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Remote Sensing And GIS-Based Hydrological Modelling: A Review Of Application And Challenges.

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Abstract: Hydrological modelling plays a crucial role in understanding the predicting water cycle dynamics, which is essential for effective water resource management. This review paper provides a comprehensive overview of the current state of hydrological modelling, with a focus on geosciences-based approaches, remote sensing application, and GIS integration. We discuss the benefits and challenges of using remote sensing data in hydrological modelling, including the potential for improved parameter estimation and model calibration. The paper also explores the role of GIS in water resource management, highlighting its capabilities in spatial analysis, data integration and visualization. Furthermore, we examine the classification of hydrological models and their applications in various context. Finally, we identify the challenges for hydrological modelling, emphasizing the need for increased integration of geosciences, remote sensing, and GIS to improve model accuracy and predictability.

Keywords: Hydrological modelling, geosciences, remote sensing, GIS, water resource management.

Introduction: Despite the limitations imposed by complex geological features, remote sensing approaches offer valuable insides into groundwater assessment, leveraging the spatial completeness and efficiency of data acquisitions. Satellites remote sensing data, particularly from Landsat and SPOT platform, have demonstrated significant utility in groundwater studies over the past three decades (Hoffmann and Sander 2007). Geographic Information System offer unparalleled spatial data analysis capabilities, rendering them and indispensable tool in multidisciplinary fields like water resource engineering. By facilitating the modelling and analysis of spatially distributed data at varying resolutions, GIS provides a robust framework for addressing complex water resources challenges (Khatami and Khazaei 2014). Remote sensing involves acquiring information about the Earth surface through sensors on board satellites or airborne platforms, capturing images across various spectral ranges including visible, thermal and radar frequencies. While Geographic Information system (GIS) is spatially enabled computer system designed to capture, store, analyse and visualize spatial relationship geospatial data, facilitating the examination of spatial relationship and patterns (Manson et al. 2015). The synergy of remote sensing and GIS has been instrumental and advancing our understanding of natural resources and environmental dynamics, providing critical data- driven insights and methodological framework. The recent proliferation of big data analytics and artificial intelligence has further augmented the research paradigm in remote sensing and GIScience, enabling innovative applications and bolstering the scientific evidence base (Pei et al. 2021). Remote sensing technology offers a distinct advantage in characterizing the spatial heterogeneity of landscape attribute including vegetation density and type, landform morphology, drainage patterns and soil erodibility. The integration of remote sensing data with geographic information system (GIS) provides a comprehensive framework for generating spatially explicit input layers, enabling the prediction of water shade response behaviour and yield. Furthermore, this synergistic approach facilitates the identification of optimal land suitability, soil-crop compatibility, and informed crop planning strategies, ultimately contributing to sustainable land management practices (Nagarajan et al. 2021). The convergence of cutting-edge GIS techniques and methodologies with the analytical capabilities of remote sensing has yielded a robust framework for advancing fundamental and applied research in the geosciences. This integrated approach has demonstrated exceptional utility in unravelling complex earth system processes, elucidating spatial patterns, and informing decisions-making in various fields of geoscientific enquiry (Chamine et al. 2021). This chapter provides a comprehensive review of the application of Geographic Information System (GIS) in hydrological Modelling, highlighting the key concept, and benefits of integrating GIS with hydrological model.

Hydrological modelling and classification: Hydrology a critical component of water resources management, encompasses the study of water distribution, movement and quality on earth, including groundwater system (Heywood et al. 2006). Fares 2008 defined, A hydrological model is a mathematical representation of the complex relationship between a catchment's physical characteristics and its response to hydrological event, such as precipitation and runoff, over a specified timeframe. The foundation of hydrological modelling can be traced back to the 19th century specifically to the pioneering work of Malveux 1850, who introduced the concept of measuring concentration time and developed a logical framework for estimating peak flows, laying the groundwork for modern municipal drainage design and development (Badamasi Hamza 2022).

