land

Land Use Planning for Natural Hazards

Edited by

George D. Bathrellos and Hariklia D. Skilodimou

Printed Edition of the Special Issue Published in *Land*

www.mdpi.com/journal/land

MDPI

Land Use Planning for Natural Hazards

Land Use Planning for Natural Hazards

Editors

George D. Bathrellos
Hariklia D. Skilodimou

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade • Manchester • Tokyo • Cluj • Tianjin

Editors
George D. Bathrellos
University of Patras
Greece

Hariklia D. Skilodimou
National and Kapodistrian
University of Athens
Greece

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Land* (ISSN 2073-445X) (available at: https://www.mdpi.com/journal/land/special_issues/landuse_natural_hazards).

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 978-3-03943-925-6 (Hbk)
ISBN 978-3-03943-926-3 (PDF)

© 2020 by the authors. Articles in this book are Open Access and distributed under the Creative Commons Attribution (CC BY) license, which allows users to download, copy and build upon published articles, as long as the author and publisher are properly credited, which ensures maximum dissemination and a wider impact of our publications.
The book as a whole is distributed by MDPI under the terms and conditions of the Creative Commons license CC BY-NC-ND.

Contents

About the Editors

George D. Bathrellos, Associate Professor at University of Patras, Faculty of Sciences, Department of Geology, Sector of General, Marine Geology & Geodynamics. Research interests: geomorphology (pure and applied); natural hazards; urban planning; modeling; GIS. Teaching experience: Dr. Bathrellos has taught Geomorphology, Physical Geography, GIS, Urban Planning, Environmental Management and Monitoring, and Hydrology in graduate and post-graduate courses in four Greek universities. Publications: He has contributed over 100 publications in international conferences and journals.

Selected publications:

1. Tsolaki-Fiaka, S., Bathrellos, G.D., Skilodimou, H.D. (2018): Multi-Criteria Decision Analysis for an Abandoned Quarry in the Evros Region (NE Greece). *Land*, 7 (2): 43, doi: 10.3390/land7020043, MDPI Publishing. –23 citations

2. Skilodimou, H.D., Bathrellos, G.D., Chousianitis, K., Youssef, A.M., Pradhan, B. (2019): Multi-hazard assessment modeling via multi-criteria analysis and GIS: A case study. *Environmental Earth Sciences*, 78 (2): 47, doi: 10.1007/s12665-018-8003-4, Springer. –43 citations

3. Bathrellos, G.D., Skilodimou, H.D., Chousianitis, K., Youssef, A.M., Pradhan, B. (2017): Suitability estimation for urban development using multi-hazard assessment map. *Science of the Total Environment*, 575: 119 –134, doi: 10.1016/j.scitotenv.2016.10.025, Elsevier. –137 citations

4. Bathrellos, G.D., Karymbalis, E., Skilodimou, H.D., Gaki - Papanastassiou, K., Baltas, E.A. (2016): Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environmental Earth Sciences*, 75 (4): 319, doi: 10.1007/s12665-015-5157-1, Springer. –53 citations

5. Chousianitis, K., Del Gaudio, V., Sabatakakis, N., Kavoura, K., Drakatos, G., Bathrellos, G.D., Skilodimou, H.D. (2016): Assessment of earthquake-induced landslide hazard in Greece: From Arias Intensity to spatial distribution of slope resistance demand. *Bulletin of the Seismological Society of America*, 106 (1): 174 –188, doi: 10.1785/0120150172, Seismological Society of America. –47 citations

6. Rozos, D., Skilodimou, H.D., Loupasakis C., Bathrellos G.D. (2013): Application of the revised universal soil loss equation model on landslide prevention. An example from N. Euboea (Evia) Island, Greece. *Environmental Earth Sciences*, 70 (7): 3255-3266, doi: 10.1007/s12665-013-2390-3, Springer. –65 citations

7. Papadopoulou-Vrynioti, K., Bathrellos, G.D., Skilodimou, H.D., Kaviris, G., Makropoulos, K. (2013): Karst collapse susceptibility mapping considering peak ground acceleration in a rapidly growing urban area. *Engineering Geology*, 158: 77-88, doi: 10.1016/ j.enggeo.2013.02.009, Elsevier. –108 citations

8. Bathrellos, G.D., Gaki-Papanastassiou, K., Skilodimou, H.D., Papanastassiou, D., Chousianitis, K.G. (2012): Potential suitability for urban planning and industry development by using natural hazard maps and geological - geomorphological parameters. *Environmental Earth Sciences*, 66 (2): 537–548, doi: 10. 1007/s12665-011-1263-x, Springer. –168 citations

Hariklia D. Skilodimou, Ph.D. Researcher and Teaching Staff at National & Kapodistrian University of Athens, Faculty of Geology & Geoenvironment, Department of Geography & Climatology Research interests: geomorphology (pure and applied); natural hazards; modeling; GIS. Teaching experience: Dr. Skilodimou has taught Geomorphology, Physical Geography, GIS, Urban Planning, Environmental Management and Monitoring, and Hydrology in graduate and post-graduate courses in two Greek universities. Publications: She has contributed over 100 publications in international conferences and journals.

Selected publications:

1. Tsolaki-Fiaka, S., Bathrellos, G.D., Skilodimou, H.D. (2018): Multi-Criteria Decision Analysis for an Abandoned Quarry in the Evros Region (NE Greece). *Land*, 7 (2): 43, doi: 10.3390/land7020043, MDPI Publishing. –23 citations

2. Skilodimou, H.D., Bathrellos, G.D., Chousianitis, K., Youssef, A.M., Pradhan, B. (2019): Multi-hazard assessment modeling via multi-criteria analysis and GIS: A case study. *Environmental Earth Sciences*, 78 (2): 47, doi: 10.1007/s12665-018-8003-4, Springer. –43 citations

3. Bathrellos, G.D., Skilodimou, H.D., Chousianitis, K., Youssef, A.M., Pradhan, B. (2017): Suitability estimation for urban development using multi-hazard assessment map. *Science of the Total Environment*, 575: 119–134, doi: 10.1016/j.scitotenv.2016.10.025, Elsevier. –137 citations

4. Bathrellos, G.D., Karymbalis, E., Skilodimou, H.D., Gaki - Papanastassiou, K., Baltas, E.A. (2016): Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environmental Earth Sciences*, 75 (4): 319, doi: 10.1007/s12665-015-5157-1, Springer. –53 citations

5. Chousianitis, K., Del Gaudio, V., Sabatakakis, N., Kavoura, K., Drakatos, G., Bathrellos, G.D., Skilodimou, H.D. (2016): Assessment of earthquake-induced landslide hazard in Greece: From Arias Intensity to spatial distribution of slope resistance demand. *Bulletin of the Seismological Society of America*, 106 (1): 174–188, doi: 10.1785/0120150172, Seismological Society of America. –47 citations

6. Rozos, D., Skilodimou, H.D., Loupasakis C., Bathrellos G.D. (2013): Application of the revised universal soil loss equation model on landslide prevention. An example from N. Euboea (Evia) Island, Greece. *Environmental Earth Sciences*, 70 (7): 3255-3266, doi: 10.1007/s12665-013-2390-3, Springer. –65 citations

7. Papadopoulou-Vrynioti, K., Bathrellos, G.D., Skilodimou, H.D., Kaviris, G., Makropoulos, K. (2013): Karst collapse susceptibility mapping considering peak ground acceleration in a rapidly growing urban area. *Engineering Geology*, 158: 77-88, doi: 10.1016/ j.enggeo.2013.02.009, Elsevier. –108 citations

8. Bathrellos, G.D., Gaki-Papanastassiou, K., Skilodimou, H.D., Papanastassiou, D., Chousianitis, K.G. (2012): Potential suitability for urban planning and industry development by using natural hazard maps and geological - geomorphological parameters. *Environmental Earth Sciences*, 66 (2): 537–548, doi: 10. 1007/s12665-011-1263-x, Springer. –168 citations

land

Editorial

Land Use Planning for Natural Hazards

George D. Bathrellos * and Hariklia D. Skilodimou

Department of Geography and Climatology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, Zografou, ZC 15784 Athens, Greece

* Correspondence: gbathrellos@geol.uoa.gr; Tel.: +30-2107274882

Received: 17 August 2019; Accepted: 23 August 2019; Published: 25 August 2019

The Earth's landscape has a complex evolution and is the result of the interactions involving surficial processes, climate, tectonic, and human activity. In this context, the morphological changes in landforms due to active tectonics or climate change have the potential to affect and, in some cases, even to control human activities [1–5]. On the other hand, human activity and man-made constructions have the ability to change the landscape and, in this way, have impacted on natural hazards.

Natural hazards are physical phenomena that occur worldwide and contribute to the evolution of Earth's landscape. These phenomena affected the natural environment and existing biota, even before the appearance of man on Earth. Nowadays, they are an important global problem threatening human life. Natural hazards can damage both the natural and man-made environment [6]. Their impacts differ from place to place and frequently they appear to have adverse long-term effects [7].

On a global scale, overpopulation and urban development have the ability to increase the occurrence of natural hazards and their impacts both in the developed and developing world. For instance, deforestation causes increased rates of soil erosion and sediment transport, resulting in, for example, land degradation and flooding. Generally, natural hazards occur more frequently in relation to our capability to restore the effects of past events [8–10].

The sustainability of urban development can be influenced by several factors such as economic development, socioeconomic policy, population growth, physical environment, and natural hazards [11,12]. However, during planning, development, and management of an urban environment, only the economic and social parameters are usually taken into account. Consequently, in vulnerable locations, e.g., steeply sloping areas or those with degraded soils, the natural hazards that often occur, such as mass movements, can cause extensive damage, disrupt social and economic networks and lead to the loss of human lives and property [13–17].

Therefore, in order to minimize the loss of human life and reduce the economic consequences, proper planning and management of natural hazards are essential. However, consideration of the natural hazards and their influence on landscape evolution during the land use planning stage is essential.

In many cases, land use planning for addressing natural hazards is based on the probability of an event occurring, with little or no consideration of the consequences associated with natural hazard events [18]. For instance, floodplains are fertile, level, easy to excavate, near water and, thus, are favorable sites for urban development. In several cases, urbanization of floodplains has increased the probability of flooding, thereby causing disasters. Flood damage in such environments appears to increase, despite the construction of flood control works such as dams and river channelization [19–22].

The relationship between natural hazards and land use seems to be two-way. On the one hand, natural hazards and their associated consequences have the ability to cause changes in the landscape and thus, affect land use. On the other hand, human activities and land-use changes can lead to natural hazards.

In order to avoid the aforementioned effects, it is necessary for the decision-makers, engineers, planners, and managers to take into account the physical parameters of an area, as well as susceptibility to the natural hazards. The geology and the geomorphology of an area are important in the assurance of sustainable land management and in the protection of human life in urban areas [23].

In conclusion, is important that engineers, policymakers, and planners employ land use planning based on natural hazard maps in the evaluation and selection of suitable areas for sustainable urban development with fundamental concerns for the protection of the environment and of human life.

This special issue focuses on land use planning for natural hazards. Various types of natural hazards such as land degradation and desertification, coastal hazard, floods, and landslides, as well as their interactions with human activities, are presented in this volume.

Briassoulis H. [24] examines the use of Land Use Planning (LUP) to combat Land Degradation and Desertification (LDD). Various and interdependent socio-economic, cultural, political and institutional criteria play an important role in LDD or contribute to the management of land resources [25]. The paper presents desertification and the pertinent institutional context and studies whether and how LDD concerns enter the LUP process and the issues arising at each stage. The provision of an enabling, higher-level institutional environment should be prioritized to support phronetic-strategic integrated LUP at lower levels, which future research should explore theoretically, methodologically and empirically to realize the integrative potential of LUP and foster its effectiveness in combating LDD at the local and regional levels.

Tragaki, et al. [26] assess coastal hazard vulnerability based on geomorphic, oceanographic and demographic parameters in the Peloponnese (southern Greece). Nowadays, coastal areas around Greece are susceptible to climate change-related hazards [27]. The paper assesses the physical and social vulnerability of the Peloponnese to both coastal erosion and flooding caused by climate change-related hazards. The Coastal Vulnerability Index (CVI) and the Social Vulnerability Index (SVI) were estimated. The results showed that about 20% of the shoreline along the western and northwestern coast of the study area has high and very high physical vulnerability. Moreover, high and very high social vulnerabilities characterize communities along the northwestern part of the Peloponnese. The recognition of highly vulnerable coastal areas is very useful for coastal land use planning.

Two papers apply methods that provide vital information for land use planning and flood hazard mitigation. Rijal et al. [28] examine flood hazard mapping in the rapidly urbanizing city of Birendranagar, Nepal. Natural hazards and urbanization can interact to increase land-use changes in Nepal [29], and floods have caused loss of life and property in Birendranagar. The study focuses on the underlying land-cover dynamics and flood hazards of the study area. The spatiotemporal urbanization dynamics and associated land-use and land-cover (LULC) changes of the city from 1989 to 2016 allowed areas with high flood hazard risk to be identified. The urban area expanded nearly by 700%, while the cultivated land declined simultaneously by 12% between 1989 and 2016. This, and the loss of forests contributed significantly to increased flood hazard. Steep slopes, excessive land utilization, and intense monsoonal precipitation aggravated hazards locally.

Bathrellos et al. [30] undertake spatio-temporal analysis of flooding in the drainage basin of the Pinios River (Thessaly, Central Greece). The paper identifies the flood hazard by using historical flood events which occurred between 1979 and 2010, old topographic maps and geomorphic parameters. The flood occurrences increased during the period 1990–2010, most flood events were in October. The majority of occurrences are recorded in the southern part of the study area. There is a certain amount of clustering of flood events in the areas of former marshes and lakes as well as in the lowest and flattest parts of the study area. The applied method provides valuable information for land-use planning at a regional scale leading to the determination of the safe and non-safe areas for urban activities.

Skilodimou et al. [31] examine the relation of physical and anthropogenic factors with landslide activity in a mountainous part of northern Peloponnese in southern Greece. The existing landslides, lithology, slope angle, rainfall, road network along with land use of the study area were analyzed. The results prove that Plio-Pleistocene fine-grained sediments and flysch, relatively steep slopes and a rise in the amount of rainfall are strongly associated with the occurrence of landslides. A 100m wide zone along each road increases the probability of landslides while the extensively cultivated land of the study area is strongly related to landslide activity. This procedure may be utilized in landslide hazard assessment mapping as well as to new and existing land use planning projects.

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

References

1. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The spatial distribution of Middle and Late Pleistocene cirques in Greece. *Geogr. Ann. A* **2014**, *9*, 323–338. [CrossRef]
2. Skilodimou, H.D.; Bathrellos, G.D.; Maroukian, H.; Gaki-Papanastassiou, K. Late Quaternary evolution of the lower reaches of Ziliana stream in south Mt. Olympus (Greece). *Geogr. Fis. Din. Quat.* **2014**, *37*, 43–50.
3. Kokinou, E.; Skilodimou, H.D.; Bathrellos, G.D.; Antonarakou, A.; Kamberis, E. Morphotectonic analysis, structural evolution/pattern of a contractional ridge: Giouchtas Mt., Central Crete, Greece. *J. Earth Syst. Sci.* **2015**, *124*, 587–602. [CrossRef]
4. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The significance of tectonism in the glaciations of Greece. *Geol. Soc. Spec. Publ.* **2017**, *433*, 237–250. [CrossRef]
5. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H.; Gaki-Papanastassiou, K.; Kouli, K.; Tsourou, T.; Tsaparas, N. Pleistocene glacial and lacustrine activity in the southern part of Mount Olympus (central Greece). *Area* **2017**, *49*, 137–147. [CrossRef]
6. Bathrellos, G.D.; Skilodimou, H.D.; Chousianitis, K.; Youssef, A.M.; Pradhan, B. Suitability estimation for urban development using multi-hazard assessment map. *Sci. Total Environ.* **2017**, *575*, 119–134. [CrossRef] [PubMed]
7. Alcántara-Ayala, I. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* **2002**, *47*, 107–124. [CrossRef]
8. Guzzetti, F.; Carrara, A.; Cardinali, M.; Reichenbach, P. Landslide hazard evaluation: A review of current techniques and their application in a multi-scale study, Central Italy. *Geomorphology* **1999**, *31*, 181–216. [CrossRef]
9. Tsolaki-Fiaka, S.; Bathrellos, G.D.; Skilodimou, H.D. Multi-criteria decision analysis for abandoned quarry restoration in Evros Region (NE Greece). *Land* **2018**, *7*, 43. [CrossRef]
10. Skilodimou, H.D.; Bathrellos, G.D.; Chousianitis, K.; Youssef, A.M.; Pradhan, B. Multi-hazard assessment modeling via multi-criteria analysis and GIS: A case study. *Environ. Earth Sci.* **2019**, *78*, 47. [CrossRef]
11. Fedeski, M.; Gwilliam, J. Urban sustainability in the presence of flood and geological hazards: The development of a GIS-based vulnerability and risk assessment methodology. *Landsc. Urban Plan.* **2007**, *83*, 50–61. [CrossRef]
12. Thapa, R.B.; Murayama, Y. Drivers of urban growth in the Kathmandu Valley, Nepal: Examining the efficacy of the analytic hierarchy process. *Appl. Geogr.* **2010**, *30*, 70–83. [CrossRef]
13. Bathrellos, G.D.; Kalivas, D.P.; Skilodimou, H.D. Landslide susceptibility mapping models, applied to natural and urban planning, using G.I.S. *Estud. Geol.-Madrid* **2009**, *65*, 49–65. [CrossRef]
14. Rozos, D.; Bathrellos, G.D.; Skilodimou, H.D. Comparison of the implementation of Rock Engineering System (RES) and Analytic Hierarchy Process (AHP) methods, based on landslide susceptibility maps, compiled in GIS environment. A case study from the Eastern Achaia County of Peloponnesus, Greece. *Environ. Earth Sci.* **2011**, *63*, 49–63. [CrossRef]
15. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Skianis, G.A.; Chousianitis, K.G. Assessment of rural community and agricultural development using geomorphological-geological factors and GIS in the Trikala prefecture (Central Greece). *Stoch. Environ. Res. Risk Assess.* **2013**, *27*, 573–588. [CrossRef]
16. Papadopoulou-Vrynioti, K.; Bathrellos, G.D.; Skilodimou, H.D.; Kaviris, G.; Makropoulos, K. Karst collapse susceptibility mapping considering peak ground acceleration in a rapidly growing urban area. *Eng. Geol.* **2013**, *158*, 77–88. [CrossRef]
17. Bathrellos, G.D.; Kalivas, D.P.; Skilodimou, H.D. Landslide Susceptibility Assessment Mapping: A Case Study in Central Greece. In *Remote Sensing of Hydrometeorological Hazards*; Petropoulos, G.P., Islam, T., Eds.; CRC Press, Taylor & Francis Group: London, UK, 2017; pp. 493–512, ISBN-13: 978-1498777582.

18. Saunders, W.S.; Kilvington, M. Innovative land use planning for natural hazard risk reduction: A consequence-driven approach from New Zealand. *Int. J. Disaster Risk Reduct.* **2016**, *18*, 244–255. [CrossRef]
19. Bathrellos, G.; Skilodimou, H. Geomorphic Hazards and Disasters. *Bull. Geol. Soc. Greece* **2006**, *39*, 96–103. (In Greek)
20. Goudie, S.A. *Encyclopedia of Geomorphology*; Goudie, S.A., Ed.; Taylor & Francis Group: New York, NY, USA, 2006; pp. 378–379.
21. Bathrellos, G.D. An overview in Urban Geology and Urban Geomorphology. *Bull. Geol. Soc. Greece* **2007**, *40*, 1354–1364. [CrossRef]
22. Bathrellos, G.D.; Karymbalis, E.; Skilodimou, H.D.; Gaki-Papanastassiou, K.; Baltas, E.A. Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environ. Earth Sci.* **2016**, *75*, 319. [CrossRef]
23. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Papanastassiou, D.; Chousianitis, K.G. Potential suitability for urban planning and industry development by using natural hazard maps and geological-geomorphological parameters. *Environ. Earth Sci.* **2012**, *66*, 537–548. [CrossRef]
24. Briassoulis, H. Combating Land Degradation and Desertification: The Land-Use Planning Quandary. *Land* **2019**, *8*, 27. [CrossRef]
25. Briassoulis, H. Desertification. In *Science and Policy. An A to Z Guide to Issues and Controversies*; Steel, B., Ed.; CQ Press: Thousand Oaks, CA, USA, 2014; pp. 138–145.
26. Tragaki, A.; Gallousi, C.; Karymbalis, E. Coastal hazard vulnerability assessment based on geomorphic, oceanographic and demographic parameters: The case of the Peloponnese (Southern Greece). *Land* **2018**, *7*, 56. [CrossRef]
27. Karymbalis, E.; Chalkias, C.; Chalkias, G.; Grigoropoulou, E.; Manthos, G.; Ferentinou, M. Assessment of the sensitivity of the southern coast of the Gulf of Corinth (Peloponnese, Greece) to sea-level rise. *Cent. Eur. J. Geosci.* **2012**, *4*, 561–577. [CrossRef]
28. Rijal, S.; Rimal, B.; Sloan, S. Flood hazard mapping of a rapidly urbanizing city in the foothills (Birendranagar, Surkhet) of Nepal. *Land* **2018**, *7*, 60. [CrossRef]
29. Rimal, B.; Zhang, L.; Keshtkar, H.; Sun, X.; Rijal, S. Quantifying the Spatiotemporal Pattern of Urban Expansion and Hazard and Risk Area Identification in the Kaski District of Nepal. *Land* **2018**, *7*, 37. [CrossRef]
30. Bathrellos, G.D.; Skilodimou, H.D.; Soukis, K.; Koskeridou, E. Temporal and spatial analysis of flood occurrences in drainage basin of Pinios River (Thessaly, central Greece). *Land* **2018**, *7*, 106. [CrossRef]
31. Skilodimou, H.D.; Bathrellos, G.D.; Koskeridou, E.; Soukis, K.; Rozos, D. Physical and anthropogenic factors related to landslide activity in the Northern Peloponnese, Greece. *Land* **2018**, *7*, 85. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

land

MDPI

Article

Combating Land Degradation and Desertification: The Land-Use Planning Quandary

Helen Briassoulis

Department of Geography, University of the Aegean, 81100 Lesvos, Greece; e.briassouli@aegean.gr; Tel.: +30-225-103-6411

Received: 15 December 2018; Accepted: 28 January 2019; Published: 1 February 2019

Abstract: Land-use planning (LUP), an instrument of land governance, is often employed to protect land and humans against natural and human-induced hazards, strengthen the resilience of land systems, and secure their sustainability. The United Nations Convention to Combat Desertification (UNCCD) underlines the critical role of appropriate local action to address the global threat of land degradation and desertification (LDD) and calls for the use of local and regional LUP to combat LDD and achieve land degradation neutrality. The paper explores the challenges of putting this call into practice. After presenting desertification and the pertinent institutional context, the paper examines whether and how LDD concerns enter the stages of the LUP process and the issues arising at each stage. LDD problem complexity, the prevailing mode of governance, and the planning style endorsed, combined with LDD awareness, knowledge and perception, value priorities, geographic particularities and historical circumstances, underlie the main challenges confronting LUP; namely, adequate representation of LDD at each stage of LUP, conflict resolution between LDD-related and development goals, need for cooperation, collaboration and coordination of numerous and diverse actors, sectors, institutions and policy domains from multiple spatial/organizational levels and uncertainty regarding present and future environmental and socio-economic change. In order to realize the integrative potential of LUP and foster its effectiveness in combating LDD at the local and regional levels, the provision of an enabling, higher-level institutional environment should be prioritized to support phronetic-strategic integrated LUP at lower levels, which future research should explore theoretically, methodologically and empirically.

Keywords: integrated land-use planning; land degradation; desertification; policy; phronetic approach

1. Introduction

Land[1] mediates all interactions between the natural environment, society and the economy [2,3]. Land resources provide ecosystem services but also pose constraints on human activity which, if violated, generate important unwanted environmental and socio-economic consequences. The alarming pace at which land resources are degrading in recent times has been recognized at the international and subglobal levels [4–7]. Sustainable Development Goal (SDG) 15, one of the 17 SDGs decided at the Rio+20 conference in 2012, is specifically geared to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" [8].

[1] "Land means the terrestrial bio-productive system that comprises soil, vegetation, other biota, and the ecological and hydrological processes that operate within the system" [1].

The wise governance of land resources in coupled human-environment systems, or land systems[2], is key to strengthening their resilience against natural hazards and numerous other environmental, technological and socio-economic disturbances [10–13]. 'Land systems science' is a term coined to denote the contemporary, interdisciplinary scientific domain concerned with the theories, approaches, analytical tools and instruments related to the analysis and resolution of land-use problems [12,14]. Land-use planning (LUP) is an instrument of land governance that has been used since ancient times to protect land and humans against natural hazards and to address pertinent land use-related issues in order to secure the sustainability of land systems [15–19].

Desertification, an extreme form of natural and human-induced land degradation, and drought, a natural hazard, threaten the smooth functioning of land systems [7]. Desertification differs from other natural hazards, such as fires, floods and earthquakes, because it is a wide-net, higher level, multi-scalar and long-term phenomenon; at the local level, it is mostly experienced as (severe) land degradation. Land degradation and desertification (LDD) is the term commonly used in official (e.g., UN, European Union) and scientific quarters, and which is adopted in this paper. The causes and consequences of LDD concern several interdependent human activities, directly implicate more than one land resources (soil, water and vegetation) and involve diverse economic sectors, social groups and institutions, spanning the local to global spectrum. The incidence of LDD exposes land resources and human populations to multiple threats: loss of land productivity, food insecurity, water shortages and scarcity, economic hardship, social deprivation and health risks [20–25].

The signing of the United Nations Convention to Combat Desertification (UNCCD), one of the three Rio Multilateral Environmental Agreements (or, Conventions)[3], in 1994[4] underlines the global significance of the phenomenon as well as the critical role of appropriate local action. Since 2012, the UNCCD has embraced SDG 15 and, more specifically, Target 15.3 that sets the ambitious goal to achieve land degradation neutrality (LDN) by 2030. Among the several actions for its effective implementation, the UNCCD and other international and sub-global organizations incite the signatory parties to use local and regional land use planning to help combat desertification and mitigate the negative effects of drought in affected areas [26] and, more recently, to address the LDN target[5] [27]. Putting this straightforward call into practice, however, presents considerable challenges, several of which have been noted since the early days of the UNCCD [28].

In complex land systems, a multitude of actors interacting on and across scales continuously place diverse demands on a multitude of interconnected resources to satisfy various, often conflicting, goals, environmental protection being one of them, that differ in priority among groups [13,29]. Conflicts arise over the allocation of land among competing uses which accrue short- and long-term costs and benefits to individuals and groups. If human activities locate in resource-poor (e.g., water), hazard-prone and other high-risk areas, biophysical constraints imply high costs of protection or, if they are ignored, significant environmental and socio-economic costs result. LUP aims to arbitrate and resolve these conflicts and issues to secure the sustainability of local and regional development [30]. In LDD-prone areas, in particular, the LDN goal makes LUP an inevitable instrument in the fight against LDD. This is a demanding undertaking because LUP is called to harmonize the LDN with numerous other goals and it is, furthermore, complicated by the ever-present uncertainty regarding future human needs, goals and priorities, environmental conditions, socio-economic and technological

---

2 "Land systems constitute complex, adaptive social-ecological systems (Berkes et al., 1998) shaped by interactions between (i) the different actors and demands that act upon land, (ii) the technologies, institutions, and cultural practices through which societies shape land use, and (iii) feedbacks between land use and environmental dynamics (Millennium Ecosystem Assessment (MA), 2003; Verburg et al., 2015)." [9], (p. 53).

3 The other two are the 'sister' Conventions of the UNCCD, the UNCBD (United Nations Convention for Biodiversity Conservation) and the UNFCCC (United Nations Framework Convention for Climate Change).

4 The UNCCD came into force in December 1996.

5 "Furthermore, through Decision 2/COP.12, the UNCCD endorsed the formulation, revision and implementation of action programmes in view of the 2030 Agenda for Sustainable Development, (United Nations General Assembly, 2015) encouraging the linkage between planning and the implementation of LDN" [27], (p. 76).

change, unpredictable events and their changing constellations. Harmonization points to the need to apply *phronesis* (practical wisdom) [31] in making land-use decisions to safeguard the potential of affected areas to successfully adapt to changing conditions and, thus, secure their resilience and enhance their sustainable development prospects.

This paper delves into this land-use planning quandary aiming to show that LUP is not a straightforward but a complex endeavor, reveal the LUP challenges facing the fight against LDD and suggest avenues to handle them to foster the effectiveness of LUP efforts. The discussion is general applying to most (democratic) socio-political contexts although geographic particularities and historical circumstances determine the actual form the issues and challenges obtain. The second section briefly presents the main features of desertification and the institutional context to combat it. The third section introduces land-use change and land-use planning and explores the issues and challenges arising at each stage of the LUP process in the context of combating LDD at the local and regional levels. The concluding section suggests necessary priority actions to realize the integrative potential of LUP and, thus, improve its effectiveness in combating LDD that indicate future research directions.

2. Desertification and the Institutional Context to Combat Desertification

2.1. Desertification

Desertification has received and, with the escalation of global warming, is receiving significant political support at the international and subglobal levels [4,6,7,22]. However, it remains a politically contentious issue; the existence of more 100 definitions is telling [32]. The UNCCD definition, which is mostly used by now, states that desertification is "land degradation in arid, semiarid and subhumid tropics caused by a combination of climatic factors and human activities" [1]. Land degradation means reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including those arising from human activities and habitation patterns, such as: (a) soil erosion caused by wind and/or water, (b) deterioration of the physical, chemical, biological and economic properties of soils and (c) long-term loss of natural vegetation [1,23].

This definition makes clear that (a) desertification is land degradation in the drylands[6], i.e., in areas with adverse biophysical conditions, (b) it leads to an extreme, often irreversible, state of degradation implying reduction or loss of both biological *and* economic productivity *and* complexity of land, (c) the natural resources concerned are climate, soil, water and vegetation, (d) it involves both natural and human-induced processes operating at multiple spatial and temporal scales, and (e) a variety of human activities and users of land are implicated.

Biophysical and human *driving forces* (indirect drivers), from the local to the global levels, underlie *the proximate causes* (direct drivers) of LDD; i.e., human activities, such as agriculture, animal husbandry, forestry, housing, tourism, transport, extraction and energy production. The associated land-using and potentially resource-degrading practices include intensive cultivation, monocultures, abandonment of traditional practices (e.g., terracing), poor or no maintenance of rural holdings, overgrazing, deforestation, forest fires, water overdrafts, extraction, drainage of wetlands, and large infrastructure works [4,5,22–24,33–36]. Their combined action modifies land resources and produces land use and land cover change which, under adverse biophysical conditions, set in motion processes of LDD.

The biophysical drivers of desertification include climate, geology, soil conditions, hydrology, topography and vegetative cover. Selected important characteristics of these drivers are: low and uneven annual and interannual rainfall distribution, extreme weather events and out-of-phase rainy and vegetative seasons; soil depth, structure and stability, organic content, stoniness of land,

[6] i.e., "areas, other than polar and sub-polar regions, in which the ratio of annual precipitation to potential evapotranspiration falls within the range from 0.05 to 0.65" [1].

soil–water balance; slope gradient and slope aspect; surface and ground water availability; and biomass productivity[7] [37]. Slow and fast physical and/or chemical processes are involved in LDD. The former include soil erosion, compaction, salinization, alkalization and nitrification. The latter include drought and extreme weather events [25,37,38].

The diverse and interdependent human (socio-economic, cultural, political and institutional) drivers of LDD play a dual role; they either underlie the incidence of LDD or contribute to its mitigation by changing the valuation, modes of utilization and management of land resources. Important among them are: population structure and dynamics (mobility and migration), poverty and social inequality; changes in technology, modes of production, social values, consumption patterns, life styles, family structure, employment composition, market and/or public policy-induced agricultural product prices, capital availability and competition among economic activities [20,25,32,39].

The institutional drivers of desertification are particularly important. They encompass international economic and environmental regimes (e.g., trade, climate change and biodiversity) as well as supranational policies, such as the European Union (EU) Common Agricultural Policy (CAP), transport policy, the Structural Funds (SFs) and their national level counterparts [40]. Several national policies negatively affect bioclimatically sensitive regions, setting the stage for their degradation. Important national level concerns include the mode of governance, which depends on the prevailing political regime, inappropriate or inexistent environmental and spatial planning legislation, problematic plan and policy implementation, unclear, uncoordinated or inexistent systems of resource rights for critical resources, such as water and soil, administrative compartmentalization and lack of coordination [33]. At the local level, land tenure and ownership constitute critical institutional influences. Rural land rental, combined with absentee ownership, land fragmentation, and vague and incompatible resource regimes often give rise to inappropriate land management and degradation, impeding the proper implementation of formal policies [25,37].

Geographic location, accessibility and the spatial distribution of economic activities, uses of land, population and infrastructure determine the particular nonlinear interactions among biophysical and human drivers and underlie the processes, such as agricultural intensification, urbanization, industrialization, etc., that judge the incidence and magnitude of LDD in a region. The urban–rural dynamics, in particular, greatly affects the long-term prospects of the phenomenon as it consolidates the complex, multi-scale influences and pressures on land resources. Lastly, biophysical and human macro-forces and events operating within a period, e.g., wars, famines, natural disasters, new technologies, price shocks and resource crises have important off-site effects on the incidence of LDD [25].

In contrast to other natural hazards, the biophysical, socio-economic and other impacts of desertification may range from localized and short-term to large-scale and long-term, owing to the diverse biophysical and human drivers that act and interact non-linearly at different speeds (fast and slow processes) on multiple spatial and temporal scales. This is the most important source of uncertainty concerning LDD with important implications for its definition, identification, assessment and choice of proper measures to combat it.

2.2. The Institutional Context to Combat Desertification

The institutional activity pertinent to LDD and drought spans the global to local spectrum. At the international level, the UNCCD is the principal direct institutional regime that provides the broad frame of actions to combat desertification. It comprises five Annexes that correspond to five groupings of world regions and related region-specific desertification problems. Annex IV (Northern Mediterranean) includes 16 signatories, of which 10 are EU member states. The organizational apparatus of the UNCCD comprises the Conference of the Parties (COP), a permanent secretariat and a Committee on Science and Technology (CST). Their mandate includes support for the elaboration,

[7] Land is considered desertified when biomass productivity drops below a certain threshold value.

implementation and co-ordination of various instruments; co-ordination of the UNCCD with its sister conventions, the United Nations Convention for Biodiversity Conservation (UNCBD) and the United Nations Framework Convention on Climate Change (UNFCCC); research and development, technology transfer, acquisition and adaptation; capacity building, education, awareness raising and provision of financial resources and mechanisms to facilitate implementation[8]. The UNCCD Secretariat provides regular monitoring and reporting on the implementation of proposed actions [33,37].

The UNCCD, acknowledging the complexity of desertification and recognizing the vital role of local level responses in sustainable resource management, offers guiding principles for an integrated 'top-down' and 'bottom-up' approach to designing interventions in affected areas and encourages multi-level communication and collaboration [33]. It prescribes general and specific obligations of the signatory parties, underlining the institutional conditions required to facilitate effective implementation. The most important obligation is the preparation of Regional Action Programmes (RAPs) and National Action Programmes (NAP), following a UNCCD-defined template [1]. These programmes should be linked to national sustainable development programmes based on participatory processes with input from the field and the scientific community. The affected countries are urged to strengthen extant and enact new, including spatial and land-use planning, legislation.

Given the implementation problems recorded over time, COP8 [41] approved a 10-year strategy to improve UNCCD implementation and secure adequate financing that prioritizes the integration of desertification concerns into development planning and policies. The most important development since that time is perhaps the agreement of the parties to endorse Target 15.3 of SDG 15 that states "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world" [3][9]. Land Degradation Neutrality (LDN) was defined as "A state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems" [27], (p. 33).

LDN is considered a hybrid lay-scientific concept that "aims to maintain and increase the amount of healthy and productive land resources, *in line with national development priorities*" (emphasis added) [42], (p. 2). As such, it represents "a flexible target that can be implemented at local, regional or national scales. *It recognizes the sovereignty of nations to manage the trade-offs* and to capitalize on the synergies between biological and economic productivity (emphasis added) [42], (p. 2). It has been hailed as "a paradigm shift in land management policies and practices ... a unique approach that counterbalances the expected loss of productive land with the recovery of degraded areas. *It squarely places the measures to conserve, sustainably manage and restore land in the context of land use planning*" (emphasis added) [43]. Practically, it could be achieved by: "(a) managing land more sustainably, which would reduce the rate of degradation; and (b) increasing the rate of restoration of degraded land, so that the two trends converge to give a zero net rate of land degradation" [44], (p. 12).

It is widely recognized that the implementation of this ambitious target requires multi-stakeholder engagement, cross-scale and intersectoral planning and strong national-scale coordination that should serve to manage and streamline diverse local, regional and sectoral governance structures[10]. If successful, LDN might reinforce the implementation of the convention and contribute to the achievement of other goals such as climate change mitigation and adaptation, biodiversity conservation, ecosystem restoration, food and water security, disaster risk reduction, and poverty eradication. In other words, it may serve as a vehicle to affect the coordination and integration of the three

---

[8] Lacking autonomous financing, the UNCCD, under the guidance of the COP, employs the Global Mechanism as a brokering body to facilitate the effective and efficient channeling of financial resources and mechanisms to affected countries. COP6 designated the Global Environment Facility as a UNCCD financial mechanism. Developing synergies with the Conventions on Biological Diversity (CBD) and Climate Change (UNFCCC) is expected to improve its financing prospects [41].

[9] Available online: https://www.unccd.int/actions/ldn-target-setting-programme; (accessed on 28 September 2018).

[10] See, [45] for a discussion of open challenges.

conventions (UNCCD, UNCBD and UNFCCCC) that variously materialize, in one way or another, in the process of using land.

The European Union has supported the fight against desertification through research funding (Framework Programmes since 1989), specific projects (e.g., INTERREG, LIFE), research at the Joint Research Centre (Ispra, Italy), technical and information support provided by the European Environment Agency, and specific measures included in the CAP (agri-environmental measures) and the Structural Funds [20]. The Thematic Strategy for Soil Protection [46] remains the only direct institutional response to the issue as efforts to institute an EU Soil Framework directive have failed, the main reason being that planning the uses of land is considered a matter of national sovereignty and not of EU competence[11]. Indirectly, provisions included in horizontal and sectoral policies, such as the EIA, SEA, Habitats and Water Framework directives, provide instruments to address LDD at national and subnational levels.

At the national level, direct desertification policies do not exist besides the NAPs. The co-ordination of their implementation has been assigned to ministries of agriculture or the environment. Most NAPs emphasize measures targeting the proximate causes, such as agriculture, forestry and animal husbandry, and not the driving forces of LDD [20]. Spatial planning activities are supposed to observe the provisions of the NAPs in affected areas. How close this requirement is being followed in practice remains an open question. Indirectly, several pieces of national horizontal environmental and sectoral legislation and policies[12] concerning soil protection, afforestation, fire protection, water resources conservation, nature conservation and other issues may contribute to mitigating the longer term occurrence of LDD. National development frameworks often prescribe the integration of pertinent measures in land use planning strategies [30].

Summarizing, LDD is a process during which extreme, irreversible states of land degradation may emerge at a higher level in the long run. Desertification constitutes an aggregate, macro-feature of the state of the land. It involves complex, non-linear, context-, scale- and path-dependent interactions between natural resources and human activities driven by numerous, multi-scalar, interacting biophysical and human driving forces, among which nature–society institutions (international environmental regimes, policies, customary land management regimes, etc.) play a pivotal role. Considerable controversy still surrounds its definition and causality [25,47,48], making it difficult to disentangle the biophysical from the anthropogenic causes, to accurately assess the land affected and/or at risk, and to predict its consequences and reversibility. Hence, it cannot be stated with certainty whether and when an area will be 'locked' in an irreversibly desertified state.

The complexity of LDD and the associated scientific uncertainty carry over to and combine with a similarly complex world of practice where numerous individual and collective actors as well as formal and informal institutions are implicated on and across multiple spatial and temporal scales in making land use decisions. Land-use planning, functioning within this milieu, is called to assist in coping with a contentious, wicked socio-ecological problem, LDD.

3. Land-Use Planning to Combat Land Degradation and Desertification: Uncovering the Complexities

3.1. Land-Use Change and Land-Use Planning

Land-use patterns and their evolution over time, i.e., land-use change, result from the constant interaction between demand and supply factors from the local to the global level, which are mediated and regulated by human decision making. The demand factors are distinguished into driving forces

---

[11] After eight years of deliberations, the proposal for an EU Soil directive was withdrawn in April 2014 because five countries (UK, Germany, Austria, France, the Netherlands) blocked the process.

[12] In EU member states, in particular, the transposition of community regulations and directives to the national legislation has provided a considerable range of measures toward this purpose.

and proximate causes. The driving forces (indirect drivers) underlie the generation of demand for various economic activities and, consequently, the demand for land of particular characteristics. Higher level factors, such as population, affluence, technology, socio-economic organization, culture, international and subglobal institutions, political systems and their change, combine with lower level factors, such as demographic and socio-cultural traits, activity-specific costs, benefits and profits, value systems, formal and customary resource regimes and rights, and resource use practices, to shape the choice, extent and intensity of actual land use [45]. Certain driving forces, such as international agreements, subglobal and national policies, and resource-conserving practices, often act as mitigating forces that moderate the unwanted impacts of land-use change. Finally, the proximate causes (direct drivers) of land-use change include various human activities and their locational requirements, preferences and impacts [45].

The supply factors encompass the biophysical and anthropogenic resources of an area, also referred to as 'capitals'—natural, physical, landesque, technological, human, social, economic, institutional, political [49–51]. The biophysical resources include climate and weather, geology and geomorphology (topography), soils, water, vegetation, fauna and flora. The anthropogenic resources comprise past and present manmade structures (buildings, settlements, archaeological sites, etc.), social infrastructure (schools, hospitals, etc.), physical-technical infrastructure (transport, communication, energy and other networks), human and social capital, institutions, land tenure, land ownership, culture and value systems. The interplay of the features, spatial distribution and dynamics of these factors influences the suitability of land resources for particular activities, their sensitivity to various uses, their accessibility and their activity-specific economic and socio-cultural value that, eventually, determine the relative priority of land for various uses. Land-use conflicts commonly arise as several activities may have similar locational preferences but their co-existence is either impossible or results in unwanted environmental and socio-economic impacts. The actual land-use pattern is determined by past land use trajectories and historic contingencies that favor the domination of one or more uses of land over other competing uses in particular areas and contexts.

