyond their span of control. The required knowledge and resources are extensive. Therefore, without clear guidance for implementation, the regulation would hinder implementation of reuse programs. As a consequence, the current practice of uncontrolled, unintentional, and indirect reuse continues, including related risks and inefficiency. Therefore, we provide an outline of the interdisciplinary approach required to design and achieve safe, responsible water reuse. Responsible water reuse requires knowledge of water demand and availability, quality and health, technology, and governance for the various types of application. Through this paper we want to provide a starting point for an interdisciplinary agenda to compile and generate knowledge (databases), approaches, guidelines, case examples, codes of practice, and legislation to help bring responsible water reuse into practice.

Keywords: water reuse; water quality; water availability; governance

1. Introduction

Freshwater is a precious resource, and shortages can lead to water stress impacting agriculture, industry and other sectors [1]. To reduce this, treated municipal (domestic) or industrial wastewater is increasingly considered as a freshwater resource. By wastewater reuse, the pressure on water resources can be reduced, which fits within the circular economy objectives [2]. However, water should only be reused in a responsible, sustainable manner, i.e., if no unacceptable additional risks for human health and the environment are introduced beyond current water sources. The main challenge for achieving such responsible water reuse is that there is considerable variation in (potential) risks and hazards, related to differences in water sources, application, and type of water treatment methods, and thus in water quality, and the use, practice, or method of application [3–10].

Applications of wastewater reuse in Europe include reuse of municipal wastewater for drinking water (e.g., Torrelee, BE [11]), as cooling water in industry (e.g., Tarragona, ES [12]) and for agricultural irrigation (e.g., Braunschweig, DE; Clermont-Ferrand, FR; Puglia, IT [13–15]), and of wastewater from the food industry for irrigation in agriculture (Lieshout, NL [16]) and horticulture (Dinteloord, NL [17]).

The EU's blueprint to safeguard Europe's water resources, stresses the need to use treated wastewater as a water resource for irrigation [3,18]. The Water Framework Directive and the Urban Wastewater Treatment Directive provide requirements for treatment of wastewater. For effluent reuse, however, the EU's blueprint identifies a lack of common standards, which led to a risk management framework by the Joint Research Centre to establish minimum quality requirements for water reuse in agriculture [19].

At current, there is no explicit EU regulation with regard to irrigation water. However, the proposed EU regulation for direct reuse of domestic wastewater for irrigation [20] has very recently been adopted by the EU Council and awaits adoption by the European Parliament [21]. It includes harmonized minimum quality requirements and risk management practices, as well as specific processes related to permits and obligations on the sharing of information on reuse. The proposed EU regulation for the direct reuse of domestic wastewater for irrigation asks for a detailed understanding of the benefits and risks of reuse for agricultural practices for each reuse program. This proposed regulation states that a water reuse risk management plan (WRRMP) is required for reclamation sites, to manage microbial and chemical risks in a proactive manner. Minimum quality requirements are proposed for different types of agricultural reuse, depending on crop category and irrigation method. Additional water quality requirements that are relevant to the specific reuse program should be added based on the WRRMP.

Earlier evaluations by independent experts [22] concluded that although many important elements are included in the proposed water quality requirements, several key aspects were inadequately addressed—in particular contaminants of emerging concern, spread of antibiotic resistance, disinfection by-products, and the potential of effect-based bioanalytical tools—and that the selection of minimum quality requirements is unclear. In this paper, the different aspects that should be considered in every water reuse case are addressed, i.e., water demand and availability, water quality (health and safety), treatment technology and governance (policy and regulations, economics, stakeholder participation and public acceptance) (Figure 1). The proposed EU guidelines for the reuse of domestic wastewater for irrigation and the WRRMP were critically reviewed with respect to practical feasibility for a specific water reuse case in the Netherlands [23]. This led to the identification of knowledge requirements for responsible water reuse. This paper provides an outlook on how the proposed regulations could be improved to encourage innovation in technically achieving, managing, monitoring, and regulating responsible water reuse.

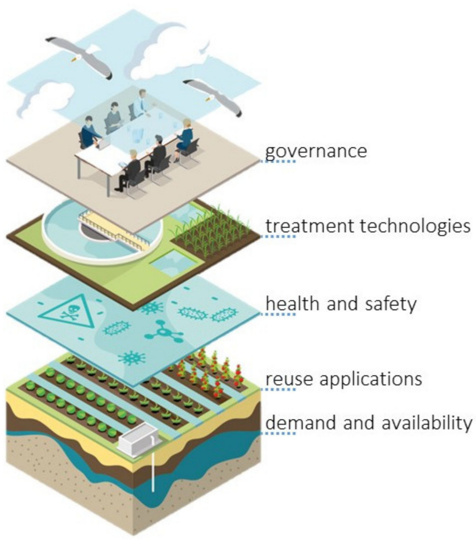

Figure 1. Different disciplines are needed for the practice of responsible water reuse.

2. Water Demand and Availability and Reuse Applications

The most common freshwater sources are groundwater and surface water, often perceived as natural waters [24,25]. However, wastewater is already often indirectly (de facto) reused in agriculture, by irrigating with surface water in which treated domestic wastewater is discharged and diluted [26]. For several regions in Europe with agricultural irrigation the impact of wastewater effluent on irrigation water quality has been estimated to be significant [24]. Globally, it has been estimated that about 65% of irrigated croplands downstream of urban areas were located in catchments affected by urban wastewater flows [27]. The main drivers for the intentional reuse of effluent are declining groundwater levels and prolonged droughts [28]. Periods of drought in Europe, even in areas with an annual rainfall excess, have led to ad hoc use of treated wastewater for irrigation without adequate risk evaluations. Aquifer recharge or subsurface water storage to prevent or reduce salinization also creates demand for (reclaimed) freshwater [29].

Quantitatively, the reuse of domestic wastewater for irrigation has high potential to play an important role in water resource management. For direct water reuse, wastewater needs to be treated to such an extent that it is suitable for irrigation. Such intentional reuse offers better control and management possibilities than currently practiced de facto reuse. There is a lack of knowledge on the required water quality for safe use in agriculture, especially with respect to emerging compounds. Innovative treatment processes need to be applied to achieve this quality reliably, affordably, and sustainably. Since the demand is generally highest when there is least water available, concepts for underground buffering need to be developed. These in turn require sufficient water quality, but also may improve water quality [30,31]. Smart combinations of various reuse applications with varying demands will increase flexibility of the system, but require innovative business models to manage shared water resources. The proposed EU regulation for reuse is limited to direct reuse of treated domestic wastewater for irrigation. Therefore, it only applies to a selection of potential water reuse applications and is missing an integrated approach. The regulation asks for a detailed understanding of benefits and risks of reuse for agricultural practices. If a water provider does not have the specific expertise and realises that the required monitoring will be costly, the proposed regulation might discourage intended reuse and thus unintendedly stimulate an increase of indirect de facto reuse.

3. Health and Safety including Water Treatment

Current wastewater and sanitation systems were designed to efficiently remove wastewater from the home and release it into the environment to prevent contact with humans. A hazard related to wastewater reuse is that it may bring the contaminants from wastewater back to the living environment. Irrigation with treated wastewater may introduce pathogens and chemicals in the soil and to the plants, some of which may affect human health by transfer through the food chain, or via contamination through the air, surface water, or groundwater. Human health risks due to the presence of pathogens or chemicals can vary widely between cases of water reuse for irrigation, depending on the type of wastewater, land use, soil type, type of irrigation, exposure scenarios, and the hydrological conditions at the irrigation site [32]. Conventional wastewater treatment processes were not designed to remove pathogens and emerging contaminants [33]. Additional and innovative water treatment technologies based on sorption, oxidation and size exclusion principles, will thus be needed to produce fit-for-purpose water efficiently [34]. Recent activities to collect all knowledge on the removal of a wide variety of pathogens and (emerging) contaminants by common and advanced treatment technologies, such as activated carbon, the use of ozone and UV with or without H_2O_2, nanofiltration, and reverse osmosis, actually shows that knowledge is available but scattered, and continuously growing and expanding to new contaminants [34,35]. Also, different exposure routes and their respective relevance differ per situation and depend on type of irrigation, type of crop, and environmental fate of chemicals present in the reclaimed water in the soil. In each water reuse case, the following questions on water quality need to be addressed: Which risks related to the presence of pathogens or chemicals are relevant in this particular case and what water treatment technologies are effective?

Pathogens in domestic wastewater include bacteria, viruses, protozoa and helminths. These are mostly enteric pathogens causing gastrointestinal disease that enter the wastewater by excretion from infected persons. Pathogens are currently not monitored in wastewater, so what is known about the presence of common and rare pathogens in various wastewater types is coming from research and is scattered [36]. Real-time quantitative polymerase chain reaction (PCR) analyses could serve as a relatively simple and cheap screening tool for pathogens in wastewater [37], although it needs to be considered that these methods cannot make a distinction between DNA from living or dead pathogens and thus could result in false positives. Viruses, bacteria, and parasites are only removed or inactivated to a limited extent in conventional (activated sludge and sedimentation) wastewater treatment processes [36]. So, for many reuse applications in agriculture, microbial safety requirements will require additional treatment or other risk management actions. In the proposed EU regulation for reuse of domestic wastewater for irrigation, minimum requirements are set only for the microbial parameters *Escherichia coli* (*E. coli*), *Legionella spp.* and helminth eggs, and several technical minimum requirements are also associated to microbial safety. Choosing *E. coli* as the general indicator to evaluate whether a reuse system is capable of producing water that is safe for the different irrigation purposes could result in a false sense of safety, as *E. coli* is very sensitive to disinfection processes in comparison to other microbial hazards [38]. Reused wastewater will generally contain more organics which stimulates microbial growth including opportunistic pathogens like *Legionella*. The requirement for *Legionella spp.* is only in greenhouses where there is a risk of aerosolization. This is potentially a high-risk setting for *Legionella pneumophila*, given water temperatures in these irrigation systems. However, several urban wastewater systems have been associated with *Legionella pneumophila* outbreaks [39–42], particularly linked with wastewater influenced by high organic/high temperature waste streams such as from breweries or paper mills, so inclusion of reuse systems based on these waters is warranted. In addition, the proposed monitoring of *Legionella spp.* includes many non-pathogenic *Legionella* species that can be abundant in water systems, while the vast majority of severe infections is due to *Legionella pneumophila*. Its management might even increase the risk as *Legionella* species live in competition in biofilms. Disturbing the biofilm by disinfection of *Legionella spp*. might actually allow *Legionella pneumophila* to proliferate in the new situation [43]. Setting the requirement specifically for *Legionella pneumophila* would thus be a better indicator of risk.

There is discussion about the significance of the water route for human exposure to antibiotic resistant bacteria, but it is clear that many types of antibiotic-resistant bacteria and genes are present in wastewater [44]. WHO has indicated that discharge and exposure via domestic wastewater should be kept as low as reasonably achievable [45,46]. To demonstrate this, it would be beneficial to provide guidance and select a reference for antibiotic resistance, such as extended-spectrum betalactamase (ESBL) *E. coli*, given that it is widespread and one of the resistant bacteria of concern present at relatively high concentrations with good methods available for enumeration in wastewater.

Risks of chemicals for human health or the environment depend on the hazardous properties of the concerned chemicals and the margin between safe exposure levels and the realistic exposure that is occurring [47]. Exposure levels can be monitored, but in a risk management scheme exposure levels may also be predicted to some degree based on (expected) levels in wastewater, treatment efficiency, distribution and degradation in water, soil and air, and absorbance in plants [32,48]. Wastewater presents a continually evolving composition of chemicals in complex mixtures depending on human activities. Humans can thus be exposed to chemicals in reclaimed water via different exposure routes, partly depending on (professional) activities of the exposed individuals. For persistent chemicals, concentrations in wastewater-irrigated soils may even slowly rise with each successive wastewater application [32,49].

No minimum requirements for chemicals are included in the proposed regulation, but these are to be determined for specific chemicals in specific settings based on the outcomes of the WRRMP. This plan refers to existing EU legislation on chemicals in food and the environment. A list of relevant chemicals to consider for the validation and performance monitoring of reclamation plants can be based on their known or expected presence in wastewater, legislative criteria for (ground) water, and food safety requirements for crops such as maximum residue levels. Minimum requirements for these chemicals at the point of compliance, such as the outlet of the reclamation plant, can be defined based on relevant exposure routes and realistic worst-case fate and transport processes of chemicals from the release via STP towards human and environmental exposure. Wastewater also contains nutrients that can be useful for crop production, such as nitrogen, phosphorus, potassium and organic matter [50]. Required concentrations of nutrients vary in different crop production stages and there are some associated health hazards (e.g., nitrate). Reclaimed water for irrigation may also negatively impact agricultural productivity, especially through salt content [51]. Limit concentrations of chemicals in reused wastewater are either based on crop requirements or on human or environmental health concerns. Relevant chemicals can be derived by integrating information on occurrence in wastewater and their risks including legislative food safety requirements. Following the proposed regulation, environmental monitoring systems of water reuse systems would need to include the whole water pathway, i.e., at the reclamation plant, at the point of use and further downstream in the environment. This generally exceeds the span of control of individual water providers or managers.

Indirect potable reuse through drinking water production from domestic and industrial wastewater impacted surface water has provided several decades of experience on monitoring and managing water quality risks. Due to increased knowledge on possible adverse effects and increased analytical possibilities, the number of chemical parameters included in monitoring programs of water utilities increased exponentially in the last decade [52]. In accordance with the European Drinking Water Directive [53], utilities aim at a tailored risk-based monitoring program and this approach is also applicable to water reuse applications. Risk-based monitoring programs can be designed based on knowledge of the chemical composition of the wastewater and effluent, vulnerability of receiving groundwater and potential exposure routes. It is expected that a risk-based monitoring workflow for water reuse for irrigation can be based on the available technologies currently in use for drinking water purposes [47,54]. These can be complemented with bioanalytical tools that give information on the integrated effect of mixtures of chemicals related to a specific health effect [55,56]. By referring to a list of EU legislations on microbial and chemical risks from which requirements and obligations are also to be taken into account, many additional water quality requirements are indirectly included in the proposed regulation. Guidance on which requirements from these legislations should be included in a WRRMP needs to be further developed. Practical case studies can provide insight in what monitoring is practical, feasible and meaningful.

Awareness of the number of chemicals emitted to the aquatic environment in wastewater has also resulted in increased attention for and exploration of the merits of additional post-treatment at wastewater treatment plants [57]. Additional biological and technological treatments, such as activated sludge, membrane bioreactors, moving bed biofilm reactors, and nature-based solutions such as constructed wetlands may also be used in water reuse applications to mitigate risks [58]. The relevance of a treatment technology to a specific reuse case can be evaluated based on reliable removal efficiency data. Recently developed relevance and reliability criteria support the selection of appropriate technologies [59].

4. Governance

While water scarcity urges the practice of water reuse, large variation in potential hazards and risks forces to ensure responsible water reuse. This gives rise to a particular challenge in governance. A precautionary option for water reuse for irrigation would be to set a standard list of requirements, focused on expected exposures via food crops. Concentrations in harvested crop, environment, and biota can be measured or estimated based on fate and behaviour of chemicals and pathogens after release from the water treatment site [60,61]. The introduction of related uncertainty/extrapolation factors may lead to relatively conservative water quality standards that will need to be met and therefore monitored. Location specific risk-based approaches, where hazards and risk management measures are prioritized on a case-by-case basis, are expected to be more applicable. This avoids overly stringent quality standards that could discourage the development of reuse schemes by imposing burdensome treatment and/or costly monitoring requirements [62]. However, to require each reuse system to conduct their own specific evaluation of all relevant contaminants, their toxicity and uncertainties would make the regulations very difficult to implement and harmonize between reuse systems and member states. Hence, this risk-based approach requires additional efforts to provide guidance on how to define the minimum set of requirements relevant to specific water reuse cases.

The WRRMP evaluation process can be supported by the development of a database of relevant hazard and safety levels and guidance material on the development of monitoring requirements. Existing risk management methods, databases and tools such as the AquaNES Quantitative Microbial Risk Assessment (QMRA) tool [35] may be useful in this regard, even if they were not developed specifically for water reuse cases. Another applicable method is the framework for risk-based monitoring of groundwater sources for drinking water production established in the joint research program of Dutch and Flemish drinking water companies [52]. Also, EFSA has developed a guidance for predicting environmental concentrations of plant protection products and their transformation products [63]. Although this was originally developed for exposure assessment for soil organisms, this may also be applied for the evaluation of water reuse risks on human health and the environment.

The heterogeneity of water reuse cases and risk management needs, stresses the value of a progressive and enabling regulatory regime [64]. For a mature governance arrangement, it is critical to engage stakeholders and pursue the normalization of water reuse in society. Ensuring long-term collaboration and engagement of stakeholders and customers is one of the key success factors in the development of water reuse schemes [62]. Building confidence and gaining trust through early consultation allows for a location specific approach that deals with uncertainty regarding risks and their perception. Involvement of stakeholders is also advocated by Goodwin and co-workers in a water reuse safety plan approach [65]. An important element in the engagement of stakeholders, in particular the general public, is the societal legitimation of water reuse [66]. The use of long-term narratives around the benefits of adopting water reuse and the recognition that de facto reuse is common practice could support public acceptance [67]. A clear explanation of risks and risk management can support public acceptance by applying the principles of risk communication [68]. Unfortunately, the WRRMP in the new EU regulation for direct reuse of domestic wastewater [20] does not include stakeholder engagement requirements. This is however critical, since this WRRMP points to risk management actions that are generally beyond the control of the water provider in reuse utilities.

The governance arrangement of water reuse cases needs to address economic aspects as well. An important factor hampering the development of water reuse is related to the total costs of treatment and of monitoring the reuse system as a whole [15,62]. For those cases in which reclaimed water is used for agricultural purposes, there will also be substantial costs associated with the conveyance system and delivery management for irrigation [15]. On the other hand, water reuse cases are often undervalued as the range of (environmental) benefits are not accounted for. Giannoccaro et al. [15] point out that also often transaction costs are not considered. The costs for water reuse treatment are incurred by different organisations (public or private water industry) than those organisations benefitting from the availability of reclaimed water (e.g., farmers). This is a general challenge for the transition to the circular economy in which a new distribution of societal values is needed that goes beyond a cost–benefit analysis of a particular (e.g., water) reuse case. The circular economy will require systematic changes in the whole value chain for water, benefitting the economic development of water reuse practices [69,70].

5. Feasibility of the Proposed Regulation for a Specific Water Reuse Case

The practical feasibility of the proposed regulation was evaluated by going through the WRRMP key risk management tasks for a sub-surface irrigation (SSI) case (research pilot) using effluent of a sewage treatment plant (STP) at Haaksbergen, the Netherlands. In this SSI case, STP effluent is actively added to a controlled drainage system. Such systems allow to control groundwater levels and soil moisture conditions at an agricultural field [71]. By actively adding water, controlled drainage systems become infiltration systems, or sub-irrigation systems (SSI). SSI systems can supply STP effluent to crops while the soil is used as filter and buffer zone [3]. The research pilot in Haaksbergen runs since 2015 [72].