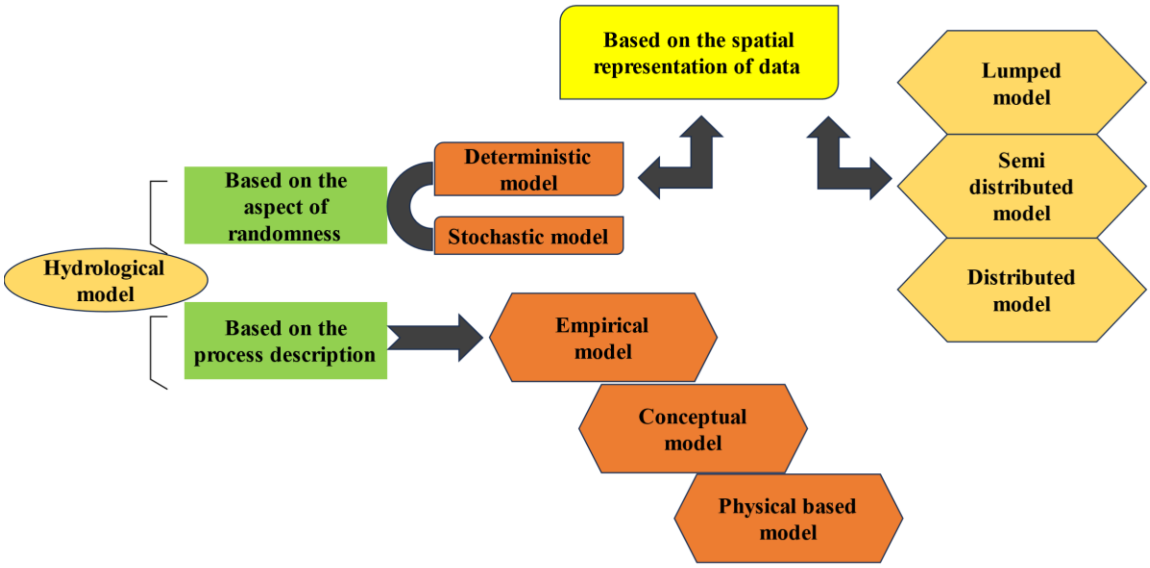

Fig1. Classification of hydrological model (Source:Aparajita Singh 2018)

Hydrological models can categorize based on their treatment of randomness as noted by Singh 2018, into distinct classes that account for the inherent uncertainties and complexities of hydrological system as follows (Fig 1). Hydrological models can be broadly categorised into deterministic and stochastic approaches. Deterministic model yields identical outputs for a given set of input values, neglecting randomness, and are further subdivided into steady and unsteady flow model, as well as Lumped, Semi-distributed, and distributed model, based on spatial representation. In contrast stochastic models produce variable output for a single set of input value, incorporating randomness, and are classified into tome-dependent, time-correlated, space-independent and space-correlated models, enabling predictions rather than forecast.

GIScience-based hydrological Modelling: A significant impediment to the seamless integration of GIS with hydrological modelling is the disparate conceptualization of spatial, temporal, and stochastic processes inherent in these two disciplines, as acknowledged by both GIS practitioners and hydrologist (Sui and Maggio1999). A systematic classification of hydrological model is essential for hydrologist, engineers, and researchers, as it facilitates a comprehensive understanding of the inherent characteristics and features of each model, thereby informing model selection and application decision (Gupta et al. 2015). A highlighted by Singh and Fiorentino 1996 and Gogu et al. 2001, the GIS and hydrological model comprises three primary components: Spatial data creation, Spatial coupling of model layer and the interface between GIS and hydrological model. The integration can be achieved through various software tools, facilitating data exchange files. Two predominant coupling approaches exist: loose coupling which involves manual file exchange between separate GIS and hydrological model modules, and tight coupling where, the GIS serves as a platform for the data processing, analysis and visualization, while the hydrological model operates independently. Integrating GIS into hydrological modeling enables the incorporation of spatial analysis and mapping capabilities, transcending the traditional view of GIS as merely a cartographic tool, and instead, leveraging its functionality to enhance hydrological modelling frameworks, thereby affording system developers greater flexibility in system design. The embedding of hydrological models within GIS platforms has led to the development of specialized tools, where in hydrological modelling functionalities are integrating into commercial GIS software, leveraging built-in GIS capabilities, although often resulting in simplified modelling approaches that require external calibration (Sui and Maggio 1999). Fig 2.