Land-use change, either autonomous or planned, takes two forms; *modification* of an existing land use type (e.g., change between crops, change in forest use) or *conversion* from one land use type to another (e.g., from agricultural to urban or industrial land). Land-use planning is the main instrument of planned land-use change. It is the purposeful, anticipatory activity of intervening in an existing, always fluid and dynamic, state of affairs with the aim to modify the land-use pattern in order to achieve certain goals and reduce uncertainty about the future impacts and consequences of human activities [19,52,53]. Given differences in the suitability of land resources for particular activities, the presence of natural constraints on activity location[13] and the competition among activities for the same resources, LUP broadly aims to (a) guide the choice of activities and land uses that can make the best (socio-economically efficient) use of land resources, i.e., cause the least environmental and socio-economic harm, avoid waste and generate the highest present and future environmental and socio-economic benefits, (b) resolve land-use conflicts, thus, alleviating current negative impacts and achieving positive environmental and socio-economic outcomes and (c) distribute equitably the costs and benefits of proposed interventions among the parties involved [3,52,54–57]. Essentially, LUP strives to match the demand for land resources by human activities with their supply to optimize general and place-specific goals and the overarching goal of sustainable local and regional development.

The numerous definitions encountered in the literature over time concur on the quintessence of LUP: (a) it is a process during which the actors involved set goals related to a problem (or, problems), develop alternative courses of action, choose available or devise new means to implement a chosen alternative to achieve the goals, evaluate the outcomes and make necessary modifications during

[13] e.g., geologic faults, seismic activity, unstable slopes, floodplains, habitats of endangered species, desertification-sensitive areas, erosion-prone areas, etc.

implementation; and (b) it is not a one-off operation that produces blueprints but a continuous, iterative, future-oriented decision-making process that comprises certain basic stages, serves certain key functions and is practiced following different styles [58,59].

The LUP process comprises certain basic stages: (a) problem definition and goal setting; (b) problem description and analysis; specification of planning objectives; (c) alternative plan formulation; (d) plan evaluation and choice of the preferred alternative; (e) plan implementation; (f) plan monitoring, evaluation and modification [52,54,60]. Figure 1 schematically presents this process and briefly describes the stages. These stages are not discrete and clearly delineated, they do not necessarily follow a linear succession in practice and they may overlap as some planning activities take place contemporaneously (e.g., problem definition and description, plan formulation and evaluation). Their boundaries are blurred, continuous feedbacks occur from one to another as demand and supply-related environmental and socio-economic conditions change, new actors get involved, new information is gathered, thus, continuously modifying the definition of the planning problem and the subsequent stages.

Land-use planning, like planning in general, is both a technical and a political process [61,62] that serves three functions: an *intelligence function* (data collection and analysis to build the information base concerning the demand and supply side of the planning problem), *advance plan-making* and *action/implementation* [52]. Depending on how LUP and the elements of the process are conceived, and on whether a proactive or a reactive decision making culture prevails, different planning styles (or, modes) are followed in practice. These include the classical (and by now mostly defunct) comprehensive or synoptic planning, incremental, transactive, advocacy, mixed scanning, contingency, adaptive and participatory planning [56,61,63,64]. The last three styles are particularly important in the case of natural hazards in general and LDD in particular.

In contemporary democratic, but increasingly complex societies, desirable features of LUP necessary to enhance its performance and effectiveness are strategic orientation, coordination and integration with development planning, wide participation (bottom up decision making), flexibility and adaptation [58,65,66]. These require well developed social and institutional capital and, above all, political will to devise and implement scientifically sound and socially acceptable solutions to socio-ecological problems that are characterized by considerable uncertainty [56]. In this context, the coordinating role of the advance plan-making function is critical in bridging the technical (intelligence) with the political (action/implementation) functions of LUP, thus, underlining the role of both science and politics in judging the outcomes of the process.

On the technical front, present-day LUP employs a variety of approaches, such as the landscape, the ecosystem and the multifunctional land-use approach [67–70], quantitative and qualitative analytical methods and techniques originating in the natural and the social sciences, such as land suitability analysis, environmental impact and risk analysis, needs assessment, survey research, environmental and social impact analysis, scenario analysis, integrated environmental-economic modeling, socio-ecological systems analysis [64,71–73], and planning support systems as well as traditional and contemporary data collection techniques (e.g., Earth observation systems, censuses, surveys).

On the political front, LUP combines a broad variety of technical/technological, physical, economic, financial, social, institutional and educational means and instruments, originating in environmental and socio-economic policy sectors and in various spatial/organizational levels, to produce and support the implementation of land use plans. Formal (institutionalized) and informal negotiation, mediation, bargaining and conflict resolution mechanisms and procedures are utilized toward this purpose [74,75].

The effectiveness of land-use planning depends critically on the availability of all types of resources (or, capitals) in the right combinations, in the right place and at the right time to successfully implement the land-use plan and meet the LUP goals and objectives. These requirements are rarely met in practice due to several reasons as discussed in the context of combating LDD below.

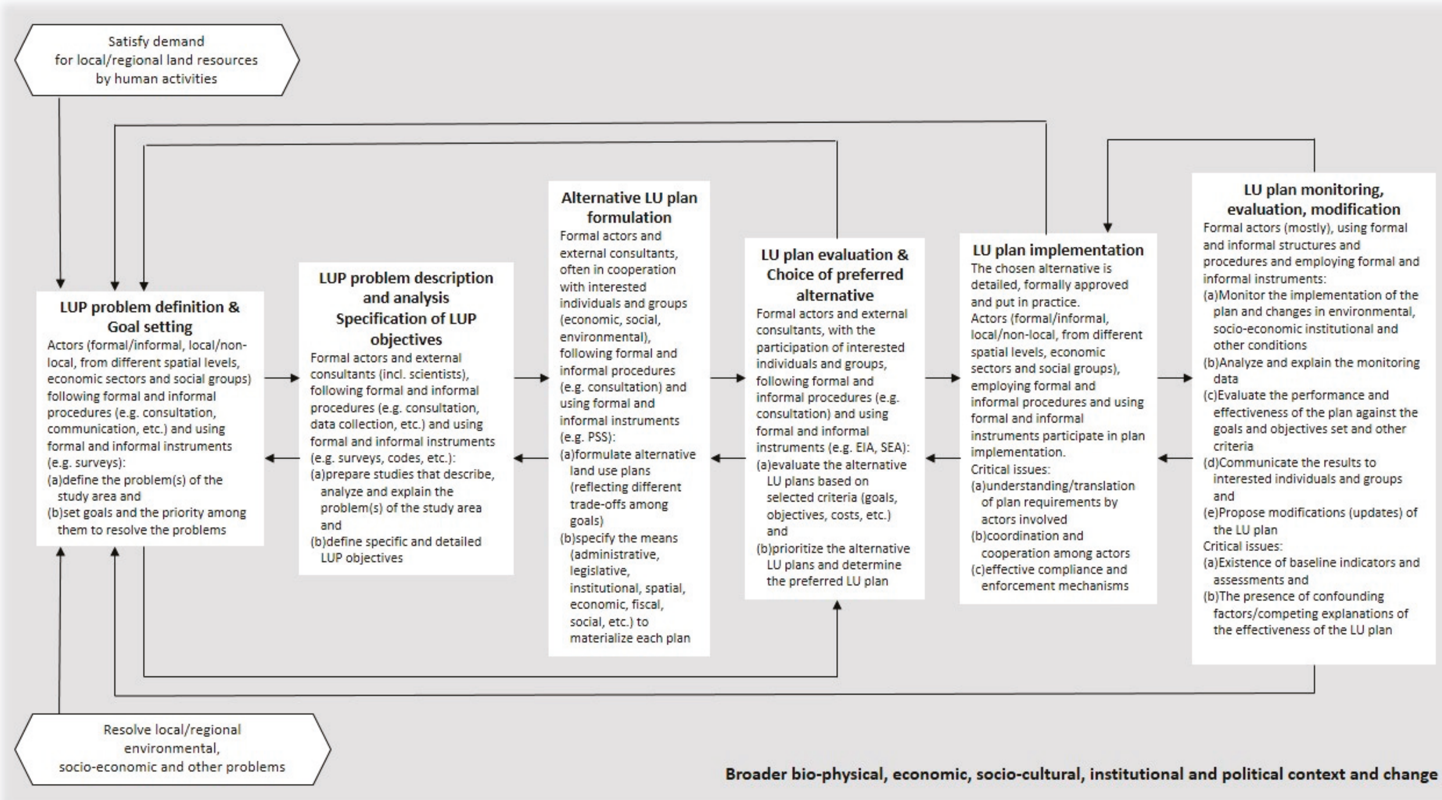


Figure 1. Schematic presentation of the land-use planning (LUP) process and description of the stages.

3.2. Land-Use Planning to Combat Land Degradation and Desertification

In affected areas, the general land-use planning problem is to determine those uses of land that will protect their land resources against LDD and will secure their socio-economic vitality (economic welfare, quality of life and social equity)—i.e., promote their sustainable development. The LDD-specific goal is to stop, reverse or moderate the degradation of land resources by properly selecting, siting and monitoring human activities. The land degradation neutrality (LDN) target gives more concrete, although not necessarily precise, direction: (a) reduce the rate of degradation by managing land more sustainably; and (b) increase the rate of restoration of degraded land, so that the two eventually produce zero net land degradation.

In order to assess the prospects of land-use planning successfully meeting the overarching goal of combating LDD and mitigating the impacts of drought at the local and the regional level, this section undertakes a reality check of the ideal LUP process; more specifically, it inquires whether and how LDD concerns enter, or may enter, the stages of the process. For each stage, the interplay of demand and supply factors is examined with regard to the actors involved, the organizational apparatus (decision structures and procedures) available and the instruments used. The use of stages is made for the purposes of analysis only because, as mentioned before, they intermingle and do not follow a given order in practice.

3.3. Problem Definition and Goal Setting

This stage concerns the question of *who* defines *what* problem and sets the LUP goals for the study area. It is the most critical stage of the LUP process and influences all subsequent stages. It takes place both formally and informally depending on the institutional status of planning and the administrative organization and culture that range from formal/centralized to informal/decentralized. A variety of mixed real world situations are encompassed in between. It is both demand- and supply-driven as the need for LUP in an area may arise from external or internal demand for its resources by economic activities and/or from the need to resolve environmental, socio-economic and other problems.

Various kinds of actors are implicated in LUP problem definition and goal setting. Some of them represent the demand and some other the supply side of the problem. Who and how can legitimately participate is determined by state laws and the associated procedures and instruments (e.g., consultation, committee membership).

Formal public actors (individuals and agencies) from various spatial/organizational levels represent spatial planning, regional and rural development, economic (agriculture, forestry, industry, extraction, tourism, energy production) and environmental sectors (water, soil, forests, nature protection, etc.). The latter potentially stand for LDD concerns. Planning consultants are also formally involved as states usually commission the preparation of LUP studies to specialized firms.

Other individual and collective actors may participate, as in decentralized systems following inclusionary, participatory processes, or they variously seek to influence formal actors and shift the LUP problem definition and the goals set to their advantage. These include economic interests placing demands on land [59], related intermediaries (e.g., construction and real estate sectors), social and environmental groups (e.g., NGOs, civic groups, etc.). In recent times, actors are increasingly non-locals (e.g., multinational firms, the EU, the World Bank) as in the case of tourism and second home development, infrastructure projects, energy production, industrial agriculture and forestry, etc. LDD concerns may be represented depending on the mandate and interests of these actors. Scientists may participate formally or they indirectly influence problem definition by disseminating scientific evidence concerning the magnitude and severity of LDD (studies, maps, indicators, etc.) among other problems.

Informal actors always co-exist with formal actors, act autonomously and in parallel with them, placing demands on land resources, making and carrying out their ‘plans’ outside the official apparatus in affected areas. They often create *de facto* land uses (e.g., informal agriculture, housing) and produce environmental, LDD-related problems (e.g., deforestation, fires, overgrazing, water overdrafting), that formal LUP is called to handle. Informal residential and tourism development in coastal LDD-sensitive areas in the Mediterranean and elsewhere and illegal deforestation in the Amazon are cases in point.

The effective legislation mandates the competences of and linkages among formal actors. The diverse linkages developing between formal and informal actors as well as among informal actors take two basic forms; coordination/cooperation or conflict. The perception and knowledge of the problems of the area, the vision regarding its future, the congruence of aspirations and the common interests among actors as well as the presence of externalities of the respective activities judge whether cooperation or conflict will result. In the case of conflicts, both formal and informal, customary conflict resolution procedures and prevailing power balances determine the outcome. Obviously, communication, common understanding and coordination among actors are necessary to produce a coherent LUP problem definition that encompasses LDD concerns. However, scientific uncertainty regarding LDD and its causes, together with lack of hard local and regional evidence, leaves ample room for multiple interpretations and adaptation to local circumstances.

The spatial, sectoral and administrative diversity and plurality of formal and informal actors, possessing differing mandates and knowledge of LDD, the compartmentalization of administrative structures even for the same resource (e.g., land, water, etc.) and turf politics [37] often result in vague and incoherent definitions that show up in goal setting. Formal LUP goal setting follows either in a top-down process, in the case of centralized systems and hierarchical modes of governance, or some form of participatory process in more decentralized systems. General national goals, often incorporating international obligations (e.g., climate change), include sustainable development, economic development, resource protection and conservation, as well as specific goals such as agricultural specialization, tourism development and energy production. Strategic goals concerning the protection of critical resources (water, soil, air, etc.), food and energy security, and others may be also specified. LDD-specific goals are included in the case of duly constituted NAPs. Agreement over general goals is usually easy to achieve especially if all actors share a common development vision for the area. Conflicts arise later when the more detailed planning objectives formulated reveal the critical trade-offs.

The priorities set among goals reveal the influence of dominant actors. The decisions regarding the uses of land are made on the basis of economic considerations mainly (demand side), often by nonlocal interests, and rarely on the basis of environmental considerations (supply side) except for symbolic purposes and extreme cases of environmental degradation, including LDD. Therefore, the protection of land resources is one of several socio-economic and environmental goals of LUP in affected areas, which depend on the specifics of each individual case but are, most likely, intricately related to LDD. The perception and knowledge of LDD which the formal and informal actors hold, that depend on scale, sector and social group, and the prevailing proactive or reactive decision culture critically determine the sense of urgency and the priority it is given compared to other problems. The possibilities range from total ignorance (theoretically possible but practically rather unlikely) to complete knowledge and concern for its impacts. At the local level, LDD is perceived as land degradation, not as desertification, and it is of direct concern to agricultural interests and environmental groups. LDD-related goals may be congruent and synergistic with certain goals, such as environmental protection, resource conservation and food security, or incompatible and antagonistic with some others, such as large-scale industrial, energy and tourism development. When goals conflict, the need for trade-offs among them and for specific LUP objectives that support consensus land use patterns arises.

LUP problem definition and goal-setting do not remain constant. They are often revised and modified especially when LUP processes are protracted. Economic, socio-cultural, environmental, administrative and political changes occurring at all levels modify environmental conditions (positively or negatively), introduce new actors, legislation and planning modes (e.g., participation), bring about changes in demand for land from new activities and different lifestyles, provide new knowledge and necessitate changes in priorities among goals. These changes create considerable uncertainty and necessitate emphasis on strategic goals, continuous top down-bottom up communication and coordination and broad actor representation and participation as well as integration, flexibility and openness as early in the LUP process as possible. However desirable these features may be, which characterize decentralized systems and are absent from hierarchical planning systems, they underline the complexity and explain the difficulties to come up with clear, coherent and consistent LUP problem definitions and goals in affected areas that prioritize combating LDD.

3.3.1. Problem Description and Analysis; Specification of Planning Objectives

Following the LUP problem definition, this stage aims, on the one hand, to set up the indispensable basis of plan making, i.e., the comprehensive and reliable description of the biophysical and human structure, dynamics and problems of the area, including LDD, and, on the other, to specify the LUP objectives.

Formal actors and external consultants are the most important actors at this stage although the role of other actors interested in the resources of the area should not be downplayed. The effective legislation may prescribe the relationships among these actors, such as formal requirements for plan development and the instruments (consultations between formal actors, consultants and the public) that have to be used. However, the most important relationships are informal, occurring during problem description, analysis and formulation of LUP objectives. New actors enter the process, such as data and information providers, new users of land and new formal actors, different from those involved in problem definition, responsible for formulating the specific LUP objectives.

Consultants take the problem definition and goals set as given but may propose modifications based on the description and analysis of the information and data collected for the affected area as well as on pertinent scientific theories, including those related to LDD. In this way, they may proactively introduce new concerns, activities and actors as well as underline the uncertainty surrounding the causes and effects of LDD and other problems of the area, thus, paving the road for feedbacks and problem redefinition and goal reformulation.

From the viewpoint of properly describing and analyzing LDD, the most important issues concern (a) the theoretical framing of the evolution and problems of the area; (b) the availability of reliable assessment techniques; and (c) the availability of suitable data. Scientific theories developed at higher spatial levels, including those contained in the NAPs, cannot satisfactorily address the causality of land use change and LDD at the local and regional level because they ignore the numerous, tangible and intangible, place-specific and contextual factors and their changes. Study area-specific theoretical frameworks are necessary to guide the situated description and analysis of the affected area for the purposes of LUP especially with respect to combating LDD [25,27,48,76].

Numerous LDD assessment methodologies, indicators and indices have been developed in the last decades to describe the extent and severity of LDD as well as to support LDD abatement decisions at the global, national and local/regional level [77–89]. The Environmental Sensitivity Assessment (ESA) methodology [79], in particular, concerns the assessment of desertification risk on the basis of selected indicators of climate, soil, vegetation and land management at lower levels (landscape/watershed, regional, national). It is continuously being used widely up to the present [90–96] and it has been refined through the application of Remote Sensing and GIS techniques [97–100].

From the viewpoint of their utility for LUP purposes at the local/regional level, the assumptions and limitations of these assessment methodologies and indicators should be kept in mind. Most of them use variables (or, indicators) for which published, regularly collected data are readily available. Issues related to the data used arise as discussed below. The operationalization of several factors (e.g., policy, land management) is based on expert judgment (for obvious reasons). Their suitability and transferability to lower levels of analysis and particular resources (point and nonpoint)[14], the assessment and mapping of LDD-related issues, such as the rate of degradation and the rate of restoration of degraded land, carrying capacity and many more remain open issues that should be treated judiciously [25,28,48,101].

The theoretical and methodological issues briefly discussed above raise important issues with respect to the suitability of existing data bases for the spatial scale and unit of analysis[15] and the time period for a LUP problem at hand. Existing data may concern units of analysis (e.g., mapping units, land units) that do not correspond to the actual decision making units in the study area [102] and may not be available for long time periods for all variables (environmental, economic, social, etc.) of interest. Aggregate land-use types (used in current data bases) may conceal more detailed uses of land at the level of the study area as human activities are multi-purpose and nonhomogeneous and more than one activities may occupy the same tract of land (the case of multifunctional landscapes) or co-exist vertically (the case of high-rise urban areas)[16]. Spatio-temporally consistent environmental, socio-economic and other data may be also lacking [102]. Lack of suitable data do not favor valid assessments and mapping of baseline values of pertinent LDD indicators (see, e.g., [38,87]), impact assessment of past interventions (e.g., policy measures) and of land-use change as well as projections of future demand (population, income, tourism, etc.) and supply of local resources (i.e., carrying capacity, potential, sensitivity and thresholds of critical biophysical and other factors). In sum, for LUP purposes the assessment methodologies and indicators should be used with caution as helpful but indicative and not the only guides to describe and assess, but not explain, the incidence and severity of LDD, to set LUP LDD-specific objectives, to operationalize the LDN target and to make land use decisions.

Numerous other factors complicate the description and analysis of affected areas such as the incidence of unexpected changes and the long time horizons that introduce uncertainty in predicting future land-use change, lack of appropriate environmental and socio-economic monitoring, and so on. Most importantly perhaps, lack of time, human and financial resources, data and expertise may preclude the use of suitable analytical techniques in area-specific analyses in LUP studies. These issues deem necessary detailed data collection and monitoring as well as analytical studies that are indispensable for formulating reliable study area-specific planning objectives in support of LUP to combat LDD, among other goals. Recent trends towards participatory data collection and analysis approaches [103,104] may partially ease the resolution of these issues.

3.3.2. Alternative Plan Formulation

Alternative land-use plans may be formulated to suggest different courses of action to match the present and future demand for land resources with the present and future supply of these resources to achieve the goals and the area-specific planning objectives set, a task critically hinging on problem description and analysis. In affected areas, the most critical question is which land use configuration can satisfy the goal of combatting LDD and the LDN target (or else, how the LDN target is integrated in LU plans) while meeting all other planning goals and objectives.

Plan formulation aiming at environmental protection and resource conservation should be proactive, guided, on the one hand, by strategic choices regarding critical land resources and, on the other, by the prevention, the precautionary and other principles [65,105]. The plans thus produced are more likely to safeguard the constant functioning of natural systems and the provision of ecosystem

---

14 Such as erosion models, agro-ecological zoning, statistical models, impact assessment and future projection models (climate, population, demand, supply, etc.).

15 As [3], (p. 117) has noted: " . . . proper analysis and meaningful resolution of environmental problems can take place only within natural spatial units, such as watersheds (Manning, 1988). However, practical considerations (data availability and ease of implementation mainly) dictate the use of administrative units most of the time, the result being fragmented, partial, and often ineffective solutions to these problems. Efforts to combine the two types of entities into geopolitical units, such as the 'environomic units' being developed in Canada (Gelinas, 1988), should be encouraged, as well as the formation of inter-jurisdictional bodies . . . "

16 The problem is more acute for small study areas that may suffer from severe LDD.

services that constitute the enabling condition of sustainable development [106]. In this context, an important consideration is the property status of land and other resources, such as water; i.e., whether they are private, state or common property [107,108] that significantly influences land-use allocation decisions[17] [109,110]. It is noted, however, that land resources, irrespective of property status, are common pool resources[18] that should be preserved for the benefit of all present and future users [111]. Given the fundamental role of soil and water resources in the LDD context and not only that, it follows that their protection should constitute a strategic LUP goal. While water resources enjoy a more or less satisfactory legislative protection and status in plan formulation, this not the case with soil resources. Land-use plans often prescribe uses of land that give rise to several soil threats—erosion, decline in organic matter, sealing, contamination, compaction, decline in biodiversity, salinization, landslides [46]—that increase the risk of LDD especially in sensitive affected areas.

Alternative plan formulation is usually carried out by planning consultants (including scientists) in cooperation and consultation with formal actors but also with diverse other interested actors, some of them entering at this stage of making critical land use allocation decisions. Guidance regarding how land-use plans should meet LDD-specific objectives such as improving the rate and extent of land restoration and reducing the rate and extent of land degradation is missing. The UNCCD sets broad goals and lacks operational guidelines and satisfactory indicators to measure progress at lower levels [32]. The NAPs usually focus on land uses related to the proximate causes of LDD—agriculture, animal husbandry, forests and, to a lesser extent, on tourism, extraction, transport, energy (e.g., renewable energy sources) and large infrastructure works (transport and energy networks, airports, etc.). They propose general activity-specific measures to minimize LDD because pertinent policy measures and instruments, such as environmental regulations, sustainable land management (SLM) practices, subsidies, etc., may be already in place and usually agree with dominant sectoral preferences. This is the case of the EU CAP agri-environmental and cross-compliance measures [33].

The focus on known proximate causes of LDD agrees with the common LUP practice where the uses of land in an area are determined by the present or future demand for land by economic activities. Activity-specific obligations are formally specified in order to avoid resource degradation and other predictable externalities. This practice of coupling demand with supply overlooks two important issues. First, the status of land resources is affected by numerous and diverse indirect drivers that modify, in one way or another, the demand for and thus, the pressures on land resources. These include outmigration, land abandonment, socio-economic restructuring, changes in urban-rural dynamics, changes in life styles (e.g., trends towards eco-living, eco-tourism, etc.), land and other taxation, and so on. This implies that, second, changes in these drivers may preclude the realization of chosen land-use combinations or, if realized, drastically modify their anticipated impacts, leading to either deterioration or effective protection of land resources. Therefore, LUP instruments, such as zoning (of hazard-prone and sensitive landscape areas), natural and cultural reserves, multifunctional land use schemes, should be coupled with economic, fiscal and other instruments, e.g., land and general taxation, incentive schemes, voluntary measures, to attain the LDN and related objectives [68,110].

This broadened perspective necessarily leads to the quest for integrated land-use planning that has been voiced since the early discussions of the issue [43,48] and more recently in discussing the materialization of the LDN goal [27,38]. The need for integrated and situated land-use plan formulation becomes evident at this stage of plan formulation as the effectiveness of any land-use plan depends on the spatial coordination of several activities, policy instruments, etc. at the level of the study area and across levels to promote individual and collective goals.

17 Private interests exert pressures on the LUP process and significantly affect the choices made.

18 Common Pool Resources (CPRs) are characterized by (a) non-excludability—they are indivisible and, thus, nobody can be ethically or practically be excluded from using them and (b) subtractability—they are finite and, thus use by one user reduces the amount of resource available to others [107,108].

The alternative land-use plans reflect, to different degrees, the trade-offs among different goals and objectives and, consequently, among the associated economic activities. This is a highly-charged political stage that, combined with uncertainty and land inertia, renders integrated land-use planning a challenging endeavor. Participatory decision making and planning is proposed, and occasionally practiced, in an effort to strike balances and arrive at land-use plans with higher chances of implementation [18,19,27,56,112]. Cross-compliance measures, that require the satisfaction of environmental goals as a condition for financial assistance, are practical, although partial, integrative instruments that may be used to integrate LDD concerns into LUP.

3.3.3. Plan Evaluation and Choice of Preferred Alternative

This stage, theoretically at least, concerns the evaluation of the alternative land-use plans on the basis of criteria flowing from the goals and objectives set in order to arrive at the preferred alternative that will be implemented. The priorities among criteria, which usually favor economic over environmental considerations, determine the final evaluation outcome. In practice, two alternatives are commonly considered: the existing land use pattern and a preferred land use pattern that meets the approval of interested actors. In this case, the evaluation essentially dissolves into a formal approval process of the preferred (and only) plan. Notice, however, that several alternatives may have been considered before the preferred one was chosen.

The actors involved in this stage are more or less the same with those participating at the previous stage. Formal evaluation instruments, such as the Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA), are commonly used, offering the opportunity to laypersons and other individuals who have not participated in the previous stages to express their opinion regarding the proposed plan or plans (in the rare case that there are more than one) through public consultation. These procedures, although they are proactive in nature, face several theoretical, methodological (analytical) and practical (data) challenges and their results are fraught with uncertainty [113]. Consequently, their potential to resolve essential questions regarding differences among alternative land use plans, in terms of goal achievement and distributive impacts, is limited. One issue of particular relevance in the LUP context is the requirement built into the EIA and SEA to evaluate alternatives for the same problem. Studies have shown that this requirement is rarely met [114]; alternatives are eliminated using qualitative reasoning mostly in support of the preferred alternative.

LDD concerns do or may enter this stage if LDD-related (or LDN-related) criteria are included in these formal procedures; they are often raised in the context of public consultations if they have not been integrated in the proposed plan(s). Their meaningful and effective application at the local and the regional levels is conditioned by the availability of data and baseline environmental and economic[19] assessments and the suitability of assessment techniques mentioned before.

3.3.4. Plan Implementation

Plan implementation remains the most critical stage of the LUP process because it constitutes the real test of whether the chosen land-use plan can materialize under actual, dynamic and fluid conditions. When land-use plans are put to practice a host of issues inevitably surface. These include omissions during previous stages (actors, local characteristics, LDD assessments, etc.), past planning and other legacies, pressures from interest groups, perception and understanding of the planning problems and prescriptions by the actors involved, conflicts between proposed/new and customary practices, endogenous and plan-induced change (externalities) and unexpected events and contingencies (natural and technological

---

[19] Economic assessments, and the respective methodologies, of the costs of LDD and the costs of various abatement options do exist but they are still not widely used in local and regional LUP practice [115–117]; (see, also, the ELD site at: http://www.eld-initiative.org/).

disasters, political and socio-economic events) in the study area and the rest of the world [118,119]. The end result is that the implemented land-use plan deviates from the chosen, legislated plan, implying that its actual environmental and socio-economic impacts will also differ from those originally assessed.

Plan implementation implicates a wide variety of formal and informal actors from various sectors, jurisdictions and spatial/organizational levels who variously contribute to the materialization of the proposed uses of land. Examples are formal local and regional administrators of various ranks, the courts, land owners/renters, farmers and their associations, real estate and building groups, banks, professionals (individuals and groups), the media, local and supralocal environmental and civic groups, residents, and so on [66]. This variety of actors engenders differences in decision culture (reactive vs. proactive), knowledge and perception of planning problems (including LDD), multiple local understandings and interpretations of planning goals, objectives and requirements of the land-use plan, different priorities among goals and interests, competences, reactions to change and local pressures, and power imbalances when conflicts arise. During implementation, the LUP problem is essentially redefined several times; issues that were not originally considered are included (e.g., safety and soil protection issues following severe floods, landslides or earthquakes). LDD may, thus, obtain significance if interest groups raise concerns during implementation that may lead to suspension or change if the approved land-use plan has potentially negative effects on soil and water resources.

The implementation of land-use plans requires cooperation and coordination among actors from various policy domains, such as agricultural, development, spatial, economic, social and environmental, the existence of formal procedures which guide their interactions as well as informal procedures based on mutual trust; i.e., on social capital. In the case of LDD, a strong commitment to the cause of combating LDD is indispensable for proper implementation of resource (soil, water, biodiversity) conservation requirements and pertinent plan provisions.

The most critical issue in plan implementation is compliance with the plan's requirements and the existence, application and effectiveness of formal and informal enforcement mechanisms (fines, penalties, etc.). Because of the inherent uncertainty of plans and the changes occurring during plan implementation, conflicts will always arise that necessitate the presence of effective conflict-resolution mechanisms. Compliance, enforcement and related mechanisms depend on local culture, tradition, familiarity with planning and on the broader mode of governance. Participatory land-use planning approaches aim at securing compliance by involving all actors early in the process. These are increasingly applied in coping with environmental problems, such as LDD, as a way to avoid non-implementation or significant deviations that will ultimately nullify the original plan. Their success is not guaranteed, however, because on the one hand socio-cultural, institutional and several practical factors condition participation and, on the other, power balances modify the outcomes that may not always favor combating LDD (e.g., development of water-intensive activities in water-deficient and degraded areas).

The less-than-satisfactory implementation record of several land-use plans reveals that the above requirements are difficult to meet in practice, the end result being implementation delays and uncertain outcomes. LDD may worsen, under unfavorable biophysical conditions and strong development pressures or, it may be reversed when pressures are reduced for other reasons (e.g., lack of development interest in the area, local resistance to development plans, etc.).

3.3.5. Plan Monitoring, Evaluation, Modification

Monitoring the implementation of land use plans aims at identifying and evaluating the issues arising and taking corrective action. Monitoring may be prescribed in the legislation and employed using suitable monitoring mechanisms (e.g., water metering, indicators, etc.) or it takes place voluntarily (see, e.g., [84]) or spontaneously when problems arise and necessitate resolution.

Monitoring is not a singular but a multiple operation involving old and new actors who, most likely, may not have complete knowledge of the land use plan and operate within narrow sectoral domains with specific mandates. Assuming that the required apparatus is in place, feeding back monitoring results (e.g., population change, land use change, soil conditions, water consumption, production levels, etc.) to formal and other actors requires proper transmission channels for the variety of actors and settings involved. Even with proper feedback, the monitoring results represent new information that is variously processed, translated and evaluated under conditions different from those prevailing when the initial land-use problem was posed and defined, planning goals were set, the land-use plan was formulated and implementation commenced [27].

Assessing and evaluating the monitoring results requires the existence of reliable local/regional level baseline indicators and assessment models, previous assessments, etc., a condition that is rarely met in practice. Evaluating the changes in the rate of LDD and of land restoration, in particular, is limited by the incomplete local/regional level assessments. Explaining the evaluation results, i.e., answering the question "what has caused the change", requires consideration of numerous endogenous and exogenous factors that may have contributed to change, in addition to the interventions associated with the land use plan. A single indicator is often difficult to describe and assess the latter because interventions are composite and complex actions. Attributing the changes in the rate of LDD and of land restoration to the land-use plan is, thus, a task that cannot yield dependable results to support plan modifications necessary to achieve the LDN and other LDD-related goals. Careful analysis of the monitoring results is needed accounting for the co-presence of several factors and concurrent changes that take place at all levels [27].

Land-use plan revisions may be prescribed in the legislation and they are usually undertaken every 10–15 years. They involve a comprehensive revision of the conditions of the study area since the official approval of the initial plan and propose required changes that reflect the changed conditions and the new demands for local and regional resources that arise with the passage of time. Whether plan revisions are prompted by or take into account LDD-related monitoring results, for shorter time intervals, is an open question that only thorough knowledge of the study area can answer.

4. Facing the Land-Use Planning Quandary

The reality check carried out in the preceding section suggests that the effectiveness of LUP as an instrument of land governance in combating LDD at the local and regional level depends on whether and how LDD concerns enter, or may enter, the stages of the LUP process. LDD problem complexity and severity, the state of scientific knowledge, market forces driving demand for land, the prevailing mode of governance (cf. [27]), the planning style followed, combined with local awareness, knowledge and perception of LDD, value systems and planning goal priorities, power balances, geographic particularities and historical circumstances are important catalyzing influences in this respect [33]. The complex nature of LDD implies that no single state agency can deal with it exclusively, as happens with simpler and less complex hazards[20]. Multiple, diverse, formal and informal, individual and collective actors are involved and numerous, disparate, formal and informal institutions from multiple organizational levels are implicated, interacting non-linearly on and across spatial and temporal scales [33,120]. All these forces generate a fluid and uncertain context within which LUP confronts important challenges. This concluding section first summarizes the main challenges and outlines necessary priority actions to realize the integrative potential of LUP and, thus, improve its effectiveness in combating LDD. Figure 2 schematically summarizes the rationale of the preceding analysis, the challenges identified and priority actions proposed.

[20] Even in this case, of, e.g., earthquakes, the responsibility for dealing with the issue may be divided among several competent state agencies.

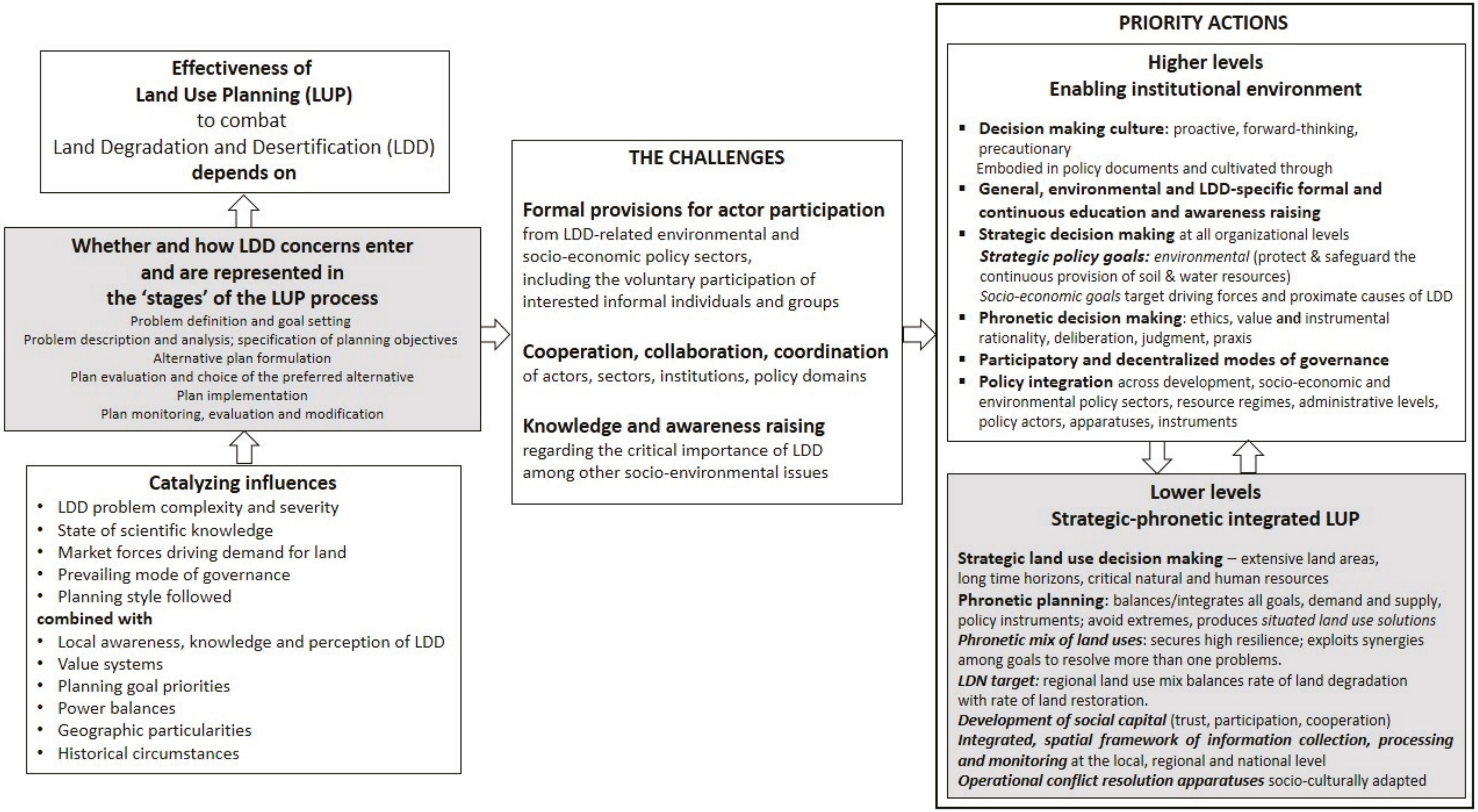


Figure 2. Enhancing the effectiveness of LUP to combat land degradation and desertification (LDD): challenges and priority actions.

The representation of LDD concerns at each stage of the LUP process depends on the existence of pertinent formal provisions for actor participation from LDD-related environmental and socio-economic policy sectors, including the voluntary participation of interested informal individuals and groups. Strong conflicts between LDD-related and socio-economic development goals are common, however, and create an adversarial context. The need thus arises for cooperation, collaboration and coordination of the numerous actors, sectors, institutions and policy domains involved to effectively resolve LUP conflicts and manage present and future environmental and socio-economic change. Hierarchical or mixed (hierarchical and market) governance systems, reactive planning styles (e.g., disjointed incrementalism), a myopic decision culture lacking a preparedness mentality, and the usual administrative and organizational compartmentalization, impede the satisfactory manipulation of these challenges as several real-world situations attest [30]. The attention and priority given to LDD in the LUP context depends on knowledge and awareness of its importance among other issues especially when strong development pressures and pro-development value systems dominate. Greater attention and concern is encountered in areas experiencing extreme LDD and lacking immediate development options and pressures. Moreover, climate change seems to have reinforced interest in effective sustainable land management to safeguard precious soil and water resources.

In order to improve the chances of LUP effectively coping with these challenges, certain priority actions are necessary at both higher and lower levels (cf. [27,118]). At higher levels, an enabling institutional environment should be provided[21] to support lower level actions. Featuring high among its crucial features is a proactive, forward-thinking and precautionary decision culture embodied in pertinent policy documents and cultivated through suitable general, environmental and LDD-specific formal and continuous education and awareness raising. Instituting strategic decision making, which is inherently long-term, should concern all spatial/organizational levels and be supported by suitable instruments. Strategic policy goals should encompass environmental, namely, protecting and safeguarding the continuous provision of soil and water resources, in addition to socio-economic goals. Socio-economic goals should target the driving forces of LDD[22] and not only the proximate causes as is current practice.

Phronesis (or, practical wisdom)[23], the most important of the principal virtues according to Aristotle, should be the guiding principle cutting across LUP decision making. The phronetic approach, first introduced by Flyvbjerg [122], underlines the situatedness of knowledge, decisions and action and emphasizes ethics, value rationality to balance instrumental rationality, deliberation, interpretation, judgment, participation, power relations and praxis. The possession and application of *phronesis* ensures the ethical employment of science (*episteme*), i.e., of universal rules, and technology (*techne*) in choosing the means in concrete, specific cases and adapting action to context [123].

Where hierarchical modes of governance and centralized planning traditions dominate, a gradual shift towards more participatory modes of governance and decentralized planning might be encouraged (and institutionalized) to benefit from greater participation of interested parties and flexibility in making decisions. However, care should be taken to ensure that participation is working for the common good and in the long run, it is based on a common understanding of LDD, and effective communication among the parties is involved as well as on cooperation around mutually agreed and shared goals and objectives. Lastly, the integrative potential of LUP can be realized only in the context of policy integration at higher spatial/organizational levels. This translates into the need for integration across development, socio-economic and environmental policy sectors, resource regimes, administrative levels, policy actors, apparatuses and instruments [39].

This enabling institutional environment is indispensable for framing and supporting the application of the widely commended and cited integrated LUP and lends it particular features

[21] As [1] has underlined already.
[22] That may be common to other socio-ecological problems.
[23] "(knowing) how to exercise judgment in particular cases" (MacIntyre, 1985: 154 cited in [121], (p. 381)).

that are necessary to achieve the integration of LDD concerns within the LUP process and address the LDN target. First, integrated LUP should develop around strategic land-use decision making, which concerns extensive land areas, long time horizons and critical natural and human resources (cf. [123]), and, thus, it is particularly relevant to LDD and to policy integration.

Second, integrated LUP should adopt the phronetic approach that is suitable when dealing with highly contentious, uncertain and 'wicked' LUP problems [31] that demand flexibility and adaptation to changing conditions, thus, requiring preparedness to cope with the impacts of LDD, LUP interventions and unanticipated events. The phronetic choice of land uses avoids prioritizing certain (usually narrow) goals only, often associated with monocultures and bound to cause serious adverse impacts; instead, it favors those that balance all goals, do not compromise the strategic ones, and support a mix of uses that secures high local and regional resilience. To achieve the LDN target specifically, the regional mix of land uses should balance the rate of land degradation with the rate of land restoration. Moreover, because the direct and indirect LDD drivers usually underlie other socio-ecological problems, phronetic land-use solutions may exploit synergies among the respective goals (e.g., food security, biodiversity conservation) to resolve more than one problems, including combating other natural hazards.