The proposed regulation focuses on risks for water quality and health, and not on the potential benefits, or the risks of the current situation (irrigation with surface water that receives domestic wastewater). As opportunities (benefits) are not considered and the proposed risk analysis is very extensive, it is not possible to find a balance and implement responsible water reuse with this currently proposed regulation. Some specific shortcomings were identified. (i) Roles and responsibilities of the different stakeholders are not clearly described. (ii) Although needed to assess potential risks, the operator likely does not have detailed information on and jurisdiction over the infrastructure from the point of release (effluent) to the point of use (irrigation). In the Haaksbergen case, irrigation takes place using an innovative subsurface system that reduces the risks from direct application of water on crops or through aerosols. However, the proposed regulation does not address subsurface irrigation and requires measurements and (environmental) monitoring which may be less relevant for this type of irrigation. (iii) In particular, for emerging chemicals and pathogens, site-specific information on their occurrence in this case study wastewater is not readily available. Also, their fate and behaviour in the soil and in crops that will be consumed by humans or cattle is unknown. Determining whether additional requirements are needed requires the operator to perform a risk assessment and compare the outcome to acceptable levels of risk or water quality. (iv) Without guidance it is an exhaustive effort to monitor all relevant exposure routes and, in practice is outside the influence of the operator, who nevertheless has this responsibility according to the proposed regulation. (v) There is no guidance on adequate validation monitoring, and this is needed to support operators and to harmonize validation monitoring.

The evaluation of the proposed guideline shed light on the challenges of the implementation of the guideline to promote responsible water reuse. It provides guidance for research agendas and needs to make practical implementation feasible. Using novel, innovative methods, feasible and uncomplicated monitoring strategies can be developed for analyses of effluent water quality at the point of release without the need to monitor (inaccessible) points of use. Rather than requesting extensive monitoring at each reuse site, decision-making tools and databases with information on environmental fate could be developed to identify whether a water reuse application may result in increased environmental exposure (soil, surface water and groundwater, crops) on or near the irrigation site, potentially resulting in risks for ecology or humans. Measuring or modelling site-specific exposure of humans, cattle, and the environment to compare to safe concentration is extensive and complex. Alternatively, national or river-basin specific risk assessments can, to some extent, be based on national concentrations of hazards in urban wastewater, efficacy of treatment processes and public health and environmental water quality standards [47,48,59]. This can be used to define a manageable set of indicator chemicals from different classes of use and with different physicochemical properties. Additional site-specific requirements may be derived by risk-based approaches. A database with acceptable risk levels or water qualities for different reuse purposes, and relevant preventive measures, would facilitate the implementation of the proposed regulations. Agriculture can benefit from treated wastewater as freshwater resource, and risks can be managed by precautionary regulations based on the most relevant exposure route. If needed, reuse can be limited to those applications with limited risk potential.

Ongoing research and innovation is already providing a basis for these goals with existing databases, novel analysis methods and innovative treatments. The EU regulation on minimum requirements for water reuse [19,20] is part of a legislative framework that is under development in the EU to support responsible reuse of wastewater for irrigation purposes. Other legislative frameworks related to water reuse are being developed worldwide (Table 1) allowing international sharing of knowledge and experience. New contaminants and new treatment technologies will continue to emerge. An integrated research agenda in the field of water reuse will support the efficient acquirement of necessary knowledge and steer innovation in the needed direction. User-friendly tools need to be developed together with end users that encapsulate this knowledge and allow stakeholders to apply this also in a non-scientific environment.

Table 1. Overview of existing and developing legislative frameworks of water reuse for industry, agriculture, or drinking water.

ISO Guidelines 20426, 20468, 20469 (2018)
WHO Guidelines for the safe use of wastewater, excreta and greywater (2006, revision ongoing)
WHO's Guidance of potable reuse (2017)
USEPA Guidelines for water reuse (2012)
US and California's Title 22 (updated in 2015)
Colorado incorporated water reuse in regulatory framework (no other states or US federal rules)
US federal regulation Food Safety Modernisation Act (2017) (relevant for crop irrigation in Latin America)
Australian Guidelines for Water Recycling (2006)
Oman national guidelines for water reuse
National standards of EU Member States (e.g. Spain Royal Decree 1620/2007)
EU Minimum requirements for water reuse in agriculture (legislation in consultation phase)
United Arab Emirates develops legal framework for water reuse (feasibility studies ongoing)
Saudi Arabia restructured water-related organizations and ministries to clarify responsibilities

6. Conclusions

Wastewater reuse is increasingly considered as an opportunity to meet the freshwater demand. This means a shift of paradigm from "safe treatment and discharge of wastewater" to "transforming used water to fit-for-purpose water". The following questions need to be addressed. To what degree are pressures on freshwater sources reduced by exploitation of treated wastewater? Which risks related to the presence of pathogens or chemicals are relevant in this particular case, and how does this impact selection of suitable water treatment technologies? What is the relevant legislation to be complied? Who are the responsible authorities and stakeholders for each of the elements of a reuse program, and are they all sufficiently involved?

The minimum requirements for microbial and chemical hazards in the proposed EU regulation do not sufficiently cover relevant risks to protect human and environmental health. The water reuse risk management plan in the proposed EU regulation is an interdisciplinary and exhaustive task and the proposed approach is not practically feasible, because it is very complex and operator influence and proposed responsibilities do not match. To support responsible water reuse, the evaluation of water reuse cases requires expert knowledge on both the benefits and risks regarding water availability, quality, and governance. Databases (on hazards, risks, background exposures and preventive measures) are needed to consistently and efficiently develop scientific, expert, and practical knowledge. Guidance material and decision-making tools are needed to disseminate expert knowledge and support decision makers and stakeholders for responsible water reuse, i.e., to make expert knowledge available for risk managers and stakeholders.

Author Contributions: Conceptualization, M.M.L.D.; P.W.M.H.S.; G.M.; J.F.; A.P.v.W.; K.J.R. and R.P.B.; writing—original draft preparation, M.M.L.D.; G.M.; P.W.M.H.S. and J.F.; writing—review and editing, R.P.B.; K.J.R. and A.P.v.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the joint research program of Dutch and Flemish drinking water companies and the Dutch Government.

Acknowledgments: We thank the editor and three anonymous reviewers for their valuable comments on the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Water Resources and Governance Approaches: Insights for Achieving Water Security

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Citation: Julio, N.; Figueroa, R.; Ponce Oliva, R.D. Water Resources and Governance Approaches: Insights for Achieving Water Security. *Water* **2021**, *13*, 3063. https://doi.org/10.3390/w13213063

Academic Editors: Fernando António Leal Pacheco, Antonio Lo Porto and Luís Filipe Sanches Fernandes

Received: 5 July 2021
Accepted: 26 October 2021
Published: 2 November 2021

Abstract: Integrated river basin management (IRBM) has been proposed as a means to achieve water security (WS), maximizing economic and social well-being in an equitable manner and maintaining ecosystem sustainability. IRBM is regulated by a governance process that benefits the participation of different actors and institutions; however, it has been difficult to reach a consensus on what good governance means and which governance perspective is better for achieving it. In this paper, we explore the concept of "good water governance" through the analysis of different governance approaches: experimental (EG), corporate (CG), polycentric (PG), metagovernance (MG) and adaptive (AG) governances. We used the Organisation for Economic Co-operation and Development (OECD) water governance dimensions (effectiveness, efficiency and trust and engagement) as a "good enough water governance" that regards water governance as a process rather than an end in itself. Results indicate that each of the five governance theories presents challenges and opportunities to achieve a good governance process that can be operationalized through IRBM, and we found that these approaches can be adequately integrated if they are combined to overcome the challenges that their exclusive application implies. Our analysis suggests that a combination of AG and MG encompasses the OECD water governance dimensions, in terms of understanding "good enough water governance" as a process and a means to perform IRBM. In order to advance towards WS, the integration of different governance approaches must consider the context-specific nature of the river basin, in relation to its ecologic responses and socioeconomic characteristics.

Keywords: water management; integrated river basin management; water security; good governance

1. Introduction

The diversity of ecosystem services that freshwater resources provide plays a key role in poverty reduction, economic growth and environmental sustainability [1]. All goods and services consumed by any society come from natural sources of matter and energy [2] and, therefore, economy and human well-being depend on natural systems' integrity [1]. However, the different uses that society exerts on water resources have increased considerably, causing a negative balance for ecosystems [3]. This precipitates the need to ensure water in quantity and quality for aquatic ecosystems as life-sustaining systems and to generate resilience derived from its lack (water shortage or droughts) or excess in short periods (risks due to floods), to promote human and economic development for all the inhabitants of the territory, advancing towards water security (WS) [4].

Grey and Sadoff provide a widespread concept of WS, highlighting the role of water as both a source of threat and a source of services, defining it as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies" [5]. Achieving it depends on the capacity of a society to manage water resources [1,6], regarding the river basin as the appropriate territorial unit [7]. Expanding on this definition, the notion of WS has been addressed in several studies, for instance, quantifying the main threats to freshwater biodiversity from both human and ecosystem perspectives on WS [8], analyzing how WS is conceptualized and operationalized according to different geographical regions and scales [9], and analyzing the relationship between WS and governance [10]. According to these studies, the following ideas emerge: WS is an integrated concept, so water management strategies must jointly address threats to biodiversity and human water securities; water crisis mainly results from governance issues, so an integrative perspective of WS is needed to improve water governance; and, the conceptualization of WS is diverse and context-specific, so it is important to include local communities' perspectives when addressing WS issues in water management.

However, achieving WS is a complex task, since it is a multi-faceted problem that goes beyond simple balancing of water supply and demand [11]. WS focuses not only on positive, but also on negative outcomes for people (water related disasters, water-borne diseases in children, conflicts over water access, supply and/or recreation), economy (hydropower production, irrigated agriculture and economic losses related to disasters), and the environment (ecosystem health, spatial extent of wetlands and estuaries, biodiversity and water quality), which are influenced by water management [12].

The multi-faceted nature of WS also refers to the water-related challenges that the world is currently experiencing. According to the 2021 United Nations World Water Development Report [13], in terms of water availability, over two billion people live in countries experiencing water stress, 1.6 billion people face economic water scarcity (water is physically available but lacks infrastructure to be accessible), and 30% of the largest groundwater systems are being depleted. In terms of water quality, globally, about 80% of industrial waste is discharged into the environment without treatment, and almost all major rivers in Africa, Asia and Latin America are regarded as polluted. In terms of extreme events, between 2009 and 2019, nearly 55,000 deaths were caused by floods around the world, causing US $76.8 billion in economic losses, and droughts affected 100 million people (2000 deaths), causing US $10 billion in economic losses. In relation to water, sanitation and hygiene (WASH), the UN report states that, in 2017, 71% of the global population used a safely managed drinking water service and 45% used safely managed sanitation services; in addition, regarding water-related ecosystem services, 14 of the 18 categories of 'nature's contribution to people' are in detriment, including: regulation of freshwater quantity, coastal and freshwater quality and hazards and extreme events.

WS challenges are likely to become even greater because of climate change. According to the IPCC, an increase in the frequency, intensity and/or amount of heavy precipitation in several regions is expected to occur, with global warming up by 1.5 °C as compared to preindustrial levels, as well as an increase in the frequency and severity of floods and droughts [14]. This implies a water crisis that requires immediate action [15].

Appropriate institutional roles and management instruments are two factors that could help in meeting WS challenges [4]. In this sense, "water crises are often primarily governance crises" [16], since the processes by which decisions are adopted and applied are critical for water resources management. As a governance measure, some authors propose that power and responsibility should be shared between water resource users and state agencies to achieve more collaborative and coordinated actions [17–20]. This can be reached through integrated water resources management (IWRM) that focus on the river basin (also termed watersheds and/or catchments) as the most appropriate spatial unit for management [21]. Consequently, integrated river basin management (IRBM) has arisen as a concept that is designed to assess integrated and multi-resource problems, considering the management of land, water and related natural resources within hydrologic boundaries to achieve long-term sustainability [22,23].

River basins, either independently or when interconnected with others, are considered the most accepted territorial unit for water resources management [22,24–27]. The concept of a river basin (or watershed) can be defined, from a geological/hydrological perspective, as a topographically traced area drained by a stream system [28]. However, the IRBM concept is holistic, because it considers the relevance of addressing multiple uses of freshwater resources [25] and, therefore, involves different stakeholders' perspectives about the river basin (i.e., industry, irrigation, biodiversity, etc.). In this sense, taking into consideration that WS involves issues of health, livelihoods, ecosystems and production [5], the river basin is not only regarded as a geographical unit, but also as a political and ideological construct that is linked with changing scalar arrangements, in both ecological and regulatory (or governance) terms [29]. However, some studies have questioned its benefits to water management, in some specific cases, related to discrepancies among hydrological and political-administrative boundaries and among the local and higher orders of government [30–33]. In these cases, the concept about the proper unit of analysis must be revised to adequately advance towards WS.

In spite of the above, IRBM should be guided by a water governance system that is inclusive, multi-scalar and sustainable [19,34–36], and should have varied responses to uncertainty caused by the effects of climate change [37,38]. However, there has been no consensus on what the term "water governance" means or the characteristics that should include a "good water governance" system. In this paper, we try to shed light on this topic.

The Organisation for Economic Co-operation and Development (OECD) defines water governance as a process that involves different actors and perspectives in decision-making; it is focused on administrative and institutional dynamics and includes formal and informal organizational aspects [16]. In the academic literature it is possible to find different approaches to governance. For instance, Kooiman and Jentoft address three governance modes: hierarchical, self-governance and co-governance [39]. For their part, Turton et al. briefly analyse three broad types of governance: corporate, network and adaptive governances [40]. Partelow et al. have synthesized and compared eight different governance theories: polycentricity, network governance, multilevel governance, collective action, governmentality, adaptive governance, interactive governance theory and evolutionary governance theory, in terms of their application to coastal systems [41], while Monkelbaan has compared five governance theories: transition theory, metagovernance, polycentricity, network governance and experimentalist governance, in terms of their relevance in achieving sustainable development goals (SDGs) [42].

In this paper, we seek to advance towards an understanding of good water governance, with a focus on the OECD Water Governance Framework, by analyzing five governance approaches: corporate governance, experimentalist governance, polycentric governance, metagovernance and adaptive governance, in terms of addressing the complex task of advancing towards WS. We go further than previous studies on governance classification, arguing that these approaches could, to some degree, include features that suit the OECD water governance dimensions (effectiveness, efficiency and trust and engagement) and can be applied to freshwater systems and IRBM. For this purpose, in Section 2, we provide the theoretical background, analyzing the concept of good governance and the five governance approaches. We highlight the OECD water governance dimensions as a perspective that focuses on water governance as a process rather than an end to achieve, and we analyze these approaches to governance in accordance with their objectives, role of private and public actors and their relationship, leadership and expected outcomes. In Section 3, we assess the strengths and possible failures associated with these approaches to address the OECD framework. Then, we inform possible integration mechanisms to achieve appropriate forms of good water governance (Section 4). In this way, a particular governance approach (or a combination of them) may be more effective in solving particular environmental problems. This latter attribute supports the idea of "good water governance" as a dynamic and context-specific process, that is, a means to achieve WS, which is operationalized through IRBM [43]. We provide our main conclusions in Section 5.

2. Theoretical Background: "Good Water Governance" and Governance Approaches

2.1. Good Water Governance

Advancing towards IRBM depends on an integration of actors, institutional roles and water management instruments, where policies, guidelines and institutions must adequately address the way in which water resources are used, in order to protect the natural adaptive capacity of the ecosystems.

Different authors and international institutions have proposed different indicators or characteristics that help to resolve if governance is being well implemented. For example, the United Nations Asia Pacific Social and Economic Commission (ESCAP) suggests eight key parameters for good governance: it is participatory, consensus oriented, accountable, transparent, responsive, effective and efficient, equitable and inclusive and follows the rule of law [44]. Likewise, the World Bank developed the Worldwide Governance Indicators (WGI) project, establishing six indicators of good governance, some of which are similar to those of ESCAP: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption [45]. In particular, some specific indicators for good water governance have been proposed by Lautze et al.: openness and transparency, broad participation, predictability and ethics, including integrity (as control of corruption) [43].

According to the definition of water governance cited above, it is worth emphasizing that good governance is a process. This is supported by Grindle, who states that it is important to focus on how to change for the better, increasing the understanding of how institutions emerge, evolve and improve, suggesting moving to a concept of 'good enough governance' [46]. Particularly for water, Ashton states that good governance is a complex and multi-dimensional process guided by a philosophy or set of operating principles that facilitate interaction towards a desired situation or consequence [47]. This interaction is better achieved by the promotion of a trialogue among science, society and governments, who have specific and complementary roles in water management. Both perspectives sustain to some extent what the OECD states, regarding water governance as "a means to an end, not an end in itself" [19].

In relation to the above, a framework that we consider represents the idea of 'good enough water governance' as the one represented by the OECD through the Principles on Water Governance [19]. According to this organization, governance is good if "it can help to solve key water challenges, using a combination of bottom-up and top-down processes while fostering constructive state-society relations". These principles are grouped into three main dimensions: effectiveness, efficiency, and trust and engagement.

Governance must be effective, defining clear, sustainable water policy goals, to implement them and to meet expected targets. Among its principles, we highlight: "clearly allocate and distinguish roles and responsibilities for water policymaking, policy implementation, operational management and regulation, and foster co-ordination across these responsible authorities; encourage policy coherence through effective cross-sectoral co-ordination, especially between policies for water and the environment, health, energy, agriculture, industry, spatial planning and land use; and adapt the level of capacity of responsible authorities to the complexity of water challenges to be met, and to the set of competencies required to carry out their duties".

Governance must be efficient in terms of maximizing the benefits of sustainable water management at the least cost to society. Among its principles, we highlight: "produce, update, and share timely, consistent, comparable and policy-relevant water and water related data and information, and use it to guide, assess and improve water policy; ensure that sound water management regulatory frameworks are effectively implemented and enforced in pursuit of the public interest; and promote the adoption and implementation of innovative water governance practices across responsible authorities, levels of government and relevant stakeholders".

Governance should build trust and engagement, ensuring the inclusion of actors through democratic legitimacy and fairness for society. Among its principles, we highlight:

"promote stakeholder engagement for informed and outcome-oriented contributions to water policy design and implementation; encourage water governance frameworks that help manage trade-offs across water users, rural and urban areas, and generations; and promote regular monitoring and evaluation of water policy and governance where appropriate, share the results with the public and make adjustments when needed".

The complexity of water-related problems has led to the emergence of different governance approaches which, in some way, aim to achieve a 'good enough water governance' process.

2.2. Governance Approaches

2.2.1. Corporate Governance

Corporate governance (CG) is the system by which companies (whether public or private) are directed, governed and controlled, promoting transparency and responsibility between stakeholders that belong to corporations or other types of organizations [48]. The objective of this governance approach is to create a regulatory and operational framework, so that companies, owners and regulators are more transparent, accountable and efficient in the decision-making processes. In this sense, well-governed companies could have lower financial and non-financial costs associated with risks related to WS issues.

In terms of the relationship among actors, company's employees and suppliers take leadership in CG due to their importance in decision-making. They are related to a company that has intrinsic attributes: mission/vision, corporate culture (reflected in its values), nature of its financial structure (capital, incomes, debts and profits) and the sector/industry where it operates. Companies are also affected by other actors: (i) clients/customers demand products/services, including price and quality, and their preferences may be shaped by their attitude towards sustainability; (ii) governments act as regulators of companies' behavior, setting and overseeing the framework in which they operate, such as policies, prices/tariffs, taxes, water allocation, water planning, environmental laws and compliance regimes, among others; (iii) investors (shareholders, lenders and fund managers) provide finance, pursue responsible investment and can have their own systems for information access and verification, in relation to the company's behavior [48].

In the case of water, CG is closely linked to the concept of corporate water stewardship, which, within a IWRM framework, is regarded as "actions by water users themselves to contribute to the management of the shared resource towards public good outcomes" [49]. This concept is related to the role of corporations in water stewardship, which is in turn defined as "the use of water that is socially equitable, environmentally sustainable and economically beneficial, achieved through a stakeholder-inclusive process that involves site and catchment based actions" [50]. In these terms, we understand that an expected outcome of corporate water stewardship is to promote dialogue and collaboration between corporations and water users to achieve WS. Therefore, companies (as large water users) are especially asked to understand the impacts generated by water's use, to be part of the solution to water problems and to work collaboratively and transparently with other actors to have more sustainable management at the basin scale [51]. In this context, companies are asked to act as custodians of water as a public good [52].

