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Editorial

Theoretical and Practical Approaches in Watershed Management Across Different Environmental Contexts

Demetrio Antonio Zema [1,*] and Manuel Esteban Lucas-Borja [2]

[1] AGRARIA Department, Mediterranean University of Reggio Calabria, Loc. Feo di Vito, 89122 Reggio Calabria, Italy
[2] School of Advanced Agricultural and Forestry Engineering, Department of Agroforestry Technology and Science and Genetics, Campus Universitario, Castilla La Mancha University, 02071 Albacete, Spain; ManuelEsteban.Lucas@uclm.es
* Correspondence: dzema@unirc.it

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Received: 11 December 2024
Accepted: 13 January 2025
Published: 15 January 2025

Citation: Zema, D.A.; Lucas-Borja, M.E. Theoretical and Practical Approaches in Watershed Management Across Different Environmental Contexts. *Resources* **2025**, *14*, 14. https://doi.org/10.3390/resources14010014

A watershed is defined as 'a topographically delineated area that is drained by a stream system' [1]. This area can be considered as a whole system composed of different subsystems (e.g., agricultural or urban systems), being the site of different complex processes (i.e., hydrological, geomorphological, ecological) that are affected by large temporal and spatial variability. From a strictly hydrological point of view, the different processes are dependent on several natural and anthropogenic factors [2] which shape the history and evolution of a watershed. Moreover, this physiographic unit provides several ecosystem services, from water regulation to nutrient cycling, that are essential for humankind. The demand for these services has dramatically increased in recent decades, continuing to grow as global environmental change intensifies in the 21st century [3]. Watershed services, such as food and energy production, water supply, and healthy, pleasant living environments, must be utilised sustainably. This has been widely recognised in recent years, leading to several terms for these activities with a particular focus on approaches that either mimic or work with natural processes [4]. To preserve the watershed's ability to provide these services, it is essential to assess and model watershed functions and processes. These activities are the knowledge basis for short-term landscape restoration after natural or anthropogenic disturbances and long-term land planning and management of natural resources. Moreover, watershed assessment and modelling are in line with the indications by the United Nations Agenda 21 for sustainable development, which recommends the integrated management of land resources, which broadly include soils, water, and biota and, in general, all ecosystem components for watershed protection [5]. A watershed approach is recommended for land resources management, and the watershed scale is adopted as a spatial unit of analysis in a defined area for ecological, social, and economic purposes [6].

Watershed management includes land use planning, control of erosion and sedimentation processes, flooding mitigation, conservation of soil, water, and forests, as well as promotion of food production, security, and livelihoods [7].

Managing natural resources at the watershed scale results in multiple benefits for environmental protection and resource provision to people [2,8,9]. 'Watershed management' was identified by the California Department of Conservation in 2015 as 'the study of the relevant characteristics of a watershed aimed at the sustainable distribution of its resources and the process of creating and implementing plans, programmes, and projects to sustain and enhance watershed function that affects the plant, animal, and human communities within a watershed boundary'. In other words, watershed management consists of organising and guiding land, water, soil, and other natural resources in watersheds to provide the appropriate goods and services while mitigating impact on the resources themselves [1]. This process is multifaceted and interdisciplinary: it involves not only technical and scientific knowledge about hydrology, geomorphology and ecology, but also requires social, economic, policy and education approaches targeted at preserving and valorising the inter-relations among soil, water and plants as well as the connection between upland and downstream areas [10]. These multidisciplinary aspects and the reciprocal inter-relations among the different watershed components require an integrated approach, which is actualised in the so-called 'integrated watershed management'. This involves the integration of technologies within the natural boundaries of a drainage area for optimum development of land, water, and plant resources to sustainably meet the basic needs of people and animals [2,11]. Integrated watershed management has now become increasingly prominent, since the related theoretical approach and associated practice include various social, technical, and institutional dimensions as well as conservation, social, and economic objectives [12].

The implementation of this integrative approach over the last few decades has been sped up by three drivers: (i) the rapid and recent advances of computer science (big data processing and application of mathematical simulation models) and geospatial technology (remote sensing imagery, geographical information systems, global positioning systems); (ii) the incredible development of communication capacity which has allowed a real-time sharing of information and data of different types; and (iii) the involvement of many stakeholders, decision-makers and local and global communities in the monitoring and planning activities of integrated watershed management.

However, integrated watershed management heavily relies on hydrological and geomorphological sciences and technologies, which influence all drivers and effects of natural evolution and human actions on the watershed. These drivers range from issues of water quality, hydrogeological hazards, vegetation and fauna restoration, and soil conservation. The simulation tools of these effects (e.g., the hydrological models and ecological monitoring techniques) have undergone special development from theoretical and practical points of view.