Third, integrated LUP should foster participation, communication and cooperation, i.e., the development of social capital [27], as the most important precondition for generating situated, ecologically sound and socially responsive integrated land-use solutions with high implementation potential. This echoes with certain NAPs[24] that prescribe detailed analyses of affected areas and case-by-case decision making.

Strategic-phronetic integrated LUP, as it might be called, targets both the demand (driving forces and proximate causes) and the supply side (resource conservation and protection) of LDD. It echoes the adaptive co-management approach [125] and combines a variety of policy instruments to support the development and implementation of situated land use solutions. These include SLM, spatial management instruments (impact zoning, transfer or purchase of development rights, land reserves, land banking, etc.), and fiscal and economic instruments, such as subsidies, tax breaks and resource use fees. Its effective implementation hinges on the existence of an integrated, spatial framework of information collection, processing and monitoring[25] at the local and regional levels [31] and of operational, socio-culturally adapted conflict resolution apparatuses. Lastly, it is essential that issues arising during implementation should be fed back to higher level institutions to introduce necessary changes in the enabling institutional environment and the decision-making apparatuses and instruments to facilitate adaptation to changing conditions and needs that local level action has revealed. Future research is required to explore the theoretical, methodological and empirical issues that should be addressed in order to provide operational guidance for its implementation to combat LDD in the context of other local and regional socio-ecological matters.

Funding: This research received no external funding.

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

References

1. UNCCD. *United Nations Convention to Combat Desertification*; UNCCD: Paris, France, 1994.
2. Manning, E.W. *The Analysis of Land-Use Determinants in Support of Sustainable Development*; International Institute for Applied Systems Analysis: Laxenburg, Austria, 1988.
3. Briassoulis, H. Pollution prevention for sustainable development: The land-use question. *Int. J. Sustain. Dev. World* **1994**, *1*, 110–120. [CrossRef]

[24] Such as the Greek NAP [124].
[25] Preferably based on hybrid, administrative-environmental spatial units.

4. MEA. *Ecosystems and Human Well-Being: Desertification Synthesis*; Millennium Ecosystem Assessment; World Resources Institute: Washington, DC, USA, 2005.
5. FAO. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW)—Managing Systems at Risk*; Food and Agriculture Organization of the United Nations: Rome, Italy; Earthscan: London, UK, 2011.
6. UNCCD. *The Global Land Outlook*, 1st ed.; United Nations Convention to Combat Desertification: Bonn, Germany, 2017.
7. IPBES. *Summary for Policymakers of the Assessment Report on Land Degradation and Restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*; Scholes, R., Montanarella, L., Brainich, A., Barger, N., ten Brink, B., Cantele, M., Erasmus, B., Fisher, B., Gardner, T., Holland, T.J., et al., Eds.; IPBES Secretariat: Bonn, Germany, 2018.
8. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; Resolution adopted by the General Assembly on 25 September 2015; A/RES/70/1; 4th Plenary Meeting; United Nations: New York, NY, USA, 2015.
9. Meyfroidt, P.; Chowdhury, R.; de Bremond, A.; Ellis, E.C.; Erb, K.H.; Filatova, T.; Garrett, R.D.; Grove, J.M.; Heinimann, A.; Kuemmerle, I.T.; et al. Middle-range theories of land system change. *Glob. Environ. Chang.* **2018**, *53*, 52–67. [CrossRef]
10. Global Land Programme. *Science Plan and Implementation Strategy*; IGBP Report No. 53/IHDP Report No. 19; IGBP Secretariat: Stockholm, Sweden, 2005; 64p.
11. Verburg, P.H.; Erb, K.-H.; Mertz, O.; Espindola, G. Land System Science: Between global challenges and local realities. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 433–437. [CrossRef] [PubMed]
12. Verburg, P.H.; Crossman, N.; Ellis, E.C.; Heinimann, A.; Hostert, P.; Mertz, O.; Nagendra, H.; Sikor, T.; Erb, K.-H.; Golubiewski, N.; et al. Land system science and sustainable development of the earth system: A global land project perspective. *Anthropocene* **2015**, *12*, 29–41.
13. Dearing, J.A.; Braimoh, A.K.; Reenberg, A.; Turner, B.L.; van der Leeuw, S. Complex land systems: The need for long time perspectives to assess their future. *Ecol. Soc.* **2010**, *15*, 21. [CrossRef]
14. Land. *Land System Science*, Special Issue. 2017; 6.
15. Marsh, G.P. *Man and Nature; or, the Earth as Modified by Human Action*; The Belknap Press of Harvard University Press: Cambridge, MA, USA, 1965; (Originally published in 1864).
16. Meyer, W.B.; Turner, B.L., II (Eds.) *Changes in Land Use and Land Cover: A Global Perspective*; Cambridge University Press: Cambridge, UK, 1994.
17. Turner, B.L., II; Clark, C.; Kates, R.W.; Richards, J.F.; Mathews, J.T.; Meyer, W.B. (Eds.) *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years*; Cambridge University Press: Cambridge, UK, 1990.
18. Burby, R.J. *Cooperating with Nature: Confronting Natural Hazards with Land-Use Planning for Sustainable Communities*; Joseph Henry Press: Washington, DC, USA, 1998.
19. Burby, R.J.; Deyle, R.E.; Godschalk, D.R.; Olshansky, R.B. Creating hazard resilient communities through land-use planning. *Nat. Hazards Rev.* **2000**, *1*, 99–106. [CrossRef]
20. Bowyer, C.; Withana, S.; Fenn, I.; Bassi, S.; Lewis, M.; Cooper, T.; Benito, P.; Mudgal, S. *Land Degradation and Desertification*; European Parliament; Policy Department A, Economic and Scientific Policy: Brussels, Belgium, 2009.
21. Low, P.S. (Ed.) Economic and Social Impacts of Desertification, Land Degradation and Drought. White Paper I. UNCCD 2nd Scientific Conference; Prepared with the Contributions of an International Group of Scientists. 2013. Available online: http://2sc.unccd.int (accessed on 2 November 2018).
22. Geist, H. *The Causes and Progression of Desertification*; Routledge: London, UK, 2017.
23. Imeson, A. *Desertification, Land Degradation and Sustainability*; Wiley: London, UK, 2011.
24. D' Odorico, P.; Battachan, A.; Davis, K.F.; Ravi, S.; Runyan, C.W. Global desertification: Drivers and feedbacks. *Adv. Water Res.* **2013**, *51*, 326–344. [CrossRef]
25. Reynolds, J.F.; Stafford-Smith, M. *Global Desertification: Do Humans Cause Deserts?* Dahlem University Press: Berlin, Germany, 2002.
26. Enne, G.; Zanolla, C.; Peter, D. (Eds.) *Desertification in Europe; Mitigation Strategies, Land-Use Planning*; EC, DG for Research Environment and Climate, Office of the Official Publications of the European Communities: Luxembourg, 2000.

27. Orr, B.J.; Cowie, A.; Castillo Sanchez, V.M.; Chasek, P.; Crossman, N.D.; Erlewein, A.; Louwagie, G.; Maron, M.; Metternicht, G.I.; Minelli, S.; et al. *Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface*; United Nations Convention to Combat Desertification (UNCCD): Bonn, Germany, 2017; Available online: https://www.unccd.int/sites/default/files/documents/2017-08/LDN_CF_report_web-english.pdf (accessed on 2 November 2018).
28. Van der Leeuw, S.E. Some potential problems with the implementation of Annex IV of the convention to combat desertification. In *Desertification in Europe; Mitigation Strategies, Land-use Planning*; Enne, G., Zanolla, C., Peter, D., Eds.; EC, DG for Research Environment and Climate, Office of the Official Publications of the European Communities: Luxembourg, 2000; pp. 249–262.
29. Turner, B.L.I.I.; Lambin, E.F.; Reenberg, A. The emergence of land change science for global environmental change and sustainability. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 20666–20671. [CrossRef] [PubMed]
30. Metternicht, G. *Land Use Planning*; Working paper. Global Land Outlook; United Nations Convention to Combat Desertification: Bonn, Germany, 2017.
31. Flyvbjerg, B. Phronetic planning research. Theoretical and methodological reflections. *Plan. Theory Pract.* **2004**, *5*, 283–306. [CrossRef]
32. Briassoulis, H. Desertification. In *Science and Policy. An A to Z Guide to Issues and Controversies*; Steel, B., Ed.; CQ Press: Thousand Oaks, CA, USA, 2014; pp. 138–145.
33. Briassoulis, H. Governing desertification in Mediterranean Europe: The challenge of environmental policy integration in multi-level governance contexts. *Land Degrad. Dev.* **2010**, *22*, 313–325. [CrossRef]
34. Turney, D.; Fthenakis, V. Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3261–3270. [CrossRef]
35. Hernandez, R.R.; Easter, S.B.; Murphy-Mariscal, M.L.; Maestre, F.T.; Tavassoli, M.; Allen, E.B.; Barrows, C.W.; Belnap, J.; Ochoa-Hueso, R.; Ravi, S.; et al. Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* **2014**, *29*, 766–779. [CrossRef]
36. Kaoshan, D.; Bergot, A.; Liang, C.; Xiang, W.-N.; Huang, Z. Environmental issues associated with wind energy—A review. *Renew. Energy* **2015**, *75*, 911–921.
37. Briassoulis, H. Complex Environmental Problems and the Quest for Policy Integration. In *Policy Integration for Complex Environmental Problems: The Example of Mediterranean Desertification*; Briassoulis, H., Ed.; Ashgate: Cheltenham, UK, 2005; pp. 1–49.
38. Grainger, A. Is Land Degradation Neutrality feasible in dry areas? *J. Arid Environ.* **2015**, *112 Pt A*, 14–24. [CrossRef]
39. Briassoulis, H. (Ed.) *Policy Integration for Complex Environmental Problems: The Example of Mediterranean Desertification*; Ashgate: Cheltenham, UK, 2005.
40. Wilson, G.A.; Juntti, M. (Eds.) *Unraveling Desertification: Policies and Actor Networks in Southern Europe*; Wageningen Academic Publishers: Wageningen, The Netherlands, 2005.
41. COP8. *Report of the Conference of the Parties on Its Eighth Session, Held in Madrid from 3 to 14 September 2007*; United Nations Convention to Combat Desertification; ICCD/COP(8)/16/Add.1; United Nations: Bonn, Germany, 2007.
42. UNCCD. *Towards a Land Degradation Neutral World*; United Nations Convention to Combat Desertification: Bonn, Germany, 2015; Available online: https://knowledge.unccd.int/sites/default/files/inline-files/Towards%20a%20Land%20Degradation%20Neutral%20World%20A%20Sustainable%20Development%20Priority.pdf (accessed on 2 November 2018).
43. UNCCD. *Achieving Land Degradation Neutrality*; United Nations Convention to Combat Desertification: Bonn, Germany, 2015; Available online: https://www.unccd.int/actions/achieving-land-degradation-neutrality (accessed on 2 November 2018).
44. UNCCD. *Land Degradation Neutrality. Resilience at Local, National and Regional Levels*; United Nations Convention to Combat Desertification: Bonn, Germany, 2015; Available online: http://catalogue.unccd.int/858_V2_UNCCD_BRO_.pdf (accessed on 27 September 2018).
45. Briassoulis, H. Factors affecting changes in land use and land cover. In *UNESCO Encyclopedia of Life Support Systems (EOLSS)*; EOLSS Publishers: Oxford, UK, 2003.
46. CEC. *Thematic Strategy for Soil Protection*; Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions; COM(2006)231 Final; Commission of the European Communities: Brussels, Belgium, 2006.

47. Hermann, S.M.; Hutchinson, C.F. The Scientific Basis: Links between Land Degradation, Drought and Desertification. In *Governing Global Desertification: Linking Environmental Degradation, Poverty and Participation*; Johnson, P.M., Mayrand, K., Paquin, M., Eds.; Ashgate: Aldershot, UK, 2006; pp. 11–26.
48. Bestelmeyer, B.T.; Oki, G.S.; Duniway, M.C.; Archer, S.R.; Sayre, N.F.; Williamson, J.C.; Herrick, J.E. Desertification, land use, and the transformation of global drylands. *Front. Ecol. Environ.* **2015**, *13*, 28–36. [CrossRef]
49. Scoones, I. *Sustainable Rural Livelihoods: A Framework for Analysis*; IDS Working Paper, 72; IDS: Brighton, UK, 1998.
50. Scoones, I. Livelihoods perspectives and rural development. *J. Peasant Stud.* **2009**, *36*, 171–196. [CrossRef]
51. Blaikie, P.; Brookfield, H. *Land Degradation and Society*; Routledge: London, UK, 1987.
52. Kaiser, E.J.; Godschalk, D.J.; Chapin, F.S. *Urban Land Use Planning*, 4th ed.; University of Illinois Press: Urbana, IL, USA, 1995.
53. Van Lier, H. The role of land use planning in sustainable rural systems. *Landsc. Urban Plan.* **1998**, *41*, 83–91. [CrossRef]
54. Food and Agriculture Organization (FAO). *Guidelines for Land-Use Planning*; FAO: Rome, Italy, 1996.
55. Godschalk, D.R. Land Use Planning Challenges: Coping with Conflicts in Visions of Sustainable Development and Livable Communities. *J. Am. Plan. Assoc.* **2004**, *70*, 5–13. [CrossRef]
56. Randolph, J. *Environmental Land Use Planning and Management*, 2nd ed.; Island Press: Washington, DC, USA, 2004.
57. Godschalk, D.R.; Beatley, T.; Berke, P.; Brower, D.J.; Kaiser, E.J. *Natural Hazard Mitigation: Recasting Disaster Policy and Planning*; Island Press: Washington, DC, USA, 1999.
58. Healey, P. *Collaborative Planning*; Shaping Places in Fragmented Societies; UBC Press: Vancouver, BC, Canada, 1997.
59. Healey, P. *Urban Complexity and Spatial Strategies*; Routledge: London, UK, 2007.
60. Food and Agriculture Organization (FAO). *Planning for Sustainable Use of Land Resources*; FAO Land and Water Bulletin 2; FAO: Rome, Italy, 1995.
61. Faludi, A. *A Reader in Planning Theory*; Pergamon: Oxford, UK, 1973.
62. Howe, E.; Kaufmann, J. The ethics of contemporary American planners. *J. Am. Plan. Assoc.* **1979**, *45*, 243–255. [CrossRef]
63. Bolan, R. Emerging views of planning. *J. Am. I. Plan.* **1967**, *33*, 233–245. [CrossRef]
64. Briassoulis, H. Theoretical Orientations in Environmental Planning: An Inquiry into Alternative Styles. *Environ. Manag.* **1989**, *13*, 381–392. [CrossRef]
65. ESDP. *European Spatial Development Perspective: Towards Balanced and Sustainable Development of the Territory of the EU*; European Commission, Office for Official Publications of the European Communities: Luxembourg, 1999.
66. Albrechts, L. Strategic (spatial) planning reexamined. *Environ. Plan. B* **2004**, *31*, 743–758. [CrossRef]
67. White, R.P.; Tunstall, D.; Henninger, N. *An Ecosystem Approach to Drylands: Building Support for New Development Policies*; Information Policy Brief No.1; World Resources Institute: Washington, DC, USA, 2002.
68. Vreeker, R.; de Groot, H.I.F.; Verhoef, E.T. Urban Multifunctional Land Use: Theoretical and Empirical Insights on Economies of Scale, Scope and Diversity. *Built Environ.* **2004**, *30*, 289–307. [CrossRef]
69. Vasishth, A. A scale-hierarchic ecosystem approach to integrative ecological planning. *Prog. Plan.* **2008**, *70*, 99–132. [CrossRef]
70. Sayer, J.; Sunderland, T.; Ghazoul, J.; Pfund, J.-L.; Sheil, D.; Meijaard, E.; Venter, M.; Klintuni Boedhihartono, A.; Day, M.; Garcia, C.; et al. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 8349–8356. [CrossRef] [PubMed]
71. McHarg, I. *Design with Nature*; Natural History Press: Garden City, NY, USA, 1969.
72. Food and Agriculture Organization (FAO). *Land Evaluation: Towards a Revised Framework*; Land and Water Discussion Paper 6; TC/D/A1080E/1/04.07; FAO: Rome, Italy, 2007; ISSN 1729-0554. Available online: http://www.fao.org/nr/lman/docs/lman_070601_en.pdf (accessed on 2 November 2018).
73. Binder, C.R.; Hinkel, J.; Bots, P.W.G.; Pahl-Wostl, C. Comparison of frameworks for analyzing social-ecological systems. *Ecol. Soc.* **2013**, *18*, 26. [CrossRef]
74. Susskind, L.; Ozawa, C. Mediated Negotiation in the Public Sector: The Planner as Mediator. *J. Plan. Educ. Res.* **1984**, *4*, 5–15. [CrossRef]
75. Forester, J. Planning in the face of Conflict. *J. Am. Plan. Assoc.* **1987**, *53*, 434–446. [CrossRef]
76. Geist, H.J.; Lambin, E.F. Dynamic causal patterns of desertification. *BioScience* **2004**, *54*, 817–829. [CrossRef]

77. Dharumarajan, S.; Bishop, T.F.A.; Hedge, R.; Singh, S.K. Desertification vulnerability index—An effective approach to assess desertification processes: A case study in Anantapur District, Andhra Pradesh, India. *Land Degrad. Dev.* **2018**, *29*, 150–161. [CrossRef]
78. Helldén, U.; Tottrup, C. Regional desertification: A global synthesis. *Glob. Planet. Chang.* **2008**, *64*, 169–176. [CrossRef]
79. Kosmas, C.; Ferrara, A.; Briasouli, H.; Imeson, A. Methodology for mapping Environmentally Sensitive Areas (ESAs) to Desertification. In *The Medalus Project: Mediterranean Desertification and Land Use. Manual on Key Indicators of Desertification and Mapping Environmentally Sensitive Areas to Desertification*; Kosmas, C., Kirkby, M., Geeson, N., Eds.; European Union: Brussels, Belgium, 1999; pp. 31–47. ISBN 92-828-6349-2.
80. Kosmas, C.; Poesen, J.; Briassouli, H. Key indicators of desertification at the ESA scale. In *The Medalus Project: Mediterranean Desertification and Land Use. Manual on Key Indicators of Desertification and Mapping Environmentally Sensitive Areas to Desertification*; Kosmas, C., Kirkby, M., Geeson, N., Eds.; European Union: Brussels, Belgium, 1999; pp. 11–30. ISBN 92-828-6349-2.
81. Kosmas, K.; Tsara, M.; Moustakas, N.; Karavitis, C. Identification of indicators for desertification. *Ann. Arid Zones* **2003**, *42*, 393–416.
82. Kosmas, C.; Kairis, O.; Karavitis, C.; Ritsema, C.; Salvati, L.; Acikalin, S.; Alcalá, M.; Alfama, P.; Atlhopheng, J.; Barrera, J.; et al. Evaluation and Selection of Indicators for Land Degradation and Desertification Monitoring: Methodological Approach. *Environ. Manag.* **2013**, *54*, 951–970. [CrossRef] [PubMed]
83. Panagiotis, T.N.; Nadia, P.; Kapsomenakis, J. Spatial and temporal variability of the Aridity Index in Greece. *Atmos. Res.* **2013**, *119*, 140–152.
84. Reed, M.S.; Dougill, A.J. Linking degradation assessment to sustainable land management: A decision support system for Kalahari pastoralists. *J. Arid Environ.* **2010**, *74*, 149–155. [CrossRef]
85. Salvati, L.; Mancino, G.; De Zuliani, E.; Sateriano, A.; Zitti, M.; Ferrara, A. An expert system to evaluate environmental sensitivity: A local scale approach to desertification risk. *Appl. Ecol. Environ. Res.* **2013**, *11*, 611–627. [CrossRef]
86. Sommer, S.; Zucca, C.; Grainger, A.; Cherlet, M.; Zougmore, R.; Sokona, Y.; Hill, J. Application of indicator systems for monitoring and assessment of desertification from national to global scales. *Land Degrad. Dev.* **2011**, *22*, 184–197. [CrossRef]
87. Verón, S.R.; Paruelo, J.M.; Oesterheld, M. Assessing desertification. *J. Arid Environ.* **2006**, *66*, 751–763. [CrossRef]
88. Xu, D.; You, X.; Xia, C. Assessing the spatial-temporal pattern and evolution of areas sensitive to land desertification in North China. *Ecol. Indic.* **2019**, *97*, 150–158. [CrossRef]
89. Zdruli, P.; Pagliai, M.; Kapur, S.; Cano, A.F. (Eds.) *Land Degradation and Desertification: Assessment, Mitigation and Remediation*; Springer: Berlin, Germany, 2010.
90. Capozzi, F.; Di Palma, A.; De Paola, F.; Giugni, M.; Iavazzo, P.; Topa, M.E.; Adamo, P.; Giordano, S. Assessing desertification in sub-Saharan peri-urban areas: Case study applications in Burkina Faso and Senegal. *J. Geochem. Explor.* **2018**, *190*, 281–291. [CrossRef]
91. Contador, J.F.L.; Schnabel, S.; Gutiérrez-Gómez, A.; Fernández, M.P. Mapping sensitivity to land degradation in Extremadura. SW Spain. *Land Degrad. Dev.* **2009**, *20*, 129–144. [CrossRef]
92. Jiang, L.; Bao, A.; Jiaper, C.; Guo, H.; Zheng, G.; Gafforov, K.; Kurban, A.; De Mayer, P. Monitoring land sensitivity to desertification in Central Asia: Convergence or divergence? *Sci. Total Environ.* **2019**, *658*, 669–683. [CrossRef] [PubMed]
93. Labbaci, A.; Kabbachi, B.; Ezaidi, A.; Thorne, J. An Assessment of Sensitivity to Desertification in Western High Atlas of Morocco: An Application to Ain Asmama Site. In *Recent Advances in Geo-Environmental Engineering, Geomechanics and Geotechnics, and Geohazard*; Kallel, A., Erguler, Z.A., Cui, Z.D., Karrech, A., Karakus, M., Kulatilake, P., Shukla, S.K., Eds.; Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable Development); Springer: Cham, Switzerland, 2019.
94. Lahlaoi, H.; Rhinane, H.; Hilali, A.; Lahssini, S.; Moukrim, S. Desertification assessment using MEDALUS model in watershed Oued El Maleh, Morocco. *Geosciences.* **2017**, *7*, 50. [CrossRef]
95. Prăvălie, R.; Săvulescu, I.; Patriche, C.; Dumitraşcu, M.; Bandoc, G. Spatial assessment of land degradation sensitive areas in south-western Romania using modified MEDALUS method. *Catena* **2017**, *153*, 114–130. [CrossRef]

96. Tsesmelis, D.E.; Karavitis, C.A.; Oikonomou, P.D.; Alexandris, S.; Kosmas, C. Assessment of the Vulnerability to Drought and Desertification Characteristics Using the Standardized Drought Vulnerability Index (SDVI) and the Environmentally Sensitive Areas Index (ESAI). *Resources* **2019**, *8*, 6. [CrossRef]
97. Boudjemline, F.; Semar, A. Assessment and mapping of desertification sensitivity with MEDALUS model and GIS—Case study: Basin of Hodna, Algeria. *J. Water Land Dev.* **2018**, *36*, 17–26. [CrossRef]
98. Leman, N.; Ramli, M.F.; Khirotdin, P.K. GIS-based integrated evaluation of environmentally sensitive areas (ESAs) for land use planning in Langkawi, Malaysia. *Ecol. Indic.* **2016**, *61*, 293–308. [CrossRef]
99. Rabah, B.; Aida, B. Adaptation of MEDALUS Method for the Analysis Depicting Land Degradation in Oued Labiod Valley (Eastern Algeria). In *Advances in Remote Sensing and Geo Informatics Applications*; El-Askary, H., Lee, S., Heggy, E., Pradhan, B., Eds.; Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable Development); Springer: Cham, Switzerland, 2019.
100. Symeonakis, E.; Karathanasis, N.; Koukoulas, S.; Panagopoulos, G. Monitoring sensitivity to land degradation and desertification with the Environmentally Sensitive Area Index: The case of Lesvos island. *Land Degrad. Dev.* **2016**, *27*, 1562–1573. [CrossRef]
101. Vogt, J.V.; Safriel, U.; Von Maltitz, G.; Sokona, Y.; Zougmore, R.; Bastin, G.; Hill, J. Monitoring and assessment of land degradation and desertification: Towards new conceptual and integrated approaches. *Land Degrad. Dev.* **2011**, *22*, 150–165. [CrossRef]
102. Briassoulis, H. Policy-Oriented Integrated Analysis of Land-Use Change: An Analysis of Data Needs. *Environ. Manag.* **2001**, *27*, 1–11. [CrossRef]
103. Whitfield, S.; Reed, M.S. Participatory environmental assessment in drylands: Introducing a new approach. *J. Arid Environ.* **2012**, *77*, 1–10. [CrossRef]
104. Stringer, L.C.; Fleskens, L.; Reed, M.S.; de Vente, J.; Zengin, M. Participatory Evaluation of Monitoring and Modeling of Sustainable Land Management Technologies in Areas Prone to Land Degradation. *Environ. Manag.* **2014**, *54*, 1022–1042. [CrossRef]
105. Buxton, M.; Haynes, R.; Mercer, D.; Butt, A. Vulnerability to Bushfire Risk at Melbourne's Urban Fringe: The Failure of Regulatory Land Use Planning. *Geogr. Res.* **2011**, *49*, 1–12. [CrossRef]
106. Sadler, B.; Jacobs, P. A key to tomorrow: On the relationship of environmental assessment and sustainable development. In *Sustainable Development and Environmental Assessment: Perspectives on Planning for a Common Future*; Jacobs., P., Sadler, B., Eds.; Canadian Environmental Assessment Research Council: Ottawa, ON, Canada, 1991; pp. 3–32.
107. Ostrom, E. *Governing the Commons: The Evolution of Institutions of Collective Action*; Cambridge University Press: Cambridge, UK, 1990.
108. Bromley, D. *Environment and Economy*; Blackwell Publishers: Cambridge, UK, 1991.
109. Harou, P.A. What is the role of markets in altering the sensitivity of arid land systems to perturbation? In *Governing Desertification*; Do Humans Cause Deserts; Reynolds, J.F., Stafford-Smith, D.M., Eds.; Dahlem University Press: Berlin, Germany, 2002; pp. 253–274.
110. Deininger, K. *Land Policies for Growth and Poverty Reduction*; The World Bank: Washington, DC, USA, 2003.
111. National Research Council. *The Drama of the Commons*; The National Academies Press: Washington, DC, USA, 2002.
112. Hessel, R.; van den Berg, J.; Kaboré, O.; van Kekem, A.; Verzandvoort, S.; van Kekem, A.; Verzandvoort, S.; Dipama, J.-M. Linking participatory and GIS-based land use planning methods: A case study from Burkina Faso. *Land Use Policy* **2009**, *26*, 1162–1172. [CrossRef]
113. Morgan, R.K. Environmental impact assessment: The state of the art. *Impact Assess. Proj. A* **2012**, *30*, 5–14. [CrossRef]
114. CEC. *On the Application and Effectiveness of the EIA Directive*; Directive 85/337/EEC, as amended by Directives 97/11/EC and 2003/35/EC; COM(2009)378 Final; Commission of the European Communities: Brussels, Belgium, 2009.
115. Nkonya, E.; Gerber, N.; Baumgartner, P.; von Braun, J.; De Pinto, A.; Graw, V.; Kato, E.; Kloos, J.; Walter, T. *The Economics of Desertification, Land Degradation, and Drought toward an Integrated Global Assessment*; IFPRI Discussion Paper 01086; International Food Policy Research Institute and ZEF: Bonn, Germany, 2011.
116. UNCCD. The Economics of Desertification, Land Degradation and Drought: Methodologies and Analysis for Decision-Making. Background Document; United Nations Convention to Combat Desertification 2nd Scientific Conference. 2013. Available online: http://2sc.unccd.int (accessed on 2 November 2018).

117. Giger, M.; Liniger, H.; Sauter, C.; Schwilch, G. Economic Benefits and Costs of Sustainable Land Management Technologies: An Analysis of WOCAT's Global Data. *Land Degrad. Dev.* **2018**, *29*, 962–974. [CrossRef]
118. Glavovic, B.C.; Saunders, W.S.A.; Becker, J.S. Land-use planning for natural hazards in New Zealand: The setting, barriers, 'burning issues' and priority actions. *Nat. Hazards* **2010**, *54*, 679–706. [CrossRef]
119. Sapountzaki, K.; Wanczura, S.; Casertano, G.; Greiving, S.; Xanthopoulos, G.; Ferrara, F.F. Disconnected policies and actors and the missing role of spatial planning throughout the risk management cycle. *Nat. Hazards* **2011**, *59*, 1445–1474. [CrossRef]
120. Briassoulis, H. The Institutional Complexity of Environmental Policy and Planning Problems: The Example of Mediterranean Desertification. *J. Environ. Plan. Manag.* **2004**, *47*, 115–135. [CrossRef]
121. Shotter, J.; Tsoukas, H. Performing phronesis: On the way to engaged judgment. *Manag. Learn.* **2014**, *45*, 377–396. [CrossRef]
122. Flyvbjerg, B. *Making Social Science Matter*; Cambridge University Press: Cambridge, UK, 2001.
123. Healey, P. In Search of the "Strategic" in Spatial Strategy Making. *Plan. Theory Pract.* **2009**, *10*, 439–457. [CrossRef]
124. GNCCD. *Greek National Action Plan for Combating Desertification*; Greek National Committee for Combating Desertification: Athens, Greece, 2001.
125. Plummer, R.; Crona, B.; Armitage, D.R.; Olsson, R.; Tengö, M.; Yudina, O. Adaptive comanagement: A systematic review and analysis. *Ecol. Soc.* **2012**, *17*, 11. [CrossRef]

© 2019 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

land

MDPI

Article

Coastal Hazard Vulnerability Assessment Based on Geomorphic, Oceanographic and Demographic Parameters: The Case of the Peloponnese (Southern Greece)

Alexandra Tragaki, Christina Gallousi and Efthimios Karymbalis *

Department of Geography, School of Environment, Geography and Applied Economics, Harokopio University, 70 El. Venizelou Av., 17671 Kallithea, Athens, Greece; atragaki@hua.gr (A.T.); xgallousi@gmail.com (C.G.)
* Correspondence: karymbalis@hua.gr; Tel.: +30-210-9543159

Received: 5 April 2018; Accepted: 26 April 2018; Published: 1 May 2018

Abstract: Today low-lying coastal areas around the world are threatened by climate change-related hazards. The identification of highly vulnerable coastal areas is of great importance for the development of coastal management plans. The purpose of this study is to assess the physical and social vulnerability of the Peloponnese (Greece) to coastal hazards. Two indices were estimated: The Coastal Vulnerability Index (CVI) and the Social Vulnerability Index (SVI). CVI allows six physical variablesto be related in a quantitative manner whilethe proposed SVI in this studycontains mainly demographic variables and was calculated for 73 coastal municipal communities. The results reveal that 17.2% of the shoreline (254.8 km) along the western and northwestern coast of the Peloponnese, as well as at the inner Messiniakos and Lakonikos Gulfs, is of high and very high physical vulnerability. High and very high social vulnerabilities characterize communities along the northwestern part of the study area, along the coasts of the Messinian and Cape Malea peninsulas, as well as at the western coast of Saronikos Gulf.

Keywords: sea-level rise; storm surge; physical vulnerability; social vulnerability; Peloponnese; Greece

---

1. Introduction

Coastal areas have always been attractive settling grounds for human populations. They constitute the transitional zone between land and the marine environment; a particular area with unique natural and socioeconomic characteristics thatencourage the concentration of human activities [1]. Land cover change is considered an important element of recent environmental change at a global level. The rate of land-cover alteration in the coastal regions is increasing dramatically worldwide due to the increasing and intensifying human use of the land. These changes have also been analyzed in semi-arid and dry Mediterranean areas, concentrating specificallyon the consequences of farmland abandonment and reforestation carried out at different scales [2]. The Mediterranean coastal zone has a history of a millennia of, more or less, intensive human use. During the last century, the population along the Mediterranean coasts has grown impressively. Changes in the coastal landscapes are mainly due to changes in human land use that in turn are the result of changes in the wider socio-economic environment. In the era of globalization, coastal rural space takes up new content due to the changes related to the fact that rural locales are no longer agricultural sites, as in the past [3]. Moreover, plenty of rural places in coastal zone have now become "peri-urban" areas. At the present moment, besides the regions surrounding the largest cities, population increase has slowed in the remaining areas. Demographic dynamics have highlighted the gap between populations living in urban centers as opposed to the surrounding rural areas. Since the 1980s, however, several Mediterranean cities have undergone a rapid transition from the traditional "compact growth" model to the more "dispersed" ones, characterized by huge expansions of the built up area around the core [4,5]. Following economic growth, the most recent challenge was a drastic low-density sprawl coupled with impressive deconcentration processes in inner coastal cities. The mobility of the urban population to coastal rural/peri-urban areas has brought to the fore new issues related to land use/land cover change and to the changing perceptions of rural place, of local needs, and of priorities for rural development [6]. These changes in land use and land cover increase the exposure of coastal communities to a range of natural hazards [7]. Hence today low-lying coastal areas around the world are threatened by climate change-related hazards, such as the accelerated global mean sea-level rise and extreme storm surge events [8–13].

Global mean sea-level rise is caused by an increase in the volume of the oceans. This in turn is caused by thermal expansion (due to the warming of the oceans), loss of ice by glaciers and ice sheets, and a reduction of liquid water storage on land [14]. Although the exact rates of present and future global mean sea-level rise due to global warming are uncertain, it is predicted to reach approximately 53–98 cm by the year 2100 [15]. The most adverse projections are reported by Pfeffer et al. [16], who project asea-level rise likely to reach 0.8 m to 2 m. According to this study, the IPCC has not successfully modeled the dynamic development (decline) of the Greenland and Antarctic glaciers, a view also supported by other researchers (e.g., [17,18]).

Extreme storm surge events constitute an additional hazard. Storm surges, also referred to as meteorological residuals or meteorological tides, constitute along with the waves and the tidal oscillations the main components of extreme water levels along the coastal zone [9,19]. Storm surges are forced by wind driven water circulation towards or away from the coast and by atmospheric pressure driven changes of the water level; i.e., the inverse barometric effect. Some studies report an increased intensity and frequency of extreme water levels along several coastal regions in the world [20–23]. Hence the anticipated increase in extreme total water levels due to relative sea-level rise can be further enforced by an increase of the extreme storm surge level, which can exceed 30% of the relative sea-level rise [24].

Present sea-level trends in the Mediterranean basin have been estimated by analyzing available tide-gauge records longer than 35 years anda sea-level trend between 1.2 and 1.5 $\pm$ 0.1 mm/year has been calculated for the longest records [25]. Decadal sea-level trends in the Mediterranean are not always consistent with global values. In particular, during the 1990s the Mediterranean has shown enhanced sea level rise of up to 5 mm/year compared to the global average (mostly attributed to higher warming). The sea-level trend for the period between 1944 and 1989, observed in Alexandria (Egypt), at the only long-term gauge station in the Eastern Mediterranean, is 1.9 $\pm$ 0.2 mm/year and is the highest of the other stations in the basin [25]. According to the recent reports [15], mean sea-level in the Mediterranean is expected to rise at the rate of 5 cm/decade during the 21st century.

Regional projections of storm surge levels have been generated along the Mediterranean [26–28]. These projections show a general decreasing trend in the storminess of storm surge extremes in the Mediterranean Sea for a period of 150 years (1951–2100) under most of the considered climate change scenarios. This decreasing trend is mostly related to the frequency of local peaks and the duration and spatial coverage of the storm surges. However, the magnitudes of sea surface elevation extremes may increase in several Mediterranean sub-regions during the 21st century. There are clear distinctions in the contributions of winds and pressure fields to the sea-level height for various regions of the Mediterranean Sea, as well as on the seasonal variability of extreme values. The Aegean and Adriatic Seas are characteristic examples, where high surges are predicted to be mainly induced by low pressure systems and favorable winds, respectively [29].

Among the significant negative effects of the climate change-related coastal hazards are: coastal erosion with consequent loss of land of great economic, social, and environmental valueand infrastructure, frequent flooding of the low-lying coastal plains, inundation of ecologically significant wetlands, and threats to cultural and historical resources. Hence the identification of "sensitive" sections of coastline as well as the assessment of social vulnerability of the coastal communities is necessary for the development of coastal management plans. The understanding of a coastlines' response to both long-term and short-term sea-level rise as well as the assessment of the vulnerability of the coastal communities have become an important issue in recent years. Various approaches (mainly in the form of indices) have been proposed to predict the evolution of the coastal zone under the influence of sea-level rise. The relative physical vulnerability of different coastal environments to sea-level rise may be quantified by considering information regarding the important variables that contribute to coastal evolution in a given area, such as coastal geomorphology and slope, shoreline displacement, rate of relative sea-level change, tide range, wave height, and other related factors. Indices based mainly on these physical variables have been used to assess the physical vulnerability of coasts in the USA, Europe, Brazil, India, and Greece [30–37].

Recently, research on hazards in coastal areas has highlighted the need to incorporate other variable than physical variables in an attempt to capture the so-called social vulnerability [33,38–40]. Social vulnerability is described by various characteristics that condition a community's ability to respond to, cope with, recover from, and adapt to environmental hazards. According to a steadily growing literature, the socio-economic and demographic features are the main factors influencing social vulnerability [41]. In this context, investigations have been made relating to the evaluation of risk in coastal zones by taking into account not only natural but also socio-economic variables [39,42–45].

The aim of this study is to assess the overall vulnerability (physical and social) of the Peloponnese (southern Greek mainland) to both coastal erosion and flooding caused by climate change-related hazards. The assessment relies on the calculation of a Coastal Vulnerability Index (CVI) and a Social Vulnerability Index (SVI). The use of a quantitatively derived social vulnerability index, such as the proposed SVI, is important for two reasons. First, the method provides a useful tool for comparing the spatial variability in social vulnerability using a single value derived from multivariate characteristics. Second, SVI can be linked (statistically and spatially) to more physically based indices in calculating the overall vulnerability of a specific place. Not only does this index significantly contribute to the methods and metrics used in vulnerability science, but it also provides important comparative information for policy makers and emergency managers.

2. Study Area

The Peloponnese is a peninsula that covers an area of some 21,549.6 km^2 and constitutes the southernmost part of mainland Greece (Figure 1). It is actually an island separated fromthe central part of the country by theGulf of Corinth, a restricted marine embayment, with a nearly 105 km longitudinal axis lying in the E-W direction. At the western end of the Gulf, the Peloponnese is connected to the mainland of Greece by the bridge of Rio-Antirio. To the east the Peloponnese is separated from the Greek mainland by the Corinth Canal (an artificially dredged channel, 8 m deep and 21 m wide) which links the Gulf of Corinth with the Saronikos Gulf. The study area has mountainous interior and deeply indented coasts, especially along its eastern coastline (Figure 1). It possesses four south-pointing peninsulas: the Messinian, the Mani, the Cape Malea, and the Argolid in the far northeast, which are separated by the NW-SE trending Gulfs of Messinakos, Lakonikos, and Argolikos.

The Peloponnese consists of 152 municipal communities (a municipal community is the lowest level of government within the organizational structure of Greece), 73 of which are coastal (Figure 1). It has a population of 1,047,000, which corresponds to less than 10 % of the total population of Greece. Most of its population is concentrated in the coastal zone. The average population density in the coastal municipal communities is 77.8 inhabitants/km^2, whereas the mean value for Greece is 82.29 inhabitants/km^2. Its GDP contributes less than 7% of total GDP in Greece. Unemployment rates are higher than the national rates and three times higher than the average unemployment rate in the EU-28. The economy of the study area is distributed between the primary sector (mostly agricultural activities) and tourism related servicesand a small yet gradually growing industrial activityover the last years. Despite the dominance of the mountainous terrain, the Peloponnese hosts some of the most fertile lands in the country, producing renowned wine labels and top quality olive oil. Tourism is the region's heavy industry with high quality services and infrastructure facilities mainly along the coastline. Nowadays, the infrastructure works in transportation create new challenges for the area. The national road that connects Athens with Patras (the capital of the Peloponnese and the third largest city in Greece), extends along the north shoreline of the Peloponnese, while numerous cities and settlements, such as Patras, Kalamata, Korinthos, Nafplio, etc., are coastal (Figure 1).

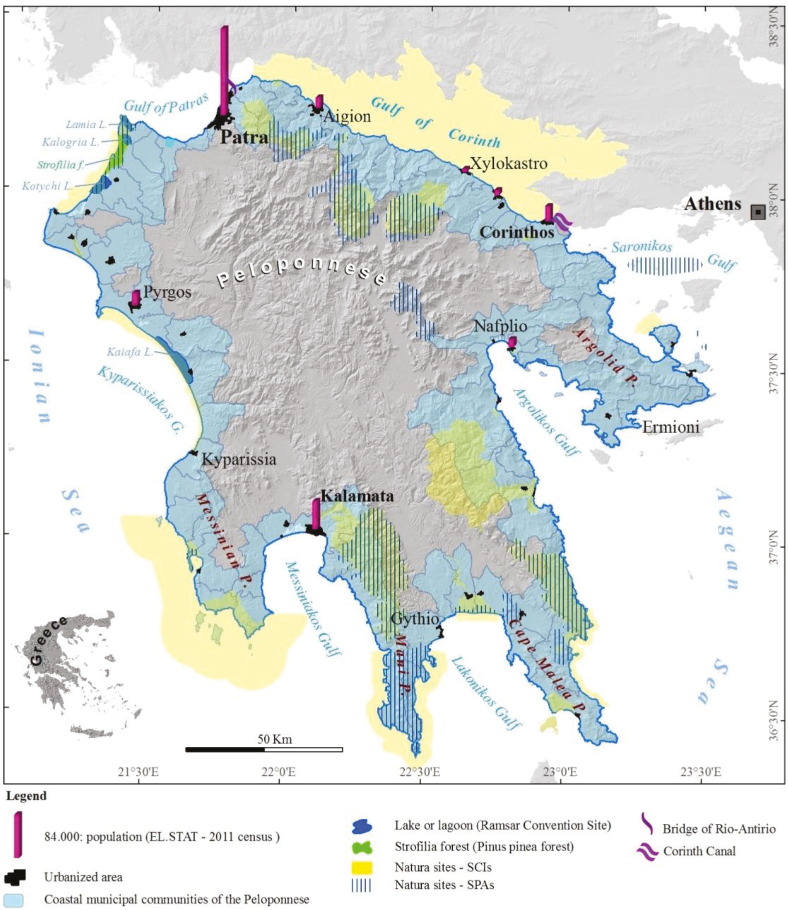


Figure 1. Hill-shaded map of the Peloponnese. The map also shows the 73 coastal municipal communities of the study area.

