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Research Article

Flood Resilient Smart Cities - Software Based Urban Flood Risk Assessment Techniques: A Critical Review

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Abstract: Flooding is a critical global challenge that poses significant threats to urban areas, impacting lives, infrastructure, and economies. This study provides a comprehensive review of various software applications used in flood risk assessment, including Geographic Information Systems (GIS), remote sensing technologies, and hydrological modeling tools. Particular emphasis is placed on the integration of GIS and remote sensing technologies for flood risk assessment in smart cities and developing countries. By analyzing historical precipitation data, land-use patterns, and topographic information, the study highlights the advantages of combining multiple software solutions to enhance predictive accuracy and support effective flood response strategies. The findings underscore the need for advanced, integrated approaches to improve resilience and adaptability in urban planning. This research aims to guide government authorities in developing robust, flood-resilient urban environments capable of mitigating future risks.

Keywords: Flood Risk Assessment, GIS, Remote Sensing, Hydrological Modeling.

I. INTRODUCTION

Flooding has emerged as one of the most pressing natural disasters globally, particularly impacting urban areas where infrastructure is vulnerable. According to the United Nations Office for Disaster Risk Reduction (UNDRR), natural disasters account for approximately 40% of all socioeconomic losses worldwide, with floods being among the most destructive. The increasing frequency and intensity of flooding events are attributed to climate change and urbanization, necessitating improved flood risk assessment methodologies.

This research investigates the integration of various software tools for effective flood risk assessment. The significance of this study lies in its potential to enhance decision-making processes for urban planners and policymakers by providing a comprehensive understanding of flood dynamics. Specifically, this paper focuses on cities like Islamabad and Rawalpindi, where rapid urbanization has exacerbated flood risks. The rationale behind this research stems from the need to develop an integrated framework that combines multiple software applications to analyze flood risks comprehensively. By leveraging Geographic Information Systems (GIS), remote sensing technologies, and hydrological modeling tools, this study aims to identify high-risk zones and optimize flood response strategies.

II. SIGNIFICANCE OF FLOOD RISK ASSESSMENT

Floods are challenging to control, but their impact can be mitigated through effective strategies and tools. Flood risks arise from a combination of human vulnerability [1] and physical exposures, and addressing these requires a thorough understanding of modelling approaches and the use of advanced tools. Accurate flood prediction, readiness, prevention, mitigation, and damage assessment can significantly reduce losses and hazards. Various software tools have been developed to analyze and manage flood risks, each with its unique applications, advantages, and limitations. By integrating these remote sensing techniques the flood risk assessment can be done for promotion of smart cities in developing countries. The movement, distribution, and behavior of water within a catchment region are simulated and analyzed using hydrological models for flood risk assessment. By forecasting water flow, levels, and possible inundation areas under various scenarios—such as intense rainfall, snowmelt, or dam breaches [2] these models assist in evaluating flood hazards. Planning, making decisions, and creating flood mitigation plans all depend on them. Here's a summary:

2.1. Empirical Models:

Rather of being rooted in the physical processes that drive hydrology, empirical models—also referred to as "black box" models— rely only on observed data and statistical relationships. Without exploring the mechanisms that link inputs like rainfall and outputs like streamflow, these models are made to show correlations between the two. The Rational Method, which uses a straight forward formula that links rainfall intensity, area, and a runoff coefficient to estimate peak discharge from a watershed, is a typical example. The USDA's Curve Number (CN) method [3] which forecasts runoff based on rainfall, soil type, and land use, is another popular empirical technique. Despite their simplicity and ease of use, these models can only be applied to the particular circumstances for which they were created.

2.2. Conceptual Models:

A compromise between empirical and physically based models is offered by conceptual models. Soil moisture, groundwater, and surface water are examples of conceptual storage compartments that they use to simplify hydrological processes. Water movement between these compartments is represented by mathematical equations in these models, which must be calibrated using observed data to guarantee correctness. The NAM model, which is frequently used for rainfall-runoff simulations, and the Sacramento Soil Moisture Accounting Model (SAC-SMA) [5], which models soil moisture dynamics and runoff generation, are two examples. Conceptual models are appropriate for long-term water balance research and regional flood risk assessments because they blend usability and complexity. However, their accuracy may decline in areas with little hydrological data, and they need enough data for calibration and validation, and their accuracy may decrease in regions with limited hydrological data.

