Hydrological Modeling of Urban Watersheds to Predict Flood Risks Under Extreme Rainfall Events

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Abstract: Hydrological Models (HM) effectively quantify water flow and distribution at regional and watershed scales. They have been used to model the relationship between precipitation and runoff. They assist urban planners and hydrological experts examine the intricate interaction between runoff and rainfall at various catchment and metropolitan scales. The transportation of water is a crucial issue, particularly on land. This study evaluates various HM research across many contexts, including geographic analysis within the Watershed Modelling Scheme (WMS). It aims to focus only on the essential aspects of Hydrology and HM to examine water within a watershed. This paper provides a foundational comprehension of the empirical hydrological techniques used to quantify runoff and a concise overview of two-dimensional methodologies. The study determined that Hydrology Modelling is predicated on a) Loss Techniques, b) Direct Run-off, and c) Two-Dimensional approaches. This analysis determined that the widely used hydrology models in various situations are the Hydrologic Engineering Center-HM Software (HEC-HMS) and the Soil Water Analysis Tool (SWAT). The HEC-River Analysis Systems (HEC-RAS) is crucial for evaluating flood management strategies in hydraulic water depth (ID) and 2D modeling. Hydrological models emerged as a primary tool for assessing flood danger in assessed and ungauged basins.

Keywords: Hydrological Modeling; Urban Watersheds; Flood Risks; Rainfall.

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I. Introduction

Scholars have shown heightened interest in hydrology in the past few years due to its significance for humanity and the environment. Hydrology Models (HM) are a subset of earth sciences, facilitating the preparation and oversight of water resources Sahu, Shwetha & Dwarakish (2023). Such models are extensively used to improve the discourse on water management. These representations are frequently used as readily available tools in water resources, technology, and administration. Most of these algorithms can also be employed for forecasting and flood prediction.

HM is created to manage, forecast, and comprehend watershed water resources. HMs are crucial for assessing water resources, such as the governance of the environment. The objective of an HM is to analyze the complex and nonlinear connection between precipitation and runoff through mathematical equations and various variables; this comprehension enhances the knowledge for decision-making in water resource management and the conveyance of water both on the ground and underground Kolahi, Davary & Omranian Khorasani (2024).

There was a significant rise in hydrology and hydraulic simulations in both humid and dry regions, which were used to analyze the effects of various variables on runoff generation and water movement. The use of hydrological and HM in ecological studies has risen. HM is essential for investigating the effects of contemporary human activities on hydrologic systems. They are crucial for research and assessments of the influence of Land Use (LU) and Land Cover (LC) on runoff and flood drowning, as well as for analyzing the effects of their actions on runoff Megahed et al. (2023). Hydrological catchment studies focus significantly on surface runoff within a watershed, since it immediately or indirectly affects most hydrological processes.

The HM seeks to forecast stream characteristics and peak departure, with its applicability having advanced since the advent of remote sensing data. The primary objective in hydrological research is the calculation and estimation of runoff. HM is beneficial for enhancing urban catchments to mitigate flood risk. Access to data renders these models accessible in most industrialized countries. Hydrological data is often lacking in underdeveloped nations, particularly concerning observational data. The augmentation of Remote Sensing (RS) Ren et al. (2023) information for gathering inundation zones might facilitate the simulation of floods when integrated with HM. HM replicates flood features with remote sensing data. With the rapid advancement of the Watershed Modelling Scheme (WMS) Sahu, Shwetha & Dwarakish (2023, geographical information structures and remote sensing technologies have been pivotal in developing HM. The RS sector has enhanced access to information, and the Geographical Information Systems (GIS) Sowmiya Narayanan & Manimaran (2024) is a crucial resource that constitutes many data types. Combining WMS with GIS and RS enhances the precise assessment of water management at local and watershed scales.