The Peloponnese is also of great environmental significance since it hosts ecologically important areas. Along its northwestern coast there is a 28 km zone with sandy beaches, dunes, lagoons (Kalogria, Strofilia, Lamia, and Kotychi, which is a Ramsar Convention site and the most significant lagoon in the Peloponnese), marshy areas, salt and freshwater wetlands, and the most extensive Pinuspinea forest in Greece (Strofilia forest) (Figure 1). Along the shore of the Kyparissiakos Gulf exists the significant wetland of Kaiafa Lake and a unique sand dune ecosystem of great ecological value.

From the above description it is more than evident that the Peloponnese deserves an assessment vulnerability study to spot regions of very high or high physical and social vulnerability, in order to promote relevant integrated management planning.

3. Materials and Methods

3.1. Physical Vulnerability

For the assessment of the physical vulnerability of the Peloponnese to climate change-related coastal hazards we applied the index proposed by Thieler and Hammar-Klose [31], which modified the initial CVI [38]. The CVI allows six physical variables: coastal geomorphology, shoreline shifting rate, coastal slope, relative sea-level rise rate, mean wave height, and mean tidal range to be related in a quantitative manner. In each variable a relative risk value is assigned based on the potential magnitude of its contribution to the physical changes on the coast as sea-level rises. The variables are ranked from 1 to 5 according to Table 1, with rank 1 indicating very low vulnerability and rank 5 indicating very high vulnerability. The theoretical minimum and maximum values of the CVI are 0.4 and 51.0 respectively. The ranges of vulnerability ranking, used in this study, are those proposed for the coastal environment of Greece [36]. The CVI is calculated as the square root of the product of the six variables divided by their total number.

$$\mathrm{CVI} = \sqrt{\frac{\mathrm{a{\cdot}b{\cdot}c{\cdot}d{\cdot}e{\cdot}f}}{6}}, \tag{1}$$

where, a: geomorphology, b: shoreline erosion/accretion rate, c: coastal slope, d: relative sea-level rise rate, e: mean significant wave height and f: mean tide range.

Categorization of coastal geomorphology classes in this study (Table 1) was undertaken using recent ortho-rectified aerial photographs (taken in 2009). Since this variable also represents the bedrock outcropping along the shoreline, data for the rock types were interpreted from the geological maps of Greece (at 1:50,000 scale),published by the Greek Institute of Geology and Mineral Exploration (IGME).

Table 1. Ranges for vulnerability ranking of the six CVI variables. The ranges of vulnerability ranking, used in this study, are those proposed for the coastal environment of Greece [36].

Variables	Vulnerability Categories				
	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts	Medium cliffs, indented coasts	Low cliffs, alluvial plains	Cobble Beaches, Lagoons	Sandy beaches, deltas
Shoreline Erosion (−)/ Accretion (+) rate (m/year)	>(+1.5)	(+1.5)–(+0.5)	(+0.5)–(−0.5)	(−0.5)–(−1.5)	<(−1.5)
Coastal Slope (%)	>12	12–9	9–6	6–3	<3
Relative Sea-Level rise (mm/year)	<1.8	1.8–2.5	2.5–3.0	3.0–3.4	>3.4
Mean Wave Height (m)	<0.3	0.3–0.6	0.6–0.9	0.9–1.2	>1.2
Mean Tide Range (m)	<0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8
Physical Vulnerability	very low	low	moderate	high	very high

Shoreline change rates were derived from ortho-rectified aerial photographs taken in 1969 and 2009, obtained from the Hellenic Military Geographical Service and the Hellenic Cadastre (Ktimatologio S.A.), respectively. The photomosaics of these photographs were manipulated within the GIS environment to digitize the shorelines of 1969 and 2009. The thematic layers of the 1969 and 2009 shorelines (in vector format) were overlaid, and with the use of GIS-based distance analysis functions, the final shoreline change map for the 40-year time period was obtained with estimated accretion and erosion rates.

To estimate the coastal slope values, a slope map of the coastal zone of the Peloponnese has been created with the use of the 1:5000 scale, topographic maps. With these maps as the main elevation source, the 5 m resolution Digital Elevation Model (DEM) of the coastal belt with an elevation from 0 to 50 m was created for the study area. Next, for this zone, the slope map was implemented within the ArcGIS spatial analysis extension environment, and a map of slope zones (according to Table 1) was constructed. Finally, for the assignment of the proper slope categorization to each coastline segment, an intersection of slope zones with the coastline was performed.

The coast of the Peloponnese relative sea-level change is the sum of the eustatism component and the local long-term tectonic vertical land movements. Published information concerning the late Holocene relative sea-level trends at the broader area of the Peloponnese was considered [46].

Mean annual values of the significant wave height were abstracted from the "Wave and Wind Atlas of the Hellenic Seas" [47], which are based on offshore measurements for the period between 1999 and 2007 (POSEIDON program), whereas tidal range was deduced from published information [48]. Every section of the coastline was assigned a risk value based on each specific data variable and the CVI was calculated.

GIS software ArcGIS (ver. 10.2), provided the platform for the coastal mapping and the calculation of the CVI. For each variable, the entire coastline of the study area is segmented into five sensitivity classes, and a sensitivity rank number is assigned to each segment of the coast (indicating the vulnerability level in terms of the given variable). The method of computing the CVI in the present study is similar to that applied by Pendleton et al., [49] Thieller and Hammar-Klose [31] and Abuodha and Woodroffe [50]. The difference is that instead of the "raster" approach, input parameters and final CVI values were estimated in coastline segments.This modified approach seems appropriate for medium scale. The size of each segment was 50 m. As mentioned above, for each of the six variables, a ranking on a scale of 1–5 was assigned to each segment (with rank 1 representing very low vulnerability and rank 5 indicating very high vulnerability) following the classification scheme outlined in Table 1. The final CVI map was generated by combining all of the variables. This map contains nearly 3500 segments of the coastline, each of which has a unique identity in its corresponding attribute table. Another column was added to this attribute table for the CVI formula so that the system generated the CVI values for all of the coastline segments of the Peloponnese. The combined CVI value was added as an attribute value for each coastline segment. Subsequently, the "natural breaks" classification method was used to categorize coastline segments according to their CVI magnitude for the construction of the final CVI zonation maps.

3.2. Social Vulnerability

Six variables have been used as indicators to assess social vulnerability of the coastal municipal communities of the Peloponnese: population density, share of women in total population, share of persons above 65 in total population, share of children below 5 in total population, share of foreign-born in total population, and share of low educated in total population. Demographic and socio-economic data were collected for all 1033 Greek municipal communities. Data were provided by the Hellenic Statistical Authority (EL.STAT) based on the 2011 Population and Household Census.

Since the six different variables used for the SVI calculation are measured in different units and scales, data must be standardized in order to be suitable for multivariate analysis and correlation tests. As most of the relevant data are not normally distributed, the method chosen is that of range standardization given by the following formula:

$$x'_{A,i} = \frac{x_{A,i} - x_{A,min}}{x_{A,max} - x_{A,min}}, \tag{2}$$

where $x'_{A,i}$: the standardized value of the variable A referring to the municipal community i, $x_{A,i}$: the observed value of the variable A referring to the municipal community i, $x_{A,min}$: the minimum observed value of the variable A, and $x_{A,max}$: the maximum observed value of the variable A.

All observation values are therefore between 0 (the case with the lowest value) and 1 (the case with the highest value). The six new standardized values were placed in an additive model to compose the SVI for each municipal community, making the assumption of an equal contribution of each variable to the community's overall vulnerability. The produced indicator is a relative measure of the overall vulnerability for each municipal community. The SVI_i for the municipal community i is therefore given by the following formula:

$$SVI_i = \sum_{A=1}^{6} x'_{A,i}, \quad (3)$$

At a second stage, SVI_i scores are classified based on standard deviations from the mean into five categories, ranging from less than -1σ on the lower end to more than $+1\sigma$ on the upper end. Value 1 is given to the less vulnerable municipal communities while value 5 is given to the most vulnerable ones.

For each index (CVI and SVI) maps were produced depicting the geographic distribution of physical and social vulnerability along the coastal zone of the Peloponnese.

4. Results and Discussion

4.1. Coastal Vulnerability Index

The "coastal geomorphology" variable is non-numerical and expresses the relative response of different types of coastal landforms to sea-level rise. Geomorphology is ranked qualitatively according to the relative strength of the coastal landforms and rocks outcropping along the coast. The coastal zone of the Peloponnese is made up of a wide variety of features. The predominant coastal landform is steep marine cliffs made up of rocks highly resistant to coastal erosion, such as limestone and metamorphic rocks (592.9 km—40.0%) followed by sandy and shingle beaches, located along the coastal alluvial plains and river deltas (343.2 km, which is 23.2 % of the coastline), cobble pocket beaches (217.1 km—14.6%), medium rocky cliffs and indented coasts (180.6 km—12.2%) and low rocky cliffs or cliffs made up of less resistant to erosion formations (147.9 km—10%) (Table 2, Figure 2). Steep cliffs made up of hard geological formations (limestone and metamorphic rocks) offer maximum resistance and were classed with a rank of 1, whereas medium rocky coastal cliffs and indented coasts or cliffs of medium slope made up of weaker formations were assigned sensitivity ranks of 2 and 3, respectively. Cobble pocket beaches are susceptible to the effects of both natural marine processes and relative sea-level rise and are given a rank of 4 (high vulnerability). Sandy beaches, river deltas and fan-deltas were assigned a sensitivity rank of 5, while stabilized dune formations are considered that provide a kind of protection to the land behind them and were assigned a vulnerability rank of 4 (Table 2).

Table 2. The coastline length (as percentage % of the total shoreline length) in each vulnerability category (1–5) for the physical variables (a–f) of the CVI.

	Variables	**Physical Vulnerability Classes**				
		1 Very Low	**2 Low**	**3 Moderate**	**4 High**	**5 Very High**
a.	Geomorphology	40.0	12.2	10.0	14.6	23.2
b.	Shoreline Change	0.2	2.8	91.2	5.3	0.5
c.	Coastal Slope	55.5	8.3	7.9	14.1	14.3
d.	Relative Sea-level Rise	0.0	100.0	0.0	0.0	0.0
e.	Significant Wave Height	33.4	39.4	23.4	3.8	0.0
f.	Tidal Range	100.0	0.0	0.0	0.0	0.0
	CVI values	<1.2	1.2–3.2	3.2–5.2	5.2–7.1	>7.1
	CVI (%)	46.5	18.7	17.5	12.0	5.2

The shoreline change variable attempts to capture the historical trend of shoreline movement by determining the overall patterns of erosion or accretion. Shoreline change is one of the more complex parameters because the trend is typically variable over time [49]. The ranking of the shoreline change rate is based on the range of change in beach width values. A shoreline length of 1350.9 km, which corresponds to 91.2% of the coastline, is relatively stable (mean shoreline shifting rate within

±0.5 m/year), between 1969 and 2009. Nearly 78.2 km (5.3%) of the coastline is retreating with a mean rate between −0.5 and −1.5 m/year and a very small segment of the shoreline (7.8 km—0.5%), which mainly consists of sandy beaches at the aprons of the Alfios and Evrotas River deltas, have undergone fast erosion (with rates > −1.5 m/year). Nearly 41.5 km (2.8 %) of the shoreline has been prograded with a mean accretion rate between +0.5 and +1.5 for the period between 1969 and 2009, while a very small percentage of the coastline (0.2%—3.3 km) is prograding faster with a mean accretion rate higher than +1.5 m/year (Table 2). Accretion occurs at the mouth of some streams (Figure 2) due to increased sediment supply, especially during the rainy period of the year [51,52].

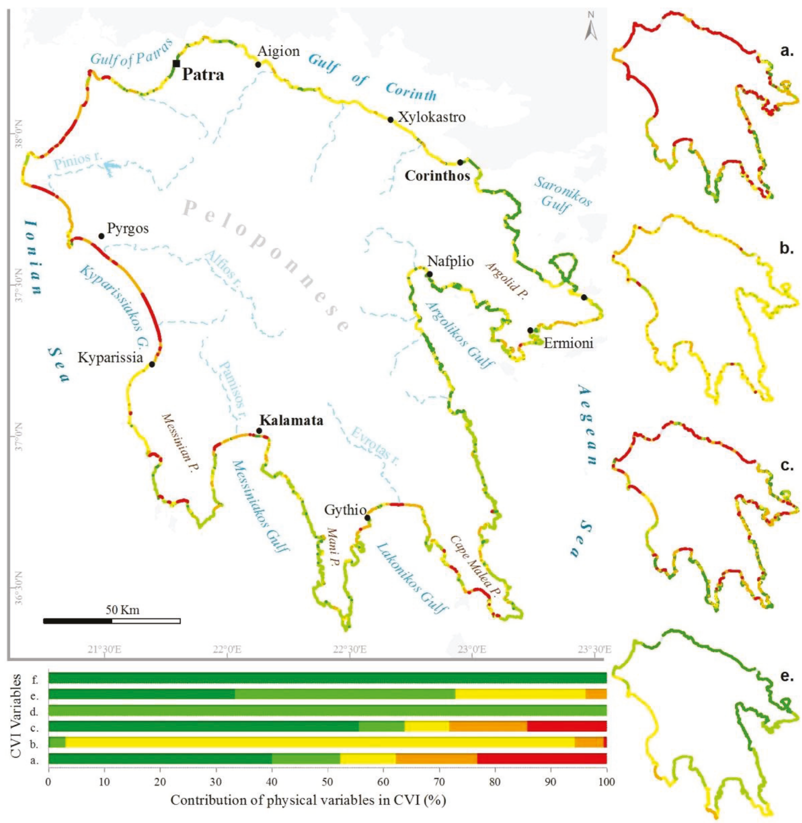


Figure 2. Maps of classification of the Peloponnese coastline into five physical vulnerability classes according to the variables of the Coastal Vulnerability Index (CVI) values. Inset maps (**a**–**c**,**e**) indicate the vulnerability ranking of various segments of the coast based on the CVI variables ((**a**) geomorphology, (**b**) shoreline change rate, (**c**) coastal slope and (**e**) mean significant wave height). Since the variables of relative sea-level rise and tidal range are considered to have the same value along the entire coastline of the Peloponnese, the figure does not include vulnerability ranking maps for these variables. The bar diagram shows the length (in percentage %) of shoreline in each vulnerability category for the CVI variables.

Determination of the regional coastal slope identifies the relative sensitivity of inundation and the potential rapidity of shoreline retreat because low-sloping coastal regions are thought to retreat faster than steeper regions [51]. The ranges for vulnerability ranking of the coastal slope variable are the same as those used in similar studies from around the world [31,49]. Regions with coastal slopes lower than 3% were characterized with very high vulnerability, whereas coastal cliffs with slopes higher than 12% were classified as areas of very low vulnerability (Table 1). Nearly 56.0% of the coastal zone of the study area (which corresponds to 822.9 km) belongs to the very low vulnerability class. Very low vulnerability area lies mainly along the western coast of the Saronikos Gulf as well as along the east and west coasts of the four NW-SE trending peninsulas: the Messinian, the Mani, the Cape Malea, and the Argolid. On the other hand,14.3% of the study coastal zone (which corresponds to 211.4 km) is low-lying and is characterized as very highly susceptible to inundation. This very highly vulnerable area lies partly along the southern coastline of the Gulf of Corinth as well as along part of the western coast of the Peloponneseand at the coast of the inner parts of the Messinakos, Lakonikos and Argolikos Gulfs (Figure 2). Low-lying coasts are occupied by beaches developed along the fronts of alluvial plains and river deltas. Nearly 14.0% of the coast (208.4 km) is comprisedof slope between 3 and 6% and is considered highly vulnerable, whereas 116.4 km (7.9%) of the coastal zone is of moderate vulnerability, having a slope between 6% and 9% (Table 2).

Due to the lack of recent accurate long-term sea-level measurements, the values for the variable of relative sea-level rise were estimated coupling the effects of eustatism and local land level movements caused by tectonics. The relative sea-level rise is considered to have the same value along the coastline of the Peloponnese (Table 2, Figure 2) and took a value < 2.0 mm/year based on estimations from studies relevant to eustatic sea-level rise in Greece [46]. This ranking is in agreement with the mean eustatic global sea-level rise rate for the time period between 1850 and 1950 [9], as well as with the trend of the sea-level for the period 1985–2001 at the station of Kalamata (0.6 $\pm$ 0.1 mm/year) [19].

Wave heights are proportional to the square root of wave energy, which is a measure of the capacity for erosion.The wave climate of the Peloponnese coastline is affected by offshore significant wave heights between 0.1 and 1.0 m [47], according to the output of the wave model (POSEIDON program), which has been calibrated with the use of offshore field measurements. A significant part of the coastline of the Gulf of Patras, as well as the entire coast of the Gulfs of Corinth and Argolikos is dominated by offshore significant wave heights <0.3 m. Thus, 494.8 km (33.4%) of the Peloponnese coastline is considered to have very low vulnerability (rank 1). Nearly 584.4 km (39.4%) of the coastline, located mainly along the northwestern and eastern shore of the Peloponnese, including also the coasts of Messiniakos and Lakonikos Gulfs, is characterized by offshore significant wave heights between 0.3 and 0.6 m (rank 2). Approximately 23.0% of the study area (which corresponds to 346.2 km), that lies mostly along the western coast of the Peloponnese and partly the NW-SE facing coasts of the Messinian, the Mani, and the Cape Malea peninsulas are of moderate vulnerability since offshore wave heights range between 0.6 and 0.9 m. Finally, small segments (56.3 km—3.8%) of the southwestern shores of the Messinian and Mani peninsulas are dominated by significant wave heights between 0.9 and 1.2 m and are ranked as highly vulnerable (Figure 2e).

The tidal range is linked to both inundation and erosion hazards [30]. For the vulnerability ranking of the tidal range variable for the Peloponnese, the ranges proposed for Greece were considered (Table 1). These ranges were proposed taking into account the tide range variations for the Greek seas, which are generally less than 10 cm [48]. However, the overall fluctuation of sea-level exceeds 0.5 m due to meteorological forcing (differences in barometric pressure, wind, and wave setup) [53]. In this study, tidal range is ranked as such that extremely microtidal (tidal range < 0.2 m) coasts are at low risk and less microtidal (tidal range > 0.8 m) coasts are at high risk. The reasoning is that although a large tidal range dissipates wave energy, limiting beach or cliff erosion to a brief period of high tide, it also delineates a broad zone of intertidal area that will be most susceptible to inundation following long-term sea-level rise [30]. Furthermore, the velocity of tidal currents depends partially on the tidal range. High tidal range is associated with stronger tidal currents that are capable of eroding and transporting sediment [30]. The coast of the Peloponnese is a microtidal environment with tidal (astronomical) range <4 cm. As such, the tidal range variable is ranked with the value 1 (very low vulnerability) (Table 2, Figure 2).

The CVI values alongside the Peloponnese range between 0.82 and 11.18. The median value of the index for the study area is 4.11 and the standard deviation is 2.17. The geographical distribution of the vulnerability of the Peloponnese coast to climate change-related coastal hazards is presented schematically in Figure 2. CVI values above 7.1 are classified as having very high vulnerability. Nearly 77.6 km, corresponding to 5.2% of the total coastline length, was assigned to this category. A total length of 177.2 km (12.0%) of the coastline is classified as having high vulnerability (CVI values between 5.2 and 7.1). The deltaic plains of the most extensive deltas (those of Alfios and Pinios Rivers) of the western Peloponnese as well as the coastal plains of the inner Messiniakos and Lakonikos Gulfs are characterized by very high and high levels of vulnerability, primarily due to the low regional coastal slope, the high erodible of the coastal landforms, the high rates of erosion and the relatively high offshore mean significant wave heights. About 17.5% (259.5 km) of the shoreline, mainly along the Northern Peloponnese is moderately vulnerable (with CVI values between 3.2 and 5.2) while 18.7% (277.8 km) is of low vulnerability (CVI values between 1.2 and 3.2). Finally, values below 1.2 are assigned to the very low vulnerability category with 46.5% (689.7 km) of the shoreline belonging to this class (Table 2). The low and very low vulnerability categories are primarily located at the western rocky coasts of the Peloponnese, as well as along the NW-SE oriented cliffy coasts of the Messinian, Mani, and Cape Malea peninsulas (Figure 2).

4.2. Social Vulnerability Index (SVI)

Densely populated areas are thought to be more vulnerable, as the total amount of people and assets per km^2 poses a higher vulnerability of total damage in case of a disaster. Additionally, high population density increases the evacuation time as well as the consequences of a disaster (injuries and fatalities). In our case-study, population density ranges from 5.8 to 1352.7 inhabitants/km^2 with a mean score of 109.9 (standard deviation: 196.99). In respect to this criterion, 25 municipal communities (which correspond to 34.2% of the 73 total communities) are classified as low vulnerable, whereas the other 48 communities belong to the moderate vulnerability class (Table 3). Higher population densities are concentrated primarily along the southern coast of the Gulf of Corinth and at the western part of the Peloponnese (Figure 3a).

Table 3. Number of coastal communities (as percentage% of the total coastal municipal communities of the Peloponnese) in each vulnerability category (1–5) for the social variables (a–f) of the SVI.

Variables		Social Vulnerability Classes				
		1 Very Low	2 Low	3 Moderate	4 High	5 Very High
a.	Population Density	0.0	34.2	65.8	0.0	0.0
b.	Share of Women in t.p.	16.4	5.5	65.8	12.3	0.0
c.	Share of Persons above 65 in t.p.	13.7	26.0	50.7	5.5	4.1
d.	Share of Children below 5 in t.p.	4.1	11.0	57.5	16.4	11.0
e.	Share of foreign-born in t.p.	0.0	8.2	39.7	17.8	34.2
f.	Share of Low Educated in t.p.	8.2	31.5	45.2	4.1	11.0
SVI	Number of Communities	8	15	22	14	14
	(%)	11.0	20.5	30.1	19.2	19.2

Women, especially those living in less developed economies or in low status households, have limited access to knowledge and resources and are therefore less efficient in protecting or helping themselves out of a disaster [54]. Their care-giving role is an additional aggravating factor. Thus, relevant literature considers high shares of women in a population a high risk factor. In our case-study, the share of women in the total population ranges from 28.9% to 51.6%, with amean value of 48.9% (standard deviation: 0.028). Most of the communities (48 out of 73) are moderately vulnerable, 16 municipal communities (21.9%) belong to the very low and low vulnerability classes, while 9 (12.3%) of them are highly vulnerable (Table 3 and Figure 3b).

Elders, especially those living alone, often have mobility limitations and special needs that may require the assistance of others. Hence high values of "share of persons above 65 in total population" indicate high vulnerability. The shares of elders within the communities populations range from 10.7% to 38.9%, with a mean score of 23.55% (standard deviation: 0.058). Most of the communities (37 corresponding to 50.7%) fall into the moderate vulnerability category, whereas 29 (39.7%) show low and very low vulnerabilities (Table 3). Regarding this particular variable, four highly and three very highly vulnerable coastal communities are located in the southern part of the Peloponnese (Figure 3c).

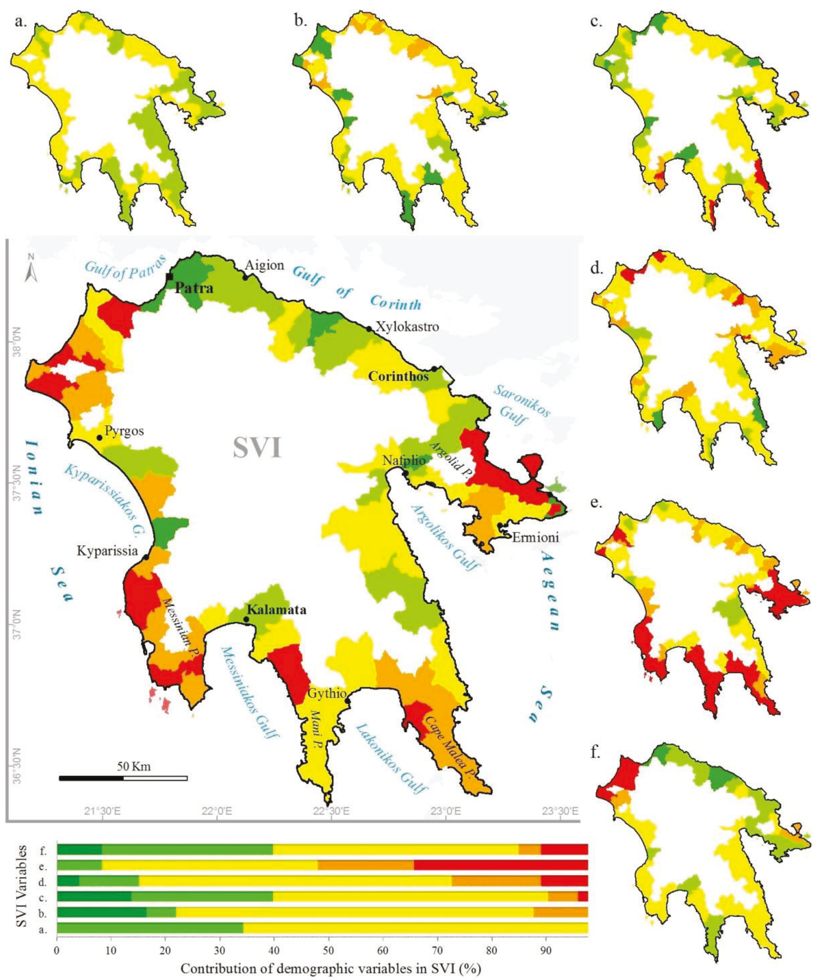


Figure 3. Maps of classification of the coastal municipal communities of the Peloponnese into five social vulnerability classes according to the variables of the Social Vulnerability Index (SVI) values. Inset maps (**a**–**f**) indicate the social vulnerability ranking of the communities based on the categorization of the SVI variables' values ((**a**) population density, (**b**) share of women in total population, (**c**) share of persons above 65 in total population, (**d**) share of children below 5 in total population, (**e**) share of foreign-born in total population and (**f**) share of low educated in total population). Inset bar diagram show the length (in percentage %) of shoreline in each vulnerability category for the SVI variables.

Children (<5 years) can hardly protect themselves during a disaster for they lack the necessary resources, knowledge, as well as life experience to survive. The values of the variable "share of children below 5 in total population" range between 2.9% and 9.8%, with a mean score of 5.34% (standard deviation: 0.057). Vulnerability increases with the values of this parameter. The majority of the coastal municipal communities (42–57.5%) show moderate vulnerability, 20 out of 73 (27.4%), primarily located at the north and northwest part of the Peloponnese, belong to the high and very high vulnerability classes, while the rest show low and very low vulnerabilities (Table 3, Figure 3d).

Racial and ethnic minorities are supposed to be more vulnerable to hazards for they are more likely to be poor [55]. Since we lack detailed ethnic data at this administrative level, we usethe "share of foreign-born in total population". Non-natives are thought to be more vulnerable for different reasons: (i) disaster communication is made more difficult due to limited language skills (ii) the impact may be greater due to higher social and economic marginalization as well as to cultural differences. Across the coastal municipalities of Peloponnese, the shares of foreignersrange from 2.9% to 35.1% of total population with mean score of 11.8% (standard deviation: 0.057). A significant number of communities (38 out of 73—52%), especially those of the Argolid, Cape Malea, Mani, and Messinian peninsulas are characterized by high and very high vulnerability (Figure 3e). A concentration of highly and very highly vulnerable communities is also observed at the northwestern part of the Peloponnese.

"Share of low educated in total population" is a variable that reflects the socio-economic status of an area. Low education implies limited access to information, followed by poor prevention measures and is often related to social and economic deprivation. The share of low-educated within the municipalities populationgoes from a minimum value of 9.5% to a maximum of 21.6% with mean score of 14.9% (standard deviation: 0.033). In respect to this demographic feature, most of the coastal municipal communities of the Peloponnese belong to the moderate, low, and very low vulnerability categories (Table 3). The geographic distribution of this parameter shows the presence of highly and very highly vulnerable communities at the northwestern part of the study area. Some communities along the southwestern shores of Saronikos Gulf are also of high vulnerability (Figure 3f).

In order to compose the SVI and due to the different scales of measures used for each variable, the values have been standardized [56]. The SVI ranges from a minimum value of 0.91 (lowest social vulnerability) to 2.67 (highest social vulnerability) with a mean score of 2.11 (standard deviation: 0.25). The geographical distribution of the social vulnerability to climate change-related coastal hazards for the Peloponnese is presented schematically in Figure 3. Most communities exhibit low or moderate levels of social vulnerablity since more than 6 out of 10 communities are classified in the first three groups. However, the share of highly and very highly vulnerable communities goes up to almost 38.4% (Table 3). High and very high levels of social vulnerability are clustered in communities along the coasts of the Messinian and Cape Malea peninsulas, as well as along the western coast of Saronikos Gulf and at the northwestern part of the Peloponnese. In contrast, the communities along the southern coast of the Gulf of Corinth, and most of the communities along the east coast of the Gulf of Patras, as well as most of the Argolikos Gulf coastal communities to the east, have moderate to very low social vulnerability levels (Figure 3).

The comparison among the final two CVI and SVI maps shows that seven coastal municipal communities of the Peloponnese (Vouprasia, Lechena, Vartholomio, Gastouni, Amaliada, Zacharo, and Elos) show high and very high levels of overall (both physical and social) vulnerability to costal hazards. The high overall vulnerability of these communities is a function of high or very high values of SVI while more than 80% of their coastal zone is also of high and very high physical vulnerability. The highly vulnerable (physically and socially) communities are concentrated at the northwestern coastal zone of the Peloponnese, while there is one highly vulnerable community at the inner part of the Lakonikos Gulf (Figure 4).

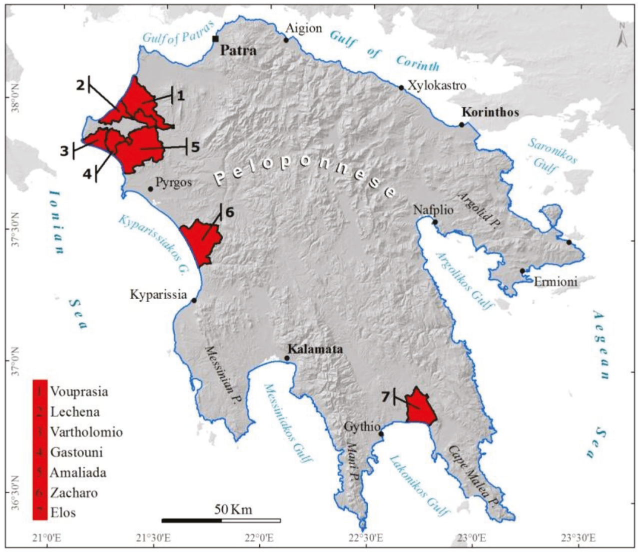


Figure 4. Location map of the seven more vulnerable (both physically and socially) municipal communities of the Peloponnese. These municipal communities have high or very high values of SVI while more than 80% of their coastal zone is also of high and very high physical vulnerability.

5. Conclusions

Of the six physical vulnerability variables, "geomorphology", "regional coastal slope", and "mean significant wave height" introduce the greatest variability to the CVI values. Among the other three parameters, "shoreline change rate" shows a small variation, while "tidal range" and "relative sea-level rise rate" have the same values along the entire coastline. On the other hand, all six variables used as indicators to assess social vulnerability, show a great variability. Among the social vulnerability variables,"share of foreign-born in total population", "share of children below 5 in total population" and "share of low educated in total population" are those that increase the SVI values within the study area.

The application of the proposed methodology reveals that there are differences among the geographical distribution of physical and social vulnerability. Nearly 17.2% of the shoreline (254.8 km) consisting primarily of low-lying sandy beaches and deltaic plains, has high and very high levels of physical vulnerability. Coastline segments of high physical vulnerability level are geographically concentrated at the western and northwestern coast of the Peloponnese, as well as at the inner coastal areas of Messiniakos, and the Lakonikos Gulfs. The highly and very highly social vulnerable communities are concentrated along the northwestern coast of the Peloponnese, along the coasts of the Messinian and Cape Malea peninsulas, as well as at the western coast of Saronikos Gulf. There are seven high risk coastal municipal communities in the study area (Vouprasia, Lechena, Vartholomio, Gastouni, Amaliada, Zacharo and Elos) andthey present high and very high values of social vulnerability. Accordingly, more than 80% of their coastal zone is also of high and very high physical vulnerability. Six of them are located in the northwestern Peloponnese and host ecologically important sites.

This study provided a comprehensive and detailed spatial GIS digital database of topographic, geological, and physio-geographical characteristicsfor 1481.7 km of shoreline, as well as population and demographic data for the coastal municipal communities of the Peloponnese, which can be renewed and expanded further to incorporate newly available data (e.g., storm surge, socio-economic status, land values), including new variables (e.g., sediment budget, environmental parameters) in the future for better results of physical and social vulnerability assessment.

The implementation of the indices used in this study, at the national scale could assist in a preliminary identification of the hazardous and vulnerable coastal areas of the country. CVI and SVI can be also integrated and used in the policies defined by Agenda 2030 for Sustainable Development, which is a plan of action for the people, the planet and for prosperity that also seeks to strengthen universal peace and freedom. The main target of Goal 13 is to take urgent action to combat climate change and its impacts. After the initial assessment of the most physically vulnerable segments of the coastlines to coastal hazards, focusing on regions with specific socio-economic and environmental interest is required, in order to re-examine the study area on a larger, more detailed, scale. The results of the categorization of the coasts in different risk categories can be a useful tool for managers of coastal areas and for those responsible for carrying out national protection policies, strategies and planning of the coastal zone against climate change driven natural hazards. Hence the application of CVI and SVI along the Greek coast would strengthen resilience and adaptive capacity to climate-related hazards and coastal natural disasters in the country.

Author Contributions: A.T. analyzed the demographic data and developed the Social Vulnerability Index; C.G. created and organized the GIS spatial database and created the maps of the geographic distribution of the vulnerability variables (physical and social); E.K. analyzed the data regarding the Coastal Vulnerability Index; A.T, C.G. and E.K. wrote the paper.

Acknowledgments: We would like to thank G.B. and H.S., Guest Editors of this Special Issue, for their helpful suggestions as well as the anonymous reviewers for their comments and corrections that significantly improved the paper.

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

References

1. Costanza, R. The ecological, economic, and social importance of the oceans. *Ecol. Econ.* **1999**, *31*, 199–213. [CrossRef]
2. Bellot, J.; Bonet, A.; Pena, J.; Sánchez, J. Human impacts on land cover and water balances in a Coastal Mediterranean county. *Environ. Manag.* **2007**, *39*, 412–422. [CrossRef] [PubMed]
3. Chalkias, C.; Papadopoulos, A.; Ouils, A.; Karymbalis, E.; Detsis, V. Land cover changes in the coastal peri-urban zone of Corinth, Greece. In Proceedings of the Tenth International Conference on the Mediterranean Coastal Environment, Rhodes, Greece, 25–29 October 2011; Volume 2, pp. 913–923.
4. Salvati, L.; Munafò, M.; Morelli, V.G.; Sabbi, A. Lowdensitysettlementsand land use changes in a Mediterranean urban region. *Landsc. Urban Plan.* **2012**, *105*, 43–52. [CrossRef]
5. Catalán, B.; Saurí, D.; Serra, P. Urban sprawl in the Mediterranean? Patterns of growth and change in the Barcelona metropolitan region 1993–2000. *Landsc. Urban Plan.* **2008**, *85*, 174–184. [CrossRef]
6. Romano, B.; Zullo, F. The urban transformation of Italy's Adriatic Coast Strip: Fifty years of unsustainability. *Land Use Policy* **2014**, *38*, 26–36. [CrossRef]
7. Satta, A.; Puddu, M.; Venturini, S.; Giupponi, C. Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. *Int. J. Disaster Risk Reduct.* **2017**, *24*, 284–296. [CrossRef]
8. Church, J.; White, N. Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.* **2011**, *32*, 585–602. [CrossRef]
9. Losada, I.J.; Reguero, B.G.; Méndez, F.J.; Castanedo, S.; Abascal, A.J.; Mínguez, R. Long-term changes in sea-level components in Latin America and the Caribbean. *Glob. Planet. Chang.* **2013**, *104*, 34–50. [CrossRef]
10. Hinkel, J.; Lincke, D.; Vafeidis, A.T.; Perrette, M.; Nicholls, R.J.; Tol, R.S.J.; Marzeion, B.; Fettweis, X.; Ionescu, C.; Levermann, A. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3292–3297. [CrossRef] [PubMed]
11. Hogarth, P. Preliminary analysis of acceleration of sea level rise through the twentieth century using extended tide gauge data sets (August 2014). *J. Geophys. Res. Oceans* **2014**, *119*, 7645–7659. [CrossRef]
12. Hoggart, S.P.G.; Hanley, M.E.; Parker, D.J.; Simmonds, D.J.; Bilton, D.T.; Filipova-Marinova, M.; Franklin, E.L.; Kotsev, I.; Penning-Rowsell, E.C.; Rundle, S.D.; et al. The consequences of doing nothing: The effects of seawater flooding on coastal zones. *Coast. Eng.* **2014**, *87*, 169–182. [CrossRef]

13. Jevrejeva, S.; Moore, J.C.; Grinsted, A.; Matthews, A.P.; Spada, G. Trends and acceleration in global and regional sea levels since 1807. *Glob. Planet. Chang.* **2014**, *113*, 11–22. [CrossRef]
14. Allen, J.C.; Komar, P.D. Climate controls on US west coast erosion processes. *J. Coast. Res.* **2006**, *22*, 511–529. [CrossRef]
15. IPCC. Summary for policy makers. In *Climate Change 2013: The Physical Science Basis*; Stocker, T.F., Qin, D., Plattner, G.K., Tigno, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK, 2013.
16. Pfeffer, W.T.; Harperand, J.T.; O'Neel, S. Kinematic constraints on Glacier Contributions to 21st Century Sea-Level Rise. *Science* **2008**, *321*, 1340–1343. [CrossRef] [PubMed]
17. Rohling, E.J.; Grant, K.; Bolshaw, M.; Roberts, A.P.; Siddall, M.; Hemleben, C.H.; Kucera, M. Antarctic temperature and global sea-level closely coupled over the past five glacial cycles. *Nat. Geosci.* **2009**, *2*, 500–504. [CrossRef]
18. Grinsted, A.; Moore, J.C.; Jevrejeva, S. Reconstructing sea-level from paleo and projected temperatures 200 to 2100 AD. *Clim.Dyn.* **2010**, *34*, 461–472. [CrossRef]
19. Lowe, J.A.; Woodworth, P.L.; Knutson, T.; McDonald, R.E.; McInnes, K.L.; Woth, K.; von Storch, H.; Wolf, J.; Swail, V.; Bernier, N.B.; et al. *Past and Future Changes in Extreme Sea Levels and Waves. Understanding Sea-Level Rise and Variability*; Wiley-Blackwell: London, UK, 2010.
20. Ullmann, A.; Monbaliu, J. Changes in atmospheric circulation over the North Atlantic and sea-surge variations along the Belgian coast during the twentieth century. *Int. J. Climatol.* **2010**, *30*, 558–568. [CrossRef]
21. Izaguirre, C.; Méndez, F.J.; Espejo, A.; Losada, I.J.; Reguero, B.G. Extreme wave climate changes in Central-South America. *Clim. Chang.* **2013**, *119*, 277–290. [CrossRef]
22. Wang, X.L.; Feng, Y.; Swail, V.R. Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophys. Res. Lett.* **2014**, *41*, 1026–1034. [CrossRef]
23. Weisse, R.; Bellafiore, D.; Menéndez, M.; Méndez, F.; Nicholls, R.J.; Umgiesser, G.; Willems, P. Changing extreme sea levels along European coasts. *Coast. Eng.* **2014**, *87*, 4–14. [CrossRef]
24. Vousdoukas, M.; Voukouvalas, E.; Annunziato, A.; Giardino, A.; Feyen, L. Projections of extreme storm surge levels along Europe. *Clim. Dyn.* **2016**, *47*, 3171–3190. [CrossRef]
25. Marcos, M.; Tsimplis, M.N. Coastal sea-level trends in Southern Europe. *Geophys. J. Int.* **2008**, *175*, 70–82. [CrossRef]
26. Marcos, M.; Jordà, G.; Gomis, D.; Pérez, B. Changes in storm surges in southern Europe from a regional model under climate change scenarios. *Glob. Planet. Chang.* **2011**, *77*, 116–128. [CrossRef]
27. Jordà, G.; Gomis, D.; Álvarez-Fanjul, E.; Somot, S. Atmospheric contribution to Mediterranean and nearby Atlantic sea level variability under different climate change scenarios. *Glob. Planet. Chang.* **2012**, *80–81*, 198–214. [CrossRef]
28. Conte, D.; Lionello, P. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. *Glob. Planet. Chang.* **2013**, *111*, 159–173. [CrossRef]
29. Androulidakis, Y.; Kombiadou, K.; Makris, C.; Baltikas, V.; Krestenitis, Y. Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions. *Dyn. Atmos. Oceans* **2015**, *71*, 56–82. [CrossRef]
30. Gornitz, V. Global coastal hazards from future sea-level rise. *Glob.Planet. Chang.* **1991**, *89*, 379–398. [CrossRef]
31. Thieler, E.R.; Hammar-Klose, E.S. *National Assessment of Coastal Vulnerability to Sea-Level Rise*; U.S. Atlantic Coast; U.S. Geological Survey: Reston, VA, USA, 1999.
32. Pendleton, E.A.; Thieler, E.R.; Williams, S.J. *Coastal Vulnerability Assessment of Cape Hatteras National Seashore (CAHA) to Sea-Level Rise*; USGS Open File Report; US Geological Society: Reston, VA, USA, 2008.
33. Diez, P.G.; Perillo, G.M.E.; Piccolo, C.M. Vulnerability to sea-level rise on the coast of the Buenos Aires Province. *J. Coast. Res.* **2007**, *23*, 19–126. [CrossRef]
34. Rao, K.N.; Subraelu, P.; Rao, T.V.; Malini, B.H.; Ratheesh, R.; Bhattacharya, S.; Rajawat, A.S. Sea-level rise and coastal vulnerability: An assessment of Andhra Pradesh coast, India through remote sensing and GIS. *J. Coast. Conserv.* **2008**, *12*, 195–207. [CrossRef]
35. Gaki-Papanastassiou, K.; Karymbalis, E.; Poulos, S.; Seni, A.; Zouva, C. Coastal vulnerability assessment to sea-level rise based on geomorphological and oceanographical parameters: The case of Argolikos Gulf, Peloponnese, Greece. *Hell. J. Geosci.* **2011**, *45*, 109–121.

