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Editorial

Application of Various Hydrological Modeling Techniques and Methods in River Basin Management

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1. Introduction

The techniques of hydrological modeling have greatly improved in the recent past and have been instrumental in the management of river basins. This Special Issue presents state-of-the-art research to cope with the integrated problems of water resource management. The river basins are vital hydrological features that are both vital ecosystems as well as economic assets, and they come up with numerous challenges, including climate change, alteration of land use, and rise in water usage. Such challenges call for new strategies that involve the incorporation of big data, sophisticated computational models, and optimization techniques to assist in the decision-making process.

The research studies in this issue are quite diverse in the methods that have been used, for instance, the application of well-known hydrological models such as the Soil and Water Assessment Tool (SWAT). Some of the advanced machine learning algorithms have been used include Random Forest (RF), Extreme Gradient Boosting (XGB), and deep learning models. The optimization methods, namely the Gray Wolf Optimizer (GWO), have been incorporated with the modeling approaches to enhance the accuracy and the effectiveness of the predictions of patterns as well as sediment transport rates and evapotranspiration. Also, the incorporation of remote sensing data coupled with Geographic Information Systems (GIS) also enhances the spatial and temporal accuracies of these models.

Some of the themes highlighted in these articles include the identification of erosion hotspots and analyzing sediment accumulation in reservoirs as well as optimizing irrigation strategies to improve water use efficiency. In addition, the following studies highlight the need for the prediction of the reactions in the context of climate change and the potential ways of viewing the future impacts and vulnerabilities of the river basin systems. These advancements in the modeling techniques do not only increase the understanding of the phenomenon but also provide factual information that will benefit decision-makers, water resource managers, and other stakeholders. This particular edition stresses the importance of modeling in bridging the gap between the academic knowledge and the application. This research discusses aspects of managing river basins. It assists in developing sustainable and adaptable measures for preventing the deterioration of water sources and impacts caused by people.

2. Main Contributions of This Special Issue

Li et al. (contribution 1) optimized the Community Land Model (CLM5) in the Songhua River Basin (SRB) and incorporated the CaMa-Flood model to enable the utilization of multi-source meteorological data as well as surface characteristics in a detailed

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manner. This integration made it possible to perform high-resolution simulations of the runoff process over almost two decades with the seasonal variation in the discharge and identification of the flood-prone areas. The model had a coefficient of correlation of 0.65 to 0.80 with the discharge observed, thus making it useful in the understanding of the seasonal variation in hydrology as well as in flood management and prediction under different climate conditions.

Zhen and Bărbulescu (contribution 2) In the Buzău River in Romania, various machine learning models, such as convolutional neural network-long short-term memory (CNN-LSTM), sparrow search algorithm-backpropagation neural network (SSA-BP), and particle swarm optimization-extreme learning machine (PSO-ELM), were compared to predict the flow of the river. The outcomes highlighted the fact that the CNN-LSTM, especially when the model was trained with data collected after the construction of the dam, provided the best results in terms of accuracy and computational time. This type of model comparison not only shows the potential of using hybrid neural network approaches but also shows the importance of such comparisons in the real world for the application and management of river flows, which can then be used as a basis for choosing the most suitable model depending on the given hydrological and infrastructure conditions.

In the Seybouse Basin of Algeria, Inan et al. (contribution 3) used the Soil Water Assessment Tool (SWAT) model to assess the groundwater recharge in a semi-arid region. This model was calibrated with rainfall data and hydrometric station data, and the results were found to be efficient as proven by various performance measures, including Nash–Sutcliffe efficiency and R^2. The study shows that the SWAT can be used to effectively simulate hydrological processes in data-scarce arid regions. It also shows the need to develop accurate methods of estimating groundwater recharge for effective management of water resources in arid and semi-arid regions.