2.3. Physical-Based Models:

The most realistic and precise kind of hydrological models are those that are physically based. They use mathematical representations based on basic concepts like mass conservation, momentum conservation, and energy balance to mimic the real physical processes controlling water movement. A large amount of input data is needed for these models, including specifics on topography, soil characteristics, land use, and climate. Physically based models include the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), which represents different parts of the hydrological cycle; the Soil and Water Assessment Tool (SWAT), [6] which models the effects of land management practices on hydrology; and MIKE SHE, a fully integrated model that includes evapotranspiration, surface water, and groundwater processes. Despite the great accuracy and adaptability of these models, their complexity demands a great deal of computing power and knowledge, making them best suited for large-scale flood risk studies and detailed analyses of land-use or climate change impacts.

2.4. Data Driven Models:

Data-driven models use statistical methods, machine learning, or artificial intelligence to examine and forecast hydrological behavior using past data. These models are independent of the physical principles governing hydrology, in contrast to physically based models. To make predictions, they instead look for links and patterns in the data. Examples include Random Forest algorithms, which employ numerous decision trees to increase prediction accuracy, and Artificial Neural Networks (ANN), which are capable of modeling intricate nonlinear interactions. For applications involving massive datasets and real-time flood forecasts, these models are especially helpful. They may, however, perform badly in situations with sparse or inconsistent datasets and necessitate a large amount of historical data for training and validation [7].

III. SPATIAL DIMENSIONS AND SIMULATION INTERACTIONS

3.1. 1D Models:

1D hydrological models are computational tools that simulate the movement of water predominantly along a single spatial dimension, usually a river's or channel's longitudinal axis, with minimal change assumed in the lateral and vertical directions. In order to capture the dynamic interactions between flow velocity, water depth, and channel geometry, these models solve the SaintVenant equations [8] or their simplified versions, such as the kinematic or diffusive wave approximations. In order to calculate hydraulic parameters such as discharge, stage, and velocity at certain points along the channel, 1D models integrate spatial and temporal dimensions by describing flow through discrete cross-sections. 1D models are limited in their ability to represent complex flow interactions, such as lateral inundation or eddy formation, which frequently require coupling with 2D models to resolve floodplain dynamics and improve spatial accuracy, even though they are effective at modeling linear systems with well-defined channels, like rivers or engineered conduits. [9].

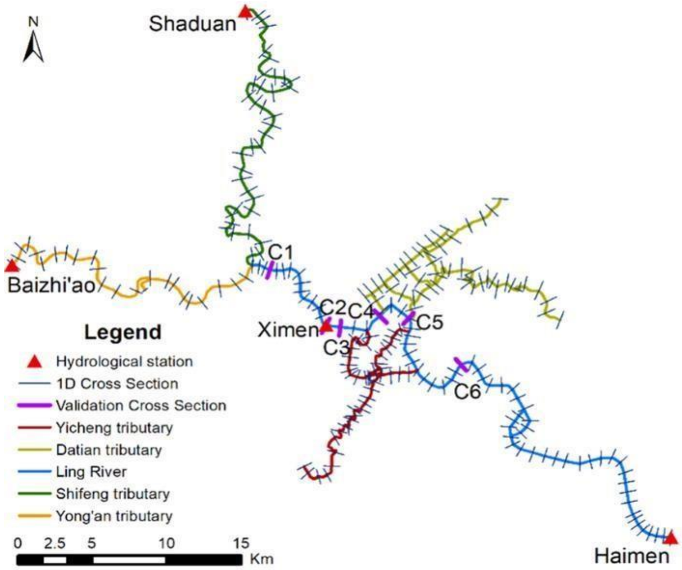

Figure 1 Schematic diagram of 1D river network generalization model. [10]

3.2. 2D MODELS.

2D hydrological models simulate water flow across a horizontal plane, accounting for variations in both the longitudinal and lateral directions. These models compute parameters such as water depth and velocity over a computational grid or mesh using depth averaged shallow water equations, which are derived from the Navier-Stokes equations. This makes them especially useful for modeling floodplain dynamics and surface water processes because it enables them to represent intricate spatial interactions including overland flow, floodplain inundation, and flow divergence or convergence. A thorough depiction of flow pathways and inundation patterns is made possible by the discretization of the domain into cells, which allows 2D models to replicate water movement and exchange between neighboring cells. Even though 2D models require more computing power than 1D models, they are frequently employed for urban drainage studies and flood mapping because they balance computational efficiency and geographic precision. [11] Babaeva, N. Y., & Naidis, G. V. (1996) [12]. Two-dimensional modelling of positive streamer dynamics in non-uniform electric fields in air. Journal of Physics D: Applied Physics, 29(9), 2423. [13]