2.2.2. Experimentalist Governance

Experimentalist governance (EG) has been defined as a recurrent process of goal setting and periodic revision based on learning, that is achieved through a comparison of the different alternatives existing under different contexts [53]. This governance approach corresponds to a form of coordination based on practice and experimentation, in the sense that "systematically provokes doubt about its own assumptions and practices [. . .] and treats all solutions as incomplete and corrigible" [42]. EG constantly adjusts its outcomes and means to achieve them through social learning, therefore, its main objective is to achieve a systematic way of constant reformulation and iteration [42].

In terms of the relationship among actors, EG promotes a decentralized and diverse structure, including various sources of resource and expertise [54]. EG, also called democratic experimentalism, would be a response to the demands from political objectives and methods that can no longer be pre-determined. Instead, they have to be discovered during the problem-solving process [55], requiring a high degree of commitment from the involved actors to advance in water management. In EG, actors performing at the lower-level are granted enough freedom to create place-based mechanisms to achieve all-encompassing framework outcomes, and sharing their experiences enables policy learning [56].

Some authors point out that EG is practiced through an iterative cycle, which consists of five steps [42,53]: first, actors discuss and agree about a common problem; second, local and central actors set overall goals and metrics for their implementation in a provisional way; third, local actors (public and/or private) are free to move towards the resolution of these objectives in any way they deem appropriate; fourth, due to their autonomy, local actors should regularly inform about their performance and participate in a peer review process to compare their results with those of others who use different means to achieve the same objectives. Finally, objectives, indicators and decision-making processes are periodically reviewed based on the challenges and opportunities revealed, and the cycle is repeated. In this sense, an expected outcome for EG is to perform this cycle in a coherent way, through active participation and deliberation; thus, leadership is taken by local actors in this process.

2.2.3. Polycentric Governance

Polycentric governance (PG) corresponds to complex systems where governance is related to different purposes, organizations and territories that jointly interact to form new systems, characterized by various decision centers at different levels [57]. According to Ostrom et al., initiators of the concept of polycentrism, this occurs when a large number of decision-making centers are formally independent from each other [58]. According to Ostrom, in a polycentric system the responsibilities at different levels of government (local, regional, national and international) are organized in such a way that they can efficiently provide public services at the local level [59]. In this sense, the main objective of PG is to effectively distribute decision-making at different levels to address water-related problems.

These different decision-making centers are composed by actors who are capable of resolving conflicts and regard each other in competitive and cooperative relationships [60]. PG distributes duties and capabilities in a way that perverse incentives and information issues at one level are counterbalanced by positive incentives and information competencies for actors at other levels [61]. This is possible through the development of nested institutions, which are norms and rules that are part of a broader system, so the local is connected to what is located on a larger scale [17]. In this sense, connection and consistency are expected outcomes for PG, since they help to achieve better responses than those observed at either highly centralized or fully decentralized structures [62].

Another characteristic of PG is that traditional and local knowledge is much more likely to be considered, since it encourages the exchange of knowledge at different spatial-temporal scales [63]. In this framework, it is important to emphasize that PG is connected to experience [64], since knowledge promotes social learning and therefore encourages trust and cooperation between actors. From this, decision-making centers are composed not only of formal bodies, but also by informal forms of organizations composed of water user groups [62,65]. In these terms, leadership in PG is more diverse than other governance perspectives, because decision-making is not concentrated in one specific group of actors and/or levels.

2.2.4. Metagovernance

Metagovernance (MG) is aimed towards the design and management of a composition of different processes related to three modes of governing: (i) hierarchical, (ii) market-based governance, and/or (iii) network-based governance, which differ in the degree of formality of institutions and actors involved and the logic of interactions between them [20,42,66]. This “governance of governance” approach [67] provides an understanding about how these governance modes relate, interact and coordinate to achieve more effective water management.

The hierarchical way of governing water is common in state structures. The fundamental idea is to preserve and strengthen public responsibility to ensure water allocation to all sectors of society [68]. This mode of governance is reliable, highly predictable and based on technocratic knowledge and the expertise of those who advise those who govern [20].

Market-based governance favors water-related decision making in a decentralized way [67]. It is based on encouraging the regulatory function of the free market through competition between the different water users, favoring resource distribution based on the greatest economic value [69]. This approach uses formal and informal rules designed to guide the economic behavior of individuals, organizations and governments [70]. Water markets belong to this mode of governance, and its proponents argue that it has been increasingly used as a strategy to deal with water scarcity, allocating water in an economically efficient way [71].

Network-based governance corresponds to the management of complex networks, which are composed of a large number of actors at local, regional and national levels, constituting political groups to civil society [66]. In this mode of governance, actors from the state, markets and civil society interact through conflict negotiations, within a framework of formal and informal rules, norms, knowledge and social imaginaries, facilitating the creation of self-regulated policies [72].

These three modes of governance have a particular way of addressing the relationship among actors. In hierarchies, formal institutions of the state take center stage and the actors involved in water resources management mostly belong to the public sector. Markets, on the other hand, give less predominance to public actors in decision-making, considering the role of the state as a protector of property rights. In network governance, civil society actors are involved in resource management decisions through informal institutions, which are generally based on traditional knowledge, transmitted orally and formed at the local level [73].

The main objective of MG is to take advantage of each of the attributes of each mode of governance, relating and applying them in a joint and coordinated manner [20]. In this sense, the relationship among actors in MG becomes complex, therefore, the figure of a meta-governor (usually state agents) takes the lead [66]. It is important to highlight that this leadership is not observed at the decision-making level, but rather at the coordination level, to achieve the expected outcome to legitimize and balance this hybridization to face specific environmental problems [66].

2.2.5. Adaptive Governance

Adaptive governance (AG) is a process that aims to create transformability [74]; this means, the capacity to create new systems (i.e., new ways of living) when economic, ecological and/or social conditions have created an unsustainable system [40]. Its premise is that, for managing a system, it is necessary to know it in depth [75]. This form of governance provides an alternative to the conventional paradigm that separates the creation of knowledge (the research) from its application (management) and, therefore, has been promoted as a necessary basis for sustainable development [76–78]. In this sense, we understand that the expected outcome of AG is to achieve sustainable societies.

AG is regarded as an ongoing problem-solving process in which institutional arrangements and ecological knowledge are verified and reviewed in a dynamic and self-organized process of learning by doing [79]. The adaptive paradigm conceptualizes WS as a term that is constantly generating new objectives according to the changing biophysical, social and institutional challenges and opportunities, regarding WS as a process rather than an end to achieve [76]. AG invites decision-makers to leave the conventional paradigm behind, moving towards new ways of acting (integrated and informed), learning (part of doing and inclusive), understanding (social learning) and working together (integrated and inclusive).

In this sense, AG encourages decision-making processes which are based on innovation to better address complex environmental problems [42].

In terms of the relationship among actors, AG also implies a broader range of stakeholders who play a role in decision-making, encouraging a form of social coordination which connects individuals, agencies and institutions at multiple organizational levels and supports flexible and learning-based approaches to water management [80]. Consequently, AG concentrate leadership on the groups of actors that provide innovative ways of managing water, however, they are challenged to provide feedback and make informed and conscious decisions [81].

3. Methods: Assessing Strengths and Failures of Each Governance Approach

Based on the features of each governance approach, we identified the main strengths and failures in order to integrate their contributions to a "good enough water governance". The analysis of each governance approach shows similitudes and differences in key elements that may contribute to the OECD water governance dimensions. The differences among their focus, leadership and expected outcomes (Table 1) highlight the interdependency that exists between the different actors that compose a river basin. From this, we understand that the association among actors and their involvement in water governance is fundamental to achieve the expected outcomes.

Table 1. Key elements of each governance approach.

Governance Perspective	Focus	Association between Actors	Leadership	Expected Outcomes
Corporate	Transparency and corporate responsibility	Interdependency	Corporation's employees and suppliers	Corporations as custodians of water
Experimental	Constant reformulation and iteration	Commitment	Diverse at the local level	Active participation and deliberation
Polycentric	Decision-making distribution	Interdependency	Diverse at multiple scales	Distributed, connected and consistent governance
Meta–governance	Coordinate and balance hierarchies, markets and networks	Complexity	Meta-governor (state as coordinator)	Legitimate and balanced stability among hierarchies, markets and networks
Adaptive	Adaptability and transformability	Complexity and interdependency	Innovative actor/group of actors	Sustainable societies

Strengths observed in different governance approaches can mean opportunities for achieving a "good enough water governance" that advances towards WS; however, they could present some weaknesses resulting in governance failures, defined as "the ineffectiveness of governance goals, a governance framework or the management thereof, to achieve policy goals" [82]. Specifically, for WS, a governance failure occurs when the institutional dimensions in water management and decision-making do not effectively consider the needs of all actors (especially the most vulnerable), encompassing administrative economic and public policy dimensions [83]. Taking this into consideration, governance fails when it does not consider different perspectives in a decision-making process that involves institutional and organizational aspects, which are reflected through mechanisms and policies related to water management. Thus, coordination at multiple levels must be considered.

4. Results and Discussion

Figure 1 illustrates the analyzed approaches and their relationship to the concept of "good enough water governance", which is embodied by the three water governance dimensions proposed by the OECD [19]. In this figure, the colored areas represent the strengths that help each governance theory to contribute to the achievement of these dimensions, while the white areas represent those dimensions that are not covered by each governance approach, due to potential failures. These approaches can be adequately integrated if they are combined to overcome the challenges of its exclusive application.

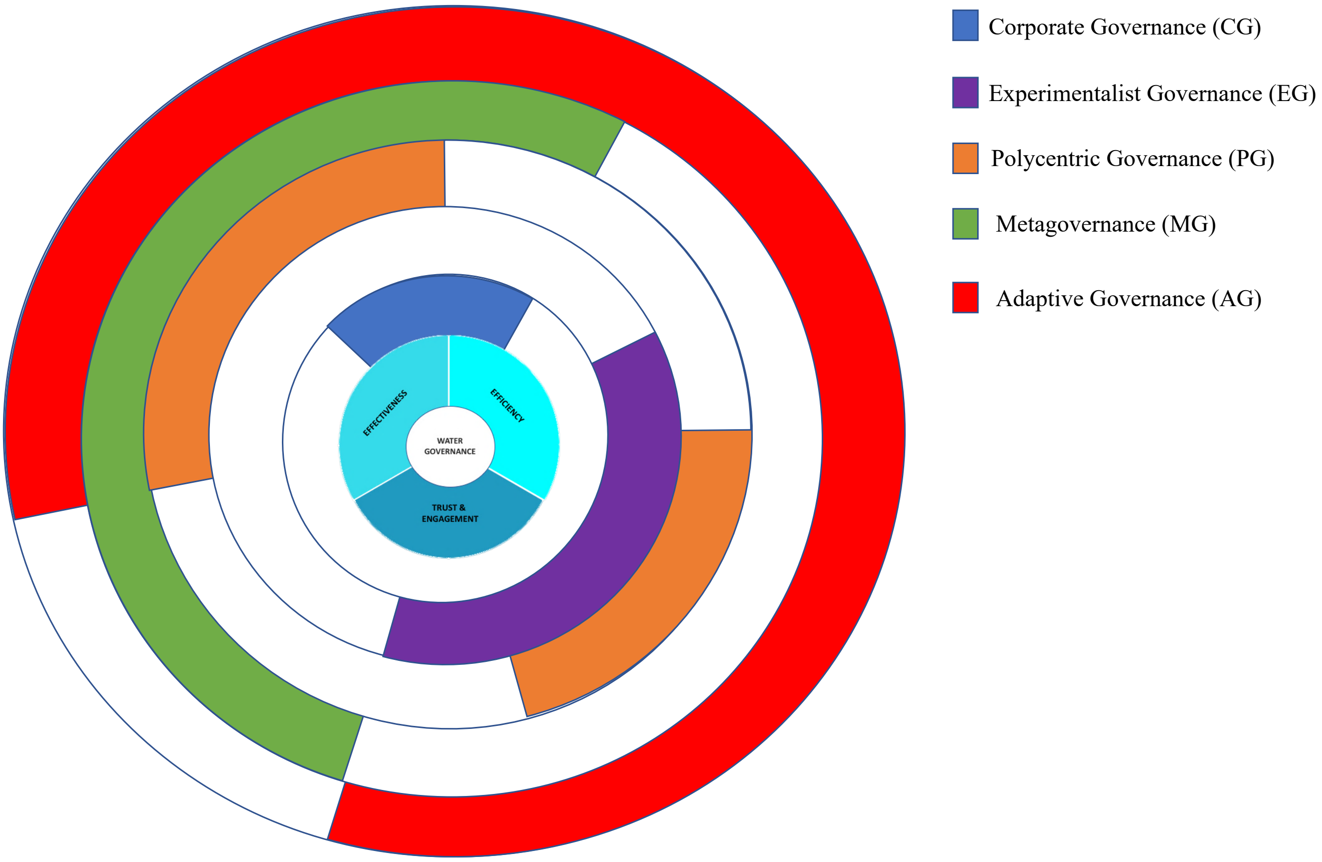

Figure 1. Water governance has different approaches on three dimensions proposed by the OECD, which can be adequately integrated if they are combined to overcome the challenges of its exclusive application. Source: Adapted from the OECD [19].

Figure 1 shows the relationship among the five governance approaches. The blue area represents CG, whose main objective is to create a regulatory and operational framework, so that companies, owners and regulators are more transparent, accountable and efficient in the decision-making processes. The main strengths of CG include the relationship between a company, its shareholders and society, as well as the promotion of fairness, transparency and accountability, the use of mechanisms to "govern" managers and the guarantee that the interests of key stakeholder groups are considered with the actions taken by the company [84]. Furthermore, the opportunity to engage companies in CG includes the consideration of issues about the regulatory environment, appropriate risk management measures and the responsibility of the senior manager and the board of directors [85].

A condition that occurs in corporate governance systems is that ownership and control are separated: the former lies with distant and diffuse shareholders, while the latter is exercised by hired managers [86]. This could mean a strength in terms of enabling economies of scale when large firms are functioning and the hiring of talented and highly qualified managers; however, this separation could enhance problems such as incentive misalignment, managers following self-serving behaviors and concentration of power in managers who lack the necessary knowledge to perform in changing environments [87].

This governance failure could be particularly important when CG seeks to safeguard accountability and respond to WS problems.

Another issue in CG is related to privatization of water and sanitation services, which are essential for other actors in the river basin, who act as customers/clients. Taking into consideration that the most economically efficient solution is not necessarily the most ethical one, company's activities must consider political economy and equity factors to deliver socially desirable outcomes in water management [85,88,89]. In this sense, CG could be appropriate in river basins that have an institutional framework in which the state plays an active role as regulator [89].

CG could be a good alternative to achieve effectiveness and efficiency. In relation to effectiveness, the clear allocation and coordination across responsible authorities and the clear distinguishing of roles and responsibilities can be observed if companies' activities are regulated by the state and take responsibilities as custodians of water. In terms of efficiency, companies usually have financial resources to update and share water-related data and information to guide, assess and improve water policy. However, some of its governance failures do not allow effectiveness to be completely addressed, in relation to achieving cross-sectoral coordination between environmental policies, other sectors (i.e., agriculture, energy, health) and the corporation's activities, and in relation to achieving the capacity to meet complex water challenges that need other actors' involvement. In terms of efficiency, CG could fail to ensure that regulatory frameworks are implemented and enforced in pursuit of the public interest, and it is not forced to adopt innovative water practices. The practice of CG sometimes becomes an obstacle to addressing trust and engagement, when CG does not involve the needs of local actors that do not perform as clients/customers. The lack of capacity to address the latter two dimensions can be solved if it is complemented by EG (purple area), since it promotes innovative practices and the active involvement of local actors in water management.

The main strength of EG is its deliberation. It promotes openness to reconsider settled practices and use the experiences of actors and their reactions to current problems to generate novel possibilities for solutions [53]. This attribute is suitable for dealing with the complexity and uncertainty of climate change effects, because it takes into consideration the local social–ecological conditions of the river basin and can adapt faster than other governance regimes. Other advantages of EG are: it provides space for diversity by adapting common goals to varied local contexts instead of imposing a one-size-fits-all solution; it creates a system for coordinated learning from local experimentation, comparing different approaches to advance to the same outcome; the provisional character of the goals and the means for achieving them are revised by experience, thus problems identified in one phase of implementation can be amended in the next iteration [90].

A failure in EG could appear when actors' interests become too diverse to promote the common interest, thus additional incentives are needed to engage these actors in collective problem solving [91]. In this sense, the transformative attribute of EG depends on other forms of governance (i.e., hierarchies) to be effective [91]. In this case, as we explain below, the hierarchical component and the coordination attributes of MG provide a good alternative to support EG.

In relation to the OECD water governance dimensions, EG could be a good alternative to achieve efficiency, trust and engagement. In terms of efficiency, EG could promote the obtention of policy-relevant water-related data and information to guide, assess and improve water policy; in addition, due to its experimental approaches, it helps to promote the adoption of innovative water governance practices. In terms of trust and engagement, due to its deliberative process, it could take local actors' opinions into consideration to promote stakeholder engagement in water policy design and implementation and promote regular monitoring and evaluation where appropriate, and to share results and make adjustments where needed. However, the diversity of actors' interests does not allow EG to address effectiveness, since it becomes an obstacle to clearly allocate and distinguish roles and responsibilities, and to foster cross-sectoral coordination and thus adapt the level of capacity to respond to complex water challenges. Also, EG cannot be completely efficient, because the possible lack of coordination could create regulatory frameworks that do not represent the public interest. This affects the capacity to overcome trade-offs across water users, so EG cannot entirely address trust and engagement. In spite of these issues, the lack of effectiveness can be solved if EG is complemented with PG (orange area), since it promotes coherence and soundness.

The main objective of PG is to distribute decision-making. The main strengths of PG are the promotion of structures where actors can innovate through experimentation and learning, and the distribution of decision-making authority reduces costs of enforcing rules by reaching legitimacy at local levels of governance [62]. In addition, PG's structures promote collaboration among policy stakeholders and equitably distribute the resources generated by policy interactions [92]. Bringing autonomy in decision-making at the local level can enhance reciprocity and voluntary cooperation and reduce failures in the implementation of rules and norms, compared to the high cost associated with the use of command-and-control mechanisms [60]. This autonomy can strengthen the sense of self-determination, and thus generate motivation to cooperate with the decisions made [93].

Besides their attributes, PG has some associated failures, such as high transaction costs related to coordination, especially in larger or geographically dispersed systems [94]. Another governance failure that could emerge is the dispersion of responsibilities, which can be challenging in terms of holding decision-makers accountable for their performance [94]. Meuleman describes some cases where dialogues culminate in never-ending talks without results, and where there were too many demands from quite a small group of participants [82]. Pahl-Wostl et al. state that problems of accountability may arise in complex polycentric systems when rules do not match with the decentralized decision-making processes [36].

In relation to the OECD water governance dimensions, PG can help to achieve effectiveness, efficiency and trust and engagement; in terms of effectiveness, due to the promotion of nested institutions and collaboration, PG brings coherence through cross-sectorial coordination among different users. PG's mutual monitoring and learning mechanisms [95] allow adaptation of the level of capacity to complex water challenges. In this sense, as we mentioned above, PG's coherence could help to avoid EG failures, because it helps to reach a common understanding of challenges and opportunities across national, regional and local levels, valuing different local experiences. In terms of efficiency, PG ensures that water management regulatory frameworks are effectively implemented in pursuit of the public interest, and in terms of creating trust and engagement, PG promotes stakeholder engagement in water policy design and implementation.