II. Background

Many studies have concentrated on current LULC data, overlooking the integration of LULC predictions to evaluate their effects on hydrological reactions. However, for efficient water resource management methods, examining hydrological alterations in projected LULC is crucial. This evaluation is essential for devising a suitable drainage system to fulfill future needs. Numerous models exist for predicting LULC, including statistical approaches such as the Markov chain approach, logistic regression, Cellular Automata (CA), and Artificial Neural Networks (ANNs). CA is a frequently used approach for urban development modeling, characterized by its open structure that facilitates integration with different models. It has robust spatial computing capabilities to model spatial heterogeneity. It lacks quantitative dimensions and the capacity to include factors that drive simulations, rendering interaction with quantitative models such as the Markov Chain (MC) imperative. Markov models (MM) are proficient in identifying long-term trends but are deficient in modeling spatial dimensions Aburas et al. (2021). Using just one model will impose constraints on the computation. Numerous studies demonstrate the integration of various models to get around the limitations of solo techniques. A survey of the existing literature on land use forecasting indicates that an amalgamation of CA and MM is extensively used and effectively mitigates the limitations inherent in each approach. This study suggests integrating CA and MC to improve simulation accuracy and boost the forecasting of spatiotemporal events Fu et al. (2022). The integrated CA-MM has enhanced proficiency in producing precise spatio-temporal land use and land cover change trends. The result combines the statistical elements of the MM with the randomized spatial characteristics of the CA technique. The CA-MM framework has been extensively utilized to predict future land use trends. The CA-MM system's ability to effectively integrate GIS and RS distinguishes it as a dependable method for modeling temporal and spatial LU variations.

Classifications of Hydrological Models

HM has been developed for the administration of water resources, with its use beginning in the mid-19th century, using reasonable ways to quantify the correlations between precipitation and runoff. In recent years, particularly within the water supply sector, there has been a significant rise in the number of densely inhabited metropolitan regions worldwide. This escalation resulted in heightened demand for water supplies and urbanized land. Environmental modeling is essential to comprehending this phenomenon. HM provides a clear numerical representation of the hydrological system. They are designed to illustrate surface stream conveyance and sub-surface processes, including fundamental apparatus for managing and monitoring water resources.

HM is often used because of the limitations of hydrological estimating techniques. Similarly, HM enhances the understanding of streamflow recurrence intervals. The flow of floodwaters over the terrain is estimated using many alternative methodologies and models. Hydrology is a crucial environmental concept determining a catchment's runoff quantity and the highest discharge point. It is extensively used in many climatic situations, including humid and arid regions. HM has been employed for over 175 years for many reasons. In rural to urban transitions, land alterations often lead to heightened erosion, higher rainfall volume, and elevated discharges within a watershed, with surface soil influencing journey duration.

Almost all modeling has been developed for use in humid regions. Rain Runoff modeling encompasses a wide range of applications and methodologies. This is divided into two main categories: I) Flood management encompasses the organization and design of alternative hydraulic structures, the operation and evaluation of existing hydraulic systems, the preparation for and response to flood damage mitigation, and the regulation of floodplain activities; II) Storage assessments involve the basin and reservoir yield analysis, as well as the evaluation of water resource possibility. The hydrology system is categorized into three primary classes based on spatial decision: Lumped, Semi-Distributed, and Distributed. These models simulate runoff within the catchment boundaries and are linked with changes in land use simulations to predict runoff. It is categorized into two primary classifications: A) model framework, empirical approach, conceptual method, and physical modeling. B) Processing specialized resolutions, such as a) Lumped Modeling, b) Semi-Distributed Modeling, and c) Distributed Modeling. The use of hydrological models and the scope of these models include surfaces, urban hydrology, and subsurface. The availability of data and reliability determine the efficacy of any HM. The HM is categorized according to the classifications in Fig. 1.