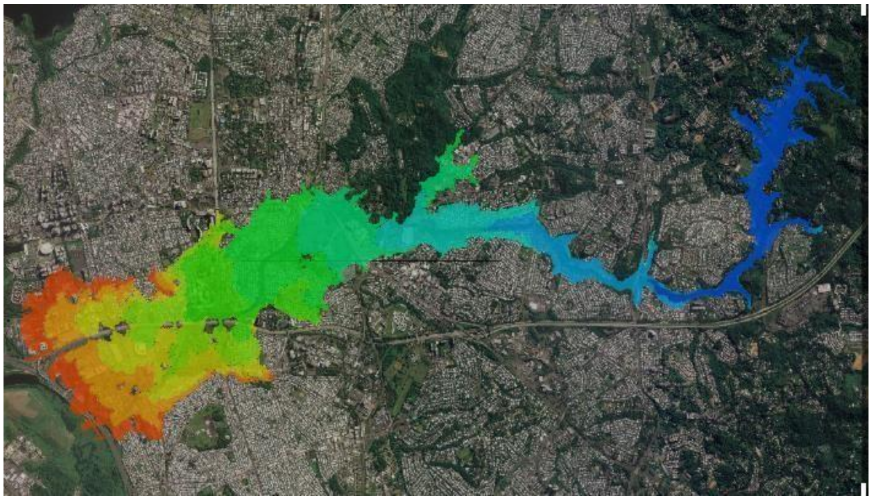

Figure 2 2D Flood mapping using LIDAR DEM [14]

3.3. 3D MODELS:

An object or environment represented digitally in three spatial dimensions—width, height, and depth—is called a 3D model. In order to replicate the dimensions and interactions of real-world objects, these models are built utilizing vertices, edges, and surfaces. 3D models may display realistic visual characteristics like color, material, and light reflection by using textural mapping and rendering techniques. They are fundamental components of many simulations that let people explore and engage with virtual environments. 3D modeling is an essential tool in domains such as architecture, gaming, and scientific visualization because these interactions—which are frequently augmented by physics-based dynamics—offer insights into spatial linkages and behaviors**.** [15]

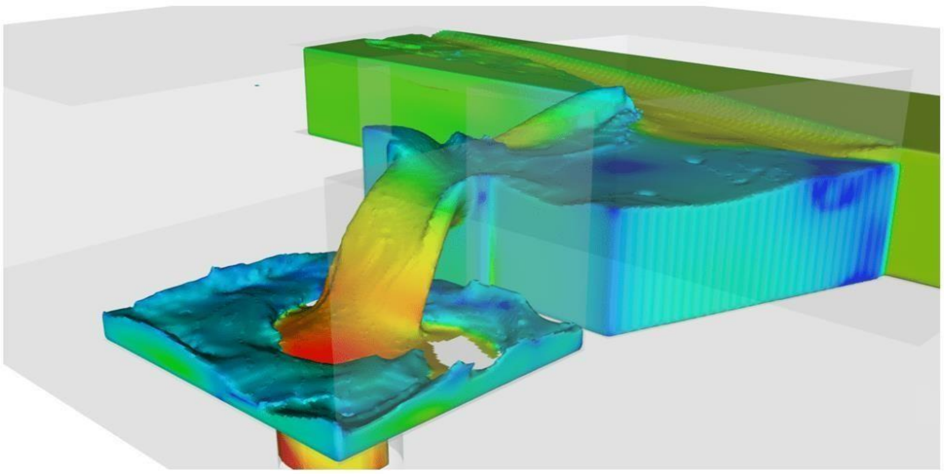

Figure 3 3D Hydrodynamic modelling [16]

IV. SOFTWARE TOOLS FOR FLOOD RISK ASSESSMENT

HEC-RAS and HEC-HMS are among the most widely used tools. HEC-RAS specializes in hydraulic modeling, while HEC-HMS focuses on hydrologic simulations, including rainfall-runoff processes. Both tools integrate seamlessly, enabling comprehensive flood risk analysis. However, their accuracy depends on the quality of input data, including meteorological and topographic information. MIKE FLOOD and TUFLOW are advanced tools for detailed 2D and coupled modeling. MIKE FLOOD excels in simulating urban and riverine flooding, leveraging its ability to integrate various data sources. TUFLOW, known for its precision in urban flood scenarios, provides high-resolution results but requires significant expertise and computational power. ISIS FREE is a user-friendly tool for river and urban flood simulations, offering essential features for flood risk analysis. However, its capabilities are limited compared to premium versions, making it less suitable for large-scale or complex scenarios. SOBEK offers comprehensive water management and flood forecasting capabilities, particularly for river and estuary systems, but its high data and computational demands can be a limitation. GIS tools and Google Earth Engine enhance flood risk assessment by providing spatial analysis and visualization capabilities. GIS integrates hydrological and topographical data to identify flood-prone areas and create risk maps. Google Earth Engine facilitates cloud-based processing of large datasets, enabling global-scale flood analysis.
These tools rely heavily on the availability and accuracy of Digital Elevation Models **(**DEMs**)** and satellite imagery. [17]