However, PG cannot be completely effective, because it could present failures related to the distinguishment of clear roles and responsibility for policy implementation, due to the numerous decision-making centers and the dispersed responsibility. In terms of efficiency, the characteristics of PG do not ensure the production and updating of relevant water data or the implementation of innovative water practices. However, these could be easily implemented if PG governance structures followed the iterative cycle of EG (identify problem—set broad goals—locals implement—report and peer review—revision of goals) and the continuous focus on monitoring. In terms of trust and engagement, the excessive dispersion of roles and responsibilities and potential accountability problems can be a problem to encourage water governance frameworks that help manage trade-offs among users. In this sense, MG (green area), through the adequate combination of hierarchies, markets and networks, could promote the reduction of trade-offs, as is explained below.

The hybridization attribute of MG allows each governance mode to be taken advantage of. Hierarchies are sometimes used to solve conflicts that require immediate actions and networks can develop more solutions to the same problem, while markets have been used to encourage civil society's involvement [66]. Investing in network-based governance has also been considered for creating trust of different actors, to increase the acceptability of hierarchical interventions when crises have arisen [72]. Also, a hierarchical intervention has been promoted when "never-ending talks" have occurred in network processes, and a network intervention has been used when a solution to a problem has not been broadly accepted through a hierarchical process [66,82]. In this sense, MG promotes democratic, participatory and context-specific decision-making through the coordination of collective action in water resource management.

MG can have some failures related to the inefficiency of efforts to combine hierarchical, network and market governance. The underlying culture influences the feasibility of certain forms of hybridization. For instance, in a consensus society, it is very difficult to implement a hierarchical mode of governance [66]. At the sectoral level, every policy division may have its own preferred governance mode, obstructing its coordination. For instance, a ministry of economic affairs may prefer a market-based governance style, while a ministry of environment may have an inclination for a hierarchical style (norms, command-and-control mechanisms, standards). From this, metagovernors have to be informed about the history, current dynamics, possible futures of a decision-making process, organizational characteristics and the type of policy problem [66]. This means that metagovernors have to be reflexive, understanding that knowing about a system could help them to adapt to constant changes and, therefore, combine and switch governance modes in a flexible way.

In relation to the OECD water governance dimensions, MG encourages effectiveness, efficiency and trust and engagement. In terms of effectiveness, MG promotes the clear allocation and distinguishment of roles and responsibilities for water policymaking and coordination across responsible authorities, policy coherence through cross-sectoral coordination among different users and adjusts the level of capacity to address complex water challenges. In terms of efficiency, the role of the metagovernor in MG seeks to ensure that water management regulatory frameworks are effectively implemented in pursuit of the public interest. In terms of trust and engagement, through a suitable hybridization of hierarches, markets and networks, MG tends to encourage governance frameworks that help manage trade-offs among users, areas and generations. However, the main goal of MG is to coordinate and balance hierarchies, markets and networks, therefore, in terms of efficiency, the production and update of water relevant data and the use of innovative water governance practices do not seem to be a priority. Governance failures could impede MG's complete achievement of trust and engagement, because of the potential difficulty to, for instance, engage stakeholders that used to organize in networks and do not accept hierarchical organizations or market-based instruments to solve a particular problem. Trust and engagement also relate to the promotion of regular monitoring and evaluation of water policy and governance, and MG could achieve it through the support of the innovative and flexible characteristics of AG (red area). AG could help MG in its decision-making process to react effectively to the social–ecological characteristics of the changing environment, achieving efficiency and trust and engagement.

In AG, decision makers develop the capacity to confront the high variability of uncertainty, which is characteristic of complex social–ecological systems [96]. AG systems self-organize as network structures that connect stakeholders at multiple organizational levels, where key persons have leadership, trust, vision and meaning and create a learning environment where knowledge and experiences develop a common understanding in decision making [79].

AG is focused on experiential and experimental social learning, as well as collaboration, which is inclusive and observed at horizontal and vertical levels. Both features are necessary to understand and respond to complex social–ecological systems. This is possible through the development of innovative institutional arrangements and incentives across diverse scales of space and time, monitoring and assessment interventions and opportunities to link science and policy [97]. In this sense, AG encompasses the innovation attributes of EG.

It is important to mention some similarities among AG and PG and the network-based governance mode in MG. PG systems are regarded as complex adaptive systems with emergent, self-organizing properties [61], which is coincident to some statements about

AG relying on polycentric institutional arrangements operating at multiple scales [65,93]. Additionally, AG and polycentricity are supported by network structures [80,94] and AG has been considered as a variation of the network-based governance mode in MG [82]. In this sense, AG relies on PG and network structures to achieve sustainable societies, and, in turn, assists PG to adopt innovative water governance practices and regular monitoring and evaluation.

AG is the governance perspective that most encompasses the OECD water governance dimensions. It addresses effectiveness in terms of policy coherence through cross-sectoral co-ordination among different users and adapting the level of capacity to complex water challenges. It addresses efficiency in terms of produce, update and share policy-relevant water-related data as information to guide, assess and improve water policy, ensuring that water management regulatory frameworks are effectively implemented in pursuit of the public interest and promoting the adoption and implementation of innovative water governance practices. It addresses trust and engagement in terms that promote stakeholder engagement in water policy design and implementation and promote regular monitoring and evaluation where appropriate, to share results and make adjustments where needed.

Although AG has major attributes to be regarded as a "good enough water governance", some critiques have arisen in terms of operationalizing the theory. AG is regarded as a process that is often neither very precise nor stable and does not give clear guidance on follow-up actions [98]. Some scholars state that AG should go beyond understanding how things are, to focus on understanding how things ought to be, since it lacks the use of repeated patterns that could help to understand how governance can stop failing [99]. In addition, it is not very clear whether AG could address unequal power relations underpinning governance structures and coordination of institutions [98]. In this sense, the coordination attributes of MG could be a complement of AG to achieve a clear distinguishment of roles and responsibilities for water policymaking and coordination across responsible authorities, and to encourage governance frameworks that help manage trade-offs among users, areas and generations. Therefore, if AG is complemented with MG in this way, it is possible to completely achieve effectiveness, efficiency and trust and engagement.

Taking all of the above into consideration, it is important to highlight the contribution that each governance theory can provide towards WS in a river basin. AG and EG are adequate to respond effectively and generate resilience towards uncertainty, mitigating climate change effects through innovation. Polycentrism shows us the importance of informal institutions that have been created through local knowledge, which is suitable for water management at the river basin scale, and which are generally invisible due to the predominance of formal institutions, which are generally acting at the macro level. MG expresses that a good coordination of different modes of governing water can generate adequate responses to specific problems. On the other hand, CG promotes that large corporations (that generally consume more water) take a more active role in the conservation of ecosystem services.

Taking this into consideration, depending on their social-ecological characteristics, there are problems that could be solved using a combination of two or three governance perspectives, while others would need to use a combination of the five governance perspectives that we show in this paper (Figure 2).

Figure 2 illustrates two possible combinations of governance approaches aimed at addressing specific WS issues. For instance, a river basin where corporations are the major users could need a CG to promote their involvement in water management and act as custodians of water. CG, in this case, can be complemented with an EG that promotes innovative practices in corporative stewardship as well as, in the case of corporation that perform at the national and international levels, the inclusions of local perspectives (Figure 2a). On the other hand, complex problems that need adaptation and transformation in accordance with the changing environment need an AG approach that promotes polycentric structures coordinated by a metagovernor that has enough knowledge to hybridize different governance modes to be flexible and to adapt (Figure 2b).

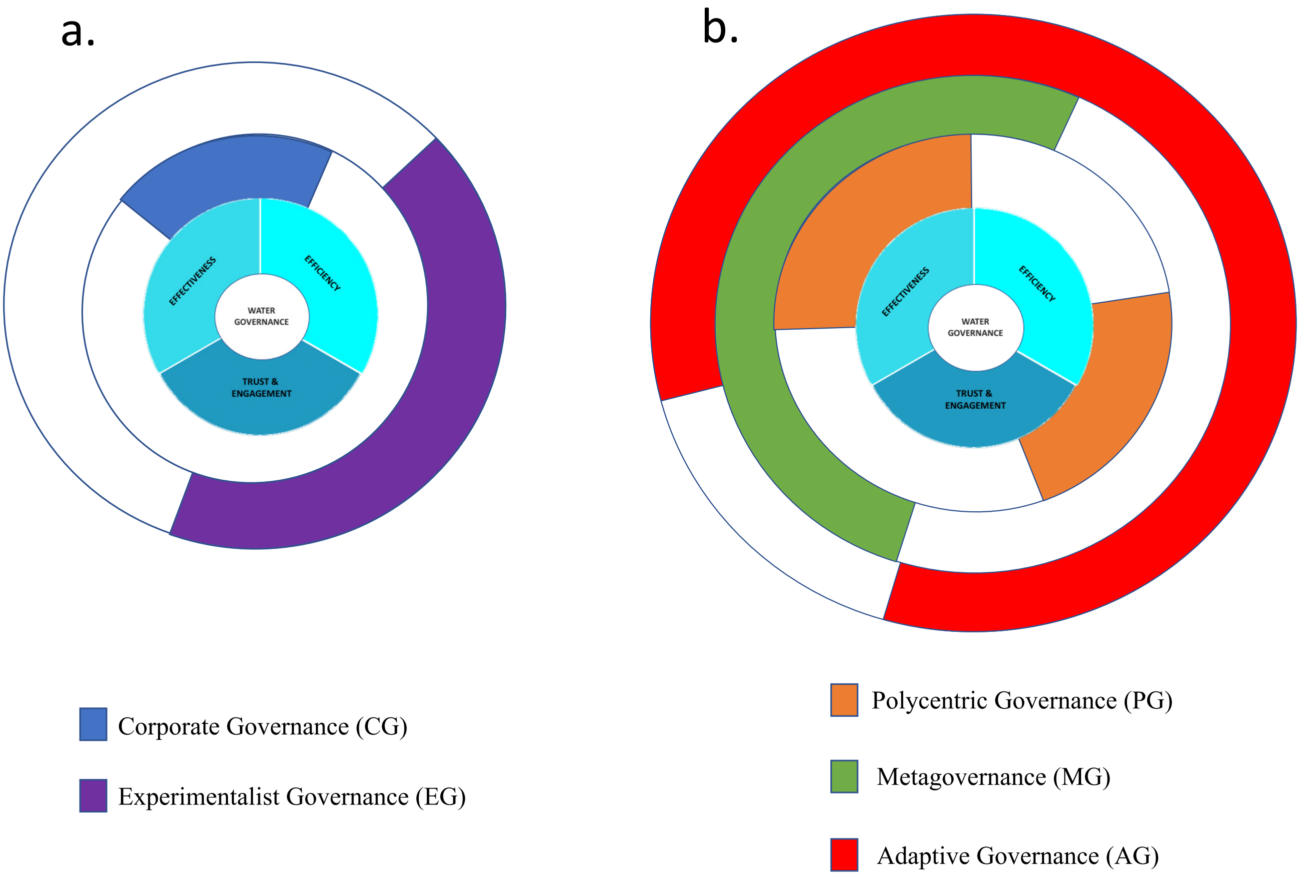

Figure 2. Two possible combinations of governance approaches to address specific WS issues. (**a**) combination of CG and EG; (**b**) combination of PG, MG and AG. Source: adapted from the OECD [19].

5. Conclusions

To advance towards water security, IRBM must recognize the multiple interconnections and associations that exist between ecological and socioeconomic systems. This should be determined by a process of sustainable and multi-scaling governance, which considers freshwater ecosystems as complex social–ecological systems and has varied responses to change and uncertainty, and where power and responsibility must be shared between water resource users and government entities in order to achieve more collaborative and coordinated actions that can better adapt to uncertainty.

In this study we observed that a combination between MG and AG could encompass the OECD water governance dimensions, complementing each other to improve strengths and to overcome failures. In this sense, an integration of these governance theories can achieve "good enough water governance", in terms of understanding it as a process and a means to operatize IRBM and advance towards WS. However, although CG, EG and PG do not encompass the three water governance dimensions, their combined application could be considered according to the problem to be solved (i.e., to achieve companies' engagement, perform local innovative practices, etc.). This integration must be dynamic, understanding that it will not necessarily work for all realities, so it is important for decision-makers to consider the context-specific ecological and socioeconomic characteristics of each territory.

There is still no consensus regarding a good water governance; however, we highlight that we can achieve a "good enough water governance" system, focusing on the process and integrating different governance approaches that have been proposed over time, which differ in their objectives, interaction between actors involved and how power and responsibility are distributed between them. For a "good enough water governance" process to exist, more instances must be generated for debate and participation, to include these different perspectives in a decision-making process that responds adequately to the social–ecological context. We invite decision makers at the national, regional and local levels to review the different proposals that exist to govern water, and to consider that focusing on one sole approach could generate water insecurity situations related to the minimal observation capacity offered by a small number of actors.

Author Contributions: Conceptualization, N.J., R.F. and R.D.P.O.; investigation, N.J.; resources, N.J., R.F. and R.D.P.O.; writing—original draft preparation, N.J.; writing—review and editing, N.J., R.F. and R.D.P.O.; supervision, R.F. and R.D.P.O.; project administration, N.J.; funding acquisition, R.F. and R.D.P.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ANID/FONDAP/15130015, and ANID PIA/BASAL FB0002.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the support given by the Doctoral Programme of Environmental Sciences, Continental Aquatic Systems, Universidad de Concepción and project PATSER/ANID/R20F0002.

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

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A Novel Method to Assess the Impact of a Government's Water Strategy on Research: A Case Study of Azraq Basin, Jordan

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Citation: Alqadi, M.; Al Dwairi, A.; Dehnavi, S.; Margane, A.; Al Raggad, M.; Al Wreikat, M.; Chiogna, G. A Novel Method to Assess the Impact of a Government's Water Strategy on Research: A Case Study of Azraq Basin, Jordan. *Water* **2021**, *13*, 2138. https://doi.org/10.3390/w13152138

Academic Editors: Fernando António Leal Pacheco, Luís Filipe Sanches Fernandes and Athanasios Loukas

Received: 4 May 2021
Accepted: 28 July 2021
Published: 3 August 2021

Abstract: Water scarcity drives governments in arid and semi-arid regions to promote strategies for improving water use efficiency. Water-related research generally also plays an important role in the same countries and for the same reason. However, it remains unclear how to link the implementation of new government strategies and water-related research. This article's principal objective is to present a novel approach that defines water-related research gaps from the point of view of a government strategy. The proposed methodology is based on an extensive literature review, followed by a systematic evaluation of the topics covered both in grey and peer-reviewed literature. Finally, we assess if and how the different literature sources contribute to the goals of the water strategy. The methodology was tested by investigating the impact of the water strategy of Jordan's government (2008–2022) on the research conducted in the Azraq Basin, considering 99 grey and peer-reviewed documents. The results showed an increase in the number of water-related research documents from 37 published between 1985 and 2007 to 62 published between 2008 and 2018. This increase should not, however, be seen as a positive impact of increased research activity from the development of Jordan's water strategy. In fact, the increase in water-related research activity matches the increasing trend in research production in Jordan generally. Moreover, the results showed that only about 80% of the documents align with the goals identified in the water strategy. In addition, the distribution of the documents among the different goals of the strategy is heterogeneous; hence, research gaps can be identified, i.e., goals of the water-strategy that are not addressed by any of the documents sourced. To foster innovative and demand-based research in the future, a matrix was developed that linked basin-specific research focus areas (RFAs) with the MWI strategy topics. In doing so, the goals that are not covered by a particular RFA are highlighted. This analysis can inspire researchers to develop and apply new topics in the Azraq Basin to address the research gaps and strengthen the connection between the RFAs and the strategy topics and goals. Moreover, the application of the proposed methodology can motivate future research to become demand-driven, innovative, and contribute to solving societal challenges.

Keywords: research gap; water strategy; Azraq Basin; water management; water governance

1. Introduction

Water scarcity is a severe problem for Jordan [1–3] and undermines the country's societal and economic development [4]. Research in the water sector is important and necessary. Essential investments in water-related research have been made using internal funding and international aid [5]. Although collaboration between academia and decision-makers at different levels, from governmental institutions through to water works and private stakeholders owing water rights, offer multiple benefits for both [6], the impacts of new water-related policies on research outcomes and vice versa remains unclear.

Academia could provide policymakers and practitioners with evidence-based knowledge from the research findings that directly feed the decision-making process [7]. Even if some research findings do not directly contribute to the decision-making process, those findings can indirectly affect policy development and practitioners' actions [8]. Therefore, decision-makers are advised to use evidence in making policy decisions [9,10] and should consider research findings in the policy development process [11].

Although there is a growing emphasis on research-based policy decisions, such as "research utilization", "knowledge transfer", "knowledge brokering", and "evidence-based policy" [12], factors such as financial constraints, shifting timescales, and decision makers' experiential knowledge may reduce the direct influence of research evidence on decision making [13]. In this work, the aim is to present a methodology based on an extensive literature review and analysis to evaluate the impact of the Jordan's water strategy (2008–2022), developed by the Ministry of Water and Irrigation, on research production. The water strategy contains a set of goals to achieve a better management of the kingdom's water resources to achieve the vision of the ministry in 2022. In particular, the focus is on the identification of research gaps that have not been accounted for during the period of implementation of the strategy.

One of the aims of conducting and publishing this research is to identify research gaps and propose ways to advance and harness knowledge in order to fill these gaps [14]. The definition of a research gap is context-dependent and can differ from topic to topic [15]. In general, Robinson et al. [16] refer to a research gap as "When the ability of the systematic reviewer to draw conclusions is limited" [16] (p. 1). Accordingly, a research gap is deemed to be a missing body of information, information that is needed to address a specific and pressing research question [17]. Understanding the nature of research gaps and their origin is regarded as the most critical step in producing good-quality research [18].

Moreover, while substantial methodological guidance already exists to identify the scope, conceptualization, analysis, and further synthesis of a "systematic literature review", a methodology to identify research gaps from these systematic reviews is still a matter of debate [18,19]. Based on the works of Müller-Bloch and Kranz [17] and Robinson et al. [16], Miles [18] identified seven types of literature gaps, namely: (1) evidence gaps arise when new-found research contradicts the conclusions of the previous study; hence, a need to collect more evidence to arrive at a concise conclusion; (2) knowledge gaps indicate the lack of knowledge (e.g., theories, methodologies) in a particular field or the delivery of some unexpected results from studies; (3) practical-knowledge gaps convey the need for new research when there is a difference between actual professional practices and research findings on a specific topic; (4) methodological gaps explore the conflict that may arise between research methods, the effects of research methods on research results, and the lack of research methods for a specific study area; (5) empirical gaps arise when a particular study area or topic has not been previously explored empirically in past research; (6) theoretical gaps explore the conflict that may arise when a certain topic is explored with a single theory or when one theory becomes superior to other theories; and (7) population gaps arise when a certain group of the population categorized based on race, ethnicity, economical status, etc. is underrepresented in the research.

Our work aims to present a comprehensive methodology for defining and identifying water-related research gaps, which can support demand-driven research, inspire new research topics to transform future research to become imaginative and innovative, and help the government to achieve the goals set within its strategy. Furthermore, the methodology developed helps to show the heterogeneous impact of the governmental strategy on various research focus areas (RFAs) and highlights the scientific fields contributing the most to the governmental strategy. The methodology was developed to evaluate the impact of Jordan's water strategy [20] on research involving the Azraq Basin (specifically) but can be applied to evaluate any context of impacts between government and academia.