In general, ref. [1] identified six steps for the integrated watershed management process (Figure 1): (1) survey of the status of the watershed and identification of its situation; (2) identification of stakeholders; (3) selection of interests and objectives; (4) setting up of the target and plan; (5) implementation of the plan; and (6) evaluation of management success and failures, reassessment of objectives, and adjustments of the plan to improve management success.

Modern watershed management that adopts the aforementioned integrated approach is often constrained by multiple factors and objectives [13]. Firstly, natural processes of watershed evolution (e.g., hydrological regime, vegetation dynamics, soil characteristics) are affected by a large level of spatial and temporal variability, making a watershed a highly dynamic system. It is clear that monitoring these natural processes (i) increases our knowledge of this intrinsic variability; (ii) provides guidelines for governing watershed's evolutionary trends; and (iii) limits the high uncertainty of watershed functioning due to the stochastic variability of natural factors (e.g., weather) and induced responses (e.g., hydrological and erosive rates).

Secondly, these natural processes are numerous and highly inter-related, which means that a driver of a watershed component (e.g., extreme precipitation turning to a flood) may exert a high impact on another component (e.g., vegetation disruption and severe changes in soil properties). Since all natural resources are interconnected in a watershed, synergistic actions from various stakeholders through integrated management are essential [14]. This requires a multidisciplinary approach (intrinsically embedded in the integrated watershed management) from land planners and authorities with the integration of different skills and knowledge of technicians. The need to work in larger interdisciplinary teams is partly due to the requirement of linking individual specialists' contributions to enable a better understanding of the 'system' under study [15].

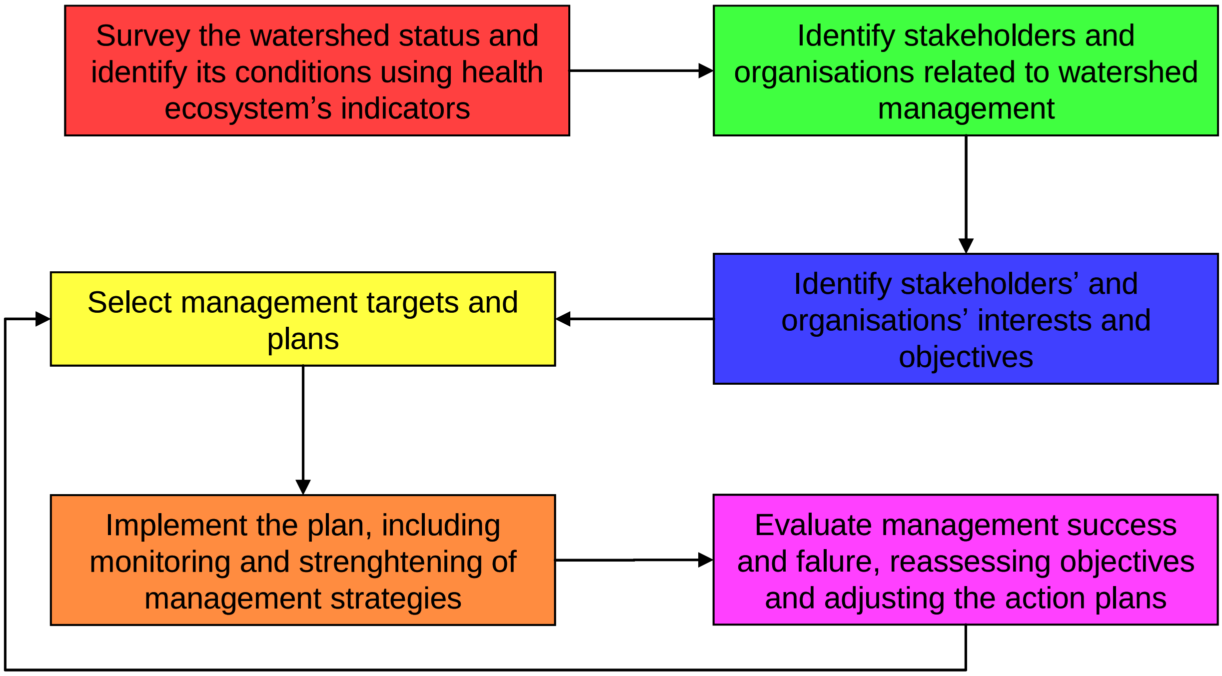

Figure 1. Conceptual model for developing an integrated watershed management plan (source: [1], modified).