By leveraging these software tools and addressing their limitations, practitioners can develop robust flood models that enhance preparedness and support effective mitigation strategies. Combining the strengths of 1D, 2D, and 3D modeling approaches ensures a comprehensive understanding of flood risks, aiding decisionmakers in reducing vulnerabilities and safeguarding communities. Several tools and software are used for flood modeling and risk assessment as shown in Table 1. HEC-RAS and HEC-HMS are reliable for river hydraulics and hydrologic modeling but require U.S. Army Corps authorization. TUFLOW and MIKE FLOOD offer detailed 1D/2D flood modeling, ideal for urban and complex flood systems but demand high computational resources. ISIS FREE is user-friendly for basic simulations, while SOBEK excels in comprehensive water management with high data demands. GIS Tools provide spatial risk mapping but rely on DEM quality, and Google Earth Engine enables large-scale flood visualization with internet-based processing.

Table 1 Software Tools for Flood Risk Assessment [18]

Tool/Software	**Application**	**Advantages**	**Limitations**	**Proposed Method/Focus**	**References**
HEC-RAS	Accurate for high-quality simulation of river hydraulic modeling	Steady/unsteady flows, topographic data, sediment transport dynamics	U.S. Army ID required	Floodplain hydraulic modeling	U.S. Army Corps of Engineers
HEC-HMS	Hydrologic modeling (rainfall-runoff processes)	Seamlessly integrates with HEC-RAS	Accuracy depends on meteorological data	Rainfall-runoff modeling	U.S. Army Corps of Engineers
TUFLOW	1D/2D modeling for flooding	High precision in urban flood modeling, demands computational resources and expertise	Requires substantial data	Urban flood analysis and mapping	BMT Group
MIKE FLOOD	2D and integrated urban/riverine flood modeling	Ideal for complex flood modeling, hardware, and expert knowledge	Limited to hardware requirements	Coupled surface and riverine flooding	DHI Group
ISIS FREE	River and urban flood simulations	User-friendly and cost-effective	Limited capabilities compared to premium versions	River flow and flood forecasting	Innovyze
SOBEK	Comprehensive water management and flood systems	Detailed analysis for river and estuary systems	High computational and data demands	Integrated water system modeling	Deltares
GIS Tools	Spatial analysis and flood risk mapping	Integrates hydrological and topographical data for risk assessment	Quality depends on DEMs resolution	Spatial risk assessment, open-source	ESRI and Mapping Tools
Google Earth Engine	Cloud-based scale flood analysis visualization	Handles large datasets and enables advanced visualization with coding	Requires internet and familiarity	Large-scale hydrological analysis	Google

V. DISCUSSION

In order to manage urban flooding issues, especially in developing nations, the paragraph emphasizes the significance of incorporating cutting-edge technology like hydrological modeling, remote sensing (RS), and geographic information systems (GIS). It places a strong emphasis on combining these methods to examine intricate information, including topography, land-use patterns, and historical precipitation, in order to accurately assess the danger of flooding. While RS offers real-time satellite images for tracking flood levels and land changes, GIS allows spatial visualization to identify high-risk zones. Predictive analysis is supported by hydrological modeling, which simulates flood situations to foresee the effects of intense rainfall. In order to optimize the synergy between these technologies and improve prediction accuracy and disaster response planning, the study recommends a multi-software approach.

The results highlight useful applications for urban planning and disaster management, including developing evidence-based policies, implementing early warning systems, and constructing infrastructure that is flood-resilient. The report also highlights the importance of adapting these solutions to the particular difficulties faced by emerging countries, where flood risks are increased by growing urbanization and scarce resources. In the end, combining these technologies helps build smart, resilient cities that can alleviate the effects of flooding, adjust to climate change, and guarantee long-term sustainability and economic stability.

VI. CONCLUSIONS

In conclusion, this study emphasizes the vital significance of an integrated, multi-software approach, especially in quickly urbanizing areas like Rawalpindi and Islamabad. In order to assess drainage system performance, identify high-risk flood zones, and facilitate well-informed decision-making, the research combines Geographic Information Systems (GIS), remote sensing, and hydrological modeling methods into a complete framework.

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