36. Karymbalis, E.; Chalkias, C.; Chalkias, G.; Grigoropoulou, E.; Manthos, G.; Ferentinou, M. Assessment of the sensitivity of the southern coast of the Gulf of Corinth (Peloponnese, Greece) to sea-level rise. *Cent. Eur. J. Geosci.* **2012**, *4*, 561–577. [CrossRef]
37. Karymbalis, E.; Chalkias, C.; Ferentinou, M.; Chalkias, G.; Magklara, M. Assessment of the Sensitivity of Salamina and Elafonissos islands to Sea-level Rise. *J. Coast. Res.* **2014**, *70*, 378–384. [CrossRef]
38. Gornitz, V.; Daniels, R.C.; White, T.W.; Birdwell, K.R. The development of a coastal vulnerability assessment database: Vulnerability to sea-level rise in the U.S. southeast. *J. Coast. Res.* **1994**, *12*, 327–338.
39. Boruff, B.; Emrich, C.; Cutter, S.L. Erosion hazard vulnerability of US coastal countries. *J. Coast. Res.* **2005**, *21*, 932–942. [CrossRef]
40. Lichter, M.; Felsenstein, D. Assessing the costs of sea-level rise and extreme flooding at the local level: A GIS-based approach. *Ocean Coast. Manag.* **2012**, *59*, 47–62. [CrossRef]
41. Flanagan, B.E.; Gregory, E.W.; Hallisey, E.J.; Heitgerd, J.L.; Lewis, B. A Social Vulnerability Index for Disaster Management. *J. Homel. Secur. Emerg. Manag.* **2011**, *8*. [CrossRef]
42. Szlafsztein, C.; Sterr, H. A GIS-based vulnerability assessment of coastal natural hazards, state of Pará, Brazil. *J. Coast. Conserv.* **2007**, *11*, 53–66. [CrossRef]
43. Gorokhovich, Y.; Leiserowitz, A.; Dugan, D. Integrating Coastal Vulnerability and Community-Based Subsistence Resource Mapping in Northwest Alaska. *J. Coast. Res.* **2014**, *30*, 158–169. [CrossRef]
44. Satta, A.; Puddu, M.; Firth, J.; Lafitte, A. *Climate Risk Management Tools: Towards a Multi-Scale Coastal Risk Index for the Mediterranean*; Plan Bleu Report; Plan Bleu: Valbonne, France, 2015.
45. Mavromatidi, A.; Briche, E.; Claeys, C. Mapping and analyzing socio-environmentalvulnerability to coastal hazards induced by climate change: An application to coastal Mediterranean cities in France. *Cities* **2018**, *72*, 189–200. [CrossRef]
46. Lambeck, K. Sea-level change and shore-line evolution in Aegean Greece since Upper Palaeolithic time. *Antiquity* **1996**, *70*, 588–611. [CrossRef]
47. Soukisian, T.; Hatzinaki, M.; Korres, G.; Papadopoulos, A.; Kallos, G.; Anadranistakis, E. *Wave and Wind Atlas of the Hellenic Seas*; Hellenic Centre for Marine Research Publication: Anavyssos, Greece, 2007.
48. Tsimplis, M.N. Tidal oscillations in the Aegean and Ionian Seas. *Estuar. Coast. Shelf Sci.* **1994**, *39*, 201–208. [CrossRef]
49. Pendleton, E.A.; Thieler, E.R.; Williams, S.J. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *J. Coast. Res.* **2010**, *26*, 176–183. [CrossRef]
50. Abuodha, P.A.O.; Woodroffe, C.D. Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast Australia. *J. Coast. Conserv.* **2010**, *14*, 189–205. [CrossRef]
51. Dwarakish, G.S.; Vinay, S.A.; Natesan, U.; Asano, T.; Kakinuma, T.; Venkataramana, K.; Jagedeesha, B.; Badita, M.K. Coastal vulnerability assessment of the future sea-level rise in Udupi coastal zone of Karnataka state, west coast of India. *Ocean Coast. Manag.* **2009**, *52*, 467–478. [CrossRef]
52. Parcharidis, I.; Kourkouli, P.; Karymbalis, E.; Foumelis, M.; Karathanassi, V. Time Series Synthetic Aperture Radar Interferometry for Ground Deformation Monitoring over a Small Scale Tectonically Active Deltaic Environment (Mornos, Central Greece). *J. Coast. Res.* **2013**, *29*, 325–338. [CrossRef]
53. Alexandrakis, G.; Karditsa, A.; Poulos, S.; Ghionis, G.; Kampanis, N.A. Vulnerability assessment for to erosion of the coastal zone to a potential sea-level rise: The case of the Aegean Hellenic coast. In *Environmental Systems in Encyclopedia of Life Support Systems (EOLSS)*; Sydow, A., Ed.; Eolss Publisher: Oxford, UK, 2009.
54. Enarson, E.; Morrow, B.H. A gendered perspective: The voices of women. In *Hurricane Andrew: Ethnicity, Gender, and the Sociology of Disasters*; Peacock, W.G., Morrow, B.H., Gladwin, H., Eds.; International Hurricane Center, Laboratory for Social and Behavioral Research: Miami, FL, USA, 1997; pp. 116–140.
55. Rygel, L.; O'Sullivan, D.; Yarnal, B. A method for constructing a Social Vulnerability Index: An application to hurricane storm surges in a developed country. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 741–764. [CrossRef]
56. Cutter, S.L.; Mitchell, J.T.; Scott, M.S. Revealing the vulnerability of people and places: A case study of Georgetown county, South Carolina. *Ann. Assoc. Am. Geogr.* **2000**, *90*, 713–737. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

land

MDPI

Article

Temporal and Spatial Analysis of Flood Occurrences in the Drainage Basin of Pinios River (Thessaly, Central Greece)

George D. Bathrellos [1,*], Hariklia D. Skilodimou [1], Konstantinos Soukis [2] and Efterpi Koskeridou [3]

[1] Department of Geography and Climatology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, ZC. 15784 Zografou, Athens, Greece; hskilodimou@geol.uoa.gr

[2] Department of Dynamic Tectonic Applied Geology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, ZC. 15784 Zografou, Athens, Greece; soukis@geol.uoa.gr

[3] Department of Historical Geology-Palaeontology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, ZC. 15784 Zografou, Athens, Greece; ekosker@geol.uoa.gr

* Correspondence: gbathrellos@geol.uoa.gr; Tel.: +30-210-727-4882

Received: 11 August 2018; Accepted: 7 September 2018; Published: 11 September 2018

Abstract: Historic data and old topographic maps include information on historical floods and paleo-floods. This paper aims at identifying the flood hazard by using historic data in the drainage basin of Pinios (Peneus) River, in Thessaly, central Greece. For this purpose, a catalogue of historical flood events that occurred between 1979 and 2010 and old topographic maps of 1881 were used. Moreover, geomorphic parameters such as elevation, slope, aspect and slope curvature were taken into account. The data were combined with the Geographical Information System to analyze the temporal and spatial distribution of flood events. The results show that a total number of 146 flood events were recorded in the study area. The number of flood events reaches its maximum value in the year 1994, while October contains the most flood events. The flood occurrences increased during the period 1990–2010. The flooded area reaches its maximum value in the year 1987, and November is the month with the most records. The type of damages with the most records is for rural land use. Regarding the class of damages, no human casualties were recorded during the studied period. The annual and monthly distribution of the very high category reaches the maximum values, respectively, in the year 2005 and in June. The analysis of the spatial distribution of the floods proves that most of the occurrences are recorded in the southern part of the study area. There is a certain amount of clustering of flood events in the areas of former marshes and lakes along with the lowest and flattest parts of the study area. These areas are located in the central, southern, south-eastern and coastal part of the study area and create favorable conditions for flooding. The proposed method estimates the localization of sites prone to flood, and it may be used for flood hazard assessment mapping and for flood risk management.

Keywords: historic flood data; old topographic maps; GIS; temporal and spatial distribution of flood events; marshy areas and lakes; flood hazard assessment

1. Introduction

Natural hazards are physical events that can cause significant damages to the natural and human environment. Endogenic or exogenic processes such as active tectonics and climate changes are capable of changing landforms and triggering natural hazards, which in some cases control human activities [1–11].

Floods are physical phenomena active in geological time and the result of excess runoff. When rivers overtop their banks, the excess water goes to the floodplain. Floodplains represent favorable sites for man to settle because they are fertile, level, easy to excavate and near water. These features have contributed to increased development and urbanization of floodplains, thereby increasing the chances of the flood occurrences that cause disasters. Despite the construction of flood control works such as dams, levees and channeling rivers, the flood damage has increased [12–16].

Floods occur frequently in some parts of the world. While for some areas, yearly flooding is necessary to sustain crops, for other areas, flooding spells disaster. Especially, in urban areas, floods are considered among the most dangerous natural hazards due to the increasing number of events. Their consequences are not only environmental, but social and economic, as well, since they may cause damages to urban areas and agricultural lands and may even result in the loss of lives [17]. Worldwide, flood events have caused the largest amount of deaths and property damage during the last decades [18]. In Europe, the annual average flood damage in the last two decades was about €4 billion per year [19]. In the Mediterranean countries, floods tend to be greater in magnitude compared to the inner continental countries, and they frequently cause catastrophic damages [20].

Flood occurrence can be estimated in space and time through a sound basis of knowledge acquired by the scientific use of a large number of historical documents [21]. It is possible to gather useful information about historical floods that occurred during a period ranging from 1–2 centuries by using historical data [22]. Payrastre et al. [21] used discharges of historical floods that occurred during a period ranging from 1–2 centuries in four watersheds of the French Mediterranean area. They estimated the flood peak discharges and the associated low and high bound of its possible values for the main floods of each studied area. Historic data are useful for floodplain management, flood insurance rating, emergency planning and flood risk management. A careful search for data and their suitable arrangement may result in a powerful tool for flood disaster prevention and land use planning [23–25].

One essential step in any flood hazard analysis and estimation is the flood hazard recognition. This statement includes the record of possible geomorphologic evidence of flood activity, historic accounts and records [26]. Hydrologic models using time series flood data can be applied to assess flood peaks, depths, volumes and to map flood hazard areas [27–31]. However, these methods require data that are often unavailable [32]. Alternatively, researchers have used historical documents and historic flood data to estimate flood hazard [22,33]. Tropeano et al. [22] analyzed historical documents for a statistical elaboration of the frequency of landslide and flood events in Northern Italy in the last five centuries. Diakakis et al. [33] used an extensive catalogue of flooding phenomena during the last 130 years to examine flood events in Greece. According to their statistical and spatial analysis, urban areas tend to present higher flood recurrence rates than mountainous and rural ones and an increasing trend in reported flood event numbers during the last few decades. Moreover, a diachronic appraisal of the landscape evolution throughout the study of old topographic maps may include information on ungauged historical floods and paleofloods [34,35]. Skilodimou et al. [35] used old topographic maps to investigate the causes of flooding generation in the southwestern coast of Attica in Greece. They proved that the former wetlands and the lagoon of the study area have been dried up and covered by buildings, causing flood occurrences.

This paper aims to provide recognition of flood hazard by using historic data in the drainage basin of Pinios (Peneus) River, in Thessaly, central Greece. For this purpose, a catalogue of historical flood events that have caused damages was studied. These data, along with old topographic maps and geomorphic parameters such as elevation, slope, aspect and slope curvature were evaluated to record the temporal and spatial distribution of flood events of the study area. The analysis, processing and the evaluation of the old maps, geomorphic parameters and flood events were performed in a GIS environment.

2. Study Area

The drainage basin of the study area is located in Thessaly, central Greece (Figure 1a), and it covers an area of about 11,200 km^2. The elevations of the study area vary from 0–2678 m a.s.l. (Figure 1b). The hydrologic basin is drained by Pinios River, which has an approximate length of 205 km. It is the third longest river in Greece and crosses a large part of the eastern part of central Greece discharging into the Aegean Sea, where it forms a delta.

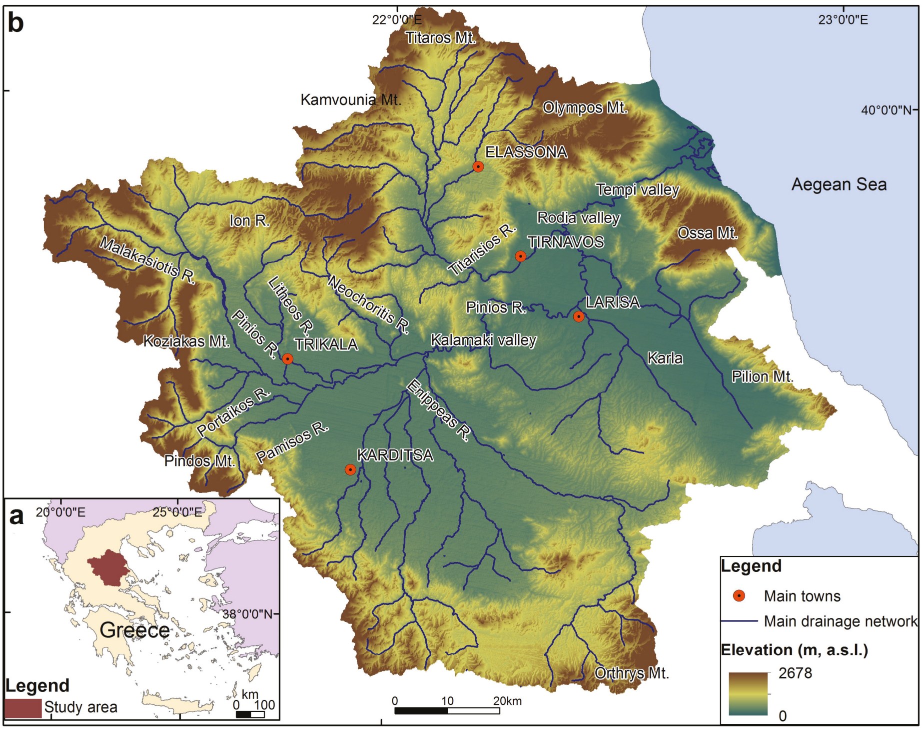


Figure 1. (**a**) Location map of the study area; (**b**) the elevations of the study area, the drainage network, the road network and the main settlements (modified from [36]).

Its course starts at the northwestern part of the Thessaly plain, from the confluence of the Ion and Malakasiotis rivers. It is surrounded by mountainous areas, which enclose its drainage basin and form its watershed (Figure 1b). To the north are the Titaros Mt. (1837 m) and the Kamvounia Mt. (1615 m); to the northeast are the Olympos Mt. (2917 m) and the Ossa Mt. (1978 m); to the east is the Pilio Mt. (1548 m); to the south is the Orthrys Mt. (1726 m); and finally, to the west are the Pindos Mt. (2204 m) and the Koziakas Mt. (1901 m).

The major tributaries of Pinios River are the Malakasiotis, Portaikos, Pamisos and Enippeas rivers to the west and south and the Ion, Lithaios, Neochoritis and Titarisios rivers to the north, which all drain large, heterogeneous areas, through extensive hydrographic networks (Figure 1b).

The plain area crossed by Pinios River is divided by the presence of a low-lying hill area into two parts (Figure 1b): (a) a western part (Trikala-Karditsa), whose altitude varies between 80 and 200 m, and (b) an eastern part (Larisa), whose altitude varies between 45 and 100 m. The mountainous and hilly area crossed by Pinios River has a quite rugged surface with altitudes exceeding 200 m. The most important gorges are the ones of Kalamaki (internal low-lying hill area), Rodia and Tempi (between Olympos and Ossa). Through these areas, the water flow velocity is high, while erosion is intense. All the above, in conjunction with the fertility of the plain areas, necessitated the construction of drainage and irrigation projects.

Fifty five percent (55%) of the study is mainly rural, semi-urban area. Irrigated agricultural land comprises 56% of the total cultivated area in the basin. The intense and extensive cultivation has led to a remarkable water demand increase, which is usually covered by the over-exploitation of groundwater resources [37].

The climate in the western and central side of the drainage basin of Pinios River is continental with cold winters and hot summers with a large temperature difference. The coastal area of the basin has a typical Mediterranean climate. Summers in the study area are usually very hot and dry, and in July and August, temperatures can reach up to 40 °C. The mean annual precipitation over the basin is about 779 mm. Rainfall is distributed unevenly in space, and it varies from about 360 mm at the eastern part of the basin to more than 1850 mm at the western mountain peaks. Generally, the rainiest months are November and December, while rainfall is rare from June–August. The mountain areas receive significant amounts of snow during the winter months. The mean annual total flow of the river is 3500×10^6 m^3. The hydrologic regime of the river is affected by both winter rainfalls and spring snowmelt. The river flow regime at the main stem is perennial. The mean average flow near its delta ranges from more than 150 m^3/s in February and March to about 10 m^3/s in August and September. The water of Pinios River is used primarily for irrigation [37,38].

The Pinios River crosses alpine formations of various units and post-alpine formations. More specifically, the alpine formations at its western part belong to the Koziakas unit, at the central part to the Sub-Pelagonian and Pelagonian units and at its eastern part to the Pelagonian and Olympos-Ossa units. At the western sub-basin, a great part of its length passes through molassic formations of the Meso-Hellenic trough (Eocene-Pliocene) and Quaternary formations, while at the eastern part, it crosses mostly Neogene and Quaternary formations. The permeable rocks and sediments of the study area are divided into two major units, the karstic one consisting of carbonate formations (limestones, marbles and dolomites) and the granule materials, which include Neocene and Quaternary sediments. Semi-permeable formations are comprised of loose to semi-coherent Quaternary and Neocene deposits along with thin-bedded limestones and ophiolites. Impermeable formations consist of schists and fine-grained Quaternary and Neocene deposits [39–41].

The plain of Thessaly has suffered from flooding since ancient times, when several structures had been constructed in order to control the Pinios River 2500 years ago. Today, despite the construction of flood protection works, floods remain an important problem of the area [42].

3. Materials and Methods

3.1. Data

In the present study, the historical flood database of Greece was used [43]. It refers to floods that occurred during the period 1979–2010. This database was required by the Directive 2007/60/EC concerning floods in Europe. In Article 4 of the Directive 2007/60/EC, the construction of a historic flood data database is assigned to every state-member as a part of the preliminary assessment of flood risk, as well as finding the sensitive to flooding areas in each country, for the database will be used for the construction of flood risk maps [44]. The database contains information such as the location of flood (county and village or locality), geographical details, dates of occurrence, characteristics of the flood (e.g., flash flood, snow melt flood, etc.), the sources of flooding (e.g., pluvial, fluvial, groundwater, etc.), the causes of flooding, the mechanism of the flood, the extent of flooded area (in km^2), the maximum distance of the flood (in km), the type of damages, the total cost of the damage caused by the flood event, the number of human casualties and the class of the total damage caused by the flood (very high, high, medium or low).

Four old topographic maps of 1881 with the scale 1:200,000 were used in the current work. The used sheets are: Ioannina-Metsovon-Grevena-Kozani-Servia [45], Larissa-Elasson-Katerini [46], Arta-Trikala-Karditsa [47] and Volos-Farsalos-Lamia [48]. Figure 2 shows a mosaic of the four old topographic maps used.

Figure 2. Old topographic maps of 1881, sheets: (**a**) Ioannina-Metsovon-Grevena-Kozani-Servia; (**b**) Larissa-Elasson-Katerini; (**c**) Arta-Trikala-Karditsa; (**d**) Volos-Farsalos-Lamia.

Finally, thematic maps were used. These maps are the digital elevation model (DEM) of the study area, which is presented in Figure 1 and the geological map of the study area. They were acquired from previous work [36]. The DEM map was used to produce the elevation, slope, aspect and slope curvature maps. The geological map of the study area was used to identify the semi-permeable and impermeable formations of the study area.

3.2. Statistical Analyses

Several works have used historic flood data to analyze flood frequency, flood peak discharges and estimate flood hazard maps [21,27,29,30]. This kind of flood frequency analysis requires hydro-climatic data, such as flow and rainfall. In many cases, this is difficult to do, because detailed data are unavailable. On the other hand, researchers have analyzed the temporal and spatial distribution of floods based on the count of events [22,33]. The scope of the present work is to recognize flood hazard and examine the temporal and spatial distribution of flood events in the study area, rather than to create a flood hazard map. Additionally, high resolution data such as discharge or rainfall during flood events were not readily available. For these reasons, the statistical analysis depends on the location of floods, dates of occurrences, the flooded area, the type of damages and the total damage caused by the floods.

For the description and assessment of historical floods, information was sourced from various national and regional authorities, scientific reports and newspaper articles. In general, the accuracy of the data used was considered acceptable as multiple checks between different sources were carried out to ensure consistency of the data. The location of events shows some uncertainty. According to [49], when there was no reference to a particular community, but the geographical determination was different (i.e., reference to river or torrent), location was determined on the basis of the other descriptive information. Thus, in some cases, as an event location is given the center of the municipal department. The historic database includes information about the causes of flooding, the flood mechanism and characteristics along with the maximum distance of the flood. The data of these records were not systematic and accurate, and they were not taken into account in the present work.

As a first step, a temporal statistical analysis was performed to identify the number of events and flooded area distribution during this period. The statistical significance of these variables was tested by *p*-values. Additionally, to identify the seasonal distribution of flood events, these parameters were analyzed for each month.

Flood events that occurred in the study area had adverse consequences and caused damages to economic activity. The type of damage was categorized into three categories: economic (positions of infrastructures, industrial and commercial centers), rural land use (positions of farmland with significant economic value production) and property [49]. The distributions of the number of each type of damage from 1979–2010 along with their monthly distribution were examined.

The total damages caused by the floods were categorized into five classes taking into account the number of human casualties, amount of monetary compensation (state compensation for damages to agriculture and for damages to settlements) or the size of flooded area [50]. The classes of the total damage and the limits of the above-mentioned parameters are presented in Table 1.

Table 1. Categories of the total damages, amount of monetary compensation and flooded area of the historical flood events.

Classes of Total Damages	Human Casualties	Compensation (Euro)	Flooded Area (Hectares)
Low		<50,000	<200
Medium		50,000–200,000	200–500
High		200,000–500,000	500–1000
Very High	≥1	>500,000	>1000

The annual and monthly distributions of the two above-mentioned parameters were studied during the period 1979–2010.

3.3. Spatial Analyses

Furthermore, a spatial analysis of the flood occurrences was carried out. The study area was divided into seven individual drainage basins. The spatial distribution of flood events in each drainage basin was examined. A spatial database was created, and ArcGIS 10.3 software was used to process the collected data.

Old maps may describe or simply locate areas that have flooded in the past. In many cases, former wetlands and lagoons that have been dried up cause flood events. Thus, the study of old topographic maps is very helpful to examine the causes of flood genesis [22,34,35]. The comparative observation of the old topographic maps of 1881 and the recent topographic maps of the study area led to a mapping of the previous wetlands. Marshy areas and lakes were digitized from the older edition survey maps, and they compared with the spatial distribution of current flood events. Finally, bibliographic data [36] were used to examine the association of the paleo-environment of Pinios River with the spatial frequency of floods.

The geomorphological setting of an area affects flood occurrences. Lowland morphology, gentle slopes and the flat areas create favorable conditions for flooding [51]. For this reason, the elevation, slope, aspect and slope curvature of the study area were examined. The selection of these geomorphological parameters and the determination of the class numbers, as well as their boundary values was based on the literature [51–54]. The elevation map was classified into two categories: (i) <100 m and (ii) >100 m. Similarly, the slope was divided into two categories: (i) <5° and (ii) >5°. The aspect map shows the slope direction and identifies the flat areas that have values = −1°. Thus, the aspect map was categorized into two classes: (i) = −1° and (ii) >−1°. In the case of curvature, negative curvatures represent concave, zero curvature represents flat and positive curvatures represent convex, respectively. Figure 3 shows the elevation, slope, aspect and the curvature maps and their categories. The areas with elevation < 100 m, slope < 5°, aspect = −1° and curvature = 0 were combined to identify the lowest and flattest areas of the study area. This was accomplished by the intersection tool of ArcGIS 10.3.

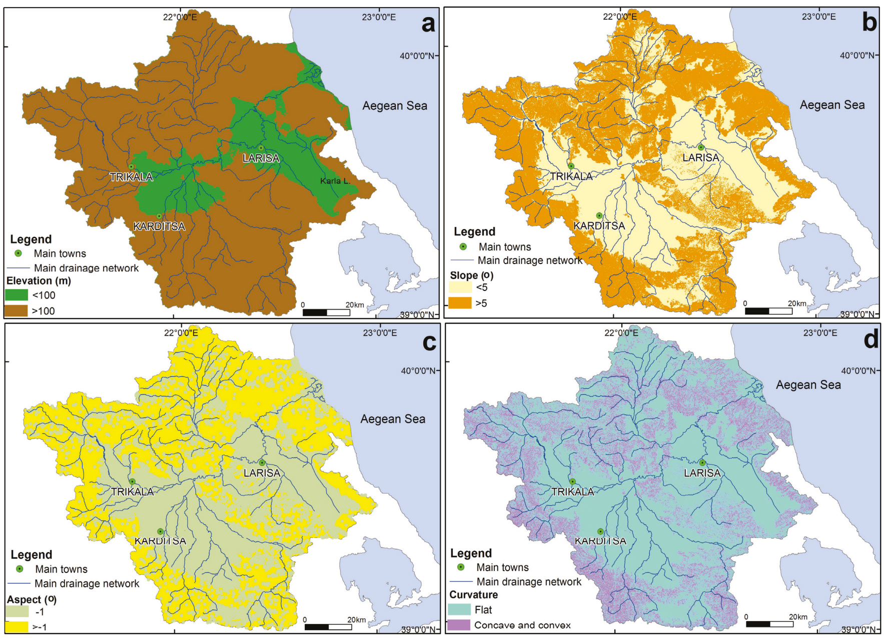


Figure 3. Thematic maps of the four geomorphological parameters: (**a**) elevation; (**b**) slope; (**c**) aspect; (**d**) curvature.

4. Results

4.1. Temporal Distribution of Flood Events

A total number of 146 flood events were recorded in the drainage basin of Pinios River during the period 1979–2010. Figure 4 shows the temporal distribution of flood occurrences during this period.

The number of flood events reached its maximum value (38) in 1994. The value of flood events was high (36) in the year 1987 and was relatively high (19) in 2002. In 1994, flood events were two-times higher than in 2002. In the 1980s, a total number of 40 flood events were recorded, while in the 1990s and 2000s, 55 and 47 were observed, respectively. Thus, there was a trend of increasing flood occurrences over the last two decades. The statistical analysis of the number of events showed that $p = 0.009$. Thus, the data used have values $p < 0.05$ and are statistically significant.

Figure 5 presents the seasonal distribution of flood events. The statistical analysis proved that October contained the most flood events (42). High values of flood occurrences were observed in March (35), in June (11) and in November (10). In October, the number of flood events was four-times higher than in June and November.

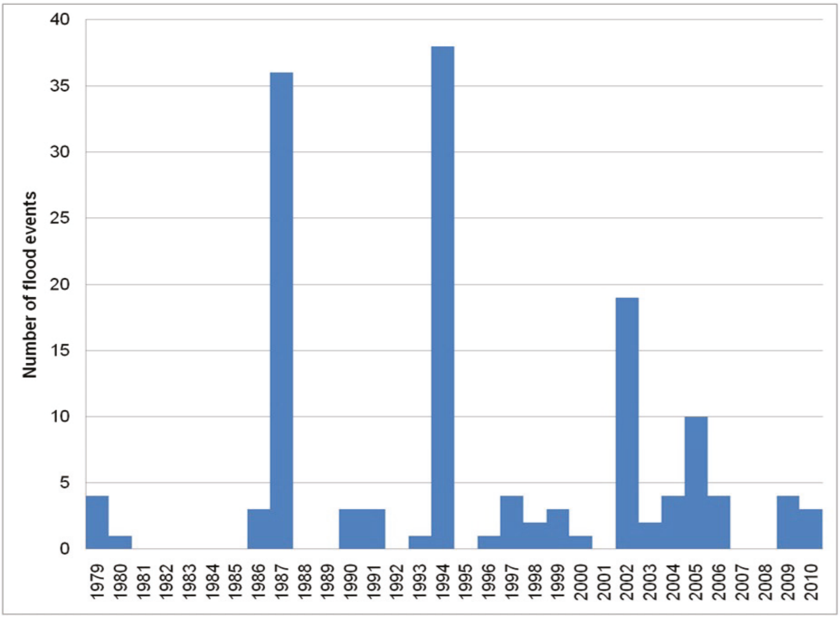


Figure 4. The annual distribution of flood events from 1979–2010.

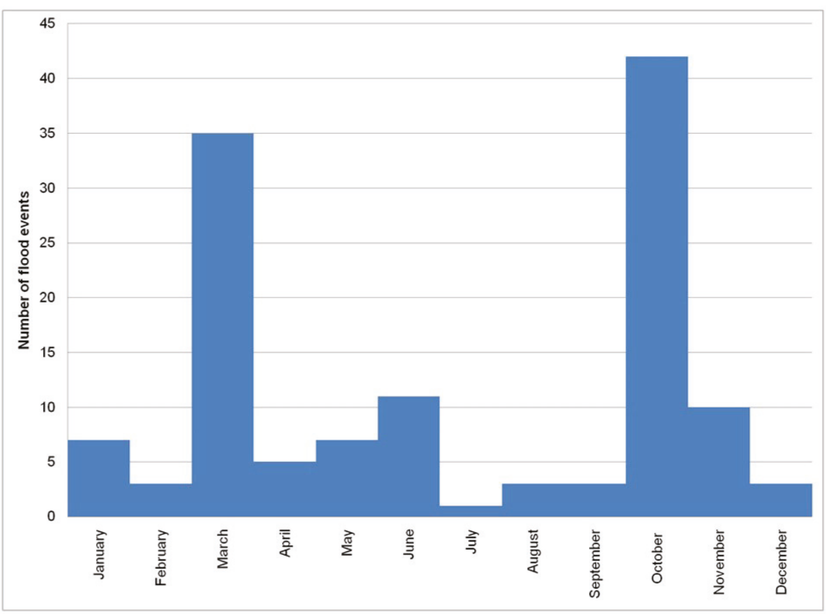


Figure 5. The monthly distribution of flood events during 1979–2010.

On the other hand, substantial differences appeared in the temporal distribution of the flooded area (Figure 6). It reached its maximum value (87.4 km^2) in 1987. Additionally, relatively high values were calculated in the years 1994 (69.5 km^2) and 1997 (64.8 km^2). The p-value was found to be 0.01, and thus, the data used were statistically significant. Regarding the seasonal distribution of flooded area (Figure 7), it reached its maximum value (136.5 km^2) in November. It presented relatively high values in March (83.2 km^2) and October (73.1 km^2).

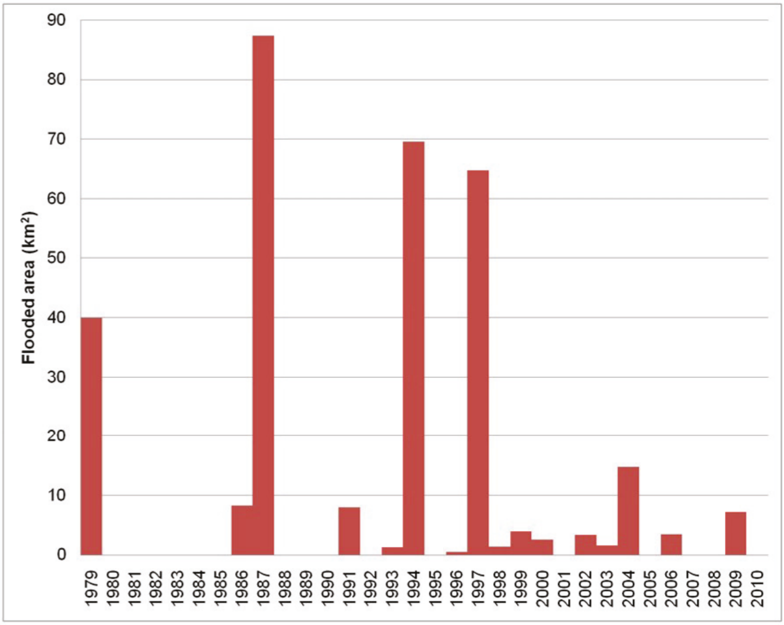


Figure 6. The monthly distribution of the flooded area during 1979–2010.

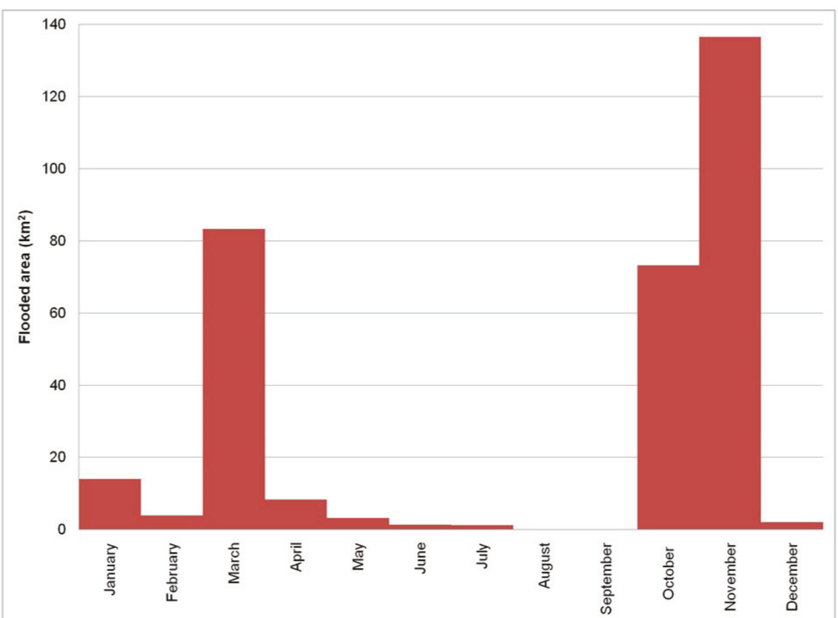


Figure 7. The monthly distribution of the flooded area during 1979–2010.

4.2. Temporal Distribution of Damages

Concerning the type of damages, their temporal and seasonal distributions are presented, respectively, in Figures 8 and 9. It is important to note that no human casualties were observed during the studied period. The values of economic damages were low during the studied period and reached the maximum value (3) in the years 1987, 1990 and 2010 (Figure 8). Similarly, their monthly distributions had relatively low values. The maximum value (4) of economic damages was recorded in March (Figure 9).

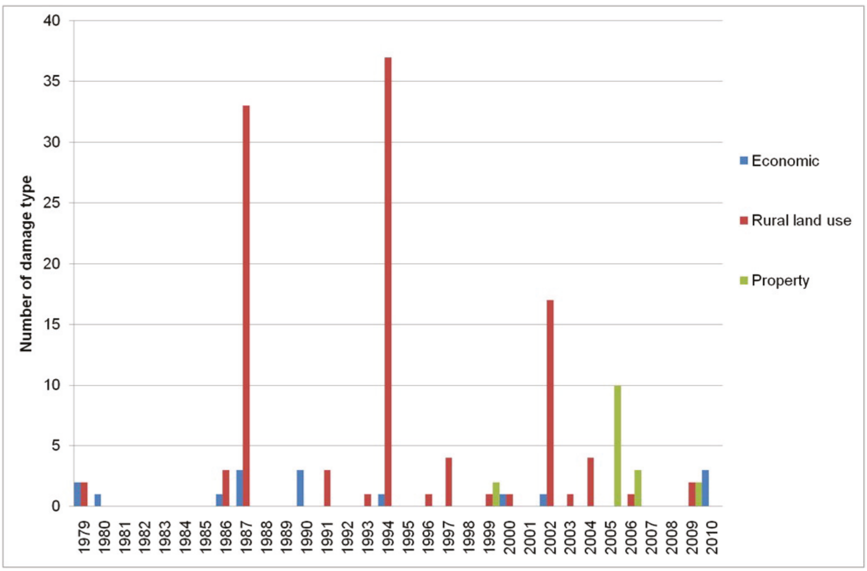


Figure 8. The annual distribution of type of damages in the study area during 1979–2010.

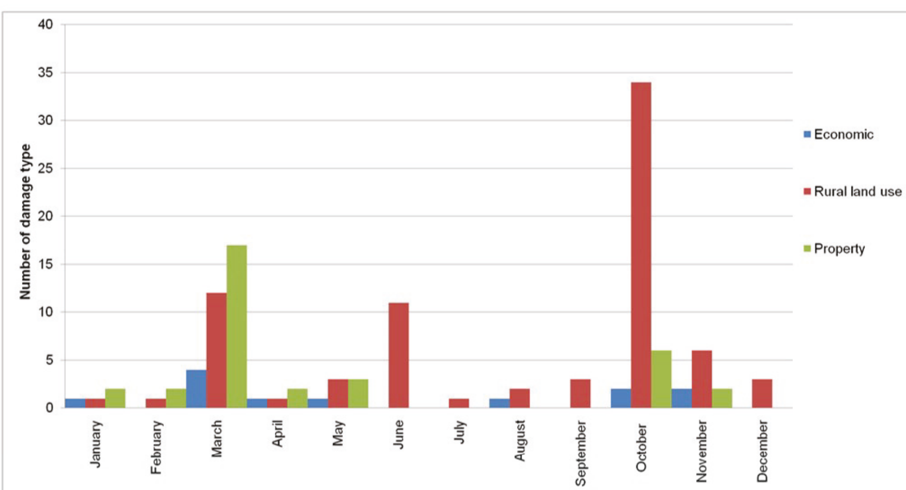


Figure 9. The monthly distribution of the type of damage.

On the contrary, the values of rural land use were the highest among all the types of damages (Figure 8). It reached its maximum value (37) in 1994, while it had relatively high values in the years 1987 (33) and 2002 (17). October was the month with the most records (34) in this type of damage (Figure 9). Additionally, high values were observed in March (12) and June (11). The maximum value (10) of the property damages was recorded in 2005 (Figure 8). March included the most number of property damages (17), while relatively high values (Figure 9) were recorded in October (six).

Figures 10 and 11 show the temporal and monthly distribution of categories of damages in the study area. The maximum value (10) of the very high category was observed in 2005, whilst its relatively high values were recorded in the years 1979 (three) and 1987 (three). Moreover, this category reached its maximum value (10) in June; a relatively high value (four) was calculated in November. The high class of damages reached its maximum value (six) in 1987 and a relatively high value (three) in the year 1994. March contained most records (five) of this class, and a high value was computed in October. The medium class reached its maximum value (24) in 1994, and a high value (12) was observed in 1987. The month with the most records (28) of this class was October; while a high value (13) was calculated in March. The annual and monthly maximum values of the low damages were observed in the year 1987 (14) and in March (13). Finally, the maximum value of the unknown class was recorded in the year 2002 (17).

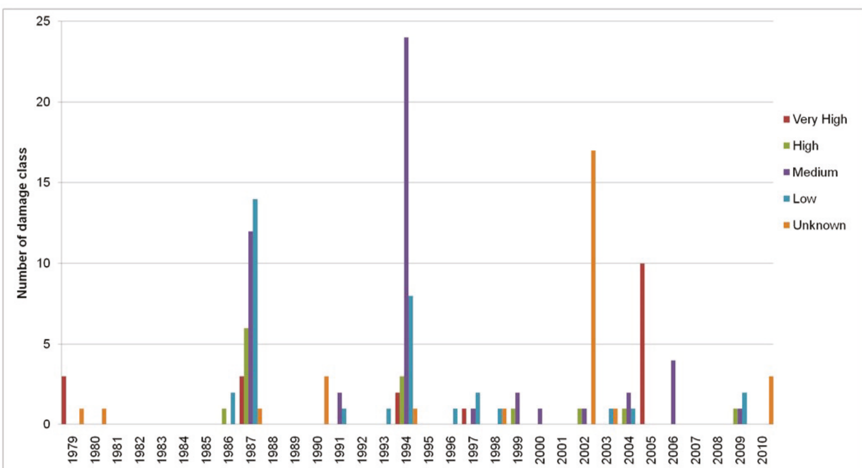


Figure 10. The annual distribution of categories of damages in the study area during 1979–2010.

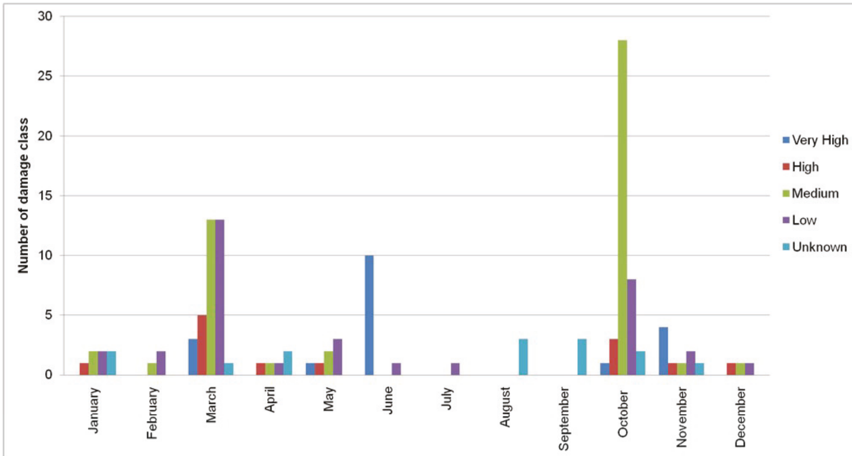


Figure 11. The monthly distribution of categories of damages during 1979–2010.

4.3. Spatial Distribution of Flood Events

The drainage basin of Pinios River were divided into seven sub-basins, which were: (a) the upper reaches of Pinios River; (b) Trikala-Neochoritis River; (c) Karditsa-Enippeas River; (d) Larisa-Karla; (e) Tempi Valley; (f) Titarisios River; and (g) the lower reaches of Pinios River. The spatial distribution of flood events in each drainage basin was examined. Table 2 shows the spatial distribution of flood events expressed as the number of events per drainage basin during the studied period. The most of floods were located in the drainage basin of Karditsa-Enippeas River.

Table 2. Spatial distribution of flood occurrences in each drainage sub-basin of the study area during the period 1979–2010.