Thirdly, the natural and anthropogenic disturbances (e.g., deforestation, wildfire, hydrogeological hazards) sum up the heterogeneity of watershed processes and their high spatial and temporal variability, adding high entropy to the watershed system. There is, therefore, a need for proper control of natural processes and mitigation of anthropogenic impacts. This need requires the adoption of tailored analysis techniques and conservation measures that are specific to the environmental conditions. This is now possible, considering the incredible advances in data processing offered by technology, such as the availability of computers with high data processing capacity, cloud storage, remote sensing, and geographic information systems (GISs). All these tools allow a detailed representation and simulation of watersheds at fine temporal scales.

Last but not least, related to the multiple ecosystem services provided in watersheds, the numerous management needs are sometimes contrasting. Their optimised management requires a careful approach by all stakeholders. For example, to maximise water supply and carbon sequestration in forests among their ecosystem services, land planners and watershed managers need to assess the trade-offs of water use and carbon stock of vegetation to store atmospheric CO_2 and provide water supply to downstream water users [3].

Therefore, it is essential to adopt effective monitoring and management tools to limit the impacts of the aforementioned constraints, valorise the natural resources in watersheds, and favour a balanced and sustainable functioning of all components. These monitoring and management tools must inform science-based decisions to reduce the risk of negative impacts of management actions [16].

In this regard, an optimal solution is the adoption of Decision Support Systems (DSSs), computerised 'knowledge-based' systems supporting the collection, analysis and processing of large bodies of data at the watershed level. Thanks to the powerful capacity given by DSSs, these data, which are of different types, scales and resolutions, can be easily and quickly managed. DSSs help decision-making, timely problem-solving, and improved efficiency in planning and management of watersheds [17]. Moreover, DSSs are also particularly efficient in modelling and analysing scenarios of climatic evolutionary trends and anthropogenic impacts, simplifying the choices of decision-makers from among the possible different actions [18]. For instance, the hydrological and eco-hydrological models, which are essential tools of DSSs, offer a high capability of predicting forest and water evolutionary trends as well as the interactions of ecosystem services. This supports a better evaluation and optimisation of the complex management options at various scales for multiple purposes and under changing climate patterns [3,19]. However, the use of these modelling tools is still difficult, considering the increasing complexity and integration of models which are needed to address the aforementioned inter-relations and variability of environmental processes in watersheds functioning under a changing environment.

Therefore, there is a need for studies that analyse the tools required to provide a better understanding of watershed physical and ecological processes and propose new strategies for the sustainable management of watershed resources (soil, water, vegetation, etc.).

In line with the aforementioned needs, this Special Issue presents six papers submitted in response to the call.

The first study [20] analysed the importance of the engagement of local stakeholders in river restoration through the appreciation and integration of local communities and their local ecological knowledge. The common river restoration problems and supportive elements that may be found in local ecological knowledge have been discussed. The study concluded that the local stakeholders' involvement and strong establishment of their position in the river restoration processes have a large potential for improving water resources management and restoration of aquatic ecosystems and remain a key factor in the successful future of river restoration.

The second paper [21] proposed strips planted with *Miscanthus x giganteus*, a perennial grass to replace the most common trees and shrubs, for runoff and erosion control on a loess slope. The results indicate the good anti-erosion effectiveness of the established strip, although, in the first years of growth, this grass has not yet reached the stage of full development.

The third article [22] explored the distributions of poached cycads, evaluating the factors driving poaching activity and suggesting possible solutions towards the conservation of *Encephalartos transvenosus* Stapf & Burtt Davy E in some of the nature reserves in South Africa. Here, the number of cycads is drastically reducing, and they are nearly extinct, which may negatively impact watersheds in protected and buffer areas, since the regeneration of this plant occurs over a long period. The results demonstrated that unemployment and trade are the leading causes of poaching of cycads, and the most effective way of stopping as perceived by the rangers is patrolling the nature reserves.

The fourth paper [23] investigated ten hill torrents in Pakistan, covering an area affected by flash flooding in 2022 due to extreme precipitation events. The authors used the Hydrologic Engineering Centre's Hydrologic Modeling System (HEC-HMS) model, a semi-distributed event-based hydrological tool. The study presents appropriate storage options with the relevant retention potentials based on hydrological analysis of these hill torrents to enhance the spate irrigation potential as flood control in the future.

In the fifth study [24], the changes in the active drainage network of a mountain watershed during extreme hydro-meteorological events as well as the consequences of the related changes on the hydrological response and the flood hazard/risk management processes in Poland were investigated. The hydrological processes in that watershed, which is prone to flash floods, were analysed by ALS-LiDAR data, GIS tools, and the SCS-CN and GIUH models. The results revealed that the significant structural changes in the active drainage network have noticeably increased the peak flow and 1%-probable flood hazard zone.