2. Study Area

A total of twelve river basins exist in Jordan [21]. The Azraq Basin is located in the north-eastern region of Jordan and covers approximately 12,700 km^2; about 94% of the basin lies in Jordan, while about 5% and 1% are in Syria and Saudi Arabia, respectively. The basin is the second-largest basin in size and the second most exploited after the Amman-Zarqa basin [21,22]. Topographically, the basin is located within the highland region in Jordan, where the elevation ranges from 490 m above sea level in the Azraq Mudflat area, in the center of the basin, to more than 1300 m above sea level on Jabal Druze area in Syria (Figure 1). Jabal Druze is considered the main recharge area of basalt aquifer [23–26]. The Azraq Basin climate is arid to semi-arid, with a dry and hot season extending from May to September, with a wet and cold season extends from October to April [27–29]. The primary water resource of the basin is categorized as renewable groundwater sources [21], and its importance is threefold: Firstly, besides supplying the Azraq area, the basin provides drinking water for major urban areas in Jordan, mainly Amman and Zarqa cities, [30–33]. Secondly, it provides water for agricultural activities surrounding the basin area [21,34–36]. Finally, the basin's ecological importance is manifested through the Azraq wetland, a prosperous provider of ecosystem services in the area, which has deteriorated over time due to over-pumping of groundwater resources [37,38].

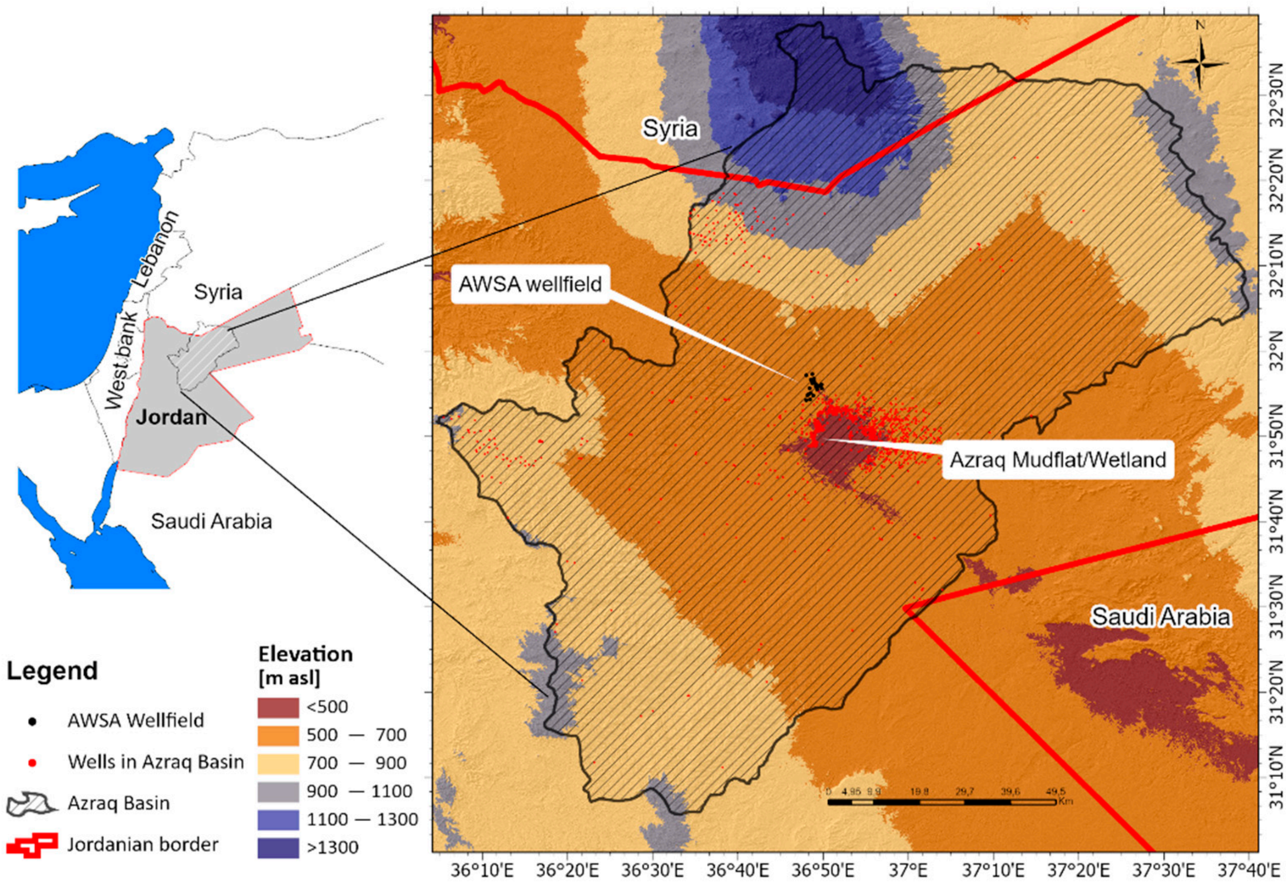


Figure 1. The elevation and extension of the Azraq Basin (the elevation unit is meters above sea level (m.a.s.l.)).

3. Methodology

3.1. Collection Process

Between December 2019 and January 2020, the research team led a one-month field research trip/excursion to Jordan. The trip/excursion consisted of 18 unstructured interviews with current and retired employees of the Jordanian Ministry of Water and Irrigation (MWI) and employees of cooperation projects between the MWI and international partners. The visit aimed to (a) understand the current archiving process of project reports in the MWI, (b) collect the final reports that were conducted under the umbrella of the MWI, and (c) propose the development of an archiving system for final reports, taking into consideration the recommendations of the MWI and international partners. We have been able to collect 2200 digital documents (e.g., final reports, report sections, letters, incomplete reports, presentations, or report drafts) present in the Ministry's record, spanning from 1963 to 2019.

In addition to the collected research from MWI, grey literature was searched online through Google searching, Scopus, Web of Science (WoS) engines, and the websites of the MWI and the MWI partners' websites (e.g., Helmholtz-Zentrum Umweltforschung GmbH (UFZ), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), United States Agency for International Development (USAID), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)). In this work, we consider only conference proceedings and final reports from the government and their partners as grey literature. Dissertations, Master's and Bachelor's theses, and posters are excluded in the review and analysis (Table 1).

Table 1. Type of literature included/excluded in this study.

Included Literature	Excluded Literature
• Technical reports by MWI (available digital copy) • Technical reports by international projects (available digital copy) • Final reports/studies	• Technical reports by MWI (only available in hard copy) • Technical reports by international projects (only available in hard copy) • Studies that are not related to Azraq Basin
• Peer-reviewed literature • Proceeding conference paper	• Studies that are included within the daily activities of the MWI employees (e.g., small study to give a license to build a specific factory)
	• Master's, Bachelor's and Ph.D. theses. • References that are cited in other documents but were not accessible.

The search for peer-reviewed publications was collected using Google Scholar (GS), Scopus, and Web of Science (WoS) search engines. The literature collection process started with GS, given that it is the most comprehensive web search engine for literature, where it contains 95% and 92% of literature that exists in WoS and Scopus, respectively [39,40]. To ensure the search remained as vast as possible, queries were used with general keywords (e.g., "Azraq Basin" OR "East* Jordan" AND "Water"). The obtained results were reviewed, and only research results related to water in the Azraq Basin were added to the literature inventory up to the year 2018; research published in and after the year 2018 was excluded. The same procedure was repeated using Scopus and WoS search engines, utilizing Publish and Perich 7 software to search and analyze academic citations [41].

3.2. Analysis Process

The MWI published the "Jordan's Water Strategy 2008–2022" report [20], aiming to ensure the availability of water for people, businesses, and nature by accomplishing a set of goals within the topics of water demand, water supply, institutional reform, water for irrigation, wastewater, and alternative water resources in the year 2022. To achieve the objective of this paper, the goals of the collected research were compared to the water strategy goals, highlighting whether or not these research goals contributed to one or more of the MWI water strategy goals (Table 2). Some of the MWI strategy goals are excluded from the analysis as they focused on a specific study area different to the Azraq Basin. For example, the MWI water strategy goal 6.b., which states, "Desalination projects at the Red Sea are operational", cannot be compared with the collected research goals because this goal targets the Red Sea; consequently, we excluded goal 6.b. from the analysis of this paper.

In the analysis process, we followed the framework that Müller-Bloch [17] introduced to identify research gaps. Research gap results were first identified by synthesizing a systematic literature review of the subject by using straightforward localization methods such as the chart method. This method organizes the reviewed literature into a chart according to the MWI strategy goals. A goal in the chart can be associated with one or more literature documents, indicating that at least one document addresses this goal, or it can be left empty, indicating a research gap. After locating a research gap, verification processes continued by double-checking if no research could be sourced to fill the gaps; finally, the goals were presented according to the number of documents that were associated with each goal. According to the classification of Miles [18], the comparison between the conducted research and the MWI goals allow the identification of a "practical-knowledge gap".

Any MWI goal that registers no contribution by the collected research is considered a research gap, and any research that contributed to the MWI strategy goals is regarded as potentially demand-driven research. To better assess the topic of demand-driven research, a comparison was conducted between the collected studies before and after the implementation of the MWI strategy, to highlight if a change in the research direction towards the MWI goals could be identified.

To study the variable impact on research involving the basin from different types of research institutions (i.e., academic, non-academic, national, and international), the peer-reviewed studies were first categorized based on the affiliations of the author. Such a procedure was only applied for peer-reviewed literature because the affiliation of each of the authors of specific grey literature is not always defined. Furthermore, the specific research focus of each study was then identified and listed according to nine main RFAs: agriculture, energy, hydrogeological field measurements, geophysics, modeling, remote sensing, socio-economy, laboratory soil sample analyses, and laboratory water sample analyses (Table 3). It is noted that the subdivision depends on the available literature, and it can vary in different catchments. The selection of the RFA is to some extent arbitrary and it is based on the main keywords and topics covered in the analyzed documents. The applied methodology, however, is not significantly affected by this choice. In fact, the key point of defining RFAs is not to identify which discipline is contributing more or less to the strategy goals, but to classify the available contribution to the goals from different communities of researchers and in terms of interdisciplinarity. Each document will have only one primary RFA and can have several secondary RFAs. The number of conducted studies were compared within each RFA before and after implementing the MWI strategy. Additionally, each RFA was categorized according to which MWI topic it targeted. A schematic diagram of the methodology we followed is shown in Figure 2.

As stated previously, the collected research did not include studies conducted after the year 2018, because the MWI published a new strategy in 2016 for the period 2016–2025, which modified the older strategy. Considering the typical time needed for writing and publishing scientific works, it was assumed that the impact of the old strategy may still have an effect on water-related research up to two years after the publication of the new strategy.

Table 2. The topics and goals of MWI strategy (2008–2022).

	1. Water demand
1.a.	Water use for agriculture shall be capped.
1.b.	Jordanians are well aware of water scarcity and the importance of conserving and protecting our limited water resources.
1.c.	The management of water resources shall duly consider the potential risks derived from Climate Change induced impacts on the water balance.
1.d.	Viable options to reduce water demand within each sector are readily available.
1.e.	Water tariffs within and outside the water sector should support water demand management
1.f.	Non-revenue water to be 25% by 2022.
	2. Water supply
2.a.	Uninterrupted safe and secure drinking water supply achieved including continuous flow in Amman. Zarqa. Irbid. and Aqaba.
2.b.	Water supply from desalination is a major source.
2.c.	Drinking water resources are protected from pollution.
2.d.	Surface water is efficiently stored and utilized.
2.e.	Treated wastewater effluent is efficiently and cost-effectively used.
2.f.	Data on the availability of water resources will be acquired via a telemetric observation network safeguarding continuous information flow. Modern information technology will provide a sound basis for the monitoring and the management of Jordan's water resources.
2.g.	Special management plans to ensure safe yield principle being applied in groundwater extraction
2.h.	The concept of utilizing greywater and rainwater is fully embedded in the codes and requirements of buildings.
2.i.	Our shared water rights are protected.
	3. Institutional reform
3.a.	National Water Law is enacted and enforced.
3.b.	Strong policy development and water resource planning strategies and capabilities forged.
3.c.	Governance functions and operational functions are separated.
3.d.	"Wholesale" operations (national infrastructure) and "retail" operations (service delivery) are separated.
3.e.	A Water Council is operational allowing for broad stakeholder input into water management
3.f.	A Water Regulatory Commission of Jordan is established.
3.g.	Commercial principles drive water management while the needs of the poor are supported
3.h.	Staff is trained. Its number is optimized. Conflicts of interests are eliminated, and a dynamic working environment is created that is responsive to the needs of the sector.
3.i.	The National Water Master Plan is institutionalized representing the binding strategic management instrument of the Water Sector as stipulated by the National Water Law.
	4. Water for irrigation
4.a.	The annual water allocation for irrigation in the Jordan Valley will be increased to 377 MCM in 2022 (293 MCM in 2007) and in the Highlands reduced to 184 MCM in 2022 (297 MCM in 2007).
4.b.	Efficient bulk water distribution as well as efficient on-farm irrigation systems are established.
4.c.	All treated wastewater generated will be used for activities that demonstrate the highest financial and social return including irrigation and other non-potable uses.
4.d.	Jordan will have one service provider for irrigation water for the whole country, whereas the retail function for irrigation water will be privatized and/or handled by empowered farmers' associations.
4.e.	Appropriate water tariffs and incentives will be introduced in order to promote water efficiency in irrigation and higher economic returns for irrigated agricultural products.
4.f.	Alternative technologies such as rainwater harvesting for enhancing irrigation water supply will be promoted.
	5. Wastewater
5.a.	All the major cities and small towns in Jordan are provided with adequate wastewater collection and treatment facilities.
5.b.	All major industries and mines have wastewater treatment plants.
5.c.	New high-rise buildings use greywater for internal non-drinking purposes.
5.d.	Public health and the environment, in particular groundwater aquifers, are protected from contaminated wastewater in the areas surrounding wastewater treatment plants.
5.e.	Treated wastewater is used for activities that provide the highest return to the economy. For irrigation use in the Jordan Valley and in the Highlands, a comprehensive risk management system is in place.
5.f.	The quality of treated wastewater from all municipal and industrial wastewater treatment plants meets national standards and is monitored regularly.
5.g.	Tariffs for wastewater collection are rationalized.
5.h.	All treatment plants are operated according to international standards and manpower is trained accordingly.
	6. Alternative water resources
6.a.	Treated wastewater will be used for the activity that provides the highest social and economic return and standards for use in agriculture will be introduced and reinforced.
6.b.	Desalination projects at the Red Sea are operational.
6.c.	Rainwater harvesting is encouraged and promoted.
6.d.	Infrastructure for desalination of sea and brackish water is sufficient.
6.e.	An alternative energy source to keep the cost of desalination as low as possible is available.

Table 3. Description of the categorization of the research focus areas (RFAs) in the collected studies.

Research Focus Area (RFA)	Included:
Agriculture	Any study related to agriculture including irrigation efficiency, crop type, farming area, abstraction amount for agriculture.
Energy	Any study related to energy including current energy costs and renewable energy production.
Hydrogeological Field Measurements	Any study related to field surveys and to field measurement campaigns (water level, water and soil parameters, land cover/use classification).
Geophysics	Any study related to the application of geophysical methods (vertical electrical sounding, transient electromagnetics, seismic refraction).
Modeling	Any study related to the application of a mathematical model (groundwater flow model, solute transport, climate, surface water model, erosion, geochemical model, decision support system, vulnerability mapping, statistical analysis).
Remote Sensing	Any study related to satellite images use and processing.
Socio-Economy	Any study related to social or/and economic aspects (income, education, employment, community development, cost of water, the degree of public satisfaction with governmental decisions, degree of awareness of water scarcity in the basin, population growth).
Laboratory Soil Sample Analyses	Any study related to collection of soil samples to conduct biological and/or chemical analysis (nutrient or contaminant), and/or to investigate the physical properties of the soil.
Laboratory Water Sample Analyses	Any study related to surface or groundwater samples to conduct chemical, biological or physical analyses.

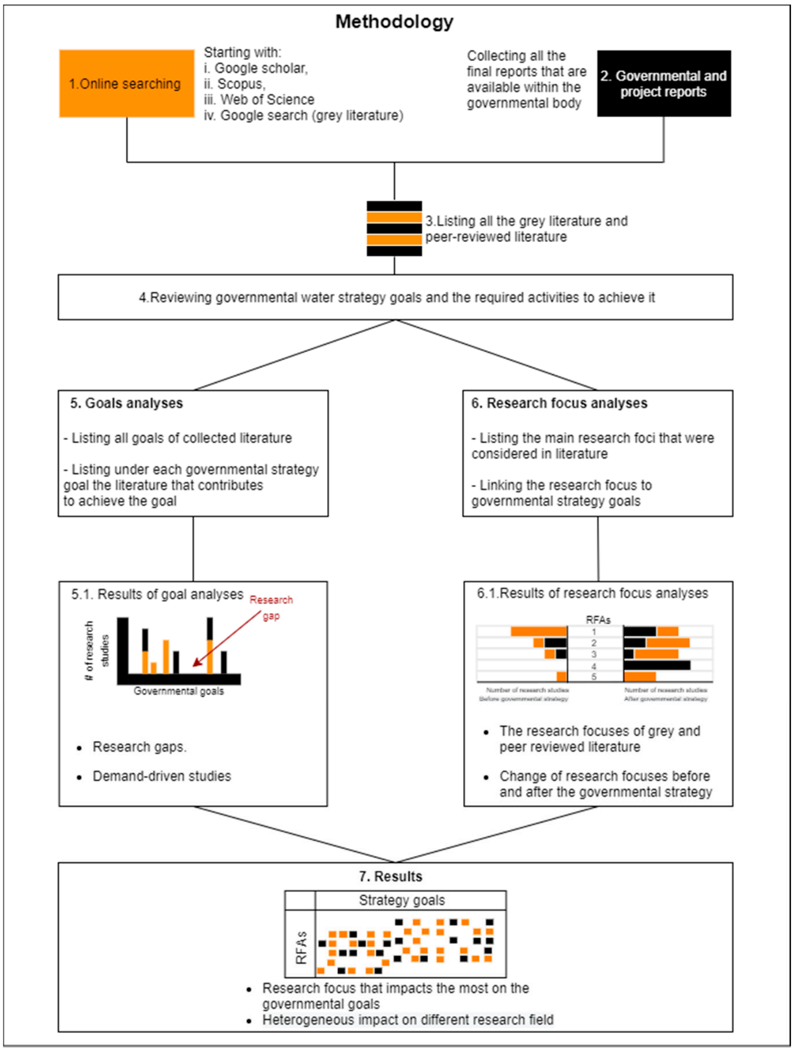


Figure 2. Schematic figure for the methodology we followed in this paper.

4. Results

4.1. Collection Process

It was noticeable that there was no systematic way for archiving project reports at the MWI. When a project is concluded within the MWI or with international partners, the final report is usually submitted to the principal employee from the MWI (focal person of the project). At times, the final reports would be submitted to more than one person. Subsequently, these submitted reports remained scattered in different departments of the institution and were not allocated to a specific storage location, system, or person. For example, to have access to a specific report, the project's focal person must be identified and contacted to retrieve a copy of the report. In some instances, the employee may have already retired, which made the retrieval process difficult.

A total of 2200 documents were collected from the MWI. From these files, 26 final reports related to water resources in the Azraq Basin were extracted. This number is not to be taken as a representation of the total number of final reports on the Azraq Basin in the MWI, given that some reports were difficult to access because they were not available as digital copies. In addition, three reports were recovered through online research, as well as nine conference proceeding articles, totaling 37 grey literature sources. During the collection process, 62 peer-reviewed articles were recovered online, encompassing the period 1980 to 2018.