Sub-Basin	Number of Floods
Upper reaches of Pinios River	4
Trikala-Neochoritis River	21
Karditsa-Enippeas River	63
Larisa-Karla	33
Tempi Valley	6
Titarisios River	7
Lower reaches of Pinios River	12

The mapping of the marshy area and lakes of the study area was based on the topographic map of 1881. They covered an area of about 161 km^2. Moreover, according to [36], two paleo-lakes existed in the study area during the Quaternary. The former marshy areas and lakes along with the boundaries of two paleo-lakes were compared with the historic flood events (Figure 12).

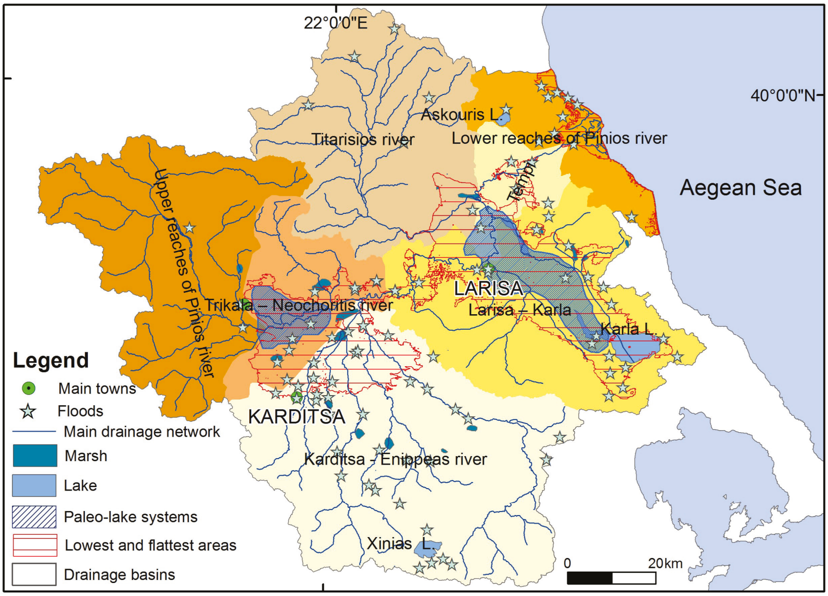


Figure 12. Marshy areas, lakes, paleo-lakes and lowest and flattest areas vs. flood occurrences in each drainage sub-basin of the study area during the period 1979–2010.

In the drainage basins of Trikala-Neochoritis River and Larisa-Karla, many flood events (12 events) were located in marshy areas, Lake Karla and paleo-lakes. In the drainage basin of Karditsa-Enippeas River, many floods (eight events) were located in or near marshy areas and Lake Xinias. In the drainage basins of Titarisios River and the lower reaches of Pinios River, few floods (two events) were located in or near marshy areas and Lake Askouris. Finally, in the drainage basins of the upper reaches of Pinios River and Tempi, no floods were associated with marshy areas.

The intersection of areas with an elevation <100 m, slope $<5^\circ$, aspect = $-1^\circ$and curvature = 0 is shown in Figure 12. The lowest and flattest areas were mainly located in the drainage basins of Trikala-Neochoritis River, Larisa-Karla and the lower reaches of Pinios River. In the drainage basins of Trikala-Neochoritis River and Larisa-Karla, they were mainly located in the areas where the former marshy areas and lakes were located. Regarding the spatial distribution of flood events, many flood events (61 events) were located in these areas.

5. Discussion and Conclusions

In the present study, the historical flood database of Greece and the old topographic maps of 1881 were used. These data were combined in a GIS environment to analyze the temporal and spatial distribution of flood events. The study area was the drainage basin of Pinios River, in Thessaly, central Greece.

The database contains floods that occurred between 1979 and 2010. A total number of 146 flood events were recorded in the drainage basin of Pinios River during this period.

The number of flood events reaches its maximum value (38) in the year 1994 (Figure 4). This may be related to flood events that occurred on 21–22 October 1994. No information about the causes of flooding, the flood mechanism and characteristics along with the maximum distance of the flood were included in the historic database. According to [55], this flood was caused by a severe storm. This intense storm caused flooding along the Pinios River and its tributaries, as well as inundation of agricultural and residential areas.

The statistical analysis showed that the data used are statistically significant. The number of flood occurrences shows a rising trend during the period 1990–2010. The study of the monthly distribution of the events demonstrates that October contains the most flood events, while March is the second month with many flood records (Figure 5).

Regarding the flooded area, it reaches its maximum value (87.4 km^2) in the year 1987 (Figure 6). This is attributed to flood event that occurred on 24–27 March 1987. The flood of March 1987 was caused by intense rainfall that produced direct runoff, as well as snowmelt. The water level of the Pinios River measured during the flood event exceeded 6.3 m in Kalamaki Valley and 8.0 m at Tempi Valley when the normal water level was less than 1 m in both locations (Figure 1b). Owing to the narrow riverbed at both locations (Kalamaki and Tempi), significant parts of the Thessaly plain upstream of each location were inundated [56].

Although October is the most flood-prone month, substantial differences appear in the monthly distribution of the flooded area. It reaches its maximum value (136.5 km^2) in November (Figure 7). This difference may be related to several reasons such as the difference in storm characteristics.

In the study area, the economic damages have low values. The type of damage with the most records is the rural land use. The maximum value is recorded in the year 1994, while the month with the maximum value is October (Figures 8 and 9). According to [55], during the flood of 21–22 October 1994, more than 70 houses in about 20 communities were totally destroyed by the flood, more than 200 suffered severe damage and another 90 minor damage, whereas 80 km^2 of agricultural land (cotton fields) were flooded. Concerning the property damages, the maximum value is observed in the year 2005, while March contains the most events (Figures 8 and 9). A flood event occurred in the study area on 16 June 2005, which caused serious damage to infrastructures and properties.

Regarding the class of damage, no human casualties were recorded in the study area between 1979 and 2010. According to [57], the most destructive events regarding human victims occurred in the city of Trikala in 1907. This flood caused at least 200 fatalities. Thus, the classification of the total damages is based on the amount of monetary compensation and flooded area of the historical flood events. The annual maximum value of the very high class is observed in the year 2005, while its monthly maximum value is recorded in June (Figures 10 and 11). This fact is related to the flood event of 16 June 2005. The amount of monetary compensation was 1,027,146 euros and was given for damages to infrastructures and properties [43]. The maximum value of the high class is recorded in the year 1987, and the maximum value of its monthly distribution is observed in March. This may be related to the flood event of 24–27 March 1987. Finally, the medium class has its maximum values in the year 1994 and in October, and this is related to the flood event of 21–22 October 1994.

The study area was divided into seven sub-basins to examine the spatial distribution of flood events (Table 2). The most occurrences are recorded in the southern part of the study area and specifically in the drainage basin of Karditsa-Enippeas River. Moreover, increased clustering of flood events is observed in the drainage basin of Larisa-Karla.

Old topographic maps of 1881 and bibliographic data were used to examine the relation of the paleo-environment of Pinios River with the spatial distribution of floods. The old topographic maps show earlier marshy areas and lakes, which nowadays, have dried up. According to [36], paleo-lake systems were located in the drainage basin of Pinios River during the Quaternary. One paleo-lake was located in the western part of the study area. Another, lower altitude paleo-lake, which was not connected to the previous one, was in the eastern part. During the Quaternary, the weathering of the carbonate rocks led to the connection of independent paleo-environments, and the Pinios River emerged. There is a certain amount of clustering of flood events in the areas of former marshes, lakes and paleo-lakes, which are located in the drainage basins of Trikala-Neochoritis River, Larisa-Karla and Karditsa-Enippeas (Figure 12).

In the study area, drainage and irrigation works along with levees were built 90 years ago, to protect it from flooding. However, incidents of annual flood events are reported in specific areas, and still, floods remain a big problem in the region [58]. Figure 12 presents the sites with earlier marshes and lakes, which are located in the lowest and flattest parts of the study area. The locations with earlier marshes and lakes are characterized by gentle slopes with low elevation and form the bottom of the drainage basin of the drainage network. These areas are developed mainly over semi-permeable or impermeable formations. The underlying geology and soil type affect the quality and the rate of infiltration. More specifically, the sediments within these wetlands may consist of materials such as clays and fine sands. These materials create a saturated layer on the surface during intense rainfall. Therefore, the specific runoff may be unable to further infiltrate the surface water into the subsurface. Consequently, these specific locations are sites where surface water runoff naturally collects and can lead to floods. Although, the wetlands and lakes have dried up, the morphology of the relief in these areas has not changed, causing flooding. According to studies carried out in other similar regions [35,52], the drainage basins that were 15% covered by wetlands had a flooding supply of 60–65% more than those not bearing wetlands. Consequently, drying up of the marshy areas and lakes of the region has strongly favored the flood events in the drainage basin of Pinios River.

The low and flat areas are located in the central, south-eastern and coastal part of the study area (Figure 12), and they contain many flood events. Usually, when a flood occurs, the lowest and flattest areas will be flooded first. Thus, these locations are areas prone to flood. This lowland morphology of the plain and the narrow passages along the river course such as Kalamaki, Rodia and Tempi gorges are the main reasons for the flooding [58]. According to [55], other reasons favoring the flood genesis due to human activities are some bridges with inadequate heights that are across the river and the construction by the farmers of "handy" barriers in the river channel for storage of irrigation water.

Endogenic processes such as active tectonics of the study area probably will not affect the flooding hazard in the near future. On the other hand, exogenic processes such as climate changes are capable of influencing future flood occurrences. Possible climate changes will cause sea level rise. Different scenarios were produced by the Intergovernmental Panel on Climate Change (IPCC), which predicts sea level rise from 0.3 to about 1.0 m until 2100 [59]. The possible sea level rise will increase the flood risk in the coastal area of the study area.

The historic flood data and old topographic maps provide valuable information for land use planning at a regional scale, leading to the determination of the safe and non-safe areas for urban activities [60]. The proposed methodology estimates the localization of sites prone to flood, and it may be utilized for flood hazard assessment mapping and for flood risk management. In areas prone to flooding, the appropriate land use planning along with the selection of the proper constructions are essential to prevent and mitigate the consequences of flood hazard occurrence. Consequently, proper land use for specific areas (i.e., parks, residential areas, etc.) may be determined. Additionally, construction of flood control works such as dams and levees, ponds, lakes and lagoons may be selected. Thus, planners, engineers and policy makers may use the applied approach for new and existing land use planning projects and for floodplain management.

Author Contributions: G.D.B conceived of the research. H.D.S. and G.D.B. designed the research and the data analysis. K.S. prepared and analyzed the data. G.D.B., H.D.S., K.S. and E.K completed the field work. H.D.S. and E.K. created the figures. G.D.B and H.D.S. wrote the paper.

Funding: This research received no external funding.

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

References

1. Cerdà, A. Effect of Climate on Surface Flow along a Climatological Gradient in Israel: A Field Rainfall Simulation Approach. *J. Arid Environ.* **1998**, *38*, 145–159. [CrossRef]
2. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The spatial distribution of Middle and Late Pleistocene cirques in Greece. *Geogr. Ann. A* **2014**, *96*, 323–338. [CrossRef]
3. Skilodimou, H.D.; Bathrellos, G.D.; Maroukian, H.; Gaki-Papanastassiou, K. Late Quaternary evolution of the lower reaches of Ziliana stream in south Mt. Olympus (Greece). *Geogr. Fis. Din. Quat.* **2014**, *37*, 43–50. [CrossRef]

4. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H.; Gaki-Papanastassiou, K.; Kouli, K.; Tsourou, T.; Tsaparas, N. Pleistocene glacial and lacustrine activity in the southern part of Mount Olympus (central Greece). *Area* **2017**, *49*, 137–147. [CrossRef]
5. Kamberis, E.; Bathrellos, G.; Kokinou, E.; Skilodimou, H. Correlation between the structural pattern and the development of the hydrographic network in a portion of the Western Thessaly basin (Greece). *Cent. Eur. J. Geosci.* **2012**, *4*, 416–424. [CrossRef]
6. Kokinou, E.; Skilodimou, H.D.; Bathrellos, G.D.; Antonarakou, A.; Kamberis, E. Morphotectonic analysis, structural evolution/pattern of a contractional ridge: Giouchtas Mt., Central Crete, Greece. *J. Earth Syst. Sci.* **2015**, *124*, 587–602. [CrossRef]
7. Chousianitis, K.; Del Gaudio, V.; Sabatakakis, N.; Kavoura, K.; Drakatos, G.; Bathrellos, G.D.; Skilodimou, H.D. Assessment of Earthquake-Induced Landslide Hazard in Greece: From Arias Intensity to Spatial Distribution of Slope Resistance Demand. *Bull. Seismol. Soc. Am.* **2016**, *106*, 174–188. [CrossRef]
8. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The significance of tectonism in the glaciations of Greece. *Geol. Soc. Spé;c. Publ.* **2017**, *433*, 237–250. [CrossRef]
9. Papadopoulou-Vrynioti, K.; Bathrellos, G.D.; Skilodimou, H.D.; Kaviris, G.; Makropoulos, K. Karst collapse susceptibility mapping considering peak ground acceleration in a rapidly growing urban area. *Eng. Geol.* **2013**, *158*, 77–88. [CrossRef]
10. Tsolaki-Fiaka, S.; Bathrellos, G.D.; Skilodimou, H.D. Multi-criteria decision analysis for abandoned quarry restoration in Evros Region (NE Greece). *Land* **2018**, *7*, 43. [CrossRef]
11. Skilodimou, H.D.; Bathrellos, G.D.; Koskeridou, E.; Soukis, K.; Rozos, D. Physical and anthropogenic factors related to landslide activity in the Northern Peloponnese, Greece. *Land* **2018**, *7*, 85. [CrossRef]
12. Morisawa, M. *Geomorphology Laboratory Manual*; Willey & Sons: Hoboken, NJ, USA, 1976; 253p.
13. Slaymaker, O. *Geomorphic Hazards*; John Wiley & Sons: Hoboken, NJ, USA, 1997; 204p.
14. Bathrellos, G.D. An overview in Urban Geology and Urban Geomorphology. *Bull. Geol. Soc. Greece* **2007**, *40*, 1354–1364. [CrossRef]
15. Bathrellos, G.; Skilodimou, H. Geomorphic Hazards and Disasters. *Bull. Geol. Soc. Greece* **2006**, *39*, 96–103. (In Greek)
16. Goudie, S.A. *Encyclopedia of Geomorphology*; Goudie, S.A., Ed.; Taylor & Francis Group: New York, NY, USA, 2006; pp. 378–379.
17. Merz, B.; Kreibich, H.; Schwarze, R.; Thieken, A. Assessment of economic flood damage. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 1679–1724. [CrossRef]
18. CEOS. *The Use of Earth Observing Satellites for Hazard Support: Assessments and Scenarios*; Final Report of the CEOS Disaster Management Support Group (DMSG); CEOS: Rome, Italy, 2003.
19. European Environment Agency (EEA). *Mapping the Impacts of Natural Hazards and Technological Accidents in Europe: An Overview of the Last Decade*; Office for Official Publications of the European Communities: Luxembourg; European Environment Agency (EEA): Copenhagen, Denmark, 2010.
20. Gaume, E.; Bain, V.; Bernardara, P.; Newinger, O.; Barbuc, M. A compilation of data on European flash floods. *J. Hydrol.* **2009**, *367*, 70–78. [CrossRef]
21. Payrastre, O.; Gaume, E.; Andrieu, H. Use of historical data to assess the occurrence of floods in small watersheds in the French Mediterranean area. In *Advances in Geosciences*; European Geosciences Union: Munich, Germany, 2005; Volume 2, pp. 313–320.
22. Tropeano, D.; Turconi, L. Using historical documents for landslide, debris flow and stream flood prevention. Applications in Northern Italy. *Nat. Hazards* **2004**, *31*, 663–679. [CrossRef]
23. Van Alphen, J.; Martini, F.; Loat, R.; Slomp, R.; Passchier, R. Flood risk mapping in Europe, experiences and best practices. *J. Flood Risk Manag.* **2009**, *2*, 285–292. [CrossRef]
24. Rijal, S.; Rimal, B.; Sloan, S. Flood Hazard Mapping of a Rapidly Urbanizing City in the Foothills (Birendranagar, Surkhet) of Nepal. *Land* **2018**, *7*, 60. [CrossRef]
25. Samanta, S.; Koloa, C.; Kumar Pal, D.; Palsamanta, B. Flood Risk Analysis in Lower Part of Markham River Based on Multi-Criteria Decision Approach (MCDA). *Hydrology* **2016**, *3*, 29. [CrossRef]
26. Jakob, M. Debris flow hazard analysis. In *Debris-Flow Hazards and Related Phenomena*; Jakob, M., Hungr, O., Eds.; Springer: Berlin, Germany, 2005; p. 794.
27. Langbein, W.B. Annual floods and the partial-duration flood series. *Trans. Am. Geophys. Union* **1949**, *30*, 879–881. [CrossRef]

28. Onyutha, C. On rigorous drought assessment using daily time scale: Non-stationary frequency analyses, revisited concepts, and a new method to yield non-parametric indices. *Hydrology* **2017**, *4*, 48. [CrossRef]
29. Lang, M.; Ouarda, T.B.M.J.; Bobée, B. Towards operational guidelines for over-threshold modeling. *J. Hydrol.* **1999**, *225*, 103–117. [CrossRef]
30. Willems, P. A time series tool to support the multi-criteria performance evaluation of rainfall-runoff models. *Environ. Model. Softw.* **2009**, *24*, 311–321. [CrossRef]
31. Smith, R.L. Threshold Methods for Sample Extremes. In *Statistical Extremes and Applications*; de Oliveira, J.T., Ed.; NATO ASI Series; Springer: Dordrecht, The Netherlands, 1985; Volume 131, pp. 623–638.
32. De Moel, H.; van Alphen, J.; Aerts, J.C.J.H. Flood maps in Europe—Methods, availability and use. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 289–301. [CrossRef]
33. Diakakis, M.; Mavroulis, S.; Deligiannakis, G. Floods in Greece, a statistical and spatial approach. *Nat. Hazards* **2012**, *62*, 485–500. [CrossRef]
34. Skilodimou, H.; Stefouli, M.; Bathrellos, G. Spatio-temporal analysis of the coastline of Faliro Bay, Attica, Greece. *Estud. Geol.-Madrid.* **2002**, *58*, 87–93. [CrossRef]
35. Skilodimou, H.; Livaditis, G.; Bathrellos, G.; Verikiou-Papaspiridakou, E. Investigating the flooding events of the urban regions of Glyfada and Voula, Attica, Greece: A contribution to Urban Geomorphology. *Geogr. Ann. A* **2003**, *85*, 197–204. [CrossRef]
36. Migiros, G.; Bathrellos, G.; Skilodimou, H.; Karamousalis, T. Pinios (Peneus) River (Central Greece): Hydrological-geomorphological elements and changes during the quaternary. *Cent. Eur. J. Geosci.* **2011**, *3*, 215–228. [CrossRef]
37. Mylopoulos, N.; Kolokytha, E.; Loukas, A.; Mylopoulos, Y. Agricultural and water resources development in Thessaly, Greece in the framework of new European Union policies. *Int. J. River Basin Manag.* **2009**, *7*, 73–89. [CrossRef]
38. Goumas, K. The irrigation in Thessaly plain: Effects to underground and surface waters. In Proceedings of the Greek Hydrotechnical Association Conference, Larissa, Greece, 2 February 2006; pp. 39–53. (In Greek)
39. Katsikatsos, G.; Migiros, G.; Vidakis, M. La structure géologique de la région de la Théssalie orientale (Grèce). *Ann. Soc. Géol. Nord* **1982**, *CI*, 177–188.
40. Migiros, G. The lithostratigraphic-tectonic structure of Orthris (Central Greece). *Bull. Geol. Soc. Greece* **1990**, *26*, 107–120. (In Greek)
41. Ferriere, J.; Reynaud, J.; Pavlopoulos, A.; Bonneau, M.; Migiros, G.; Proust, J.N.; Gardin, S. Geological evolution and geodynamic controls of Tertiary intramontane piggyback Meso-Hellenic Basin, Greece. *Bull. Soc. Geol. Fr.* **2004**, *175*, 361–381. [CrossRef]
42. Mimikou, M.; Koutsoyiannis, D. Extreme Floods in Greece: The Case of 1994. In Proceedings of the U.S.-Italy Research Workshop on the Hydrometeorology, Impacts and Management of Extreme Floods, Perugia, Italy, 13–17 November 1995.
43. Ministry of Environment and Energy. Special Secretariat for Water. Floods, Historic Floods. 2017. Available online: http://www.ypeka.gr/Default.aspx?tabid=252&locale=el-GR&language=en-US (accessed on 17 June 2018).
44. European Commission. *Directive 2007/60/EC of the European Parliament and of the Council on the Assessment and Management of Flood Risks*; European Environment Agency: Copenhagen, Denmark, 2007.
45. Hrisohoou, M. *Sheet "Ioannina-Metsovon-Grevena-Kozani-Servia"*; Topographic Map, Scale 1:200,000; Colman George: Athens, Greece, 1881.
46. Hrisohoou, M. *Sheet "Larissa-Elasson-Katerini"*; Topographic Map, Scale 1:200,000; Colman George: Athens, Greece, 1881.
47. Hrisohoou, M. *Sheet "Arta-Trikala-Karditsa"*; Topographic Map, Scale 1:200,000; Colman George: Athens, Greece, 1881.
48. Hrisohoou, M. *Sheet "Volos-Farsalos-Lamia"*; Topographic Map, Scale 1:200,000; Colman George: Athens, Greece, 1881.
49. Ministry of Environment, Energy and Climate Change. *Preliminary Flood Risk Assessment in Greece*; Ministry of Environment and Energy: Athens, Greece, 2012. (In Greek)
50. Ministry of Environment and Energy. *Special Secretariat for Water, Management Plan for the Drainage Basins of Eastern Peloponnese*; Ministry of Environment and Energy: Athens, Greece, 2017. (In Greek)

51. Bathrellos, G.D.; Skilodimou, H.D.; Chousianitis, K.; Youssef, A.M.; Pradhan, B. Suitability estimation for urban development using multi-hazard assessment map. *Sci. Total Environ.* **2017**, *575*, 119–134. [CrossRef] [PubMed]
52. Bathrellos, G.D.; Karymbalis, E.; Skilodimou, H.D.; Gaki-Papanastassiou, K.; Baltas, E.A. Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environ. Earth Sci.* **2016**, *75*, 319. [CrossRef]
53. Rozos, D.; Bathrellos, G.D.; Skilodimou, H.D. Comparison of the implementation of Rock Engineering System (RES) and Analytic Hierarchy Process (AHP) methods, based on landslide susceptibility maps, compiled in GIS environment. A case study from the Eastern Achaia County of Peloponnesus, Greece. *Environ. Earth Sci.* **2011**, *63*, 49–63. [CrossRef]
54. Pradhan, B. Flood susceptible mapping and risk area delineation using logistic regression, GIS and remote sensing. *J Spat. Hydrol.* **2010**, *9*, 1–18.
55. Koutsoyiannis, D.; Mimikou, M. *Management and Prevention of Crisis Situations: Floods, Droughts and Institutional Aspects*; 3rd EURAQUA Technical Review; Country Paper for Greece: Rome, Italy, 1996; pp. 63–77.
56. Koukis, G.; Koutsoyiannis, D.; Embleton, C.; Embleton-Hamann, C. (Eds.) *Geomorphological Hazards of Europe*; Elsevier: New York, NY, USA, 1997; Volume 5, pp. 215–242.
57. Bathrellos, G. Geological, Geomorphological and Geographic Study of Urban Areas in Trikala Prefecture—Western Thessaly. Ph.D. Thesis, National & Kapodistrian University of Athens, Athens, Greece, 2005; p. 561, (In Greek with Extended English Abstract).
58. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Papanastassiou, D.; Chousianitis, K.G. Potential suitability for urban planning and industry development by using natural hazard maps and geological—Geomorphological parameters. *Environ. Earth Sci.* **2012**, *66*, 537–548. [CrossRef]
59. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014 Synthesis Report Summary for Policymakers, August 2018. Available online: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf (accessed on 17 June 2018).
60. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Skianis, G.A.; Chousianitis, K.G. Assessment of rural community and agricultural development using geomorphological-geological factors and GIS in the Trikala prefecture (Central Greece). *Stoch. Environ. Res. Risk Assess.* **2013**, *27*, 573–588. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

land

MDPI

Article

Flood Hazard Mapping of a Rapidly Urbanizing City in the Foothills (Birendranagar, Surkhet) of Nepal

Sushila Rijal [1,*], Bhagawat Rimal [2,3] and Sean Sloan [4]

1 Faculty of Humanities and Social Science, Mahendra Ratna Multiple Campus, Ilam 57300, Nepal
2 The State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences (CAS), Beijing 100101, China; bhagawat@radi.ac.cn
3 College of Applied Sciences (CAS)-Nepal, Thapathali, Tribhuvan University, Kathmandu 44613, Nepal
4 College of Science and Engineering, Center for Tropical Environmental and Sustainability Science, James Cook University, Cairns QLD 4870, Australia; sean.sloan@jcu.edu.au
* Correspondence: sushilarijal@ymail.com

Received: 26 March 2018; Accepted: 3 May 2018; Published: 5 May 2018

Abstract: Flooding in the rapidly urbanizing city of Birendranagar, Nepal has been intensifying, culminating in massive loss of life and property during July and August 2014. No previous studies have monitored underlying land-cover dynamics and flood hazards for the area. This study described spatiotemporal urbanization dynamics and associated land-use/land-cover (LULC) changes of the city using Landsat imagery classifications for five periods between 1989 and 2016 (1989–1996, 1996–2001, 2001–2011, 2011–2016). Areas with high flood-hazard risk were also identified on the basis of field surveys, literature, and the Landsat analysis. The major LULC changes observed were the rapid expansion of urban cover and the gradual decline of cultivated lands. The urban area expanded nearly by 700%, from 85 ha in 1989 to 656 ha in 2016, with an average annual growth rate of 23.99%. Cultivated land declined simultaneously by 12%, from 7005 ha to 6205 ha. The loss of forest cover also contributed significantly to increased flood hazard. Steep topography, excessive land utilization, fragile physiographic structure, and intense monsoonal precipitation aggravate hazards locally. As in Nepal generally, the sustainable development of the Birendranagar area has been jeopardized by a disregard for integrated flood-hazard mapping, accounting for historical land-cover changes. This study provides essential input information for improved urban-area planning in this regard.

Keywords: urbanization; flood; remote sensing/GIS; Birendranagar; Nepal

1. Introduction

Hazards, defined as natural or human-induced activities that elevate the probability of material, social, or natural loss [1], are typified by the nexus of uncontrolled urbanization in contexts susceptible to natural flood, landslides, and earthquakes in Nepal. Here, urbanization is understood as processes leading toward increased population density, socioeconomic activities, and expanded built up areas and associated infrastructures [2]. Natural hazards and urbanization can interact to amplify land-use change, such as that negatively affecting agricultural areas [3,4]. In hazardous areas, including newly formed urban areas, land management and planning that would enhance resilience depend therefore on an understanding of those land-use/land-cover change (LULC) patterns that accentuate latent hazards [5].

Floods are the most common and devastating natural hazards [6] on a global scale and have been increasingly frequent and devastating since the mid-20th century [4]. Of all flood events recorded between 1950 and 2011, most have occurred during recent decades. Some 2% occurred during the 1950s, rising rapidly each decade thereafter to 3.9%, 6.6%, 13.2%, 21.9%, and 52.2% for the 1960s, 1970s, 1980s, 1990s, and 2000s, respectively [7]. Flood events also accounted more than two-third of all hydrological disasters during 2012–2014 [8] and 90.9% during 2015–2016 [9]. Flood hazards are global occurrences, yet associated economic damage and fatalities concentrate disproportionately among the continents [7]. Due to favorable geomorphological, metrological, and anthropogenic factors [10], more than 60% of the total economic and human losses during the period 1950 to 2011 were concentrated in Asia [7]. South Asia accounts for 33% of all Asian floods, 50% of associated fatalities, and 38% of the effected regions. As a proportion of South Asian totals, Nepal accounts for 7.2% of fatalities, 7.4% of the total victims, and 3.1% of economic losses, thereby ranking the country after India, Bangladesh, Pakistan, and Afghanistan [11]—8th globally in terms of flood fatalities [12] and 30th globally in terms of flood-hazard risk [13]. Of the five million Nepalese effected by natural hazards between 1971 and 2007, 68% were flood-related [14]. Between 1982 and 2014, nearly 9000 Nepalese lost their lives in flood and landslide events [15,16]. The Koshi flood event during 2008 affected 65,000 people and 700 ha of fertile land in the eastern lowland Tarai region [17]. In August 2017, floods affected 35 districts and destroyed 190,000 homes, fully or partially, with total economic losses estimated at $584.7 million [18]. While flooding in Nepal is triggered by monsoonal rainfall, steep and erosive topography, and wide catchments [4,19], its frequency and intensity increased largely due to increasing anthropogenic factors, namely, improper land-use, poorly-planned urbanization, deforestation, and settlements along river banks [20].

The study area, Birendranagar city of Nepal's Surkhet district, is rapidly urbanizing due to high rates of migration. Locals have migrated to the city in the quest of better quality of life and opportunities in the formal and informal markets [21], resulting in a 720% urban population growth rate for the period 1982–2015 (Table 1). It is a major socioeconomic hub and administrative center and an important gateway to Karnali zone, as well as a migrant-receiving area, mainly from the Dailekh district and the Karnali zone. Urban development has been haphazard due to deficient urban plans/policies and weak implementation. New and expanding urban settlements are characterized as spatially dispersed or discontiguous, and frequently arise over prime farm lands surrounding historic Birendranagar city. These urban areas, collectively defining Birendranagar city, are frequently devastated by annual flood events affecting transportation networks, and other infrastructure (e.g., bridges, markets), livelihoods, fatalities (numbering 38 in 2014 [16]), and soil erosion and transport to neighboring districts (27,092.94 Mt) of soil annually [22]. Despite their frequency, or perhaps because of their frequency, such events struggle to sustain the attention of policymakers [4]. Resilience is a vital tool with which to reduce the vulnerability [23]; however, the integration of flood-hazard risk management in regional plans and policies is hindered due to the lack of routine-based researches. Urban planning and flood hazard management to address these issues is inadequate, in part due to the lack of reliable, updated spatial databases.

Table 1. Population of Birendranagar city.

Year	1981	1991	2001	2011	2015
Population	13,859	22,973	31,381	93,718	100,458

Source: Central Bureau of Statistics (CBS), 2014.

To this end, this study uses remote sensing and GIS techniques to observe LULC changes and identify flood-risk hazards underlying the urbanization of Birendranagar city. This research will remain as an important benchmark for Nepalese planners/policymakers and land-change researchers, since its insights and outputs may serve as essential inputs for sustainable land-use plans and strategies for flood-hazard mitigation.

2. Method

2.1. Study Area

Nepal, like the focal region of this study, is increasingly urban. Nationally, the urban population grew from 2.9% of the general population in 1952/54 to 17.1% in 2011 [24] to more than 50% by 2017 [25]. Urban centers similarly increased in number from 10 to 58 over this period, and to 292 following after the local level reconstruction in 2017. Urbanization has been driven largely by internal migration, in turn sustained by regionally unequal development and economic opportunities [21,26]. Nepal experienced decade long political armed conflict during 1996–2006 [27,28], which displaced or otherwise spurred the migration of rural dwellers to growing cities in search of security. As the conflict subsided by 2006, several development activities were advanced throughout the country [29], again concentrating largely in select urban areas. Coincidentally, a peri-urban land market boom resulted in rapid, disorganized settlement expansion at the expense of arable lands [21,29].

The study area, Birendranagar city is the capital city of Karnali Province (Figure 1). After the reclassification of local administrative units as mandated by the New Constitution of Nepal, 2015, the former Village Development Committees (VDCs) were consolidated as Birendranagar city. This city spans 24,582 ha area and is divided amongst 16 wards housing 100,458 residents as of 2015 (Table 1) [24].

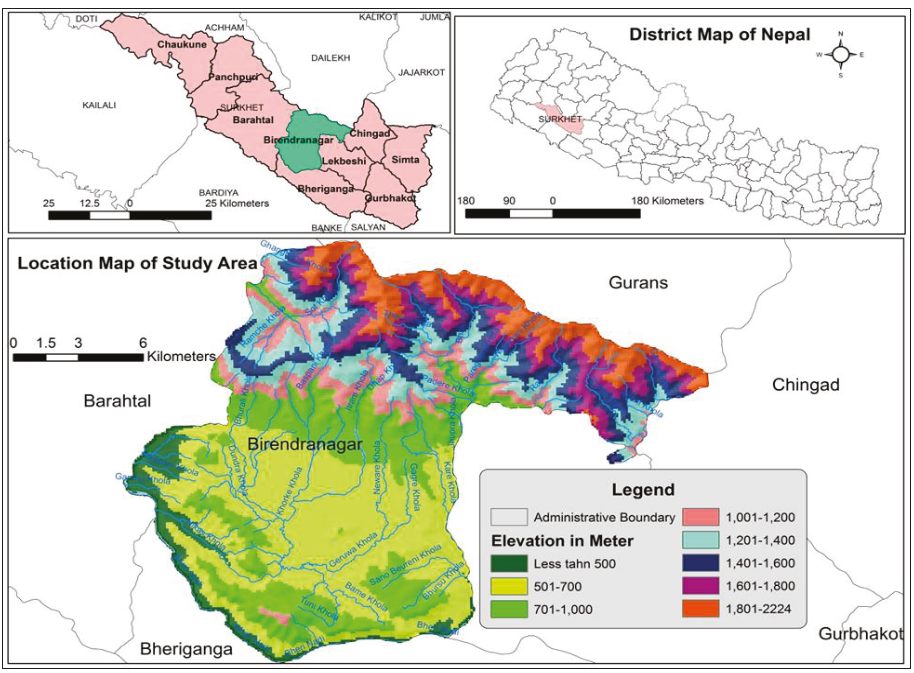


Figure 1. Location Map of the study area.

The Birendranagar city spans Nepal's sub-Himalayan and lesser-Himalayan zones, which are characterized by a warm-moist temperate, hot-dry sub-tropical, warm-dry sub-tropical, and cool-moist temperate climates, with annual temperatures ranging from 10 °C to 30 °C [22]. Elevation ranges from 380 to 2224 MASL. Birendranagar city receives intensive monsoonal precipitation, mainly between June and September, causing flooding and soil erosion, including along river banks. The study region is composed of fluvio-lacustrine sediments (sand, silt, clay, cobbles, and pebbles) deposited from the northern and southern parts of Siwalik Hills. Hard rocks in the region are comprised of sedimentary, meta-sedimentary, and metamorphic rock.

2.2. Extraction of LULC Change

Remote Sensing (RS) and Geographic information System (GIS) are successfully applied in various fields. They are effectively used for the LULC analyses [4,30–34], and flood area mapping. Multi-temporal time series of Landsat images [35] is capable of exploring accurate [36] LULC dynamics in specific time and space [21].

A city level land-use/land-cover (LULC) change analysis was realized by classifying time-series Landsat satellite imagery for 1989, 1996, 2001, 2006, 2011, and 2016. Atmospherically-corrected and maximal cloud-free Landsat images were sourced from United States Geological Survey (USGS) data portal (https://earthexplorer.usgs.gov). All scenes were verified for geometric accuracy, and data were projected on to UTM 44N (WGS 1984). For land-cover classification, six images with path/row 144/40 were selected for analysis. A "region of interest" (ROI) boundary representing municipality level study area was delineated for the classification. ENVI software was used to stack, subset, and classify the Landsat images via a maximum-likelihood (ML) algorithm [21,37,38]. A supervised approach with the ML-classifier algorithm was applied for the extraction of LULC. The land-cover classification system as recommended by Anderson et al. 1976 [39] was taken into consideration to classify the LULC and mainly seven LULC classes: urban/built-up, cultivated land, forest, shrub, sand, water, and others were identified (Table 2). Google Earth images (http://earth.google.com) and topographical maps from Survey Department, Government of Nepal (scale 1: 50,000) [40] were used to verify the LULC results. LULC transitions between each observation year were assessed using land change modeler (LCM) of TerrSet software developed by Clark Lab (www.clarklabs.org). Socioeconomic information on the drivers of urbanization were obtained from Central Bureau of Statistics [24] and use of Surkhet district profile [22].

Table 2. Land-cover classification scheme.

Land-Cover Types	Description
Urban (built up)	Urban and rural settlements, commercial areas, industrial areas, construction areas, traffic, airports, public service areas (e.g., schools, colleges, hospitals)
Cultivated land	Wet and dry crop lands, orchards
Forest	Evergreen broad leaf forest, deciduous forest, scattered forest, degraded forest
Shrub	Mix of trees (<5 m tall) and other natural covers
Sand	Sand area, other open field area, river bank
Water	River, lake/pond, canal, reservoir
Others	Cliffs/small landslide, bare rocks,

2.3. Identification of Flood Hazards

Areas of relatively acute flood hazard were further identified through field verification and informal surveys of local people during a field visit in 2014. High-hazard areas were geo-located using a GPS, and post-hazard observations were realized using high-resolution images of Google Earth. Contextual information was derived from the disaster reports of the National Planning Commission (NPC) [41] and the Ministry of Home Affairs (MoHA) [13,18], with additional information were garnered from the District Development Committee (DDC) [22]. Precipitation data for Birendranagar station were sourced from Department of Hydrology and Meteorology [42].

2.4. Urban/Built-Up Area Expansion Rate

Total urban area was estimated each observation year to measure the rate of urban expansion [21,37]. The rate of urban expansion describes the average annual growth of urban area during a given period, thus

$$\text{BER} = (B_2 - B_1)/(T_2 - T_1) * 100 \quad (1)$$

in which BER implies the urban expansion rate (*ha/year*), and B_1, B_2 refers to the urban area (*ha*) between times T_1, T_2 in years.

2.5. Classiifcation Accuracy Assessment

The verification of each Landsat classifications was realized with reference to high-resolution satellite imagery in Google Earth (http://earth.google.com), 1:50,000 scale topographical maps from the Nepalese Survey Department [40], and GPS points collected during the field visit, with the mixture of these reference data varying by classification year. Over the all-time periods of 1989–2016, some 350 sample points were interpreted across the city. Points were distributed via stratified random sampling method, with at least 50 points for each land-use/cover class. The overall accuracy, user's accuracies, and producer's accuracies were obtained for each observation year [21].

3. Result and Discussion

3.1. Land-Use Land-Cover Change between 1989 and 2016

The overall accuracies obtained for respective years were 83%, 82%, 85%, 85%, 84%, and 86% in the city. Over the 27 years of observation, the predominant LULC changes were (a) the rapid increase in urban cover after 2001, and more gradual increase in shrub lands; (b) the simultaneous losses of cultivated lands, as well as the steady but lesser decline in forest cover (Table 3, Figures 2 and 3).

During 1989–2016, urban area increased 571 ha, from 85 ha to 656 ha, with an average annual growth rate of 23.99% (Figure 2). Virtually all urban growth occurred after 2001; urban area was steady until 2001, but more than doubled between 2001 and 2006, from 113 ha to 289 ha. The decrease in cultivated lands paralleled this growth of urban areas in both timing and areas (Figure 2). Cultivated lands have declined 800 ha since 1989, from 7005 ha to 6205 ha. The increases in sandy areas and water after 2011 are mainly associated with the major flood events during 2013 and 2014.

Cultivated land was the major source of the newly expanded urban area. During 1989–1996, with the annual urban growth rate of 0.67%, urban area increased slightly by 4 ha, of which 75% (3 ha) was previously cultivated land. Subsequently, during the period 1996–2001, 24 ha new urban area was established (5.4% growth rate), 98% of which was cultivated previously (Figure 3). Between 2001 and 2006, all 176 ha of new urban cover occurred over cultivated lands (31% growth rate). The period 2006–2011 experienced unprecedented 295 ha of urban growth (20% growth rate, with 97% sourced from cultivated). This conversion rate continued for the last period, 2011–2016, despite its urban growth rate dropping to only 72 ha (2.5%).

Similar to the replacement of cultivated lands by expanding urban areas, forests have been steadily replaced by expanding shrub lands as economic development proceeded, aggravating flood hazard. The inflow of migrants to Birendranagar city and encroachments upon forest areas accelerated after the eradication program of malaria regionally in 1958. Forests were felled to supply resources for the development of Indian railway line, and subsequent development activities widely provoked deforestation and forest degeneration [43]. Also, devastating practices of deforestation under the Rana regime (1846–1951) were continued under the subsequent Panchayat system (1960–1990). More recently, the protection of forest cover to safeguard environmental integrity and ecological functions such as hydrological flow and flood protection has been prioritized in vulnerable regions like Birendranagar. The national government has launched various community-based forest management plans and

President Chure-Tarai conservation program to maintain current forest cover. These efforts likely contributed to the cessation of forest loss after 2006 in Birendranagar following earlier losses (Figure 2).

Table 3. LULC change of Birendranagar city during 1989–2016 (Area in ha).