The sixth article [25] assessed the complexity of nutrient pollution attributed to harmful algal blooms by analysing 20 years of flow and nutrient data within two headwater basins in South Florida (FL, USA). To this end, an advanced regression method and the Weighted Regression on Time, Discharge, and Season method were used. The results highlighted that nutrient management practices only had a weak impact on TP and TN flux trends in one of the two basins, where TP and TN fluxes increased in the second basin. This was presumably due to differences in contemporary point source loading and legacy nutrient pools from non-point source inputs 20 years or more before the analysis period.

The papers in this Special Issue contribute to research on the integrated management of natural resources and environment at a watershed scale. The authors have demonstrated how novel monitoring and modelling tools help in better understanding and accurately simulating natural and anthropogenic processes in watersheds in a changing world. These activities closely agree with the objectives of international government policies, which support analysis frameworks to achieve the 17 goals of the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015.

However, there is still much to do from the scientific and practical points of view to address the issues of sustainable and rational integrated watershed management. For instance, according to [26], enhanced credibility and utility of integrated watershed management for decision-makers need more comprehensive model testing with a specific focus on methods for uncertainty characterisation in watershed-scale processes. These needs are challenging, especially for data-poor environments, where the availability of observed data is a severe constraint against more informed and confident decision support. Therefore, research should explore the natural and human-induced variability in watershed-scale processes, adopting a holistic approach that includes all components of the functioning of this hydro-system.

If proper and multidisciplinary databases match the aforementioned variability in soil, water, and biota characteristics, process-based models—of ecological, hydrological or combined nature—will valorise their extraordinary simulation capacity. These tools may easily account for the pressure of climate change impacts and ensure cross-disciplinary approaches to preserve the ecological and socio-economic functions provided by watersheds on a global scale.

Finally, anthropogenic actions within integrated watershed management will continue to rely on engineering works for regulating the fluxes of water and sediments downstream of the sourcing areas. In addition, nature-based solutions (NBSs) ranging, for instance, from green infrastructures to ecological engineering works, must be prioritised in order to build a more resilient and durable ecosystem, empowering the watershed's ability to provide the required physical and ecological functions. In this regard, research should investigate novel types of NBSs across a variety of climatic and geomorphological contexts. Once a prototype is successfully experimented and validated in a specific environment, its transferability to another hydro-system is not automatic. In close agreement with [4,27], we think that these actions, including conventional engineering works and NBS solutions, should be tailored to the specific characteristics of locations in the landscape. Careful attention should be paid to how these actions interact with each other to optimise their beneficial effects and minimise the potential negative impacts.