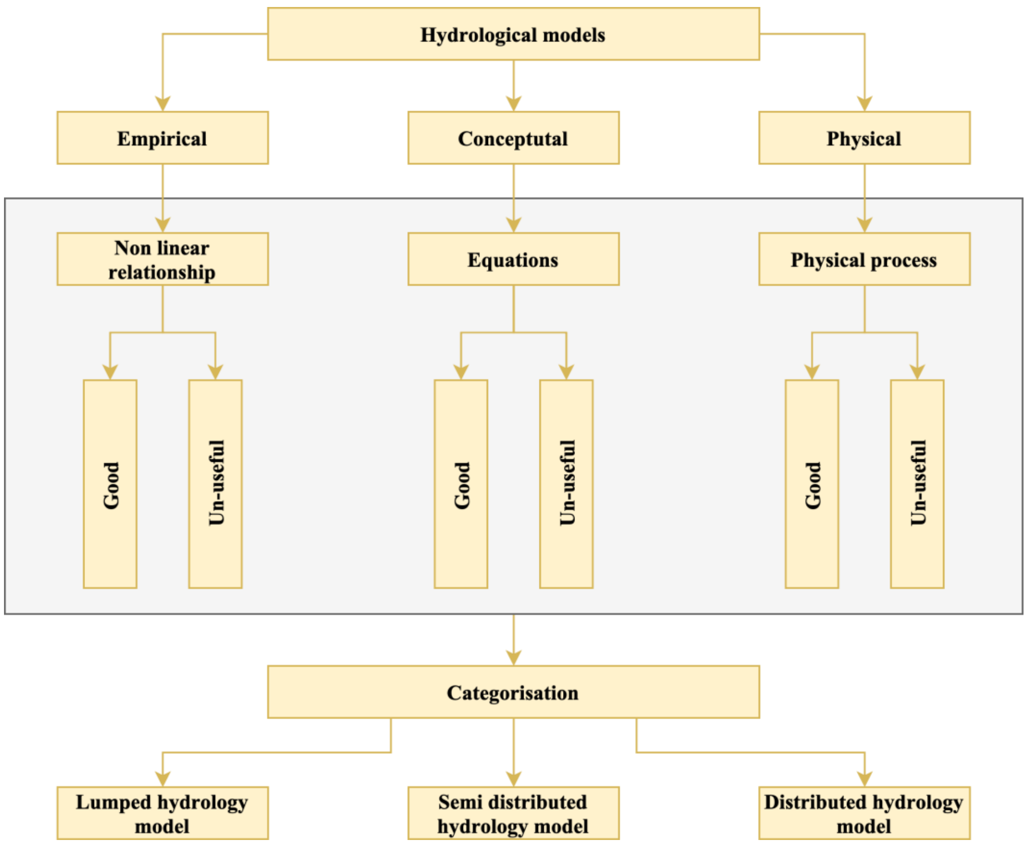

Figure 1: Hydrology Model

III. Results

The Digital Elevation Model (DEM) generated in this research, with a distance resolution of 35 meters, was utilized to partition the examined watersheds into 35k grid squares, which were further categorized into 720 river units and 34k hill gradient units. A three-order river system was generated using the approach and the Strahler River sorting technique, depending on the DEM. The river system was subdivided into 15 virtual segments using eight virtual connections. In the Liuxihe approach, the simulated river cross-section was presumed to be rectangular, and the river dimensions were assessed using RS satellite imagery (Fig. 2).