In their study, Patel et al. (contribution 4) proved how hydrological modeling has been useful in identifying the best sequence of measures for soil erosion management within watersheds. In India's Burhanpur watershed, the MCDA approach was coupled with morphometric parameters to rank the sub-watersheds for erosion potential. This analysis employed several approaches, such as the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), for ranking the areas in terms of the erosion risk. This kind of prioritization makes it easier to determine which areas need soil conservation measures most and therefore assist in the management of the watersheds that are mainly used for agricultural purposes.

In the contribution by Saavedra et al. (contribution 5), the precipitation data from the satellite-based products were used and incorporated with the HydroBID model in the Guadalquivir Basin in Bolivia to produce high-resolution and distributed inputs for hydrological simulations. This approach showed a high correlation with the observed flow, and it was able to simulate micro-basin flows well with the HydroBID model. This approach using distributed precipitation data have great application in other areas that have scarce hydrometeorological data to produce better water balance, such as using the Yalong Well River for basin flood routing.

In another study by Yue et al. (contribution 6), the hybrid monthly model runoff that forecasting incorporated was particle-enhanced swarm optimization and the flower pollination algorithm with deep belief networks (PSO-FPA-DBN). This model, which was applied in the Yalong River Basin of China, outperformed other traditional models in terms of accuracy, consistency, and computational time, thus proving the potential of data-mining approaches in simulating the variability of monthly runoff. These developments improve the flood and drought forecasting systems, hence facilitating effective water resources management.

In the paper by Ma et al. (contribution 7), the authors demonstrated an effective use of cloud seeding in hydrology and the effect of seeding on water management in three dam basins in Korea and analyzed how the results can be applied to optimize the water management of the basins. The study revealed how the effects of cloud seeding can be different in various reservoirs, and thus, certain reservoirs may need more intense cloud seeding in specific seasons to improve the water supply situation. This study also points out that although the basins are located in the same climatic zone, context-specific approaches are essential to enhance the effectiveness of cloud seeding.

In a large-scale study by Abdelkader et al. (contribution 8) across the United States, the National Water Model (NWM) was assessed for the multi-decade time period, and it was observed that the model produced satisfactory results for the streamflow with and without the presence of regulation structures. The assessments of the model's performance showed better correspondence with the observed flows during winter in the humid regions, while some arid regions needed to be captured better. This analysis highlights how the NWM can be effectively used for large-scale hydrological prediction and where there is still room to enhance the bias correction, especially in the case of regulated flows.

Valencia et al. (contribution 9) demonstrated the innovative use of the InVEST Annual Water Yield model in Colombia's Meta River Basin to assess water yield at a basin scale. Despite the model's limitations, such as low accuracy in certain subbasins, it provided valuable and enlightening insights into hydrological processes in data-scarce regions. The findings from this study contribute to the discourse on the adaptability of models like InVEST in diverse hydrological settings and inform future model enhancements for water management.

Heramb et al. (contribution 10) investigated the application of advanced hydrological modeling techniques to improve river basin management, with a focus on estimating reference evapotranspiration (ET0)—a critical factor in water resource planning. Using machine learning (ML) models such as Random Forest (RF), Extreme Gradient Boosting (XGB), and Light Gradient Boosting (LGB), coupled with the Gray Wolf Optimizer (GWO), the research demonstrates significant improvements in predictive accuracy compared to conventional empirical models. This study applied advanced machine learning (ML) models, including Random Forest (RF), Extreme Gradient Boosting (XGB), and Light Gradient Boosting (LGB), coupled with the Gray Wolf Optimizer (GWO), to estimate reference evapotranspiration (ET0) for improving river basin management [1]. Using 20 years of meteorological data from humid and sub-humid regions of India, hybrid GWO-ML models significantly outperformed empirical and standalone ML methods, achieving a reduced RMSE and increased R^2 values [2]. These findings demonstrate the potential of integrating meta-heuristic algorithms with ML to enhance sustainable water resource management [3,4].