Author Contributions: All authors equally contributed to the paper preparation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. Wang, G.; Mang, S.; Cai, H.; Liu, S.; Zhang, Z.; Wang, L.; Innes, J.L. Integrated Watershed Management: Evolution, Development and Emerging Trends. *J. For. Res.* **2016**, *27*, 967–994. [CrossRef]
2. Wani, S.P.; Garg, K.K. *Watershed Management Concept and Principles*; ICRISAT: Patancheruvu, India, 2009.
3. Sun, G.; Wei, X.; Hao, L.; Sanchis, M.G.; Hou, Y.; Yousefpour, R.; Tang, R.; Zhang, Z. Forest Hydrology Modeling Tools for Watershed Management: A Review. *For. Ecol. Manag.* **2023**, *530*, 120755. [CrossRef]
4. Hewett, C.J.M.; Wilkinson, M.E.; Jonczyk, J.; Quinn, P.F. Catchment Systems Engineering: An Holistic Approach to Catchment Management. *WIREs Water* **2020**, *7*, e1417. [CrossRef]
5. Katusiime, J.; Schütt, B. Linking Land Tenure and Integrated Watershed Management—A Review. *Sustainability* **2020**, *12*, 1667. [CrossRef]
6. Filianoti, P.; Gurnari, L.; Zema, D.A.; Bombino, G.; Sinagra, M.; Tucciarelli, T. An Evaluation Matrix to Compare Computer Hydrological Models for Flood Predictions. *Hydrology* **2020**, *7*, 42. [CrossRef]
7. Biswas, A.K. Watershed Management. *Int. J. Water Resour. Dev.* **1990**, *6*, 240–249. [CrossRef]
8. Joshi, P.K. *Meta-Analysis to Assess Impact of Watershed Program and People's Participation*; IWMI: Colombo Sri Lanka, South Asia, 2005; Volume 8, ISBN 92-9090-603-0.
9. Rockstrom, J.; Hatlbu, N.; Owels, T.Y.; Wani, S.P. *Managing Water in Rainfed Agriculture*; ICRISAT: Patancheruvu, India, 2007.
10. Ffolliott, P.F. *Land Stewardship Through Watershed Management: Perspectives for the 21st Century*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2002; ISBN 0-306-46698-8.
11. Macleod, C.J.A.; Scholefield, D.; Haygarth, P.M. Integration for Sustainable Catchment Management. *Sci. Total Environ.* **2007**, *373*, 591–602. [CrossRef] [PubMed]
12. German, L.; Mansoor, H.; Alemu, G.; Mazengia, W.; Amede, T.; Stroud, A. Participatory Integrated Watershed Management: Evolution of Concepts and Methods in an Ecoregional Program of the Eastern African Highlands. *Agric. Syst.* **2007**, *94*, 189–204. [CrossRef]
13. Vose, J.M.; Martin, K.L.; Barten, P.K. Applications of Forest Hydrological Science to Watershed Management in the 21st Century. In *Forest Hydrology: Processes, Management and Assessment*; CABI: Wallingford, UK, 2016; pp. 240–253.
14. FAO. Preparing for the Next Generation of Watershed Management Programmes and Projects. European Proceedings of the European Regional Workshop. In *Review and Assessment of Watershed Management Strategies and Approaches*; Tennyson, L., Ed.; FAO/FORC Watershed Management Consultant: Mégève, France, 2002; pp. 19–39.
15. Haygarth, P.M.; Condron, L.M.; Heathwaite, A.L.; Turner, B.L.; Harris, G.P. The Phosphorus Transfer Continuum: Linking Source to Impact with an Interdisciplinary and Multi-Scaled Approach. *Sci. Total Environ.* **2005**, *344*, 5–14. [CrossRef] [PubMed]
16. Yousefpour, R.; Jacobsen, J.B.; Thorsen, B.J.; Meilby, H.; Hanewinkel, M.; Oehler, K. A Review of Decision-Making Approaches to Handle Uncertainty and Risk in Adaptive Forest Management under Climate Change. *Ann. For. Sci.* **2012**, *69*, 1–15. [CrossRef]
17. Segal, T. Decision Support System–DSS; Investopedia: 2021. Available online: https://www.investopedia.com/terms/d/decision-support-system.asp (accessed on 3 December 2024).
18. Andreu, J.; Capilla, J.; Sanchís, E. AQUATOOL, a Generalized Decision-Support System for Water-Resources Planning and Operational Management. *J. Hydrol.* **1996**, *177*, 269–291. [CrossRef]
19. Chapman, H.D. Cation-exchange Capacity. *Methods Soil Anal. Part 2 Chem. Microbiol. Prop.* **1965**, *9*, 891–901.
20. Szałkiewicz, E.; Sucholas, J.; Grygoruk, M. Feeding the Future with the Past: Incorporating Local Ecological Knowledge in River Restoration. *Resources* **2020**, *9*, 47. [CrossRef]
21. Cooper, R.Z.; Ergas, S.J.; Nachabe, M. Multi-Decadal Nutrient Management and Trends in Two Catchments of Lake Okeechobee. *Resources* **2024**, *13*, 28. [CrossRef]
22. Ndou, T.M.; Stam, E.M.; Tshisikhawe, M.P.; Alabi, M.A.; Adeeyo, A.O. Poaching of Encephalartos Transvenosus, in the Limpopo Province, South Africa. *Resources* **2021**, *10*, 119. [CrossRef]
23. Saleem, M.; Arfan, M.; Ansari, K.; Hassan, D. Analyzing the Impact of Ungauged Hill Torrents on the Riverine Floods of the River Indus: A Case Study of Koh E Suleiman Mountains in the DG Khan and Rajanpur Districts of Pakistan. *Resources* **2023**, *12*, 26. [CrossRef]
24. Mazur, A.; Kowalczyk-Juśko, A. The Assessment of the Usefulness of Miscanthus x Giganteus to Water and Soil Protection against Erosive Degradation. *Resources* **2021**, *10*, 66. [CrossRef]
25. Bryndal, T. Changes in the Active Drainage Network and Their Impact on the Hydrological Response and Flood Risk Management Process: A Case Study for a Flysch Mountain Catchment. *Resources* **2023**, *12*, 146. [CrossRef]

26. Jakeman, A.; Letcher, R. Integrated Assessment and Modelling: Features, Principles and Examples for Catchment Management. *Environ. Model. Softw.* **2003**, *18*, 491–501. [CrossRef]
27. Lane, S.N. Natural Flood Management. *Wiley Interdiscip. Rev. Water* **2017**, *4*, e1211. [CrossRef]