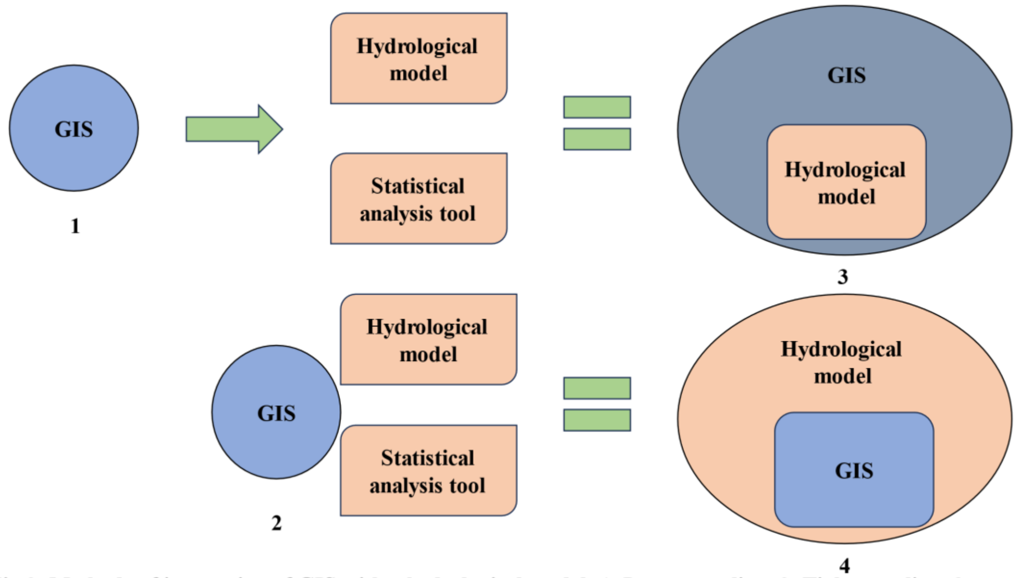

Fig 2. Methods of integration of GIS with a hydrological model: 1. Loose coupling, 2. Tight coupling, 3. Hydrological model embedded in GIS, 4. GIS embedded in hydrological model. (Source: Sui and Maggio 1999)

Use of remote sensing in hydrological modelling and Challenges: Remote sensing technology plays a vital role in hydrologic monitoring, offering three primary benefits. Firstly, remote sensing product serves as essential inputs for hydrologic models, enhancing the accuracy of monitoring process. Secondly remote sensing provides critical basin scale information, facilitating the acquisition and integration of diverse data sets into hydrologic systems. Thirdly, remote sensing enables state estimation and data assimilation, thereby refining model simulation by merging observations and improving the characterization of state variables (Xu et al. 2014). Optical remote sensing, encompassing visible and thermal domains, has limited ground penetrating capabilities, typically restricted to the upper few centimetres of the Earth surface. However, it provides valuable information on stat and flux variable, such as groundwater recharge, sites, water quality, and groundwater system simulation parameters. Specifically, the visible domain offers insights into surface characteristics, while the thermal domain, through land surface temperature measurements, facilitates the detection of thermal anomalies and informs the identification of potential ground water recharge sites and simulation parameters (Thakur et al. 2017). The integration of remote sensing and GIS enables innovative techniques for data collection, management and distribution, while addressing data quality issues and facilitating informed decisions-making through advanced methods of pattern recognition, process simulation, and spatiotemporal predictions (Pei et al. 2021). The application of remote sensing data is hindered by several challenges, including limited spatial and temporal resolution, atmospheric interference, and cloud cover limitations. Additionally detecting small scale features, distinguishing between spectrally similar and land cover types, and addressing sensor inherent limitation pose significant obstacles (Mekonnena et al. 2025). A longstanding scientific conundrum in both hydrology and remote sensing is the optimization of model complexity, particularly given the limited availability of observational data for model validation and calibration. This challenge is exacerbated by the potential non-falsifiability of hydrological and remote sensing model, as noted by Popper 1989, which can lead to flawed assumptions about the dominant processes' importance can introduce significant uncertainty highlighting the need for rigorous model evaluation and validation framework (Wagner et al. 2009).