Nagireddy et al. (contribution 11) study is relevant to the focus of this Special Issue as it demonstrates how semi-distributed hydrological models like the Soil and Water Assessment Tool (SWAT) can be utilized for effective management of water resources and sediment yield in medium-sized river basins. The study focuses on two rivers, namely the Nagavali and Vamsadhara river basins in India, which are prone to soil erosion and sedimentation due to steep slopes and huge cultivation activities. Through calibration and sensitivity analysis, some of the major factors that influence the outcome of the model were established, such as the SCS runoff curve number and hydraulic conductivity, in order to produce a realistic simulation of the streamflow and sediment yield. The study revealed that evapotranspiration was the highest water loss process, accounting for the bulk of the annual precipitation, while the sediment yield analysis identified most of both basins as having high erosion rates, hence calling for urgent soil and water conservation

measures. By identifying the focus areas of sediment sources, this study demonstrates the capability of hydrological modeling in assisting with the development of sustainable management measures, which is in line with the focus of this Special Issue on how to tackle water resource issues through the use of advanced modeling techniques. The findings of this study will be useful to policymakers and watershed managers to combat erosion and to improve the management of water resources in the vulnerable river basins.

To sum up, these research studies show how hydrological modeling is utilized in a variety of ways for the management of river basins. The incorporation of physical, statistical, and machine learning methods offers a comprehensive approach to forecasting and controlling hydrological conditions, planning of water resources, and issues including erosion, flooding, and reduction in groundwater table. Thus, further development of hydrological modeling methods with their increasing level of integration will allow water resources managers to obtain the necessary tools to support sustainable and flexible management of water resources in river basins under the conditions of climate change and growing water consumption.

3. Conclusions

The research in this Special Issue demonstrates how hydrological modeling techniques can make a huge difference in river basin management and how the findings can help with water resources management, sediment control, and sustainable development. All these studies have been designed and conducted to demonstrate the use of sophisticated models, including the Soil and Water Assessment Tool (SWAT), integrated with machine learning methods and optimization techniques, for the simulation of hydrological and land use change processes in various climatic and geographical conditions. With high-resolution meteorological, land use, soil, and remote sensing data, the studies prove the potential of estimating stream flow, evapotranspiration, and sediment output, which is very useful for the water resource managers.

The results show the potential of these models in determining the potential areas of erosion, enhancing the scheduling of irrigation water, and controlling sedimentation in reservoirs to address challenges in agriculture, flood control, and soil conservation. For instance, the research presented in the studies shows that incorporating the models along with geographical information systems (GIS) and remote sensing data enables quantification and analysis of the condition and changes over time, and, therefore, such tools are invaluable to policymakers and other stakeholders. Also, the research shows how these models can be applied to simulate conditions that would occur under the influence of climate change and provide forecasts for floods and droughts, which are crucial to increasing the basin's resilience.

The outcomes of these studies are quite useful in several sectors. For instance, in the agricultural sector, it is possible to determine the water balance accurately and, therefore, manage the water used for irrigation in a more effective manner with no waste of water and a higher production of crops. In urban planning and infrastructure, information on sedimentation and deposition can be used in preventing the siltation of reservoirs and other water bodies to ensure a constant water supply. In addition, these models assist the environmental protection measures by pinpointing the areas at high risk of soil erosion and assisting in the design of effective measures against it.

Furthermore, the studies identify the limitations and future research directions. The utilization of real-time data and sensor technology can also be enhanced to improve the model's predictive capacity. The application of the ensemble modeling approach, where multiple algorithms are used, can be useful in increasing the prediction capacities for the large and complicated basins. Hence, future work should also focus on the socio-economic

effects of model usage to attain just and feasible solutions for all the parties involved. Finally, further development of high-resolution data collection and teamwork between different fields of science will be important for the further implementation of hydrological modeling in river basin management.