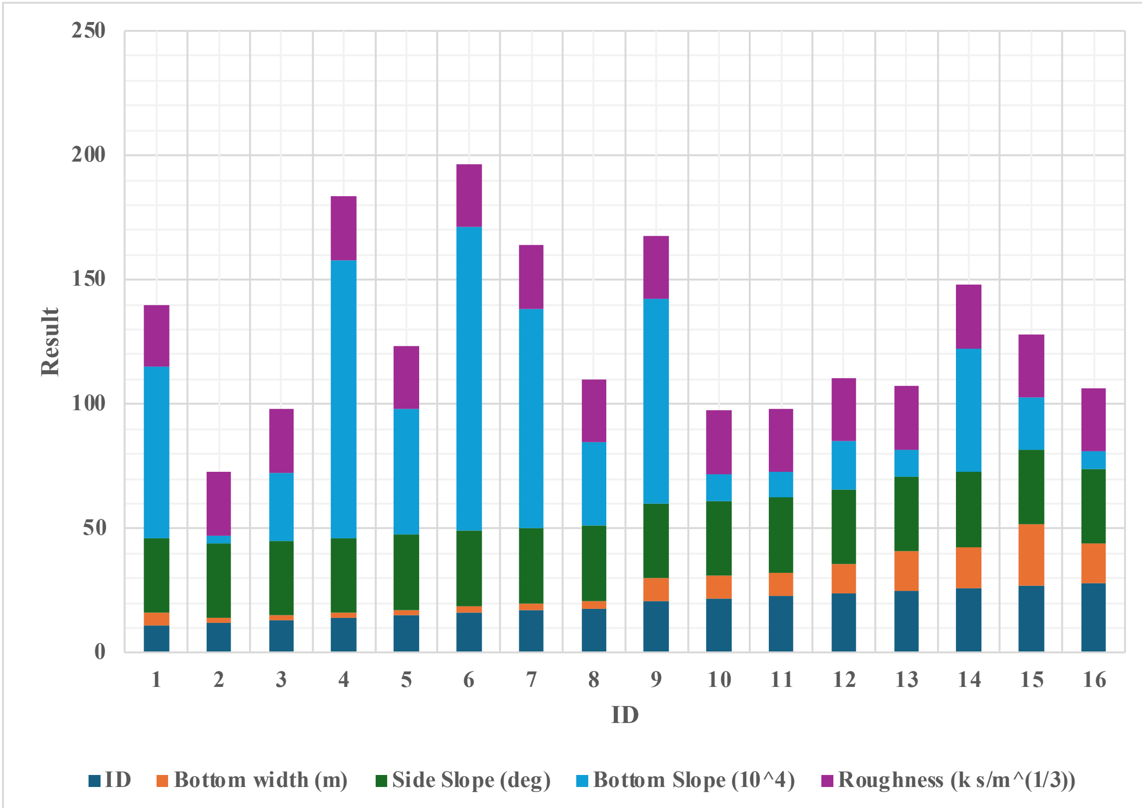

Figure 2: Cross-Section Size Analysis

In grid cells, including urban areas, the ground is impermeable, preventing infiltration and transforming all rainfall into runoff from the ground. The soil characteristics of metropolitan areas must align with their hydrological reaction. This minimal number indicates that most precipitation on urban land will transform into surface runoff. At the same time, a small portion will penetrate or be retained on the surface of populated land cells. The runoff ratios for the modeled flood operations of the three flood occurrences are 0.71, 0.74, and 0.79. The readings range from 0.5 to 0.75; hence, the hydrographs effectively correspond to rainfall, and the predicted hydrological events are deemed realistic. The model settings are satisfactory and suitable for predicting floods in the basin.

IV. Conclusion

HM evaluates many hydrological issues, including runoff quantity, surface runoff, and base and channel flow for both gauged and ungauged streams under diverse climatic conditions. Arid areas need more professionals to overcome challenges in HM. Experts should evaluate novel methodologies for determining geographical rainfall and infiltration from transient streams resulting from flash floods. RS data replicates events in arid regions rather than verifying the specifics. Observation data is gathered from outside sources and juxtaposed with HM outcomes. This research determined that extensive use of hydrology in dry, semi-arid, and humid regions can forecast runoff, flood peak periods, and inundated zones using grouped, semi-distributed, and dispersed models, indicating that every piece of information for the watershed is treated as a singular component. Thus, formulating a projection and assessing runoff is advisable for clarity. This study determined that using HM improves the comprehension of subsurface and surface-water administration for sustainability among water resource society urban planners and civil engineers.

Flood risk and its reduction represent specific uses of these models. This research recommends investigating the responsiveness of flood prevention in increasingly populous cities across various settings, using an HM for this procedure. HM is essential for handling water and forecasting the future of a catchment area. Two HM ought to be used in ungauged streams for enhanced accuracy. This analysis promotes using high-resolution RS DEM to model runoff, particularly in flat terrain.

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