LULC	1989	1996	2001	2006	2011	2016	1989–2016
Urban/built up	85	89	113	289	584	656	571
Cultivated	7005	6958	6935	6794	6371	6205	−800
Forest	13,703	13,482	13,406	13,341	13,494	13,342	−361
Shrub	3281	3566	3640	3644	3608	3798	517
Sand	276	258	253	272	274	324	48
Water	140	140	129	129	157	157	17
Others	91	89	105	111	95	99	8
Total	24,582	24,582	24,582	24,582	24,582	24,582	

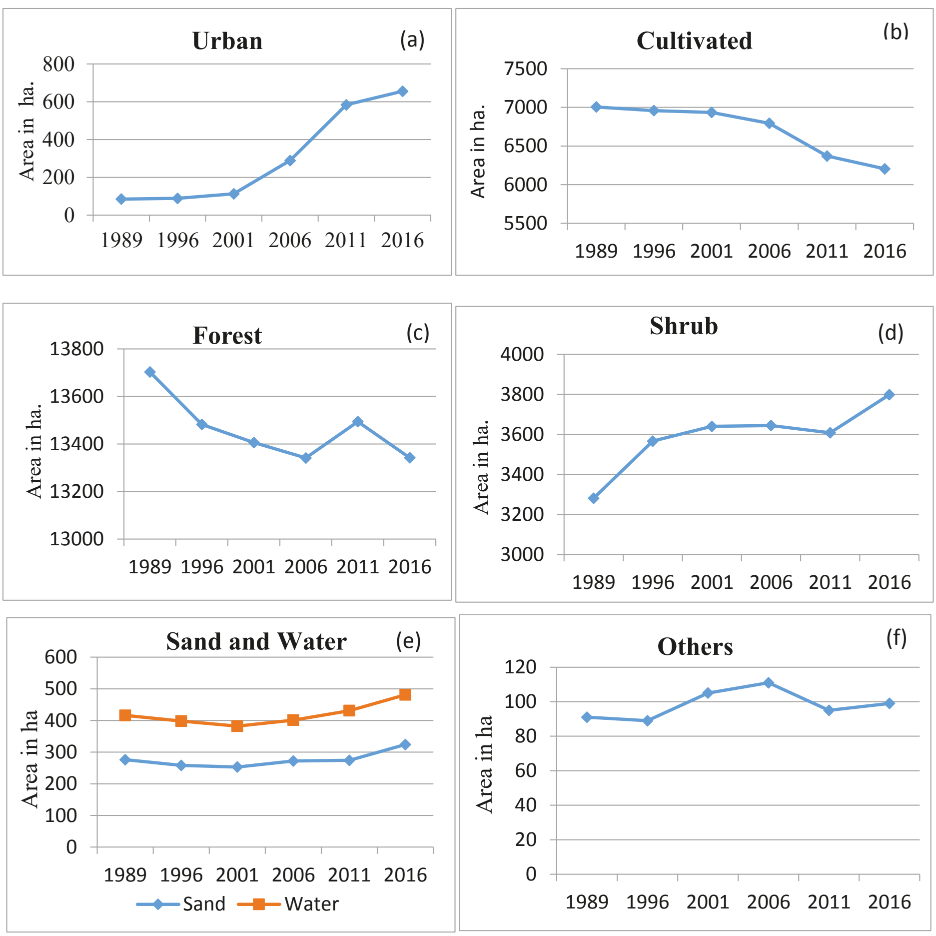


Figure 2. LULC change trend during 1989–2016. (**a**) Urban/built-up, (**b**) cultivated Land, (**c**) forest, (**d**) shrub (**e**) sand and water body, and (**f**) others.

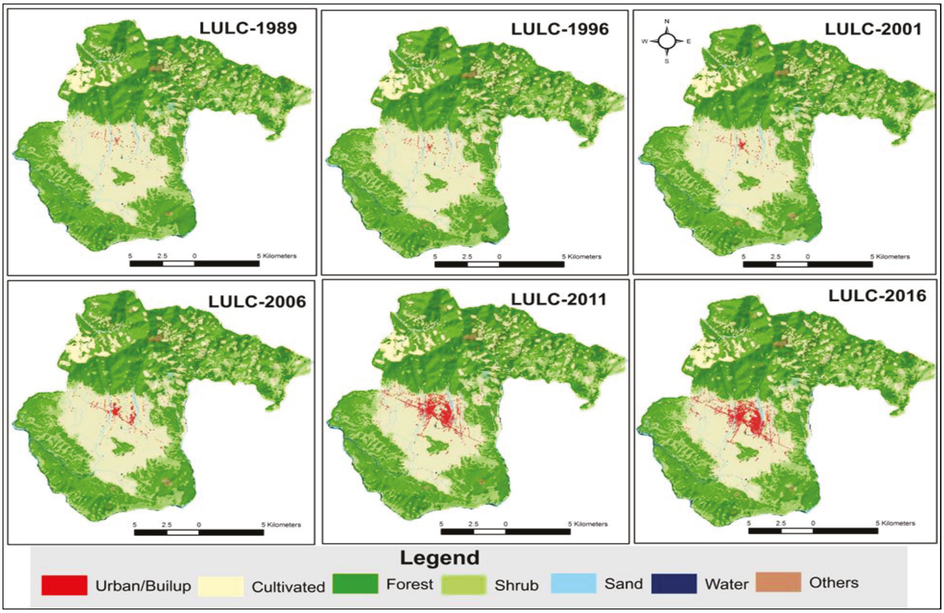


Figure 3. LULC change Maps of 1989 to 2016.

Nepal's New Constitution of 2015 mandated the reconstruction of all administrative areas and their reclassification within the federal administrative hierarchy. Birendranagar was declared the capital of Karnali Province. Hence, its recent history of urbanization is expected to continue as new governmental investments in economic and infrastructure development attract additional migrants. A ring road around the city, currently under construction, is expected to enhance the industrial, commercial, and development activities and thus to provoke urbanization and LULC change widely in the near future [44].

3.2. Flood Area Analysis

The Siwalik (Churiya) range and the southern slopes of the Mahabharat range are highly prone to geo-disasters [14,45] due to their fragile geology, steep slopes, and intense monsoonal precipitation during June through September (Figure 4), causing regular landslides and debris flow along creeks and steep slopes [20]. The highest average monthly rainfall was 488.77 mm and 428.64 mm for July and August, respectively, between 2000 and 2015 [42]. The southern belt of Churiya region and mid-hills are especially subject to intense rainfall from monsoonal low-pressure systems entering from the Bay of Bengal. The topographical slope of the study area ranges from below 4 degrees in the valley plain to 48 degrees in the Mahabharat range (Figure 5). The rocky soils cannot absorb intense rainfalls, resulting in major overland runs-off carrying soil and debris that have caused significant economic and human losses as urban expansion and deforestation have proceeded [41]. New settlements and urban expansion along river banks have disturbed river channels and drainage system. Deforestation and sand/gravel mining on the Siwalik range and upstream river beds have aggravated landslide hazards during the dry seasons. The major erosive and destructive forces of swollen rivers, which locals claim have increased in recent decades, dissipate only once steep riverine channels give way to gentler slopes, frustrating potential geo-engineering solutions to flood disasters.

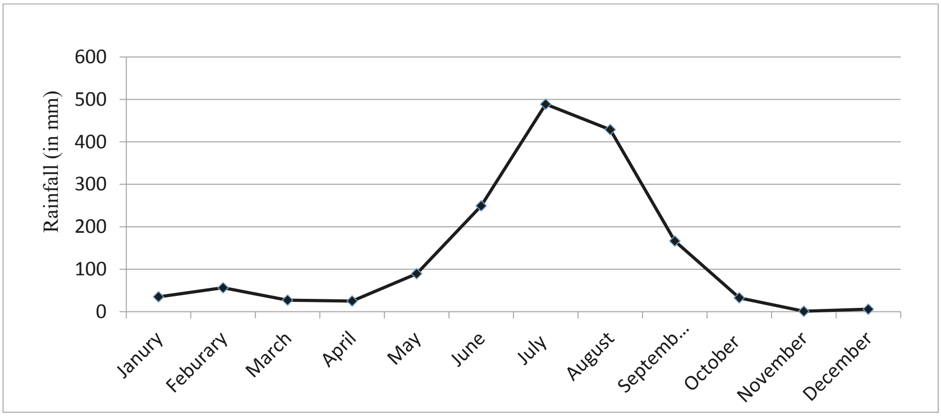


Figure 4. Trend of monthly mean rainfall of Birendranagar station during 2000–2015.

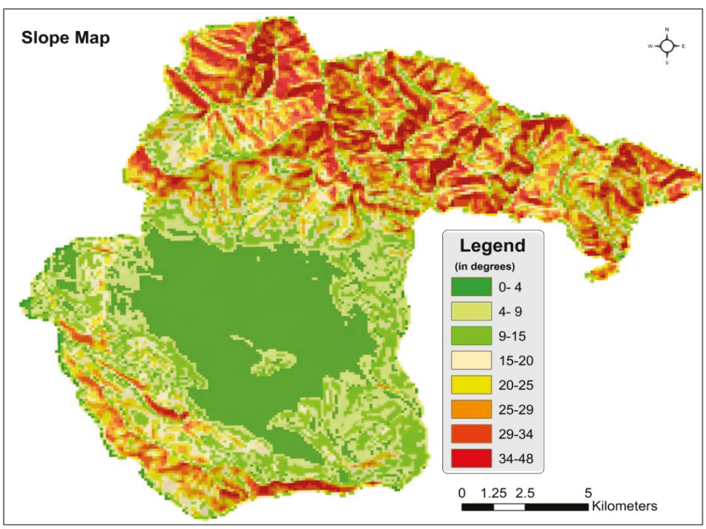


Figure 5. Slope Map of the Study Area.

Surkhet district is affected annually by monsoonal flood events, the impacts of which have been increasingly devastating in recent decades. During August, 2014, more than 12,385 people from 2327 families were displaced [46], 1581 houses were washed away, 301 houses were damaged, 15 government schools were destroyed, and 31 more were damaged, resulting in the economic loss of NRs 6 billion. Additionally, 411 irrigation projects, 99 drinking water schemes, 11 child development centers, and 663 ha of forest were swept away [43]. Latikoili, Ghatgaun, Satakhani, Chinchhu, Lekhparajul, Hariharpur, Babiyachaur, Tatapani, Taranga, Dharapani, and Kunathari settlements were the most affected areas [46]. Birendranagar city was particularly highly affected by the flooding [44] on Khorke River (Figure 6) and Itram River (Figure 7). This 2014 flood not only impacted the settlements and cultivated area, but also claimed human lives.

Figure 6. River bank erosion and sediment transportation by Khokre River (photo taken by author, 2014).

Figure 7. Affected infrastructures from the floods in the Itram River (photo taken by author, 2014).

Our survey of flooding events highlighted that the floods along the Neware river, Gagre river, Geruwa river, Tuni river, Dwari river, and Dundra river also effected the nearby settlements and farm lands. This study has identified several settlements and cultivated lands along these river banks that are at high risk of flood hazards, which are presented in Figure 8.

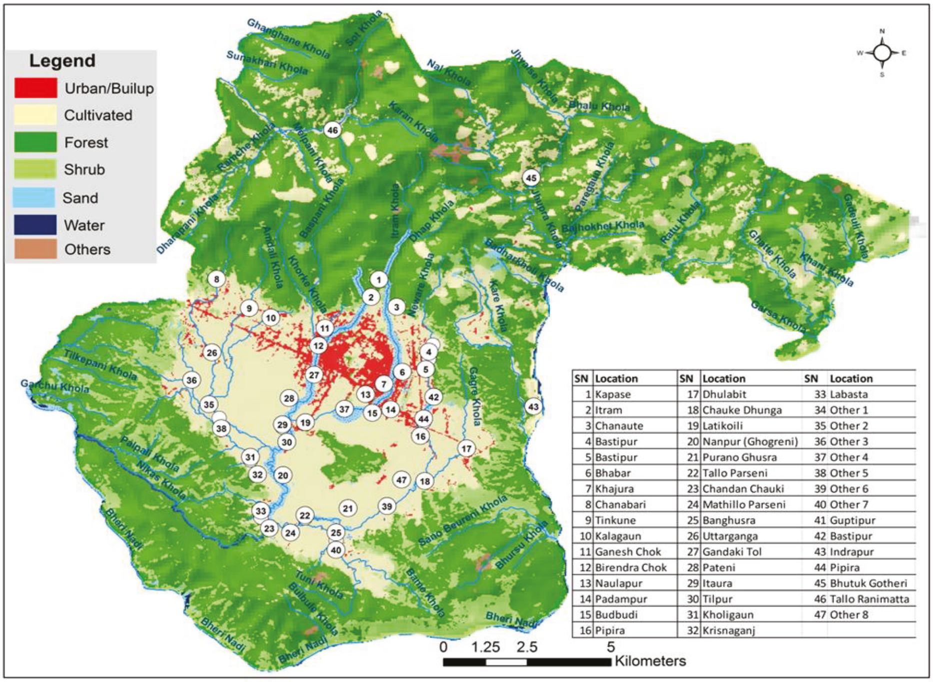


Figure 8. Flood hazard map.

4. Conclusions

The study describes the LULC changes and urbanization process surrounding Birendranagar city during 1989–2016 using Landsat imagery and extensive consultations with local residents and officials. It highlights the rapid expansion of urban/built-up area from 2001. Urban areas have expanded most aggressively over fertile farm lands and become agglomerated within the flood-prone valley, particularly along Surkhet-Jumla-Karnali Highway and cross sectional roads. Forest conservation programs have helped slow deforestation during the last two decades. While wider reforestation measures are probably required to counter soil erosion and downstream transport during monsoons, this alone is probably insufficient to reduce flood hazard to reasonable levels. New settlements and cultivated lands established along river banks have especially high monsoonal flood hazards. Therefore, careful sustainable urban planning, migration control, and redirection measures, as well as flood hazard management and monitoring programs, are also required. Flood hazard management and monitoring strategies are not yet explicitly incorporated into local urban development plans, let alone regional land-use plans [47]. Indeed, much recent urban development has been informal or otherwise not subject to specific plans and zoning. Addressing the challenges of flood hazard mitigation in Nepal is thus fundamentally a challenge of instituting good governance practices based on solid empirical foundations, whereby development is subject to local zoning plans and laws.

Author Contributions: S.R. and B.R. designed the project and wrote the manuscript. B.R. contributed to remote sensing and GIS part including field data acquisition and verification. S.S. contributed to writing and English editing. All authors revised and edited the final manuscript.

Acknowledgments: The authors thank all the scientists and local participants who have participated in the establishment of database.

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

References

1. UNISDR. *Living with Risk: A global Review of Disasterreduction Initiatives*; United Nation, Inter Agency Secretariat of the International Strategy for Disaster Reduction: Geneva, Switzerland, 2004; Volume 1.
2. Zhao, M.; Cheng, W.; Zhou, C.; Li, M.; Huang, K.; Wang, N. Assessing Spatiotemporal Characteristics of Urbanization Dynamics in Southeast Asia Using Time Series of DMSP/OLS Nighttime Light Data. *Remote Sens.* **2018**, *10*, 47. [CrossRef]
3. Eskandari, M.; Omidvar, B.; Modiri, M.; Nekooie, M.; Alesheikh, A. Geospatial Analysis of Earthquake Damage Probability of Water Pipelines Due to Multi-Hazard Failure. *ISPRS Int. J. Geo-Inf.* **2017**, *6*, 169. [CrossRef]
4. Rimal, B.; Zhang, L.; Keshtkar, H.; Sun, X.; Rijal, S. Quantifying the Spatiotemporal Pattern of Urban Expansion and Hazard and Risk Area Identification in the Kaski District of Nepal. *Land* **2018**, *7*, 37. [CrossRef]
5. Halimi, M.; Sedighifar, Z.; Mohammadi, C. Analyzing spatiotemporal land use/cover dynamic using remote sensing imagery and GIS techniques case: Kan basin of Iran. *GeoJournal* **2017**, 1–11. [CrossRef]
6. Sanyal, J.; Lu, X.X. Application of Remote Sensing in Flood Management with Special Reference to Monsoon Asia: A Review. *Nat. Hazards* **2004**, *33*, 283–301. [CrossRef]
7. Dewan, A.M. *Geospatial Techniques in Assessing Hazards, Risk and Vulnerability*; Springer: Dordrecht, The Netherlands; Heidelberg, Germany; New York, NY, USA; London, UK, 2013.
8. Guha-Sapir, D.; Hoyois, P.; Below, R. *Annual Disaster Statistical Review 2014: The Numbers and Trends*; Centre for Research on the Epidemiology of Disasters (CRED): Brussels, Belgium, 2015.
9. Guha-Sapir, D.; Hoyois, P.; Below, R. *Annual Disaster Statistical Review 2015: The Numbers and Trends*; Centre for Research on the Epidemiology of Disasters (CRED): Brussels, Belgium, 2016.
10. Karymbalis, E.; Katsafados, P.; Chalkias, C.; Gaki-Papanastassiou, K. An integrated study for the evaluation of natural and anthropogenic causes of flooding in small catchments based on geomorphological and meteorological data and modeling techniques: The case of the Xerias torrent (Corinth, Greece). *Z. Geomorphol.* **2012**, *56*, 45–67. [CrossRef]
11. Shrestha, M. Impacts of Floods in South Asia. *J. South Asia Disaster Stud.* **2008**, *1*, 85–106.
12. Upreti, B. Impact of natural disaster on development of Nepal. In *Bhandary NP. Disasters and Development, Investing in Sustainable Development in Nepal*; Subedi, J.K., Ed.; Ehime University, Japanand Bajra Publication: Kathmandu, Nepal, 2010.
13. Ministry of Home Affairs (MoHA). *Nepal Disaster Report 2011*; Ministry of Home Affairs (MoHA) and Disaster Preparedance Network (DPNeT): Kathmandu, Nepal, 2011.
14. United Nations Development Programme (UNDP). Global Assessment of Risk. In *Nepal Countary Report*; UNDP Pulchowk: Kathmandu, Nepal, 2009.
15. Department of Water Induced Disaster Prevention (DWIDP). *Annual Disaster Review 2012. Government of Nepal*; Ministry of Irrigation Department of Water Induced Disater Management, Ed.; DWIDP: Kathmandu, Nepal, 2013.
16. Ministry of Home Affairs (MoHA). *Nepal Disaster Report 2015*; Disaster Preparedance Network (DPNeT); Ministry of Home Affairs (MoHA): Kathmandu, Nepal, 2015.
17. Kafle, K.R.; Khanal, S.N.; Dahal, R.K. Consequences of Koshi flood 2008 in terms of sedimentation characteristics and agricultural practices. *Geoenviron. Disasters* **2017**, *4*. [CrossRef]
18. MoHA. Nepal Disaster Report. Available online: http;://drrportal.gov.np (accessed on 19 November 2017).
19. Dahal, R.K.; Bhandary, N.P. Geo-Disaster and Its Mitigation in Nepal. In *Progress of Geo-Disaster Mitigation Technology in Asia*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 123–156.
20. International Centre for Integrated Mountain Development/United Nation Educational Scientific and Cultural Organization (ICIMOD/UNESCO). *Preparing for Flood Disaster Mapping and Assessing Hazard in the Ratu Watershed, Nepal*; Nepal, K., United Nations Educational Scientific and Cultural Organization (UNESCO), Eds.; ICIMOD: New Delhi, India, 2007.
21. Rimal, B.; Zhang, L.; Stork, N.; Sloan, S.; Rijal, S. Urban Expansion Occurred at the Expense of Agricultural Lands in the Tarai Region of Nepal from 1989 to 2016. *Sustainability* **2018**, *10*, 1341. [CrossRef]
22. District Development Committee (DDC). *District Profile, Surkhet*; Government of Nepal, Ed.; DDC: Surkhet, Nepal, 2010.

23. Morrison, A.; Westbrook, C.J.; Noble, B.F. A review of the flood risk management governance and resilience literature. *J. Flood Risk Manag.* **2017**. [CrossRef]
24. Central Bureau of Statistics (CBS). *Population Monograph of Nepal*; National Planning Commission Secretariat; CBS: Kathmandu, Nepal, 2014.
25. Ministry of Federal Affairs and Local Development (MoFALD). *Local Level Reconstruction Report*; MoFALD: Kathmandu, Nepal, 2017.
26. Thapa, R.B.; Murayama, Y. Drivers of urban growth in the Kathmandu valley, Nepal: Examining the efficacy of the analytic hierarchy process. *Appl. Geogr.* **2010**, *30*, 70–83. [CrossRef]
27. Muzzini, E.; Aparicio, G. *Urban Growth and Spatial Transition in Nepal*; The World Bank: Washington, DC, USA, 2013.
28. Do, Q.T.; Iyer, L. Geography, Poverty and Conflict in Nepal. In *Working Paper -07-065*; Harvard Business School: Boston, MA, USA, 2009.
29. Rimal, B.; Zhang, L.; Fu, D.; Kunwar, R.; Zhai, Y. Monitoring Urban Growth and the Nepal Earthquake 2015 for Sustainability of Kathmandu Valley, Nepal. *Land* **2017**, *6*, 42. [CrossRef]
30. Dewan, A.M.; Yamaguchi, Y. Using remote sensing and GIS to detect and monitor land use and land cover change in Dhaka Metropolitan of Bangladesh during 1960–2005. *Environ. Monit. Assess.* **2009**, *150*, 237–249. [CrossRef] [PubMed]
31. Thapa, R.B.; Murayama, Y. Examining Spatiotemporal Urbanization Patterns in Kathmandu Valley, Nepal: Remote Sensing and Spatial Metrics Approaches. *Remote Sens.* **2009**, *1*, 534–556. [CrossRef]
32. Rimal, B.; Zhang, L.; Keshtkar, H.; Haack, B.; Rijal, S.; Zhang, P. Land Use/Land Cover Dynamics and Modeling of Urban Land Expansion by the Integration of Cellular Automata and Markov Chain. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 154. [CrossRef]
33. Keshtkar, H.; Voigt, W. Potential impacts of climate and landscape fragmentation changes on plant distributions: Coupling multi-temporal satellite imagery with GIS-based cellular automata model. *Ecol. Inform.* **2016**, *32*, 145–155. [CrossRef]
34. Keshtkar, H.; Voigt, W. A spatiotemporal analysis of landscape change using an integrated Markov chain and cellular automata models. *Model. Earth Syst. Environ.* **2015**, *2*, 10. [CrossRef]
35. Byun, Y.; Han, Y.; Chae, T. Image Fusion-Based Change Detection for Flood Extent Extraction Using Bi-Temporal Very High-Resolution Satellite Images. *Remote Sens.* **2015**, *7*, 10347–10363. [CrossRef]
36. Sloan, S.; Pelletier, J. How accurately may we project tropical forest-cover change? A validation of a forward-looking baseline for REDD. *Glob. Environ. Chang.* **2012**, *22*, 440–453. [CrossRef]
37. Rimal, B.; Zhang, L.; Keshtkar, H.; Wang, N.; Lin, Y. Monitoring and Modeling of Spatiotemporal Urban Expansion and Land-Use/Land-Cover Change Using Integrated Markov Chain Cellular Automata Model. *ISPRS Int. J. Geo-Inf.* **2017**, *6*, 288. [CrossRef]
38. Rimal, B.; Baral, H.; Stork, N.; Paudyal, K.; Rijal, S. Growing City and Rapid Land Use Transition: Assessing Multiple Hazards and Risks in the Pokhara Valley, Nepal. *Land* **2015**, *4*, 957–978. [CrossRef]
39. Anderson, J.R. *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*; United States Government Printing Office: Washington, DC, USA, 1976.
40. Government of Nepal (GN). *Topographical Map*; Ministry of Land Resources and Management Survey Department; Topographic Survey Branch: Kathmandu, Nepal, 1998.
41. National Planning Commission (NPC). *Post Flood Recovery Needs Assessment*; NPC; Government of Nepal; Singha Durbar: Kathmandu, Nepal, 2017.
42. The Department of Hydrology and Meteorology (DHM). *Metrological Data of Birendranagar Station, Surkhet*; Government of Nepal, Ed.; DHM: Kathmandu, Nepal, 2016.
43. UN-Habitat. *District Land Use Plan of Surkhet*; Catalytic Support on Land Issues, Participatory Land Use Planning Project; UN-Habitat: Pulchowk, Nepal, 2015.
44. UN-Habitat. *Village Development Committee Land Use Plan of Latikoili*; Catalytic Support on Land Issues, Participatory Land Use Planning Project; UN-Habitat: Pulchowk, Nepal, 2015.
45. Ghimire, M. Historical Land Covers Change in the Chure-Tarai Landscape in the Last Six Decades: Drivers and Environmental Consequences. In *Land Cover Change and Its Eco-Environmental Responses in Nepal*; Li, A., Deng, W., Zhao, W., Eds.; Springer: Singapore, 2017; pp. 109–147.

46. Informal Sector Service Center (INSEC). *Flood Victims of Surkhet District Undergoing Pains due to State Apathy*; INSEC: Kathmandu, Nepal, 2017.
47. Baan, P.J.; Klijn, F. Flood risk perception and implications for flood risk management in the Netherlands. *Int. J. River Basin Manag.* **2004**, *2*, 113–122. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

land

Article

Physical and Anthropogenic Factors Related to Landslide Activity in the Northern Peloponnese, Greece

Hariklia D. Skilodimou [1], George D. Bathrellos [1,*], Efterpi Koskeridou [2], Konstantinos Soukis [3] and Dimitrios Rozos [4]

1 Department of Geography and Climatology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, Zografou, ZC 15784, Athens, Greece; hskilodimou@geol.uoa.gr
2 Department of Historical Geology-Palaeontology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, Zografou, ZC 15784, Athens, Greece; ekosker@geol.uoa.gr
3 Department of Dynamic Tectonic Applied Geology, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, University Campus, Zografou, ZC 15784, Athens, Greece; soukis@geol.uoa.gr
4 Department of Geological Sciences, School of Mining and Metallurgical Engineering, National Technical University of Athens, 9 Heroon Polytechniou str, Zografou, ZC 15780, Athens, Greece; rozos@metal.ntua.gr
* Correspondence: gbathrellos@geol.uoa.gr; Tel.: +30-2107274882

Received: 27 June 2018; Accepted: 15 July 2018; Published: 19 July 2018

Abstract: The geological, geomorphic conditions of a mountainous environment along with precipitation and human activities influence landslide occurrences. In many cases, their relation to landslide events is not well defined. The scope of the present study is to identify the influence of physical and anthropogenic factors in landslide activity. The study area is a mountainous part of the northern Peloponnesus in southern Greece. The existing landslides, lithology, slope angle, rainfall, two types of road network (highway-provincial roads and rural roads) along with land use of the study area are taken into consideration. Each physical and anthropogenic factor is further divided into sub-categories. Statistical analysis of landslide frequency and density, as well as frequency and density ratios, are applied and combined with a geographic information system (GIS) to evaluate the collected data and determine the relationship between physical and anthropogenic factors and landslide activity. The results prove that Plio-Pleistocene fine-grained sediments and flysch, relatively steep slopes (15°–30°) and a rise in the amount of rainfall increase landslide frequency and density. Additionally, Plio-Pleistocene fine-grained sediments and flysch, as well as schist chert formations, moderate (5°–15°) and relatively steep slopes (15°–30°), along with the amount of rainfall of >700 mm are strongly associated with landslide occurrences. The frequency and magnitude of landslides increase in close proximity to roads. Their maximum values are observed within the 50 m buffer zone. This corresponds to a 100 m wide zone along with any type of road corridors, increasing landslide occurrences. In addition, a buffer zone of 75 m or 150 m wide zone along highway and provincial roads, as well as a buffer zone of 100 m or 200 m wide zones along rural roads, are strongly correlated with landslide events. The extensive cultivated land of the study area is strongly related to landslide activity. By contrast, urban areas are poorly related to landslides, because most of them are located in the northern coastal part of the study area where landslides are limited. The results provide information on physical and anthropogenic factors characterizing landslide events in the study area. The applied methodology rapidly estimates areas prone to landslides and it may be utilized for landslide hazard assessment mapping as well as for new and existing land use planning projects.

Keywords: landslides; geographic information system (GIS); frequency ratio; density ratio; human activities; land use planning

1. Introduction

Landslides are physical phenomena, active in geological time. They have affected the natural environment and existing biota since even before the appearance of man on Earth. Nowadays, they are considered as one of most significant natural hazards worldwide. Frequently, their associated consequences have adverse long-term effects. When these consequences have a major impact on human life and activities, they become natural disasters [1].

Mass movements are identified as the movement of a mass of soil, rock, debris or earth down a slope [2]. They can include falls, topples, slides, spreads and flows. These phenomena are part of the process of hill slope erosion which is responsible for the introduction of sediment into streams, rivers, lakes, reservoirs and finally the oceans [3].

Landslides can be triggered by a variety of external factors, such as intense rainfall, earthquakes and rapid stream erosion [3–9]. Additionally, human activities such as deforestation of slopes, removal of slope support in road cuts, alteration of surface runoff paths, have become important triggers for landslide manifestation [10,11].

Every year, landslides kill people and cause huge property damage in mountainous areas of the world [11]. Kumar et al. [12] reported that in the Himalayas over 2000 landslides killed more than 5000 people during 2013. In the USA, landslide events cause an estimated US$1–2 billion in economic losses and about 25–50 fatalities annually [13]. In Italy, at least 263 people were killed by mass movements during the period of 1990–1999 [14].

Much of Greece consists of hilly and mountainous terrain subject to landslide manifestation. Therefore, landslide events are common phenomena and cause significant damage to road networks, sections of urban areas and cultivated land [15–17].

Several physical process factors and human activities influence landslide activity. Landslides in the future will most likely occur under geomorphic, geologic, and hydrologic conditions that have produced past and present landslides. Types of bedrock, slope steepness, and precipitation zones represent, respectively, geologic, geomorphic and hydrologic factors. Weak, incompetent rock is more likely to fail than strong, competent rock; general steeper slopes have a greater chance of landsliding, while rainfall is considered as an important factor in slope stability, almost as important as gravity [2,3,11,15]. In addition, the frequency of landslide events commonly increases, when man-made structures induce changes in mountainous environments [3]. Human settlements, cut-and-fill construction for roads, the construction of buildings and railroads, changes in land cover, and terracing for agriculture contribute to the conditions that lead to slope failure [18,19].

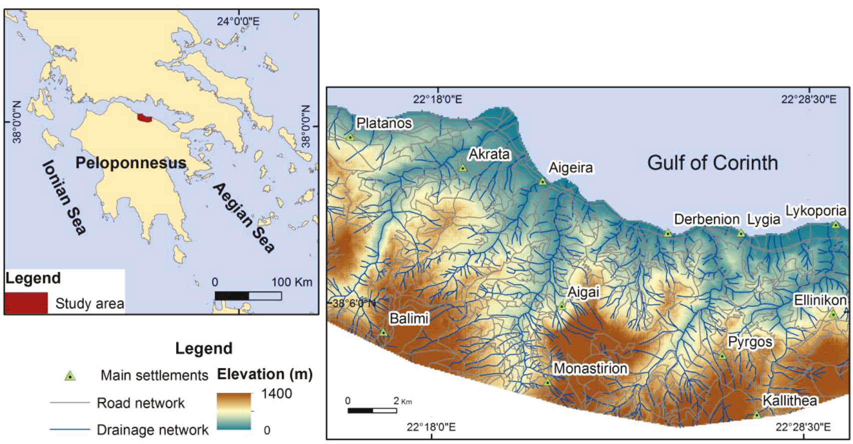
However, in most cases the influence of physical and anthropogenic factors in landslide manifestations is not well known. Determination of the actual landslide zone induced by geologic, geomorphic parameters and rainfall, along with human activities such as the road network, urban and cultivated areas is an important tool for engineers, planners, and environmental managers. This procedure is very useful to identify areas prone to landslide and assess landslide hazard, and it is also a necessary step for land use and government urban planning policies worldwide [20–23]. Moreover, the determination of the landslide zone of disturbance is vital for road engineers who must deal with the costly and sometimes life-threatening problems caused by road-induced landslides. Realistic assessment of the impact of proposed transportation construction must be quantifiable as road costs may be significantly increased by landsliding during construction [12,18,24].

During the last decades geographical information systems (GIS) and Earth observation (EO) data have become integral tools for the evaluation of natural hazard events. These current geospatial technologies are very useful for assessing future hazard occurrences and identifying the vulnerability of communities to hazards. In this sense, GIS is an excellent tool in the spatial analysis of multi-dimensional phenomena such as landslides [25–30].

The scope of the present study is to identify the influence of physical and anthropogenic factors on landslide occurrences. To accomplish this, existing landslides, lithology, slope angle and rainfall in conjunction with two types of road network and land use were taken into consideration. Statistical analysis and GIS are applied to process and evaluate the landslides and factors. Thus, the spatial distribution of landslide frequency, magnitude and the association of lithology, slope, rainfall, roads and land use with landslide occurrences in mountainous terrain were determined. The case study area was a mountainous part of the northern Peloponnesus in southern Greece.

2. Study Area

The study area is located in the northern part of the Peloponnesus, in southern Greece (Figure 1a). The region covers an area of about 194 km^2 and its altitude varies from 0 to 1400 m. The morphology of the area comprises southern mountainous land with very steep slopes reaching an altitude of 1400 m a.s.l.; intermediate semi-mountainous land with lower altitudes and steep slopes; and a northern coastal area of limited extent with low altitudes and gentle slopes. The drainage networks of the area flow with a main direction from SW to NE and discharge into the Gulf of Corinth (Figure 1b).



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

Figure 1. (**a**) Location map of the study area; (**b**) the elevations of the study area, the drainage network, the road network and the main settlements.

Climatologically, the study area is classified as Mediterranean, because of its coastal extension, without considerable temperature variations. The annual precipitation is about 800 mm in the mountainous part of the study area and about 550 mm at the lowlands.

The study area is located on the southern part of the Gulf of Corinth, and its landscape evolution is controlled by the neotectonic action of the graben, which forms the gulf. The presence of Pleistocene marine terraces in the northern part of the area proves that it has been affected until today by significant neotectonic uplift. This fact has been clearly expressed by the intense seismicity of the Gulf of Corinth [31].

The geological formations that crop out in the study area comprise both Neocene–Quaternary deposits and alpine formations. Alpine formations from two Hellenic geotectonic zones (Olonos–Pindos and Gavrovo–Tripolis) participate in the southern part of the study area. The study area is constructed by: (a) Holocene alluvial deposits, talus cones and scree; (b) Plio-Pleistocene sediments consisting of conglomerates such as clayey marls, marls, silty sands and sandstones; (c) schist-chert formations (Upper Cretaceous–Eocene); (d) Cretaceous limestones; and (e) schist-chert formations (Jurassic–Lower Cretaceous) [32].

Therefore, the study area mainly consists of Neocene deposits and, as a part of the Corinthian graben, it is characterized by intense neotectonic activity. Consequently, it is affected by many landslide events. It is an appropriate case study area because it comprises small urban areas, where there is still a potentiality of future urban growth and planning. Moreover the study area has often suffered from the consequences of several landslides, which usually cause serious damage in inhabited areas, road networks, and cultivated areas [33].

3. Materials and Methods

This study was carried out using the following:

- a topographic map (1:50,000 scale) from the Hellenic Military Geographical Service (HAGS);
- a satellite image via Google Earth, Landsat 7/Copernicus, with an acquisition date of July 2015;
- rainfall records from six stations, belonging to: (a) the Hellenic National Meteorological Service; (b) the Ministry for the Environment, Physical Planning and Public Works; and (c) the Ministry of Agriculture and Ministry of Development. These records referred to mean annual precipitation for the period of 1975–2010;
- field work data involving observations on landslide sites.

A spatial database was created, and ArcGIS 10.0 software was used to process the collected data.

3.1. Landslide Inventory Map

The landslide inventory map compilation has involved the following steps: (a) landslides were recorded from previous works [33]; (b) landslide locations were recognized on satellite images; (c) the manifestations of landslide were verified and mapped by field work. The main scarp of every recorded landslide during the field work was depicted in topographic maps at a proper scale and then digitized as a polygon layer. According to Yilmaz [34], the scarp sampling strategy gives better results than the point one. The landslides were used for the compilation of the landslide inventory map (Figure 2). A number of 270 sites of landslide manifestation were examined throughout the study area, with a varied size from 4130 m^2 to 91,000 m^2, having affected a total area of about 6.5 km^2.

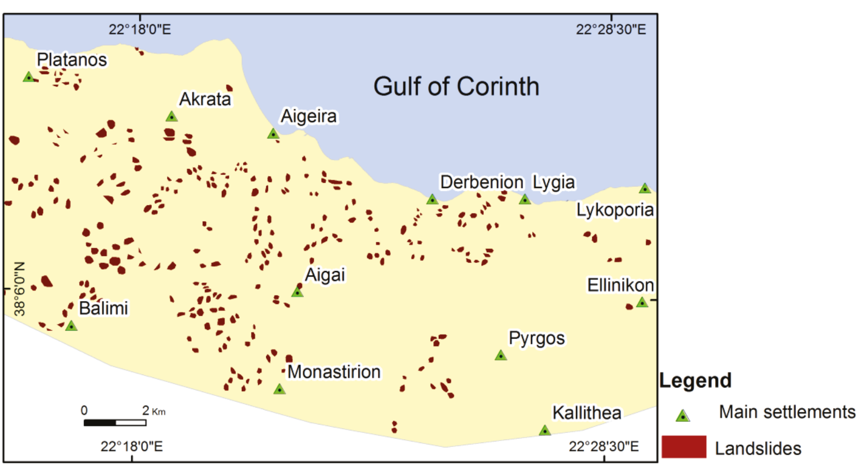


Figure 2. The landslide inventory map of the study area.

3.2. Physical and Anthropogenic Factors

The occurrence of landslides is largely a function of the interaction of several factors such as lithology, tectonic settings, geomorphological settings, earthquake, rainfall and human activities. These factors, which are directly or indirectly related with the occurrences of landslides, are commonly known as landslide-related factors [35–39]. In landslide susceptibility mapping studies, it is believed that the accuracy of the results increase when numerous landslide-related factors are included in the analytical process [40]. In many cases, this is usually difficult to do, because detailed data is hard to find. The aim of the present work is to determine the influence of physical and anthropogenic factors on landslide occurrences rather than the production of a landslide susceptibility map. Moreover, data for all the aforementioned factors was not available. For these reasons, analyses in this study depend on the physical factors which are lithology, slope angle and rainfall, while the anthropogenic factors are the road network and land use.

Each factor is separated into sub-classes. The determination of the classes' number as well as their boundary values were based on: (a) the literature review [3,11,15–21,33–39]; (b) the extended field observations in the framework of this study; and (c) personal experience from previous studies.

3.2.1. Lithology

Lithology is the main predisposing factor controlling landslide development. Different lithological units have different engineering geological behaviors and they are very important in providing data for landslide-related factors studies [3,36,39,40]. For the study area the geological formations were digitized and unified according to their engineering geological behavior [20,32,33,35], in relation to landslide manifestation. Thus, lithology includes five classes as follows: (a) fine, fine-coarse to coarse and loose to semi-coherent Quaternary formations; (b) cyclothematic formations (Plio-Pleistocene fine-grained sediments and Flysch sediments); (c) Plio-Pleistocene coarse-grained sediments; (d) thin-bedded schist chert formations; and (e) moderate to thick bedded limestones (Figure 3).

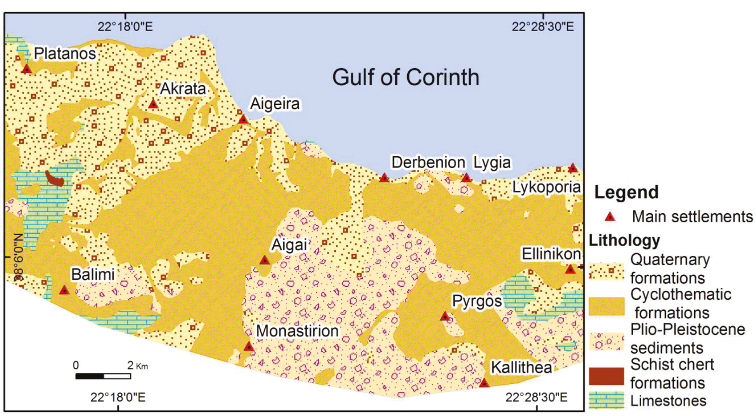


Figure 3. The lithology of the study area consisting of: Quaternary formations (fine, fine-coarse to coarse and loose to semi-coherent sediments), Cyclothematic formations (Plio-Pleistocene fine-grained sediments and Flysch sediments), Plio-Pleistocene coarse-grained sediments, thin bedded schist chert formations, and moderate to thick bedded limestones.

3.2.2. Slope Angle

The slope angle has an effect on slope stability, increasing the landslide hazard [35,39,40]. Contours with 20 m intervals and height points were digitized from topographic map (scale 1:50,000) and saved as line and point layer correspondingly. A digital elevation model (DEM) was derived from the digitized elevation data using the 3D Analyst extension of ArcGIS, and the slope layer was extracted from DEM. The slopes were classified into five classes: (a) <5°, (b) 5°–15°, (c) 15°–30°, (d) 30°–45°, and (e) >45° (Figure 4).

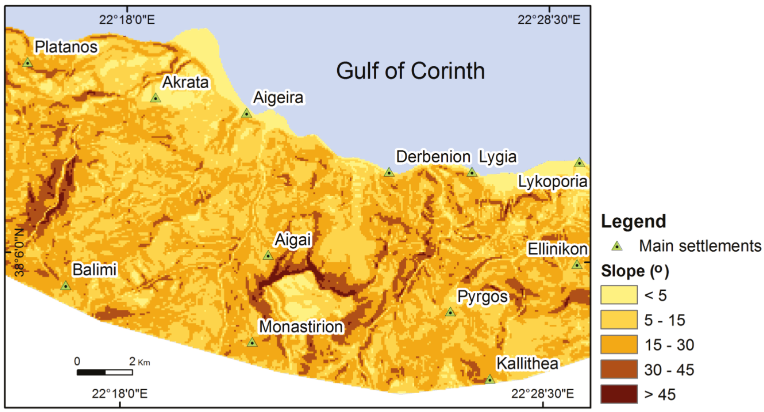


Figure 4. Map showing the spatial distribution of slopes of the study area.

3.2.3. Rainfall

Precipitation is a triggering factor for landslide occurrences [35,39]. The mean annual rainfall of the area varies between 550.7 mm and 789.8 mm. The intensity of rainfall was not analyzed due to lack of data. For the necessities of this study, the precipitation map was produced, using the data of the main meteorological stations in the area and applying the Inverse distance weighted (IDW) interpolation method. The distribution of representative rainfall depends upon the spatial distribution of the stations and elevation [41]. The stations used are uniformly distributed in the study area both hypsometrically and territorially giving accurate precipitation distribution.The precipitation map was separated into three classes, i.e.,: (a) <600 mm, (b) 600 mm–700 mm, and (c) >700 mm (Figure 5).

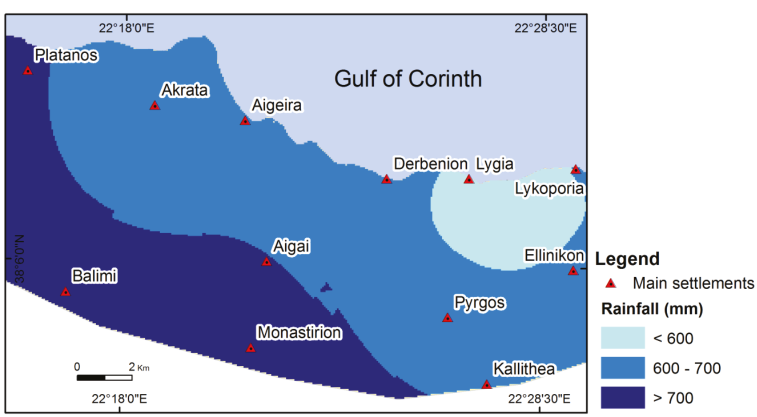


Figure 5. Map showing the spatial distribution of rainfall of the study area.

3.2.4. Road Network

The artificial and natural parts of the slopes around a road network are more sensitive in landslide manifestations [35]. The road network of the study area was digitized as a polyline layer using the topographic map. The complete road network included about: 24 km of highway, 322 km of provincial roads, 389 km rural roads, and totaled about 735 km in length (Figure 6).