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List of Contributions

1. Li, H.; Zhang, Z.; Zhang, Z. Improvement and Evaluation of CLM5 Application in the Songhua River Basin Based on CaMa-Flood. *Water* **2024**, *16*, 442. https://doi.org/10.3390/w16030442.
2. Zhen, L.; Bărbulescu, A. Comparative Analysis of Convolutional Neural Network-Long Short-Term Memory, Sparrow Search Algorithm-Backpropagation Neural Network, and Particle Swarm Optimization-Extreme Learning Machine Models for the Water Discharge of the Buzău River, Romania. *Water* **2024**, *16*, 289. https://doi.org/10.3390/w16020289.
3. Inan, C.A.; Maoui, A.; Lucas, Y.; Duplay, J. Multi-Station Hydrological Modelling to Assess Groundwater Recharge of a Vast Semi-Arid Basin Considering the Problem of Lack of Data: A Case Study in Seybouse Basin, Algeria. *Water* **2024**, *16*, 160. https://doi.org/10.3390/w16010160.
4. Patel, A.; Ramana Rao, K.V.; Rajwade, Y.A.; Saxena, C.K.; Singh, K.; Srivastava, A. Comparative Analysis of MCDA Techniques for Identifying Erosion-Prone Areas in the Burhanpur Watershed in Central India for the Purposes of Sustainable Watershed Management. *Water* **2023**, *15*, 3891. https://doi.org/10.3390/w15223891.
5. Saavedra, O.; Ureña, J.; Perales, M. Implementation of HydroBID Model with Satellite-Based Precipitation Products in Guadalquivir Basin, Bolivia. *Water* **2023**, *15*, 3250. https://doi.org/10.3390/w15183250.
6. Yue, Z.; Liu, H.; Zhou, H. Monthly Runoff Forecasting Using Particle Swarm Optimization Coupled with Flower Pollination Algorithm-Based Deep Belief Networks: A Case Study in the Yalong River Basin. *Water* **2023**, *15*, 2704. https://doi.org/10.3390/w15152704.
7. Ma, J.-H.; Yoo, C.; Song, S.-U.; Na, W.; Cho, E.; Song, S.-K.; Chang, K.-H. Different Effect of Cloud Seeding on Three Dam Basins, Korea. *Water* **2023**, *15*, 2555. https://doi.org/10.3390/w15142555.
8. Abdelkader, M.; Temimi, M.; Ouarda, T.B.M.J. Assessing the National Water Model's Streamflow Estimates Using a Multi-Decade Retrospective Dataset across the Contiguous United States. *Water* **2023**, *15*, 2319. https://doi.org/10.3390/w15132319.
9. Valencia, J.B.; Guryanov, V.V.; Mesa-Diez, J.; Tapasco, J.; Gusarov, A.V. Assessing the Effectiveness of the Use of the InVEST Annual Water Yield Model for the Rivers of Colombia: A Case Study of the Meta River Basin. *Water* **2023**, *15*, 1617. https://doi.org/10.3390/w15081617.
10. Heramb, P.; Ramana Rao, K.V.; Subeesh, A.; Srivastava, A. Predictive Modelling of Reference Evapotranspiration Using Machine Learning Models Coupled with Grey Wolf Optimizer. *Water* **2023**, *15*, 856. https://doi.org/10.3390/w15050856.
11. Nagireddy, N.R.; Keesara, V.R.; Sridhar, V.; Srinivasan, R. Streamflow and Sediment Yield Analysis of Two Medium-Sized East-Flowing River Basins of India. *Water* **2022**, *14*, 2960. https://doi.org/10.3390/w14192960.

References

1. Yan, K.; Cheng, Z.; Sun, G.; Huang, Z. Hybrid machine learning models for estimating daily reference evapotranspiration with external optimization. *Irrig. Sci.* **2020**, *38*, 631–644.
2. Zhou, J.; Wu, P.; Wang, Y.; Cao, X. Comparative study of different data-driven models for predicting reference evapotranspiration. *Water Resour. Manag.* **2021**, *35*, 857–872.

3. Dong, J.; Zhang, Y.; Liu, J.; Wang, Y. Improving reference evapotranspiration estimation with bio-inspired optimization algorithms coupled with kernel-based models. *Agric. Water Manag.* **2019**, *216*, 122–132.
4. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *FAO-56 Penman-Monteith Equation for Determining Reference Evapotranspiration*; FAO Irrigation and Drainage Paper No. 56; FAO: Rome, Italy, 1998.

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