Figure 3a shows that the production of research documents increased between 1985 and 2020. The oldest grey literature report included was published in 1985 by Rimawi and Udluft [42], and the oldest peer-reviewed article included in this analysis was from 1992 by El-Waheidi et al. [43]. Overall, it is observed that peer-reviewed research production in the Azraq Basin has continuously increased since 1998. However, the only exception was for the year 2011, with no research relating to the basin published. The years 2014 and 2016 evidenced the largest number of conducted research studies (both grey literature reports and peer-reviewed articles combined) with nine studies. The year 2018 had the highest number of peer-reviewed articles, with eight published articles compared to all other years since 1985. Conversely, the years 1996, 2014, and 2015 showed the highest grey literature number with four studies per year.

This result is consistent with overall research production in Jordan (Figure 3b). According to the database of Scopus, the total number of produced studies in Jordan increased from 139 to 4456 between 1985 and 2018. These studies consider all topics, including water-related topics. The percentage of studies that include the word "water" in the title, abstract, and keywords ranges between 8% and 16% over the whole period. At the same time, the number of studies that include the word "water" in the title, abstract, and keywords increased from 21 to 376. Therefore, the increasing trend in research production in the Azraq Basin follows the same upward trend of the number of studies produced in Jordan from all disciplines.

Most of the peer-reviewed publications were led by academic institutions. In 42 publications, only academic institutions contributed to the publication, while 12 publications were conducted by a combination of both academic and non-academic institutions. Conversely, nine publications were led by members from non-academic institutions, with only one of them in cooperation with an academic institution (Figure 4a). Academic international and national institutions published 11 and 43 studies, respectively. In contrast, non-academic international and national institutions published only three and six studies (Figure 4b).

4.2. Analysis Process

The analysis process categorized the documents based on their contribution to the MWI strategy goals and their research focus. The results showed that a total of 79 documents addressed at least one of the MWI strategy goals, 29 before and 50 after the water strategy; 20 documents are not aligned to the MWI strategy (8 before and 12 after the implementation of the water strategy). Additionally, the number of RFAs that were considered within each research varies between one and five focuses. Figure 5 shows a summary of the results of the conducted analysis process of peer-reviewed and grey literature.

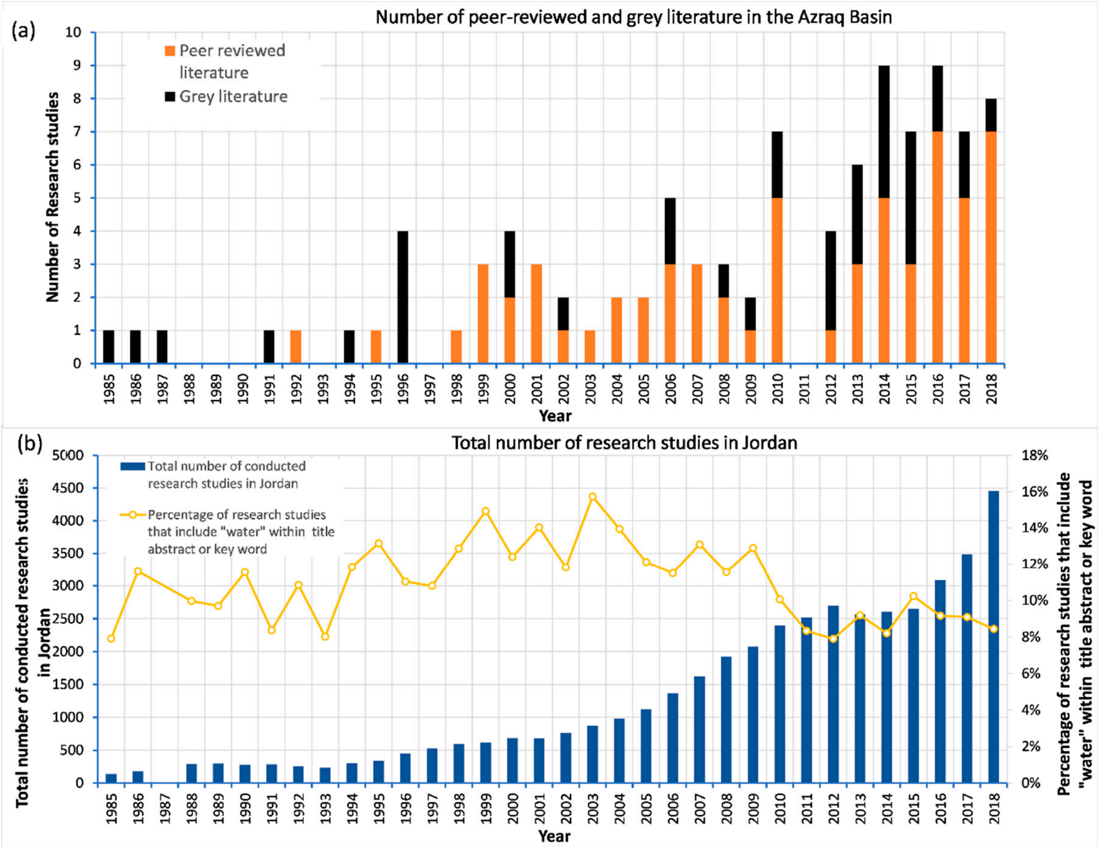
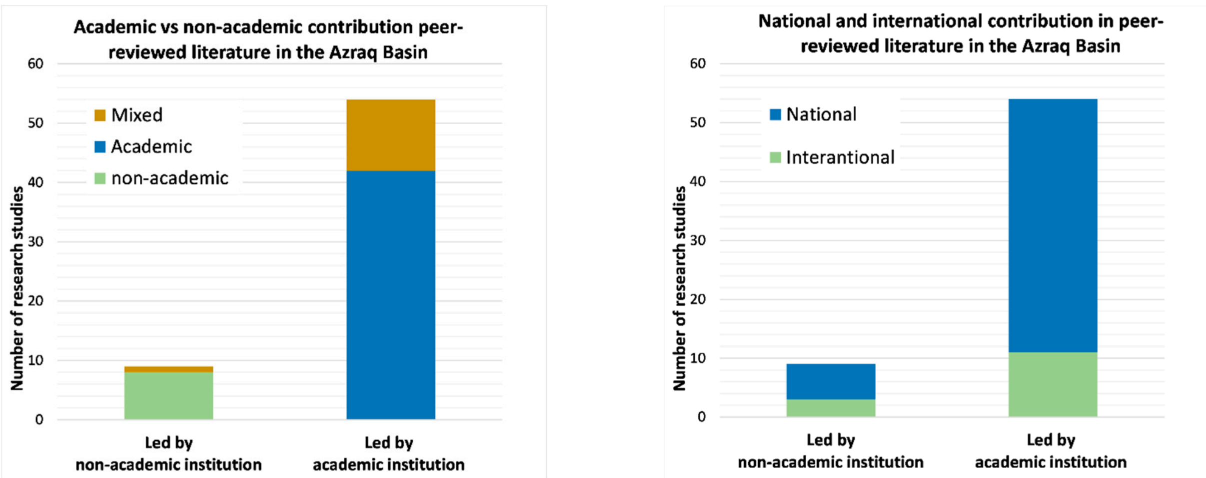


Figure 3. (**a**) Number of grey and peer-reviewed literature spanning the period (1985–2020). (**b**) Total number of documents that exist in the Scopus database produced by Jordanian institutions (blue column), percentage of number of documents stating the word "water" in the body of the document (orange line), percentage of number of documents stating the word "water" in a title, abstract or keyword of the document (grey line).



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

Figure 4. Number of peer reviewed research studies conducted by (**a**) only academic, only non-academic and combination of academic and non-academic institutions, and (**b**) national and international institutions based on the affiliation of the first author of the literature.

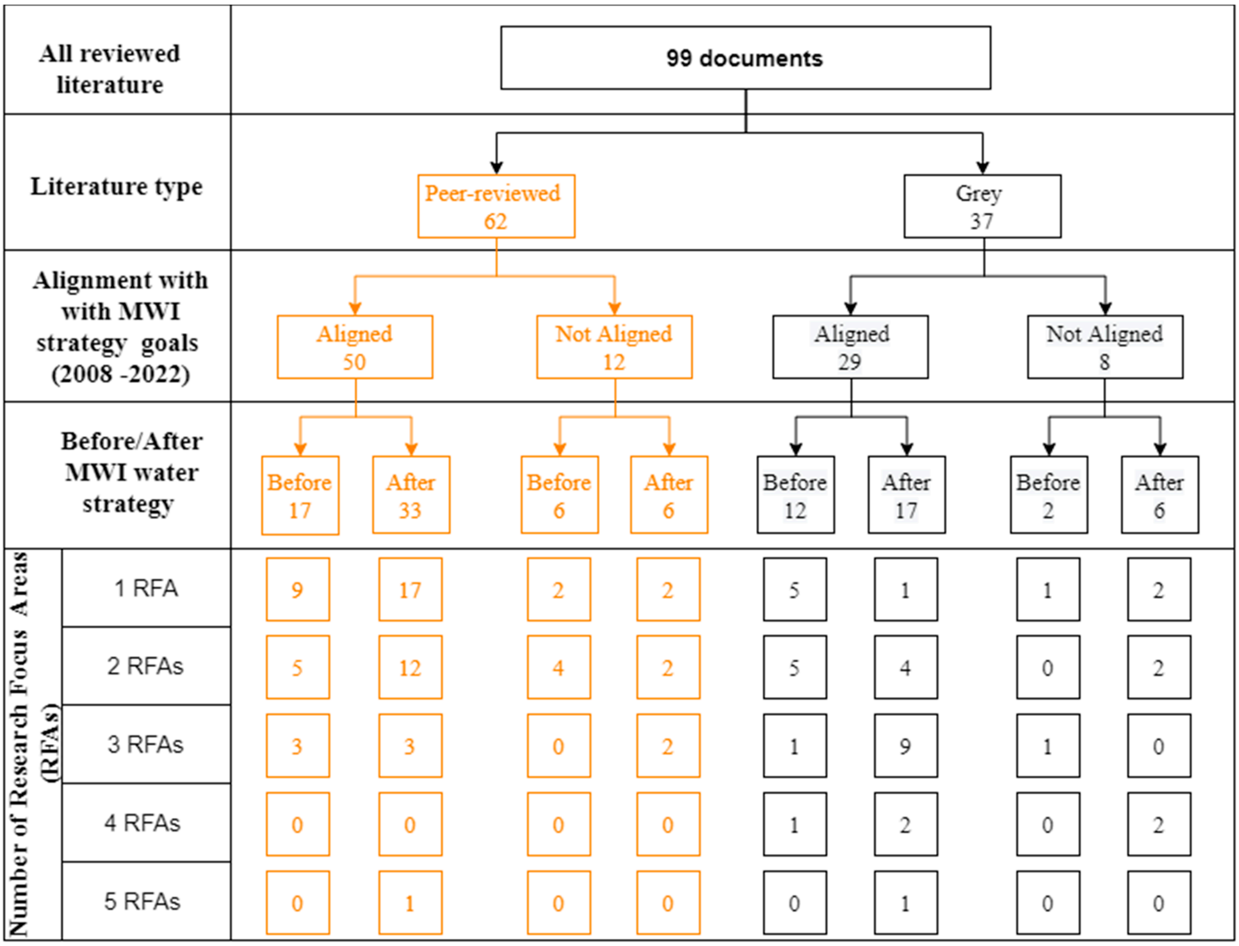


Figure 5. Summary of the results of the analysis process.

4.3. MWI Goals Analysis

The MWI strategy consists of 43 goals covering six topics (Figure 6). To define the research gaps in the Azraq Basin, the collected research goals were categorized with the MWI strategy goals (Figure 6). As stated previously, 79 studies are aligned to one or more of the MWI strategy goals. A total of 15 and 60 studies align with goals related to the two topics of water demand and supply, respectively. Water irrigation and alternative water resource goals are addressed in 13 studies and only two studies focus on goals related to wastewater.

4.3.1. Goals Related to Water Demand

The number of studies contributing to the improvement of the water demand topic recorded the second-highest number of instances after the topic of water supply. Unlike the water supply goal, each of the studies listed under the improving water demand goal contributes to only one of the goals related to water demand. However, the 15 studies focusing on water demand contributed to three of the six goals. Three studies contributed to goal 1.a., aiming to reduce the water use for agriculture in the basin. These studies investigate the options of purchasing water rights from farmers [44], introducing energy farming [45] and incentives for farmers [36], acting as a guide to the ministry in issuing legislation for these alternatives. Goal 1.b. aims to increase the awareness of people about water scarcity and the importance of conserving water resources, where five studies focus on this topic; for example, Hamberger, K. et al. [46] mapped stakeholder networks to identify the links between the main stakeholders by interviewing farmers of the basin and Al Naber, M. and Molle, F. [47] investigated the response of the farmers towards the challenges that they face and evaluated the factors that impacted the cost of the crops. Such studies may help the MWI to target the appropriate stakeholder groups who are unaware of/deny water scarcity. Al-Bakri, J. T [35], and Al-Bakri et al. [48] defined areas and the volume of illegal abstractions, and one study included the farmers in an association and conducted regular meetings that included technical and non-technical messages aiming to increase the awareness of water scarcity among farmers [49]. Goal 1.c. focuses on improving water resource management, considering the impact of climate change on the water balance. From seven studies that address this goal, three studies investigated the impact of climate change on temperature, rainfall, and runoff [32,50,51]; three studies considered the impact of climate change as an input to a groundwater model [52–54]; and one study examined droughts [55]. No study addressed the options to reduce water demand within each sector (goal 1.d.), evaluating the water tariff (goal 1.e.) or aiming to reduce the non-revenue water in the basin (goal 1.f.).

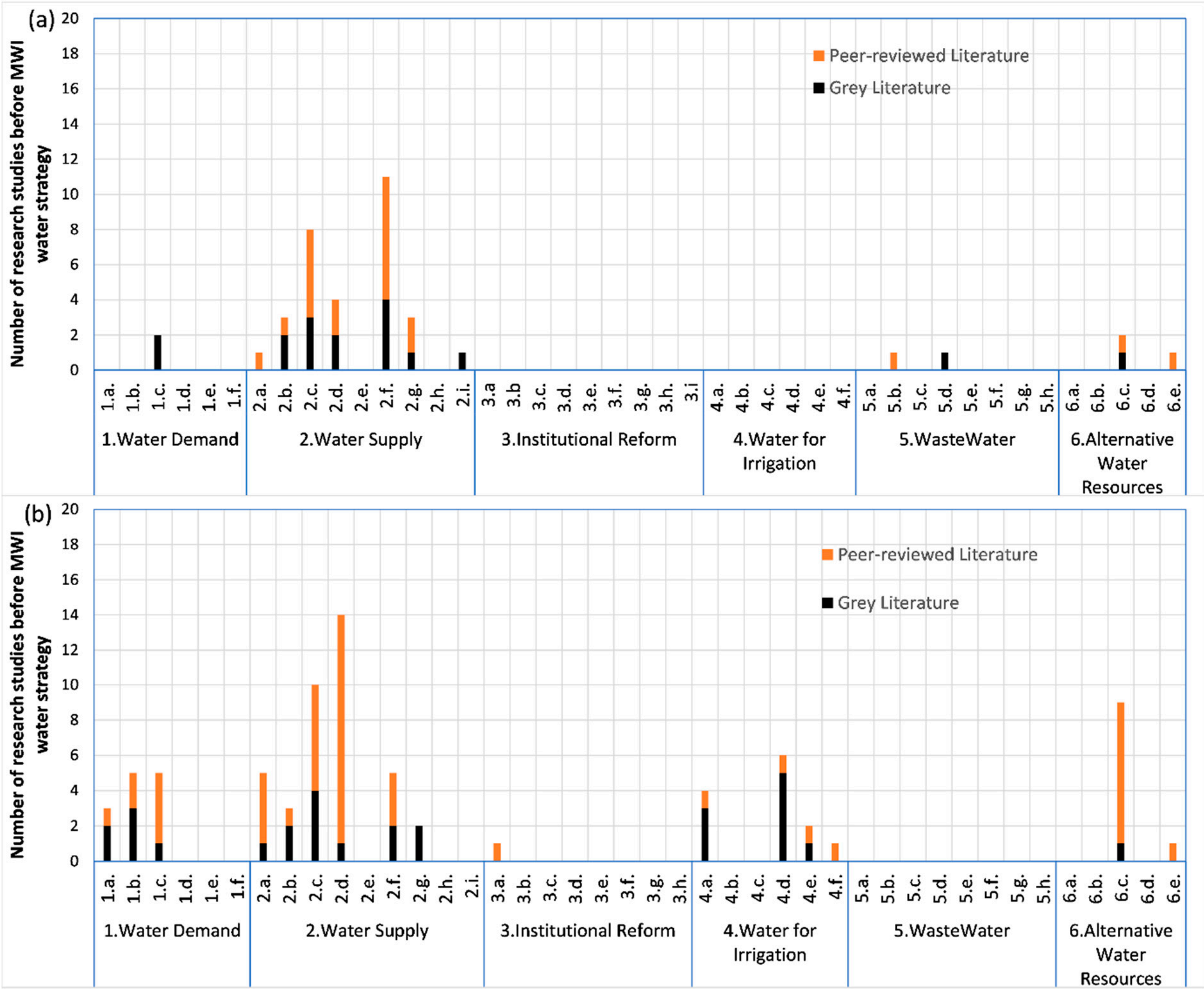


Figure 6. Number of grey and peer-reviewed studies that align with MWI water strategy goal 2008–2022 (**a**) before and (**b**) after the water strategy.

4.3.2. Goals Related to Water Supply

Approximately 60% of the references collected contribute to seven out of nine goals related to water supply; goal 2.a., which focuses on developing a secure and safe water supply in the area, is included in six studies; four focus on allocating new water sources [56–59], and two studies focus on sustainable management [52,60]. While six studies were found to be aligned with goal 2.b., which focuses on using desalinated water as a major source for water supply, four focused on saline water intrusion [43,61–63], one on hydrochemistry [42], and one on salinization scenarios [64]. Additionally, a total of 18 studies contributed to the MWI strategy goal 2.c., which focuses on protecting drinking water resources from pollution. Jasem and Alraggad [65], Al-Adamat et al. [66], and Ibrahim and Koch [67] presented a groundwater vulnerability map for the area, Gassen et al. [68] delineated the protection zones of AWSA wellfield, and the remainder contributed to this goal by investigating the quality of groundwater in AWSA wellfield area [61,62,64,69–73], in the northern region of the basin [74,75], in the southern region of the basin [76], in Qaser tuba landfill [77] and the Azraq Basin as a whole [26]. Furthermore, 18 studies contributed to goal 2.d., which focuses on improving the efficiency of storing and utilizing surface water, with 17 addressing various opportunities to utilize the surface water quantity and defining the suitable locations for managed aquifer recharge (MAR) [51,78–93]. Only Salameh et al. [94] addressed the topic of investigating the surface water quality.

Moreover, a total of 16 studies align with goal 2.f., which focuses on improving data availability and the monitoring system. Baïsset, M. et al. [73] described how to improve the data availability and monitoring system, and the remaining studies focus on assessing the availability and sustainable exploitability of water resources in the basin [23–26,29,31,52,54,64,95–99]. Only BGR/ESCWA [100] indirectly targeted goal 2.i., which focuses on the protection of shared water rights. BGR/ESCWA [100] focused on investigating the shared water resources in Jordan and Syria rather than protecting the Jordanian share rights. Contrarily, the remaining two goals related to water supply, namely: goal 2.e. "Treated wastewater effluent is efficiently and cost-effectively used." and 2.h. "the concept of utilizing greywater and rainwater is fully embedded in the codes and requirements of buildings" were neither addressed by peer-reviewed literature nor by grey literature.