The proximity to the road network is often related to an increase of landslide occurrences, so disturbance zones were created around the road network of the area. The creation of disturbance zones is referred to using the GIS term 'buffer' zone along a road network using GIS software. The classes of the buffer zones used in this analysis were: 10, 25, 50, 75, 100, 150, 200, 300 m and >300 m (6). The buffer lengths were measured on both sides of road network and represent a zone that is twice as wide as the value listed above. Therefore, a 100 m buffer describes a zone or swath 200 m wide along the road. Two sets of the aforementioned buffer zones were created along the different road types: one for highways and provincial roads and the other for rural roads.

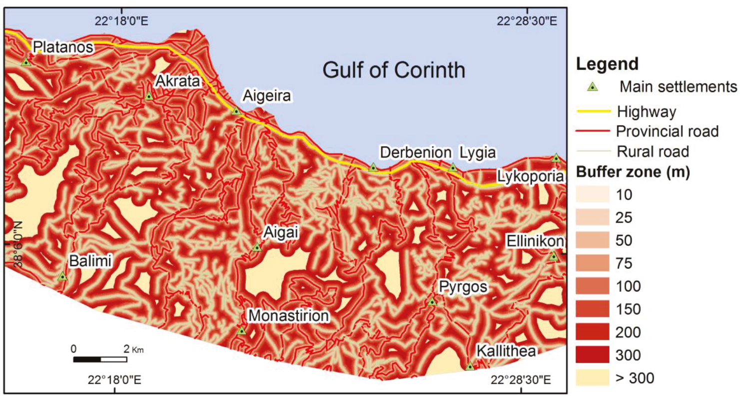


Figure 6. Buffer zones of increasing length along the highway, provincial, and rural roads of the study area.

3.2.5. Land Use

The land use of the study area was taken from the CORINE 2012 Land Cover (CLC) map, Copernicus Program [42]. The program contains land cover data for Europe including land cover class description at scale 1:100,000 published by the European Commission. The CORINE land use map was classified as follows: (a) urban area, (b) cultivated area, (c) forest, (d) shrubby area, and (e) bare area (Figure 7). The land use of the area was saved as polygon layer.

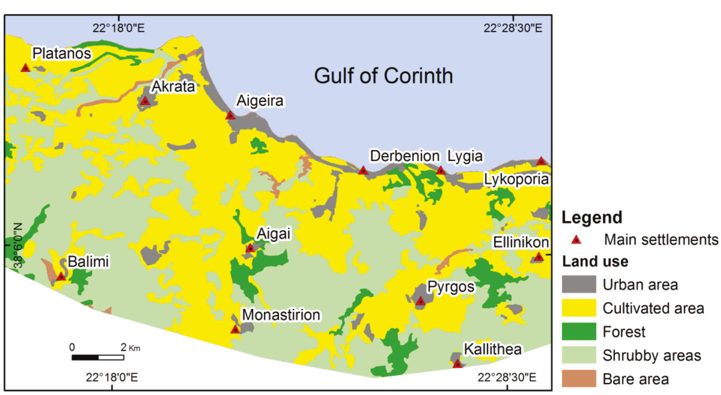


Figure 7. The land use of the study area.

To predict landslides, it is necessary to assume that landslide occurrence is determined by landslide-related factors, and that future landslides will occur under the same conditions as past landslides [3,36]. For this reason, as a first step, the relative frequency of landslides was calculated. The relative frequency is given from Equation (1):

$$FL = Ln/\Sigma Ln \quad (1)$$

where FL = the relative frequency of landslides, Ln = the number of landslide that located in each category of the landslide-related factors, and ΣLn = the total landslide events of the study area.

The landslides were transformed from polygon layer to point layer to calculate the landslide frequency. Thus, the number of landslide events, which were located in the classes of each factor was then determined by using the Spatial Analyst Tools of ArcGIS 10.0.

The next step was the estimation of the landslide frequency by applying a frequency ratio statistical analysis. This approach is based on the relationships between spatial distribution of landslides and each class of the involved factors. According to Lee and Pradhan [36], the frequency ratio is the ratio of the probability of a landslide event to a non-event for a given zone. The frequency ratio is estimated by the following Formula (2):

$$FR = FL/AC \quad (2)$$

where FR = the frequency ratio, FL = the relative frequency of landslides expressed in percentages, and AC = the area ratio for each category to the total area in a percentage form.

Furthermore, to determine the magnitude of a landslide area, the relative density of landslides was computed. The relative density of landslides is expressed by the Equation (3):

$$DL = La/\Sigma La \quad (3)$$

where DL = the relative density of landslides, La = the landslide area within each class, and ΣLa = the total landslide area.

Consequently, the area of landslides within the classes of each factor was computed by using spatial analyst capabilities. Similarly to landslide frequency, a density ratio statistical analysis was applied to specify the relationship between landslide area and the landslide-related factors. The density ratio is calculated according to the following mathematical operator (4):

$$DR = DL/AC \quad (4)$$

where DR = the density ratio, DL = the relative density of landslides expressed in percentages, and AC = the area ratio for each category to the total area in a percentage form.

4. Results

The statistical analysis described above allows discrimination of landslide frequency and magnitude in each category of the adopted factors. The physical and anthropogenic factors, their categories and the results of the statistical analysis are presented in Table 1.

Regarding the physical factors, Figure 8 shows the relative frequency (FL) and density (DL) of landslide distribution in each lithological formation of the study area. The maximum of FL (64%) and DL (61%) values are observed in the area underlain by cyclothematic formations consisting of Plio-Pleistocene fine-grained and flysch sediments. Additionally, high FL (24%) and DL (28%) values are presented in the Quaternary formations which consist of fine-grained to coarse-grained loose sediments. These values are almost two times lower in Quaternary formations than ones in cyclothematic formations. In Plio-Pleistocene coarse-grained sediments, the FL (10%) and DL (10%) values are six times lower than in cyclothematic formations. Schist chert formations have very low FL (1%) and DL (1%) values. The minimum of FR and DL values are observed in moderate to thick bedded limestones.

Table 1. The frequency (*FR*) and density (*DR*) ratio values of landslides into each category of physical and anthropogenic factors, A = area of each category in m^2, *AC* = the area ratio for each category to the total area in a percentage form, *Ln* = number of landslide in each category, *FL* = the relative frequency of landslides expressed in percentage, *La* = the landslide area within each class, and *DL* = the relative density of landslides expressed in percentage.

Lithology	A (m^2)	AC (%)	Ln	FL (%)	FR	La	DL (%)	DR
Quaternary formations	53,096,725	27	65	24	0.9	1,825,615	28	1.0
Cyclothematic formations	85,865,022	44	174	64	1.5	3,942,500	61	1.4
Plio-Pleistocene coarse-grained sediments	46,210,814	24	28	10	0.4	638,169	10	0.4
Schist chert formations	202,998	0.1	2	1	7.1	66,758	1	9.8
Limestones	8,754,203	5	1	0	0.1	10,947	0	0.0
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0
Slope angle (°)								
<5	14,298,664	7	3	1	0.2	125,782	2	0.3
5–15	71,833,677	37	124	46	1.2	2,827,163	44	1.2
15–30	90,318,029	47	136	50	1.1	3,369,873	52	1.1
30–45	16,176,882	8	6	2	0.3	154,197	2	0.3
>45	1,502,511	1	1	0	0.5	6974	0	0.1
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0
Rainfall (mm)								
<600	16,282,886	8	15	6	0.7	340,982	5	0.6
600–700	112,873,296	58	155	57	1.0	3,349,098	52	0.9
>700	64,973,582	33	100	37	1.1	2,793,907	43	1.3
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0
Highway and provincial roads network buffer zone (m)								
10	6,830,803	4	11	4	1.2	260,301	4	1.1
25	9,878,673	5	18	7	1.3	373,996	6	1.1
50	15,147,727	8	23	9	1.1	562,552	9	1.2
75	13,257,597	7	19	7	1.0	462,461	7	1.1
100	11,550,219	6	14	5	0.9	408,156	6	0.9
150	19,325,306	10	36	13	1.3	752,079	12	1.2
200	15,830,201	8	24	9	1.1	647,413	10	1.2
300	24,566,099	13	39	14	1.1	945,164	15	1.2
>300	77,743,138	40	86	32	0.8	2,071,866	32	0.8
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0
Rural roads network buffer zone (m)								
10	7,728,922	4	15	6	1.4	392,238	6	1.5
25	11,367,074	6	28	10	1.8	563,374	9	1.5
50	18,040,789	9	48	18	1.9	866,394	13	1.4
75	16,592,806	9	32	12	1.4	746,290	12	1.3
100	15,128,865	8	23	9	1.1	605,058	9	1.2
150	26,430,630	14	35	13	0.9	838,841	13	0.9
200	21,657,810	11	24	9	0.8	610,802	9	0.8
300	30,320,688	16	31	11	0.7	812,673	13	0.8
>300	46,862,180	24	34	13	0.5	1,048,317	16	0.7
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0
Land use								
Urban area	10,361,680	5	12	4	0.8	228,739	4	0.7
Cultivated area	89,597,161	46	188	70	1.5	4,158,855	64	1.4
Forest	11,307,988	6	11	4	0.7	249,236	4	0.7
Shrubby area	80,742,318	42	57	21	0.5	1,800,696	28	0.7
Bare area	2,120,616	1	2	1	0.7	46,461	1	0.7
Total	194,129,763	100	270	100	1.0	6,483,988	100	1.0

Apart from the *FL* and *DL*, the landslide frequency ratio (*FR*) and density ratio (*DR*) were calculated. According to Lee and Pradhan [36] the FR value of 1 is an average value. Thus, ratio values greater than 1 indicate a strong relationship between landslides and the given factor, and ratio values smaller than 1 indicate a poor relationship between landslides and the given factor. As demonstrated in Table 1, the schist chert formations have the maximum *FR* value (7.1), indicating a strong relationship between this lithological formation and landslide occurrences. Similarly, in cyclothematic formations the *FR* value is 1.5, showing a strong association with landslide events. For the remaining lithological formations of the study area, the *FR* values are found to be less than one, indicating a poor relation with landslides.

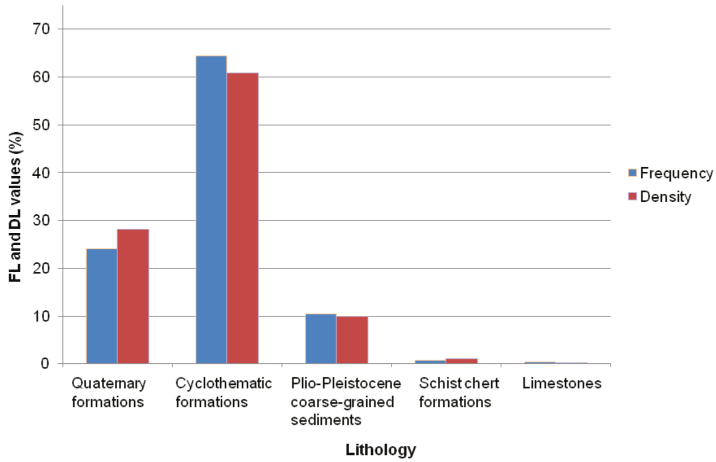


Figure 8. Relative frequency (*FR*) and density (*DL*) values within each category of lithology in the study area. The *FR* and *DL* values are expressed in percentages.

Alike the frequency ratio, the greater the density ratio values above one, the stronger the relationship between landslide occurrence and the given factor; the lower the ratio values below one, the lesser the relationship between landslide occurrence and the given factor. The maximum value of *DR* (9.8) is observed in the schist chert formations, while in the cyclothematic formations and Quaternary formations the *DR* values are 1.4 and 1.0 correspondingly (Table 1). This fact proves a strong relationship between the aforementioned formations and landslide manifestation.

Concerning the slope angle of the study area, Figure 9 shows the *FL* and *DL* distribution in each category of slope. The majority of landslide events (50%) and magnitudes (52%) are located in the class of slopes 15°–30°. Very high *FL* (46%) and *DL* (44%) values are observed in the category of medium slopes 5°–15°. The minimum *FR* and *DL* values are located in the class of very steep slopes >45° (Table 1).

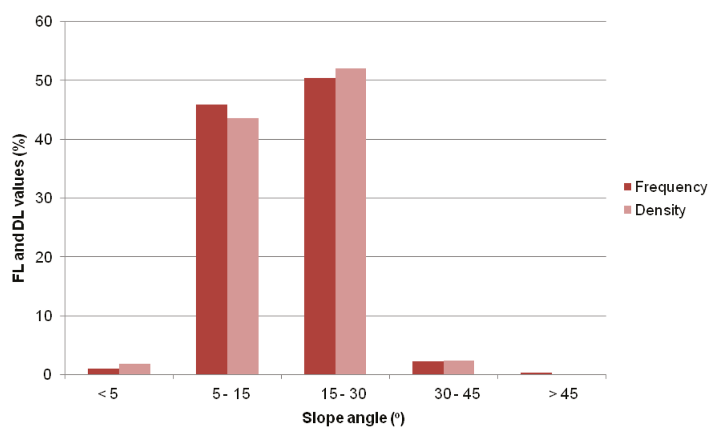


Figure 9. *FL* and *DL* values distribution in each class of slope angle. The *FR* and *DL* values are expressed in percentages.

The maximum *FR* and *DR* values are found to be 1.2 in the class of steep slopes 15°–30°. *FR* and *DR* values greater than one (1.1) have the class 5°–15°. Thus, these slopes are strongly related to landslide occurrences. The classes of slopes <5°, 30°–45°and >45° have *FR* and *DR* values <1, indicating a poor relationship between them and landslides (Table 1).

Figure 10 illustrates the *FL* and *DL* values distribution in each category of rainfall. The maximum values of *FL* (57%) and DL (52%) are attributed in the category of 600 mm–700 mm. Moreover, very high values of *FL* (37%) and *DL* (43%) are observed in the category >700 mm.

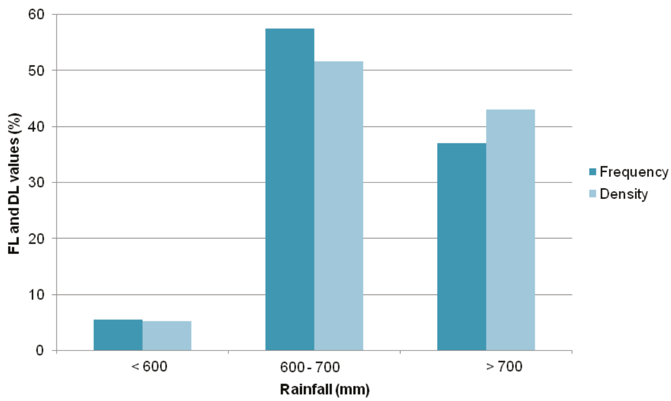


Figure 10. *FL* and *DL* values' distribution in each class of rainfall. The *FR* and *DL* values are expressed in percentages.

The maximum *FR* values 1.1 and 1.0 represent, respectively, the categories of rainfall >700 mm and 600–700 mm. These two categories are strongly related to landslide manifestation. On the contrary, the maximum *DR* value (1.3) is observed in the category >700 mm, indicating a strong relationship between this category and landslide events (Table 1).

The applied statistical analysis identifies the distribution of landslide frequency and magnitude in nine zones of increasing length measured around to the road network. The analysis was performed for two different types of road network. Figure 11 shows the distribution of *FL* and *DL* values in within each buffer zone of the highway and provincial roads. The relative frequency and density of landslides are expressed in percentages.

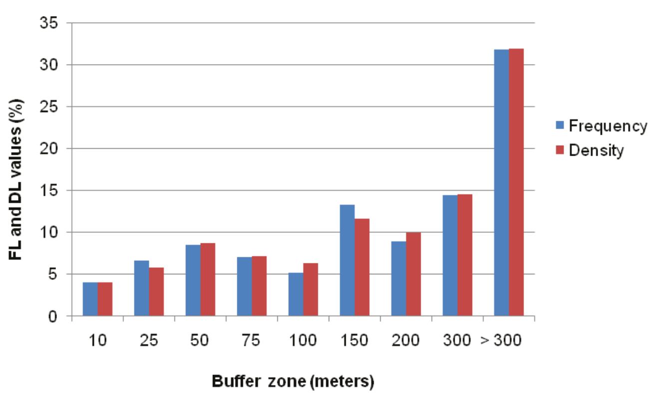


Figure 11. *FL* and *DL* values within each buffer zone extending 0 to 300 m from highway and provincial roads and >300 m in the study area. The *FL* and *DL* values are expressed in percentages.

The *FL* reaches its maximum value within the first 50 m of distance from any given highway and provincial road and decreases in distances beyond 50 m from roads. The *FL* value is greatest (9%) within 50 m buffer zone and is relatively high as far as 100 m from roads. The value of *FL* within buffer zone of 50 m is about two times higher than in distances: (i) approximately 10 m (4%) and (ii) between 75 and 100 m (5%) from roads. Moreover, the *FL* values become relatively high in distance beyond 150 m (13%) from roads. This increase is not related to roads but is likely due to other factors influencing landslide manifestation (Figure 11 and Table 1).

As in the case of *FL*, the *DL* reaches its maximum value (9%) within the buffer zone of 50 m and shows a gradational decline with buffer length (Figure 11). The *DL* value is relatively high in distances between 50 and 100 m from roads. The *DL* value in area of 10 m buffer zone is about two times lower (4%) than in 50 m buffer zone and for area of 100 m buffer zone is one and a half times lower (6%) than in 50 m buffer zone.

In the buffer zones of 10 and 25 m, the *FR* values are 1.2 and 1.3 respectively, indicating a strong relationship between these zones and the occurrence of landslides. For the distances of 50 m and 75 m from roads, the *FR* values were found to be 1.1 and 1.0, respectively, showing a strong association with landslide events. The *FR* values are <1 in distance beyond 100 m, proving a poor relation with landslide occurrences (Table 1).

The maximum *DR* value (1.3) is found to be at distance of 50 m from roads. High *DR* values (1.1) are observed at distances of 10, 25 and 75 m from roads. Thus, these zones are strongly correlated with landslide occurrences. The ratio values in areas beyond 100 m of roads are <1, showing a low probability of landslide occurrences (Table 1).

With regard to the rural roads, the maximum *FL* value (18%) is attributed to a 50 m buffer zone and is relatively high as far as 100 m from roads (Figure 12). The *FL* value within a buffer zone of 50 m is about three times higher than in distance approximately 10 m (6%) and two times higher than in distance between 75 and 100 m (9%) from roads. Similarly to *FL* values, the *DL* values have its maximum within 50 m buffer zone (13%). The *FL* and *DL* values are increased in distance beyond 150 m from rural roads (Figure 12).

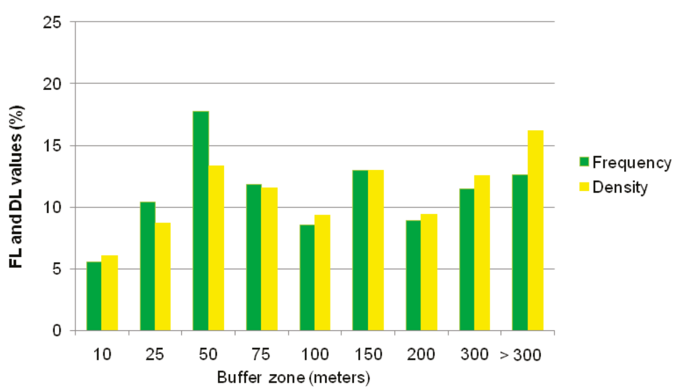


Figure 12. *FL* and *DL* values within each buffer zone extending 0 to 300 m from rural roads and >300 m in the study area. The *FL* and *DL* values are expressed in percentages.

The *FR* values reach their maximum (1.9) in 50 m buffer zone and its values are >1 in the area of the 10 m, 25 m, 75 m and 100 m buffer zones. Likewise, the *DR* values are >1 at distance 10 m, 25 m, 50 m, 75 m, and 100 m from rural roads. These observations indicate a strong relationship between landslides and the aforementioned distances (Table 1).

Concerning the land use of the study area, the calculation *FL* and *DL* provides an estimate of the influence of land use in landslide manifestation. The statistical analysis of *FL* shows that the vast majority of landslide events (70%) are located in cultivated areas, and a high value of *FL* within shrubby areas (21%). In urban and forest areas, it is seventeen and a half times lower (4% in each one) than in cultivated areas. The minimum value of *FL* is observed (1%) in a bare area (Figure 13 and Table 1).

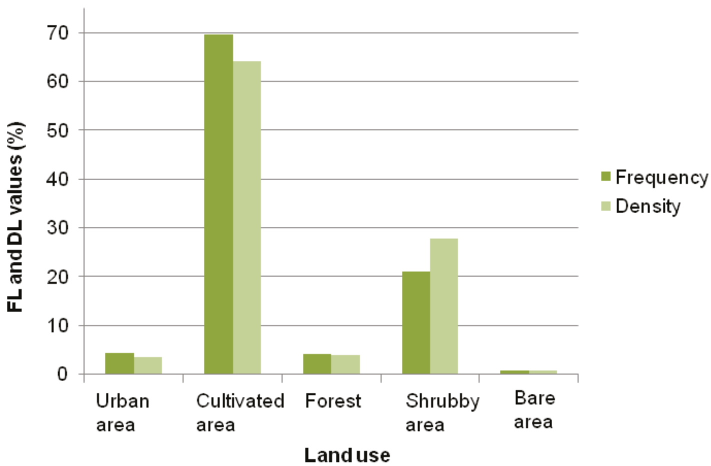


Figure 13. *FR* and *DR* values within each category of land use in the study area. The *FR* and *DR* values are expressed in percentages.

The *DL* values follow the distribution of *FL* values in each category of land use. More specifically, the maximum value of *DL* (64%) is attributed to cultivated areas. A relatively high density value (28%) is observed in shrubby areas, while the minimum density (1%) value is calculated in bare areas. The *DL* values in urban and forest areas (4% in each one) are low (Figure 13 and Table 1).

The *FR* was found to be 1.4 in cultivated areas, which proves a high probability of landslide manifestation. In the rest of the categories of land use, the ratio values are <1, indicating a strong relation with landslide manifestation (Table 1). The highest *DR* value is 1.4 and refers to the cultivated areas, showing a strong association between this land use and landslide occurrences. The remaining classes of land use have ratio values <1, indicating a low probability of landslide manifestation (Table 1).

5. Discussion

Hydrological parameters such as precipitation and human activities are capable of changing landscape characteristics. On the other hand, the geological, geomorphic conditions of a mountainous environment remain unchanged or vary little from a human perspective. These factors influence where landslides occur [3,19–24]. In many cases, the association of physical factors and human activities in landslide occurrences is not well defined. According to Lee and Pradhan [36], statistical approaches based on the observed relationship between each factor and the spatial distribution of landslides is very useful to reveal the correlation between landslide locations and factors.

In the present study physical and anthropogenic factors are analyzed and evaluated to determine their association with landslide occurrences. Lithology, slope angle, rainfall, two types of road network and land use are correlated with the existing landslides by using *FL*, *DL*, *FR* and *DR* statistical analysis and GIS. The case study area is a mountainous part of the northern Peloponnese in Greece. The results provide information on the physical the anthropogenic factors characterizing landslide events in the study area.

The statistical analysis proves that the lithological formations of the study area influence the occurrence of landslides. The events and magnitude of landslide areas reach their maximum in the area underlain by cyclothematic formations consisting of Plio-Pleistocene fine-grained sediments and flysch (Figure 8). Additionally the *FR* and *DR* values are >1 in areas where cyclothematic sediments and shist-chert formations outcrop (Table 1). The latter is possibly due to the limited extent of shist chert formations in the study area. Plio-Pleistocene sediments are fine-grained with a variety of lithological horizons. They consist of clays, marls, alternating sands of a varying degree of diagenesis and/or their mixed phases. Flysch are strongly folded sediments because of the tectonic action (nappes and upthrusts), which in many places results to the formation of thick weathering mantle. Schist chert formations consisting of alternations of cherts, siltstones, thin plated limestones and sandstones while volcanic tuffs rarely participate at places. A thick weathering mantle is formed, mainly in the cases of the surface occurrence of siltstones. The aforementioned soils, hard soil to soft rocky sediments, are weak and incompetent formations and are prone to landslides [4,32,33]. Consequently, the cyclothematic sediments and schist chert formations of the study area are strongly related to landslide occurrences.

Regarding the slope angle, the maximum *FL* and *DL* values are observed in the category of relatively steep slopes 15°–30°. High values of *FL* and *DL* are found to be in the category of moderate slopes 5°–15° (Figure 9). Additionally the *FR* and *DR* values are >1 in the classes of 5°–15° and 15°–30°, indicating a strong relationship between them and landslide events. *FR* and *DR* values <1 are observed in the remaining classes of gentle slopes (<5°–30°), steep slopes (30°–45°) and very steep slopes (>45°), showing a poor relationship between them and landslides (Table 1). According to Rozos et al. [33] this peculiar condition can be explained easily, as in nature slopes consisting of soil or hard soil to soft rocky formations (like those of the study area), and having high angles, fail almost immediately after their formation, resulting in lower slope angles. Finally the slopes with an inclination of around the angle of friction are those which fail after the action of triggering factors. On the other hand, rocky slopes are stable even in high angles suffering only from rock falls, wedge failures etc.

The *FL* and *DL* values increase with increasing in amount of precipitation (Figure 10). The maximum *FL* and *DL* values are attributed in the category of 600 mm–700 mm. FR and DR values >1 are observed in the category of rainfall >700 mm, showing a strong correlation with landslide events (Table 1). Therefore, the rainfall is an important factor in triggering manifestations of landslides [33,35].

Concerning the anthropogenic factors, nine buffer zones of increasing length measured around to two types of road network and five categories of land use are evaluated. The landslide events and magnitude of landslide areas are increased within a distance of approximately 0 to 50 m from any given road type (highway, provincial and rural road) and decreased in distances beyond 50 m from roads (Figures 11 and 12, Table 1). The relatively high values of *FL* and *DL*, which are measured in the 150 m buffer zone, are probably due to other landslide-related factors such as type of lithology or slope angle (Table 1). As already mentioned above, landslides of the study area tended to occur in locations with relatively steep slopes or consisting of cyclothematic sediments.

Consequently, the frequency and magnitude of landslides increase in close proximity to roads. According to Bathrellos et al. [35] this may be due to the fact that the road network sometimes destabilizes adjacent marginally balanced slopes, mainly by removing natural support for the upper part of the slope through undercutting the base of the slope during its construction and by adding extra weight on them. For the study area, landslide disturbance is associated with roads at distances of as much as 50 m from where they are constructed. Further away the frequency and magnitude of landslide occurrences gradually decreases. However, the 50 m buffer length, or 100 m swath, represents a sizeable area of the land surface. These results indicate that a 100 m-wide zone along road corridors increase the landslide activity.

When planning a new road, the alignments of the route should be carefully determined considering the probability of landslides during and after construction. The roads are likely to face unexpected problems of slope stability [12]. The quantification of landslide frequency, magnitude and distribution in mountainous terrain is an important consideration in calculating the cost of new roads construction and the maintenance of existing road networks [18]. Therefore, road engineers and planners in similar mountainous environments may utilize the buffer zone of 50 m during the construction of a new road or to protect the existing road network from future landslide occurrences.

The *FR* and *DR* values (Table 1) show that buffer zones with distances smaller than/or equal to 75 m from highway and provincial roads are strongly associated with landslide manifestation. For buffer zones with distances >75 m, the ratio is <1, indicating a poor relation with landslide occurrences. Conversely, the *FR* and *DR* values (Table 1) are >1 at distances lower than/or equal to 100 m from rural roads, showing a strong relationship between landslides and these distances. In the study area, a 150 m wide zone along highway and provincial road corridors or a 200 m wide zone along rural road corridors indicates a strong association with landslides. This difference may be related to the fact that the rural road network is long and dense in the study area. Thus, the closer the distance is to the road network, the greater is the relationship with landslide manifestation.

In the case of land use, the majority of frequencies and magnitudes of the landslide area are located in cultivated areas (Figure 13). The *FR* and *DR* values are >1 only in cultivated land areas, showing a strong relation to slope failures (Table 1). The variations of the vegetation in an area constitute an important parameter affecting the slope failures, as slope stability is very sensitive to changes in vegetation [33,39]. The soil cohesion is modified depending on the type of vegetation and, thus, cultivated or sparsely vegetated areas are more prone to landslide processes. Additionally, crops can increase the moisture in the soil and alter ground water conditions. In the study area, crops cover an area of about 90 km^2 and this represents 42% of the total area (Table 1). The extensive cultivated land combined with the altered ground water conditions is capable of causing landslide problems.

By contrast, the *FL* and *DL* values are limited in urban areas (Figure 13). Furthermore, the *FR* and *DR* values indicate a poor relationship between urban areas and landslide occurrences (Table 1). Most of the urban areas are located in the northern coastal part of the study area where there are few landslides.

6. Conclusions

In the present study, statistical analysis and GIS was applied to determine the relation of physical and anthropogenic parameters with landslide activity in a mountainous terrain.

Concerning the physical factors, the lithology of the study area controls landslide activity. The cyclothematic formations consisting of Plio-Pleistocene fine-grained sediments and flysch increase *FL* and *DL*. These sediments along with schist chert formations are strongly associated with landslide occurrences. Since *FL* and *DL* increase in relatively steep slopes, geomorphologic factors such as slope angle influence landslide occurrences. Moderate (5°–15°) and relatively steep slopes (15°–30°) are strongly associated with landslide events. Rainfall is an important factor in triggering the manifestation of landslides, as their frequency and density rise with an increase in the amount of rainfall. An amount of rainfall of >700 m is strongly related to landslide events.

In terms of the anthropogenic factors, the statistical analysis proves that the zone of landslide disturbance associated with roads is extensive. The frequency and magnitude of landslides increase in close proximity to roads. The maximum *FL* and *DL* values are observed within the 50 m buffer zone. This zone (100 m wide) along with any type of road corridors increase landslide occurrences. On the other hand, the buffer zone of 75 m or a 150 m wide zone along highway and provincial road corridors is strongly related to landslide manifestation. Since the rural road network is long and dense in the study area, the buffer zone of 100 m or a 200 m wide zone along rural roads is strongly connected with landslide events. The extensive cultivated land of the study area leads to an increase of *FL* and *DL*. This land use is strongly associated with landslides. Urban areas are poorly related to landslide activity, because most of the urban areas are located in the northern coastal part of the study area where landslides are limited.

The proposed methodology reveals a relatively simple and quick way of determining the association of physical and anthropogenic parameters with landslide activity in a mountainous terrain. Topographical, geological, hydrological, transportation and landslide location data can easily be found and their analysis and evaluation are simple and rapid. In regional studies, the applied procedure can be used for the localization of sites prone to landslides and for landslide hazard assessment mapping. Therefore, engineers, planners, decision-makers and environmental managers may utilize the proposed methodology in new and existing spatial planning projects. Additionally, it may be used by the local authorities to guide them in the adoption of policies and strategies aiming at landslide hazard mitigation.

Author Contributions: H.D.S. and D.R. conceived the research; H.D.S. and G.D.B. designed the research and the data analysis; K.S. prepared and analyzed the data; H.D.S., G.D.B., K.S., E.K. and D.R. completed the field work; H.D.S. and E.K. created the figures; H.D.S., G.D.B. and K.S. wrote the paper.

Funding: This research received no external funding.

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

References

1. Bathrellos, G.D.; Skilodimou, H.D.; Chousianitis, K.; Youssef, A.M.; Pradhan, B. Suitability estimation for urban development using multi-hazard assessment map. *Sci. Total Environ.* **2017**, *575*, 119–134. [CrossRef] [PubMed]
2. Cruden, D.M. A simple definition of a landslide. *Bull. Eng. Geol. Environ.* **1991**, *43*, 27–29. [CrossRef]
3. Varnes, D.J. Slope movement types and processes. In *Landslides, Analysis and Control*; Schuster, R.L., Krizek, R.J., Eds.; Transportation Research Board, Special Report 176; National Research Council: Washington, DC, USA, 1978; pp. 12–33.
4. Chousianitis, K.; Del Gaudio, V.; Sabatakakis, N.; Kavoura, K.; Drakatos, G.; Bathrellos, G.D.; Skilodimou, H.D. Assessment of Earthquake-Induced Landslide Hazard in Greece: From Arias Intensity to Spatial Distribution of Slope Resistance Demand. *Bull. Seismol. Soc. Am.* **2016**, *106*, 174–188. [CrossRef]
5. Rozos, D.; Skilodimou, H.D.; Loupasakis, C.; Bathrellos, G.D. Application of the revised universal soil loss equation model on landslide prevention. An example from N. Euboea (Evia) Island, Greece. *Environ. Earth Sci.* **2013**, *70*, 3255–3266. [CrossRef]
6. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H.; Gaki-Papanastassiou, K.; Kouli, K.; Tsourou, T.; Tsaparas, N. Pleistocene glacial and lacustrine activity in the southern part of Mount Olympus (Central Greece). *Area* **2017**, *49*, 137–147. [CrossRef]
7. Skilodimou, H.D.; Bathrellos, G.D.; Maroukian, H.; Gaki-Papanastassiou, K. Late Quaternary evolution of the lower reaches of Ziliana stream in south Mt. Olympus (Greece). *Geogr. Fis. Din. Quat.* **2014**, *37*, 43–50. [CrossRef]
8. Kamberis, E.; Bathrellos, G.; Kokinou, E.; Skilodimou, H. Correlation between the structural pattern and the development of the hydrographic network in a portion of the Western Thessaly basin (Greece). *Cent. Eur. J. Geosci.* **2012**, *4*, 416–424. [CrossRef]
9. Kokinou, E.; Skilodimou, H.D.; Bathrellos, G.D.; Antonarakou, A.; Kamberis, E. Morphotectonic analysis, structural evolution/pattern of a contractional ridge: Giouchtas Mt., Central Crete, Greece. *J. Earth Syst. Sci.* **2015**, *124*, 587–602. [CrossRef]
10. Sidle, R.C.; Pearce, A.J.; O'Loughlin, C.L. *Hillslope Stability and Land Use*; American Geophysical Union Water Resources Monograph Series; AGU Publications: Washington, DC, USA, 1985; p. 140, ISBN 9781118665503.
11. Dai, F.C.; Lee, C.F.; Ngai, Y.Y. Landslide risk assessment and management: An overview. *Eng. Geol.* **2002**, *64*, 65–87. [CrossRef]
12. Kumar, K.; Jangpangi, L.; Gangopadhyay, S. Highway vs. landslides and their consequences in Himalaya. In *Landslide Science for a Safer Geoenvironment*; Sassa, K., Canuti, P., Yin, Y., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 389–395.
13. Schuster, R.L.; Fleming, R.W. Economic losses and fatalities due to landslides. Environ. *Eng. Geosci.* **1986**, *xxiii*, 11–28. [CrossRef]
14. Guzzetti, F. Landslide fatalities and the evaluation of landslide risk in Italy. *Eng. Geol.* **2000**, *58*, 89–107. [CrossRef]
15. Sabatakakis, N.; Koukis, G.; Mourtas, D. Composite landslides induced by heavy rainfall in suburban areas. City of Patras and surrounding area, Western Greece. *Landslides* **2005**, *2*, 202–211. [CrossRef]

16. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Papanastassiou, D.; Chousianitis, K.G. Potential suitability for urban planning and industry development by using natural hazard maps and geological-geomorphological parameters. *Environ. Earth Sci.* **2012**, *66*, 537–548. [CrossRef]
17. Bathrellos, G.D.; Gaki-Papanastassiou, K.; Skilodimou, H.D.; Skianis, G.A.; Chousianitis, K.G. Assessment of rural community and agricultural development using geomorphological-geological factors and GIS in the Trikala prefecture (Central Greece). *Stoch. Environ. Res. Risk A* **2013**, *27*, 573–588. [CrossRef]
18. Larsen, M.C.; Parks, J.E. How wide is a road? The association of roads and mass-wasting in a forested montane environment. *Earth Surf. Proc. Land.* **1997**, *22*, 835–848. [CrossRef]
19. Bozzano, F.; Cipriani, I.; Mazzanti, P.; Prestininzi, A. Displacement patterns of a landslide affected by human activities: Insights from ground-based InSAR monitoring. *Nat. Hazards* **2011**, *59*, 1377–1396. [CrossRef]
20. Bathrellos, G.D.; Kalivas, D.P.; Skilodimou, H.D. Landslide Susceptibility Assessment Mapping: A Case Study in Central Greece. In *Remote Sensing of Hydrometeorological Hazards*; Petropoulos, G.P., Islam, T., Eds.; CRC Press; Taylor & Francis Group: London, UK, 2017; pp. 493–512, ISBN-13 978-1498777582.
21. Papadopoulou-Vrynioti, K.; Bathrellos, G.D.; Skilodimou, H.D.; Kaviris, G.; Makropoulos, K. Karst collapse susceptibility mapping considering peak ground acceleration in a rapidly growing urban area. *Eng. Geol.* **2013**, *158*, 77–88. [CrossRef]
22. Papadopoulou-Vrynioti, K.; Alexakis, D.; Bathrellos, G.D.; Skilodimou, H.D.; Vryniotis, D.; Vasiliades, E. Environmental research and evaluation of agricultural soil of the Arta plain, western Hellas. *J. Geochem. Explor.* **2014**, *136*, 84–92. [CrossRef]
23. Papadopoulou-Vrynioti, K.; Alexakis, D.; Bathrellos, G.D.; Skilodimou, H.D.; Vryniotis, D.; Vasiliades, E.; Gamvroula, D. Distribution of trace elements in stream sediments of Arta plain (Western Hellas): The influence of geomorphological parameters. *J. Geochem. Explor.* **2013**, *134*, 17–26. [CrossRef]
24. Youssef, A.M.; Pradhan, B.; Al-Kathery, M.; Bathrellos, G.D.; Skilodimou, H.D. Assessment of rockfall hazard at Al-Noor Mountain, Makkah city (Saudi Arabia) using spatio-temporal remote sensing data and field investigation. *J. Afr. Earth Sci.* **2015**, *101*, 309–321. [CrossRef]
25. Lu, P.; Stumpf, A.; Kerle, N. Object-oriented change detection for landslide rapid mapping. *IEEE Geosci. Remote Sens. Lett.* **2011**, *8*, 701–705. [CrossRef]
26. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The spatial distribution of Middle and Late Pleistocene Cirques in Greece. *Geogr. Ann.* **2014**, *96*, 323–338. [CrossRef]
27. Bathrellos, G.D.; Skilodimou, H.D.; Maroukian, H. The significance of tectonism in the glaciations of Greece. In *Quaternary Glaciation in the Mediterranean Mountains*; Hughes, P.D., Woodward, J.C., Eds.; Geological Society London Special Publications: London, UK, 2017; pp. 237–250. [CrossRef]
28. Youssef, A.M.; Pradhan, B.; Tarabees, E. Integrated evaluation of urban development suitability based on remote sensing and GIS techniques: Contribution from analytic hierarchy process. *Arab. J. Geosci.* **2011**, *4*, 463–473. [CrossRef]
29. Bathrellos, G.D.; Karymbalis, E.; Skilodimou, H.D.; Gaki-Papanastassiou, K.; Baltas, E.A. Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environ. Earth Sci.* **2016**, *75*, 319. [CrossRef]
30. Van Westen, C.J. Remote sensing and GIS for natural hazards assessment and disaster risk management. In *Treatise on Geomorphology*; Schroder, J.F., Bishop, M.P., Eds.; Academic Press; Elsevier: New York, NY, USA, 2013; pp. 259–298.
31. Armijo, R.; Meyer, B.; King, G.; Rigo, A.; Papanastassiou, D. Quaternary evolution of the Corinth Rift and its implications for the late Cenozoic evolution of the Aegean. *Geophys. J. Int.* **1996**, *126*, 11–53. [CrossRef]
32. Koukis, G.; Rozos, D. Geotechnical conditions and landslide movements in the Greek territory in relation to the geological structure and geotectonic evolution. *Miner. Wealth* **1982**, *16*, 53–69.
33. Rozos, D.; Bathrellos, G.D.; Skilodimou, H.D. Comparison of the implementation of Rock Engineering System (RES) and Analytic Hierarchy Process (AHP) methods, based on landslide susceptibility maps, compiled in GIS environment. A case study from the Eastern Achaia County of Peloponnesus, Greece. *Environ. Earth Sci.* **2011**, *63*, 49–63. [CrossRef]
34. Yilmaz, I. The effect of the sampling strategies on the landslide susceptibility mapping by conditional probability and artificial neural networks. *Environ. Earth Sci.* **2010**, *60*, 505–519. [CrossRef]
35. Bathrellos, G.D.; Kalivas, D.P.; Skilodimou, H.D. Landslide susceptibility mapping models, applied to natural and urban planning, using G.I.S. *Estud. Geol.-Madrid* **2009**, *65*, 49–65. [CrossRef]

36. Lee, S.; Pradhan, B. Probabilistic landslide hazards and risk mapping on Penang Island, Malaysia. *J. Earth Syst. Sci.* **2006**, *115*, 661–672. [CrossRef]
37. Tsolaki-Fiaka, S.; Bathrellos, G.D.; Skilodimou, H.D. Multi-criteria decision analysis for abandoned quarry restoration in Evros Region (NE Greece). *Land* **2018**, *7*, 43. [CrossRef]
38. Migiros, G.; Bathrellos, G.; Skilodimou, H.; Karamousalis, T. Pinios (Peneus) River (Central Greece): Hydrological-geomorphological elements and changes during the quaternary. *Cent. Eur. J. Geosci.* **2011**, *3*, 215–228. [CrossRef]
39. Donati, L.; Turrini, M.C. An objective method to rank the importance of the factors predisposing to landslides with the GIS methodology: Application to an area of the Apennines (Valnerina; Perugia, Italy). *Eng. Geol.* **2002**, *63*, 277–289. [CrossRef]
40. Ayalew, L.; Yamagishi, H.; Ugawa, N. Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. *Landslides* **2004**, *1*, 73–81. [CrossRef]
41. Cristiano, E.; Veldhuis, M.C.T.; Giesen, N.V.D. Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas—A review. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 3859–3878. [CrossRef]
42. Copernicus. Copernicus Land Monitoring Service. 2016. Available online: http://land.copernicus.eu (accessed on 31 May 2018).

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Land Editorial Office
E-mail: land@mdpi.com
www.mdpi.com/journal/land

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34
Fax: +41 61 302 89 18

www.mdpi.com

ISBN 978-3-03943-926-3