GIS and water resources management: GIS facilitate the tracking and analysis of drought and flood development, identifying areas vulnerable to extreme rainfall-runoff. The Soil Conservation Service Curve Number (SCS-CN) method, a widely used technique for estimating run off, leverages hydrologic parameters to represent stormwater runoff potential inn drainage areas, influenced by soil type, moisture and land cover. GIS plays a crucial role in spatially distributing these data, enhancing the accuracy of runoff estimate (Al-Ghobari et al. 2020). Floods, characterised by abrupt increases in stream flow, result in inundation of typically dry area due to above normal water level. Integrating GIS with flood modelling enables spatial representation of flood event with varying recurrence intervals. Moreover, the accuracy of input data and the synergistic combination of GIS methodologies with machine learning and statistical approaches critically influence the efficacy of GIS-based flood analysis (Costache et al. 2020). Remote sensing offers high-resolution spatial and temporal Water Quality (WQ) data for numerous surface water location, while ground water quality is assessed through chemical analysis with GIS, researchers can evaluate environmental degradation, potential health risk, and detect harmful algal blooms and disease outbreaks through spatiotemporal analysis of water quality dynamics (Yahya et al. 2023).

Benefits of GIS application in hydrological modelling: In groundwater studies GIS application can be categorised into four primary domains: Hydrological data management and analysis, Hydrological mapping, Vulnerability assessment, and Integration with process-based numerical model. While the first three applications represent a straightforward extension of classical GIS technology in hydrogeology, the fourth involves developing dynamic interaction between Gis and numerical model to support ground water modeling (Gogu et al. 2001). Geographic information system offers unparalleled spatial data analysis capabilities, rendering them and indispensable tool in multidisciplinary field like water resource engineering. By facilitating the modeling and analysis of spatially distributed data at varying resolutions, GIS provides a robust framework for addressing complex water resources challenges (Khatami and Khazaei 2014). GIS provides a robust framework for enhancing spatial data processing, and can be integrated with groundwater models using three primary coupling techniques: loose, tight and embedding coupling (Gogu et al. 2001). Loose coupling involves separate GIS and modelling software package, exchanging data through predefined input and output files. In contrast tight coupling enables bidirectional interaction, allowing GIS tool to access and manipulate model subroutines, while also exporting data to the model (Pathak et al. 2018). Satellite remote sensing, a cost-effective alternative to geophysical survey, has emerged as a prominent technique for data acquisition. However, to ensure the accuracy and reliability of the results, ground truthing is essential for validation. Moreover, the development of robust groundwater model necessitates the integration of high-resolution spatiotemporal data as well as meticulous calibration to guarantee the precision of the model output (Brunner et al. 2007). Geographic information system can be effectively leveraged to support a wide range of organizational functions, including internal management, control, transactions, processing's, operation managements, inventory management, and decision making. Given their versatile functionalities which overlap with those of other types of information system, GIS can readily implement to enhance various applications, thereby fostering improved operational efficiency and informed decision making (Rahmani 2021).

Conclusions: This comprehensive review underscores the significance of hydrological modelling in advancing our understanding of complex hydrological processes. The synergistic integration of GIScience and remote sensing technologies has significantly enhanced the accuracy, spatial explicitness, and predictive capabilities of hydrological model. The benefits of hydrological modelling are encompassing improved water source management, enhanced flood forecasting, and optimised decision-making. However, despite these advances, challenges persist, including data scarcity, uncertainty, scalability issues, and the need for improved model transferability.

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