4.3.3. Goals Related to Institutional Reform

Concerning goals related to institutional reform, only Leyroans [101] contended the one focusing on achieving sustainable and collective governance of groundwater resources: the Azraq Basin first needs to be recognized as a resource in "the commons" category, differentiated from being a private or public resource; second, the state needs to hold a subsidiary function that ensures the effective implementation of water management decisions made by the local population at the local level through adopting participatory methods. These recommendations mainly align with the suggested legislation to manage the issues of "traditional water rights in Jordan", aiming to balance the traditional water rights with the state's water rights moving towards achieving a national water law that is enacted and enforced (goal 3.a). The remainder of the goals were not addressed directly by the collected studies.

4.3.4. Goals Related to Water for Irrigation

According to the MWI water strategy 2008, irrigation practices in the highland region, including irrigation in the Azraq Basin, are not adequately controlled, and are categorized as exhibiting poor irrigation efficiency practices. Therefore, the MWI addressed the water irrigation topic in the strategy. The first goal 4.a. aims to reduce the annual water allocation for irrigation in the area, and a total of four studies were aligned with this goal; while GIZ [45] and Al-Tabini, R. et al. [44] analyzed the economic return of reallocation water use to sectors other than agriculture, Octavio, R. et al. [102] focused on conducting a survey to evaluate factors affecting agriculture water use, and Demilecamps, C. and Sartawi, W. [36] proposed project ideas to reduce water use in agriculture. Goal 4.d. recorded the largest number of studies contributing to the topic of water irrigation; four of the six studies focused on monitoring the abstractions in the basin, and two focused on establishing and empowering farmers' forums.

Furthermore, Al Naber, M. [47], and Molle, F. and Al-Naber, M. [103] investigated the economic returns of different crops in the basin, which aligned with goal 4.e., aiming to introduce a new tariff and incentive system to promote water efficiency in irrigation and higher economic returns for irrigated agricultural products. The promotion of methods and technology to enhance the irrigation water supply (goal 4.f.) is addressed only by Al-Zubi, J. et al. [89], who focused on water harvesting feasibility for irrigation use in the Wadi Muhweir catchment in the basin. The collected studies are neither aligned with the goal 4.b., which states, "Efficient bulk water distribution as well as efficient on-farm irrigation systems are established." nor with goal 4.c., which states that "All treated wastewater generated will be used for activities that demonstrate the highest financial and social return including irrigation and other non-potable uses.".

4.3.5. Goals Related to Wastewater

The ministry aims to expand the wastewater network in the kingdom and consequently increase the amount of treated wastewater for non-drinking purposes. Hence, eight goals were listed under the wastewater topic. However, only Baban et al. [74] addresses goal 5.b., by estimating the impacts of cesspools on groundwater in the basin under various scenarios; the estimation and analysis of these impacts will inform the MWI of future locations for implementing treatment plants, in order to minimize the threats of wastewater disposal on adjacent drinking water resources. Additionally, Al-Adamat et al. [75] targeted goal 5.d., which aims to protect the public health and environment; this study set specifications and standards procedures of septic tank usage in the Azraq Basin. The remainder of the goals related to wastewater were not addressed in any of the previous studies.

4.3.6. Goals Related to Alternative Water Resources

Given that Jordan's renewable water resources are limited [21], one of the MWI aims is to explore new water resources such as treated wastewater, greywater, and desalinated water. Therefore, the alternative water resources topic was addressed in the MWI strategy of 2008. Only two goals were addressed in the collected literature: firstly, goal 6.c., which aims to promote and encourage rainwater harvesting, where 11 studies addressed the potential of implementing rainwater harvesting in rural areas of the basin [78,80,81,84–89,91,92]. These studies differ from each other mainly in that there is primary focus on different locations of the basin. Secondly, goal 6.e., which aims to find an alternative energy resource for desalination, was found to have only two contributing studies: Sawariah [104] defined the areas with high potential for thermal water sources, and Mohsen [105] studied the feasibility of using solar energy for water desalination in the basin. The remainder of the goals in this topic were not addressed by a reference.

4.4. Research before and after the MWI Strategy

Figure 6 shows that the number of grey literature studies in alignment with the MWI strategy goals increased after the MWI water strategy implementation by 30%. A greater increase is observed in the peer-reviewed literature, where the total publications doubled during the same period. While this result may be expected considering the overall increasing trend in research production shown in Figure 3, it is noteworthy to observe that prior to the implementation of the strategy, only two studies aligned with the goals related to water demand, while this number increased to 13 studies after the implementation of the strategy. More specifically, the number of studies that align with water supply only increased from 27 studies (four of which contributed to two goals) to 33 studies (six of which contributed to two goals) before and after the MWI strategy, respectively. No study aligned with the water irrigation goals before the MWI water strategy, while 13 studies align with water irrigation goals after implementing the water strategy. Furthermore, the number of studies that align with goals related to wastewater goals reduced from two to zero before and after implementing the MWI strategy.

4.5. Research Focus Areas Analysis

The analysis showed that 60 studies of the collected studies have more than one RFA, indicating that a large part of the collected studies are interdisciplinary. In such cases, the

RFAs were categorized as either primary or secondary in nature, where the secondary area supports the primary RFA; for example, in the work of Abu Rajab and El-Naqa [63], geophysics is the study's primary RFA. However, the researchers collected and analyzed water samples to support the geophysics analysis; in this case, the laboratory water sample analyses are categorized as a secondary RFA. The following section represents a review of the collected studies categorized according to the primary RFA. Moreover, a complete overview is given in Appendix A.

About 35% of the collected documents focused on modeling in terms of: (a) estimating the recharge rate [50,106], (b) enhancing the recharge amount [78,80,81,84,85,87–90,92], (c) studying the impact of climate change on water resources [53], (d) assessing surface water and drought [51,55,107], (e) locating potential areas for groundwater abstraction [58,59], (f) analyzing time series [32,108], (g) building water quality models [70], (h) building groundwater models [29–31,54,96–98], (i) delineating isohyetal maps for rainfall [93], (j) creating vulnerability maps [65–67], and (k) proposing sustainable water management plans [52,60].

Although the modeling RFA had the most significant percentage among the collected literature, the basin was still an exciting area for researchers to conduct geophysical investigations to (a) study the saline water body in the basin [43,57,61–63,69,109], (b) investigate the suitability of water harvesting of Laval tunnels in the north of the basin [86,110], in the Dier al Kahif region [82], and in the Asra dam [83]; (c) investigate the impact of Qaser Tuba landfill on groundwater [77]; and (d) identify the geological formations of the Bishrya dam [111].

Socio-economy was the main focus of the studies that investigated: (a) the water governance in the basin [22,101], (b) the farming system and practices [36], (c) the socio-economic factors that impact the farmer's practices [44,46,102,112,113], (d) the impact of governmental regulations and socio-economic impacts on farmers and agriculture practices [47,103,114], (e) the challenges of managing groundwater in the basin [49], action plan to manage the groundwater [115], and (f) the socio-economic impact of applying solar farming in the basin [45]. Furthermore, two studies focused mainly on energy topics: one study to investigate the feasibility of applying solar energy for water desalination in the basin [105], and another study to investigate the potential for using thermal water as an alternative energy source [104].

Beyond the studies that conducted sampling campaigns as secondary RFAs [61,63,66,67,77,87,88], sampling campaigns were the main RFA in 20 studies. Water samples were collected, and isotopes were analyzed to (a) study the recharge rate in the Azraq Basin [23], (b) define the recharge origin in the basin [24,25,116], (c) group water types [26,42,76], (d) study the salination process [64,71–73], (e) evaluate nitrate leaching to groundwater [74,75], and (f) inspect the eutrophication process of surface water [94]. Soil samples were collected in the basin to (a) explore soil suitability for agriculture [117–119], (b) define the source of sulfur and gypsum [120], (c) estimate the recharge rate [33], and (d) map the soil moisture of the Al-Bagureyya area [121].

Hydrogeological field measurement was the main RFA to (a) review the groundwater resources [79,95,99,100]; (b) create geological maps [122]; (c) delineate protection zones [68]; and (d) to set an action plan [56]. Furthermore, Remote sensing techniques were used in the basin to (a) estimate the abstraction [34,35,123,124]; (b) create hydrological maps [91,125], and (c) study land change over time in the basin [126–129]. The agriculture RFA was not the main focus of any of the collected research; however, it was considered in 13 studies [36,45,47,49,52,60,74,103,112–114,124,130], and more reports with regard to agriculture are expected to be found in the ministry of agriculture, as shown in Table A1.

Figure 7 shows that the number of studies increased in all the RFAs after the implementation of the strategy, except in the laboratory sample analysis; the number of studies that focus on soil and water analysis decreased from 8 and 10 before the strategy to four and eight studies after the strategy, respectively. However, in the laboratory water sample analysis RFA, the number of peer-reviewed studies increased from five studies before the strategy to six studies after the strategy.

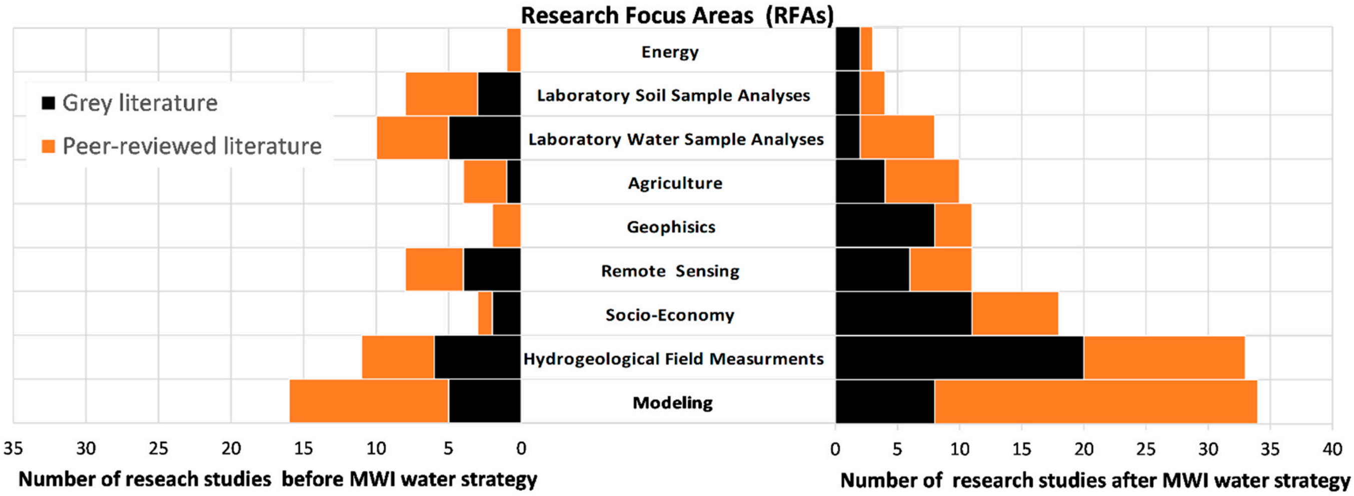


Figure 7. Research focus of the collected literature before and after the implementation of MWI water strategy.

Energy and agriculture were not the focus of any grey literature study before the MWI strategy implementation. However, after 2008, the work of GIZ [45] and Mesnil A. et al. [115] considered energy in their research and eight grey literature documents considered agriculture by calculating crop water requirement [35,124], investigating farming systems [36,49,103,112,113], and evaluating the economic return of current agriculture activities [45]. Additionally, the socio-economic component was only considered by Al-Adamat et al. [75] and Ibrahim [122] among the grey literature studies and by Al-Zu'bi et al. [60] among the peer-reviewed studies before the implementation of the water strategy, while it increased to 11 grey literature studies [22,36,45,46,56,87,102,103,112,113] and seven peer-reviewed studies [44,47,52,80,88,101,114] beyond 2008.

The total number of RFAs within each literature varied between one and five RFAs in both grey and peer-reviewed literature. The percentage of literature that focused only on one or two RFAs was approximately 86% of the peer-reviewed literature and 57% of grey literature. Furthermore, the documents that considered three RFAs represent approximately 13% of peer-reviewed literature and approximately 28% of grey literature. Approximately 13% of the collected grey literature studies considered four RFAs, while no peer-reviewed study considered four RFAs. However, only a single report [87] and an article [88] considered five RFAs, both of which were publications of a project conducted by the BGR in the basin. No peer-reviewed study, conducted by academic institutions, considered more than three RFAs (Figure 8).

In Figure 9, it was shown that before the implementation of the water strategy, only the studies with a research focus on remote sensing and modeling targeted three topics of the strategy [29–31,42,50,51,60,64,74,85,91,96,97,100,105,125]. In contrast, after the MWI strategy publication, the studies with a research focus on remote sensing, modeling, socio-economy, and hydrological field measurement targeted four of the five water strategy topics, wherein each of the conducted studies was targeting one or two topics of the MWI strategy. Only the modeling work of Al-Zubi [89] targeted three topics, namely: water supply, water for irrigation, and alternative water supply. The water supply topic was targeted by all research focuses, except energy, which targeted water demand, irrigation water, and alternative water resources only after the MWI water strategy came into effect. Conversely, only CES [50] and Ayed [51] include modeling as an RFA and targeted the water demand topic's goals before the strategy. Laboratory soil and water sample analyses and geophysics have neither contributed to the water demand topic before nor after the water strategy.

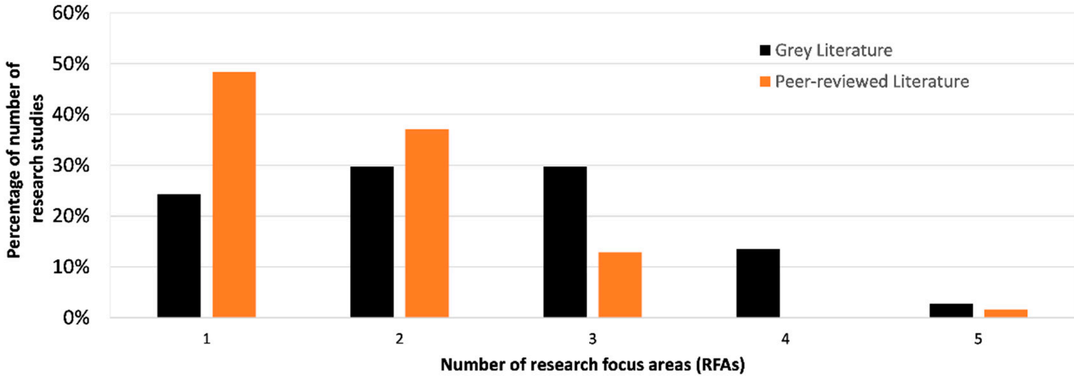


Figure 8. Number of research focus areas in grey and peer-reviewed studies.

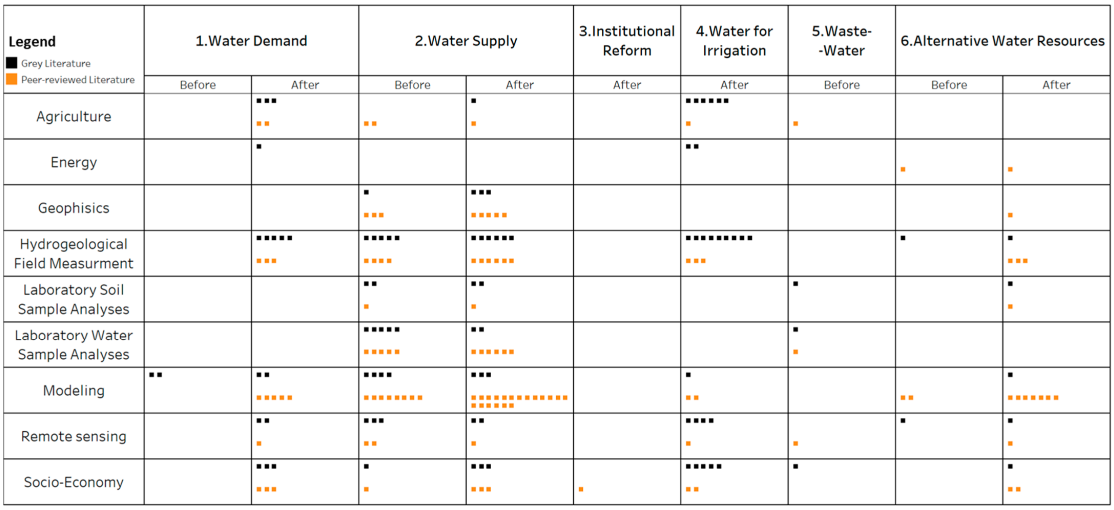


Figure 9. Relationship between the research focus areas (RFAs) and the MWI strategy topics.

4.6. Analysis of Research Topics Addressed by Documents Not Aligned to the Water Strategy Goals

As stated previously, 20 documents did not align with the MWI water strategy goals (Figure 10). These documents covered topics such as geology [99,110,121,123], soil [33,118–120,122,128], land use change [126,128,129], and time series analysis [107,108]. Although the research of Ibrahim [122], Al-Amoush and Rajab [110], Ahmad and Davies [120], Al Adamat et al [131] and UN-ESCWA and BGR [99] aimed to deepen the knowledge of the hydrogeological conditions of the Azraq Basin, these publications do not align with the MWI water strategy goals on the basis that they do not explicitly answer questions related to water management and availability, which are the core of the strategy. Nonetheless, the references [57,99,110,120,122] provide valuable information for the activities under the responsibility of the Ministry of Energy and Mineral Resources. Similarly, the MWI strategy did not explicitly address the topics of soil and land use change, which is a competence of the Ministry of Agriculture. Therefore, three studies [126,128,129] focusing on land use change, and six studies [33,117–119,121,127] focusing on soil science cannot directly contribute to the goals of the strategy. Amro et al. [33] contains important isotopic analysis that could be used to estimate the groundwater recharge in the catchment. However, since such an analysis is missing, the research was not considered to be aligned with the MWI strategy. Molle et al. [22] and Al Naber and Molle [114] represent a comprehensive overview of Jordan's water governance and policy, and their impact on Azraq Basin water resources as well as the responses of people to these policies. Such an assessment is needed for all individual basins of Jordan; this would provide the government with a compass to achieve improved water governance; however, such an assessment is not foreseen in the water strategy. The works of Shatnawi et al. [107] and Goode et al. [108] focus on time series analysis of hydrological variables. However, neither aligned with the MWI water strategy because their analyses did not explicitly address any of the goals. In particular, Goode et al. [108] presented trend analyses for groundwater levels and groundwater quality in the Azraq Basin, as a result of a cooperation project between USGS and the MWI, and still it did not align with the goals outlined in the MWI strategy. A similar event occurred in two reports [112,113], which were a result of the cooperation project between USAID and MWI. Both reports present a comprehensive socio-economic survey of groundwater wells of the basin, and it is stated in the reports that "This study was requested by the Ministry of Water and Irrigation". In these cases, there is, however, no output that explicitly fits the water strategy goals. Therefore, the fact that these 20 documents did not match the MWI strategy goals does not necessarily mean that these documents were not demand-driven research. Moreover, our analysis shows that the water strategy may in the future consider a more holistic approach in the definition of its goals.

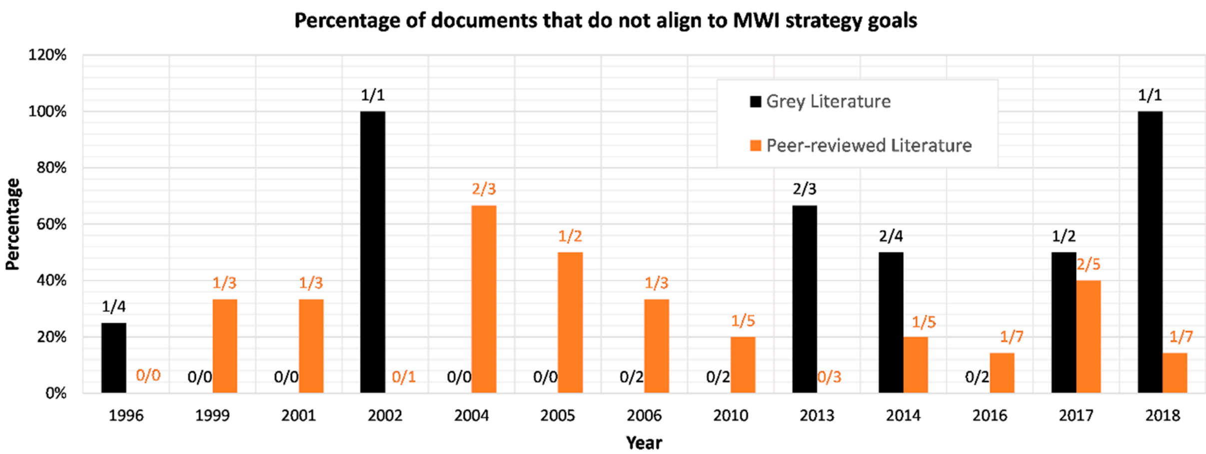


Figure 10. Percentage of studies that do not align with the MWI water strategy. The numbers above the bars represent the number of documents that do not align with MWI strategy and the total number of documents per year (the figure only represents the years, where the documents do not align with the MWI strategy goals).

5. Discussion

5.1. Research Gaps

Beyond the "practical-knowledge gap" identified in the comparison between conducted research and the MWI goals, the literature review allowed the recognition of a "knowledge gap", as defined by Miles [15]. In fact, a standard methodology to define a "practical-knowledge gap" in water-related research was not found; this study contributes to filling this gap. Decision-makers in the water sector need comprehensive studies and research to decide on a particular goal in a governmental water strategy. When missing research hinders taking a decision about a goal, it was deemed to be a "water-decision-research-gap", which is the inability to take a final decision about a governmental water strategy goal through conducting a systematic peer and grey-literature review at the basin level. It is essential to highlight when studies and research contribute to a specific goal; this contribution, however, does not guarantee that the necessary research is enough to make a decision related to the goal, and it could be that further research is needed. For instance, many studies contributed to the goal 2.d. [51,78–93], which aims to store and utilize surface water efficiently; however, only Salameh et al. [94] focused on the surface water quality of the Rajil dam in the basin, while the remainder (17 studies) focused on the amount and the suitable location for surface water harvesting. Therefore, the lack of surface water quality research hinders the decision-maker's ability to derive a conclusion from the literature review to make well-informed decisions related to the goal 2.d. Thus, the lack of surface water quality studies in various locations in the basin, in this case, is a water-decision research gap.

Furthermore, although several researchers have studied water harvesting at the local level, it is still necessary to conduct further studies at the same level (local level), similar, for example, to the study by Al-Zubi [89], which compared the feasibility of implementing water harvesting techniques at a micro and macro level in Wadi Muhweir for irrigation purposes. Goal 2.d. could be achieved if similar studies in all the locations (e.g., all main wadis and dams) were to be conducted. Furthermore, some goals (such as wastewater as an alternative water supply) in the strategy are found to be codependent, and they were not achieved because they required other goals (the goals related to wastewater) to be achieved prior, such as goal 6.a., which promotes treated wastewater as an alternative resource for agriculture; however, to study the treated wastewater viability as an alternative water resource, the goals in the wastewater topic (topic 5) must be further studied. This leads to the conclusion that a timeline for the strategy's topics and goals would help researchers to conduct demand-driven research.

It is crucial to clarify that when it is stated that a goal is not covered by literature, that this is in reference to the collected literature for the Azraq Basin within this research. The goal may be partially addressed by research work conducted on the national level, such as [132,133], that targeted the goals of wastewater topic in Jordan, or addressed by research performed in other regions or subbasins that share similar hydrological and socio-economic conditions, or addressed by reports that are not accessible according to the presented methodology, such as studies that were conducted by private engineering companies and were shared with the ministry.

5.2. Heterogeneity Impact of Research on Goals

A clear presentation of goals in governmental water strategies, such as the MWI water strategy 2008–2022, can be perceived as a prerequisite for increasing the researcher's ability to conduct demand-driven research and to contribute to achieving these goals. As stated previously, the impact of the research on the strategy goals varies, where some of the RFAs have contributed to most of the topics that were addressed by the governmental strategy (e.g., modeling RFA), while other areas contributed the least (e.g., energy RFA). Such an assessment helps the government and researchers to address the goals from a different perspective. For instance, the energy RFA contributed to the goals related to water demand, the water for irrigation, and alternative water resources with only three studies. Consequently, beyond the aforementioned topics, there is a strong argument for the need to conduct more studies about energy and water supply or energy and wastewater in the basin.

5.3. Implications for the Identification of Research Needs

The application of the proposed methodology to the Azraq river basin demonstrated that some goals were not addressed by any of the research study collected (Figure 6), which directly translates to a research gap existing. However, there can be multiple reasons that justify the occurrence of such a gap and that can explain the lack of research documents. For instance, the lack of infrastructure for a centralized wastewater treatment in the basin partially hinders research for goals 5.a., 5.e., 5.f., 5.g., 5.h., and 6.a. In fact, the Arzaq Basin is not yet connected with wastewater treatment plants but only cesspools at the present time. Therefore, studies evaluating the current impact of all wastewater disposal sites on groundwater are needed, especially for newly proposed locations that might threaten the groundwater quality, contributing to goals 5.b. and 5.d. Beyond the environmental impact assessment of the proposed sites, socio-economic assessments, technical and economic feasibility assessments are equally crucial for installing new wastewater treatment systems in the area. Therefore, it is essential to highlight that during the field visit to the MWI in January 2020, MWI staff indicated that reports on the new wastewater plant proposal in Azraq exist but could not be accessed.

The fact that a goal is addressed by several research studies does not necessarily imply that further research is not required. For example, setting a cap on water use for agricultural purposes was addressed partly by three studies [36,44,45]. However, innovative approaches to upgrade tools and technologies focusing on optimizing energy consumption and irrigation efficiency are urgently needed such that Jordanian farmers can contribute to the achievement of the goal. Goal 1.b. aims to increase awareness within the Jordanian society on the issues of water scarcity and some of the collected studies already provided measures for the farmer's awareness [46,47]. Still, there is a need to conduct similar studies that analyze the level of awareness for other social groups, such as students and industrial stakeholders, including tourism, to set up effective educational programs concerning water scarcity for different grades. Likewise, the following areas of assessment and evaluation still require further investigation to achieve the MWI's strategic goals:

i. **Investigate and improve the existing water distribution systems** in terms of technical aspects (i.e., hydraulic), management, energy efficiency, operation and maintenance, water losses, and billing and collection systems; contributing to **goal 2.a.**
ii. **Examine the deep aquifer area** in terms of water quality and quantity; contributing to **goal 2.a.**
iii. **Explore the potential of using desalinated water** in terms of technical, economic, and environmental aspects for both saline groundwater abstraction and building treatment plants; contributing to **goal 2.b.**; and also in terms of using an alternative energy source for desalination; contributing to **goal 6.e.**
iv. **Assess the existing monitoring systems** and provide proposals to improve them in terms of water quality; contributing to **goal 2.c.;** and water quantity; contributing to **goal 2.f.**
v. **Evaluate the current situation of the dams** in terms of sedimentation and water quality, focusing on conducting economic feasibility studies for sediment removal and water treatment; contributing to **goal 2.d.**
vi. **Investigate the current use of water in the recharge area** of the transboundary basin enhancing research cooperation with Syrian partners, contributing to **goal 2.i.**
vii. **Study the current irrigation systems** in terms of estimating the cost of changing it into a more efficient system; contributing to **goal 1.a.**; and drafting a farmer's incentives system for the MWI as a result of the economic and environmental benefits of these efficient systems, contributing to **goal 4.a.**, and
viii. **Examining the feasibility of installing rainwater harvesting techniques at the farm level**, similar to Zubi [82], as an alternative water resource for irrigation is still needed, thus contributing to **goals 4.f. and 6.c.**

5.4. Application to Other Areas

The developed methodology could be applied to other basins and other water strategies. However, the RFAs can be modified according to the collected research topics and the strategy's goals. If a new topic is presented, it can be added to one of the existing research areas or a new RFA may be added. Furthermore, when the methodology is applied at a national level, the corresponding national goals should be added to the methodology, and the goals addressed at a basin level should be removed. Conversely, mapping the RFAs and governmental goals can be implemented in topics other than water. This concept creates demand-driven research and helps researchers to address the goals by using the RFAs not addressing specific governmental goals.

Furthermore, to have a comprehensive water management strategy, the responsibility should not only be on the water provider [134] and the method could be developed to include other governmental strategies besides the water strategy. For instance, in the case of Jordan, this method could further be extended to cover the goals of the strategy of the ministry of agriculture and the ministry of environment. The method could be developed as a platform that connects different ministries and research institutions, where researchers can update the platform with new research and address the gaps that are identified with the methodology presented in this work. Finally, the governmental body may update the strategy goals accordingly.

6. Conclusions

A comprehensive methodology to define research gaps in water-related studies was developed and tested by investigating the impact of Jordan's water strategy (2008–2022) on research production in the Azraq Basin. The number of documents focusing on the basin increased after issuing the MWI strategy but there is no significant proof that this increase is due to issuing the MWI strategy, as the total number of published studies in Jordan addressing all topics also shows a positive rate of increase. Therefore, categorization of the research produced according to the MWI strategy goals is suggested, to better identify if and how they are addressed by peer-reviewed and grey literature. The results showed that the number of documents that align with the MWI strategy varies depending on the goal of the strategy and the RFAs considered within the document.

Involving governmental actors in the research design and literature collection process represents one of the most innovative and relevant points in the proposed methodology. In fact, grey literature is generally not easily accessible without involving actors from the ministries and its relevance in filling research gaps has been demonstrated in our work. The methodology allows the identification of a methodological research gap. This lack of research may hinder taking decisions related to governmental water strategy goals at the basin level. Thus, the inability to take decisions related to governmental water strategy goals through conducting a systematic peer and grey-literature review at the basin level was defined in this paper as the "water-decision research gap". Although the methodology indicates that the conducted research in the basin aligns with the ministry's water strategy, it does not guarantee that the research affects the strategy, mainly because proper communication between the government and researchers does not exist.

The methodology not only defines the research gaps but also evaluates the relationship between academia and government. In the Azraq Basin, 54 of the 62 peer-reviewed literature documents are led by academic institutions, and approximately 75% of them are conducted without cooperating with any governmental body or non-academic institution. Furthermore, approximately 75% of the peer-reviewed documents published by academic institutions are produced by national universities. This shows the vital role of the national academic institutions in water-related research and the importance of strengthening the relationship between academia and the government.

It is expected that the water strategy would have had a larger impact on the produced research if the goals of the strategy were formed based on the research outputs of each basin individually. This would help researchers to fill the gaps accordingly, and the conducted research would then be more demand-driven. Conversely, if researchers were to explicitly state the goals of the MWI strategy that were targeted in their work, this would help the ministry to update the strategy and develop a living document of the water strategy. The concept of linking the RFAs with the governmental strategy goals would inspire researchers to target the strategy's goals with interdisciplinary and transdisciplinary approaches that address all of the strategy topics. We expect that this link will enhance research production in the basin by reflecting the RFAs across each strategy topic for every goal. This may lead to the creation of innovative and imaginative research and eventually improve the connection between decision-makers and researchers. The government could further profit by conducting a systematic literature review to optimize the allocation of the budget available for future studies.

Author Contributions: Conceptualization, M.A. and G.C.; methodology, M.A. and G.C.; investigation, M.A., A.M. and M.A.W.; resources, M.A.W.; data curation, M.A.; writing—original draft preparation, G.C., M.A., A.A.D. and S.D.; writing—review and editing, G.C., M.A., A.A.D., S.D., M.A.R. and M.A.W.; visualization, M.A.; supervision, G.C. and M.A.R.; project administration, M.A.; funding acquisition, G.C., M.A.R. and S.D. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this project came from Stiftung Fiat Panis, Deutscher Akademischer Austauschdienst (DAAD), BMBF (Stärkung der innovationsrelevanten Rahmenbedingungen und angewandten Forschung in MENA-Ländern)-WD2D. This work was supported by the German Research Foundation (DFG) and the Technical University of Munich (TUM) in the framework of the Open Access Publishing Program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful for MWI, Water D2D project, Stiftung Fiat Panis and the DAAD scholarship. We would also like to thank Christopher Cochrane for proofreading the manuscript.

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

Appendix A

Table A1. List of the analyzed documents, goals, and RFAs.

#	Reference	MWI Goals	Research Focus Areas (RFAs)
1	[22]	not align	Hydrogeological Field Measurement, Socio-Economy
2	[23]	2.f.	Laboratory Water Sample Analyses
3	[24]	2.f.	Laboratory Water Sample Analyses
4	[25]	2.f.	Hydrogeological Field Measurement, Laboratory Water Sample Analyses
5	[26]	2.c., 2.f.	Laboratory Water Sample Analyses, Modeling
6	[29]	2.f.	Modeling
7	[30]	2.a.	Modeling
8	[31]	2.f.	Modeling
9	[32]	1.c.	Modeling
10	[33]	not align	Laboratory Soil Sample Analyses
11	[34]	1.b., 4.d.	Hydrogeological Field Measurement, Remote sensing
12	[35]	4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
13	[36]	1.a., 4.a.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
14	[42]	2.b.	Laboratory Water Sample Analyses, Modeling
15	[43]	2.b.	Geophysics, Hydrogeological Field Measurement
16	[44]	1.a., 4.a.	Hydrogeological Field Measurement, Modeling, Socio-Economy
17	[45]	1.a., 4.a.	Agriculture, Energy, Hydrogeological Field Measurement, Socio-Economy
18	[46]	1.b.	Hydrogeological Field Measurement, Modeling, Socio-Economy
19	[47]	1.b., 4.e.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
20	[48]	1.b., 4.d.	Hydrogeological Field Measurement, Remote sensing
21	[49]	1.b., 4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
22	[50]	1.c.	Modeling
23	[51]	1.c., 2.d.	Modeling
24	[52]	1.c., 2.a., 2.f.	Agriculture, Modeling, Socio-Economy
25	[53]	1.c.	Modeling
26	[54]	1.c., 2.f.	Modeling
27	[55]	1.c.	Modeling
28	[56]	2.a., 2.g.	Hydrogeological Field Measurement, Socio-Economy
29	[57]	2.a.	Geophysics, Hydrogeological Field Measurement
30	[58]	2.a.	Modeling
31	[59]	2.a.	Modeling
32	[60]	2.a., 2.g.	Agriculture, Modeling, Socio-Economy
33	[61]	2.b., 2.c.	Geophysics, Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses
34	[62]	2.b., 2.c.	Geophysics, Hydrogeological Field Measurement
35	[63]	2.b.	Geophysics, Laboratory Water Sample Analyses
36	[64]	2.b., 2.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses, Modeling
37	[65]	2.c.	Modeling

Table A1. *Cont.*

#	Reference	MWI Goals	Research Focus Areas (RFAs)
38	[66]	2.c.	Laboratory Water Sample Analyses, Modeling, Remote sensing
39	[67]	2.c.	Laboratory Water Sample Analyses, Modeling
40	[68]	2.c.	Hydrogeological Field Measurement, Remote sensing
41	[69]	2.c.	Geophysics, Hydrogeological Field Measurement
42	[70]	2.c.	Modeling
43	[71]	2.c.	Laboratory Water Sample Analyses
44	[72]	2.c.	Laboratory Water Sample Analyses, Modeling
45	[73]	2.c., 2.f.	Geophysics, Laboratory Water Sample Analyses, Modeling
46	[74]	2.c., 5.b.	Agriculture, Laboratory Water Sample Analyses, Remote sensing
47	[75]	2.c., 5.d.	Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses, Socio-Economy
48	[76]	2.c.	Laboratory Water Sample Analyses, Modeling
49	[77]	2.c.	Geophysics, Laboratory Soil Sample Analyses
50	[78]	2.d., 6.c.	Hydrogeological Field Measurement, Modeling
51	[79]	2.d.	Hydrogeological Field Measurement
52	[80]	2.d., 6.c.	Modeling, Socio-Economy
53	[81]	2.d., 6.c.	Modeling
54	[82]	2.d.	Geophysics, Hydrogeological Field Measurement
55	[83]	2.d.	Geophysics, Hydrogeological Field Measurement
56	[84]	2.d., 6.c.	Modeling
57	[85]	2.d., 6.c.	Modeling
58	[86]	2.d., 6.c.	Geophysics, Hydrogeological Field Measurement
59	[87]	2.d., 6.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Modeling, Remote sensing, Socio-Economy
60	[88]	2.d., 6.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Modeling, Remote sensing, Socio-Economy
61	[89]	2.d., 4.f., 6.c.	Modeling
62	[90]	2.d.	Modeling
63	[91]	2.d., 6.c.	Hydrogeological Field Measurement, Remote sensing
64	[92]	2.d., 6.c.	Modeling
65	[93]	2.d.	Modeling
66	[94]	2.d.	Laboratory Water Sample Analyses
67	[95]	2.f.	Hydrogeological Field Measurement
68	[96]	2.f.	Modeling
69	[97]	2.f., 2.g.	Modeling
70	[98]	2.f.	Modeling
71	[99]	not align	Hydrogeological Field Measurement
72	[100]	2.f., 2.i.	Modeling, Remote sensing
73	[101]	3.a.,3.b.	Socio-Economy
74	[102]	4.a.	Hydrogeological Field Measurement, Modeling, Socio-Economy
75	[103]	2.g., 4.e.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
76	[104]	6.e.	Energy
77	[105]	2.b., 6.e.	Energy, Modeling
78	[107]	not align	Modeling
79	[108]	not align	Modeling
80	[109]	not align	Geophysics, Hydrogeological Field Measurement
81	[110]	not align	Geophysics, Hydrogeological Field Measurement
82	[111]	2.c.	Geophysics, Hydrogeological Field Measurement
83	[112]	not align	Agriculture, Hydrogeological Field Measurement, Modeling, Socio-Economy
84	[113]	not align	Agriculture, Hydrogeological Field Measurement, Modeling, Socio-Economy
85	[114]	not align	Socio-Economy, Hydrogeological Field Measurment, Agriculture
86	[115]	4.d.	Energy, Hydrogeological Field Measurement, Socio-Economy
87	[116]	2.f.	Laboratory Water Sample Analyses
88	[117]	not align	Laboratory Soil Sample Analyses
89	[118]	not align	Laboratory Soil Sample Analyses
90	[119]	not align	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses
91	[120]	not align	Laboratory Soil Sample Analyses
92	[121]	not align	Laboratory Soil Sample Analyses, Remote sensing
93	[122]	not align	Hydrogeological Field Measurement, Remote sensing, Socio-Economy

Table A1. *Cont.*

#	Reference	MWI Goals	Research Focus Areas (RFAs)
94	[124]	4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
95	[125]	2.g.	Hydrogeological Field Measurement, Remote sensing
96	[127]	not align	Modeling, Remote sensing
97	[128]	not align	Modeling, Remote sensing
98	[129]	not align	Hydrogeological Field Measurement, Modeling, Remote sensing
99	[131]	not align	Modeling

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ISBN 978-3-0365-4109-9