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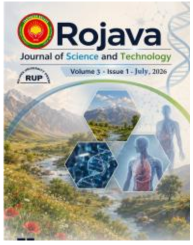

An Integrative Review and Conceptual Framework for Flood Resilience in Brazil: SWAT+GWFlow, Rock Dust, and Socio-Hydrological Governance

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ABSTRACT

Flood risk in Brazil is intensifying under the combined pressures of climate change, land-use transformation, urban expansion, and institutional fragility. Although hydrodynamic flood models, watershed-scale hydrological models, and governance studies have each advanced substantially, they are often examined independently. This study presents an integrative literature review and conceptual framework that links current knowledge on watershed modelling, soil-management interventions, sustainable land management, and socio-hydrological governance, with particular emphasis on the complementary roles of HydroPol2D and SWAT+GWFlow and rock dust soil amendments. The review draws on peer-reviewed literature published between 2000 and 2025 to examine advances in flood modelling, surface–groundwater interactions, agricultural land management, and institutional approaches to flood-risk reduction. The analysis indicates that HydroPol2D is valuable for high-resolution flood inundation and impact assessment, while SWAT+GWFlow provides a stronger representation of long-term watershed processes, including land use, soil-water interactions, and groundwater dynamics. The analysis further suggests that rock dust amendments may improve soil structure, infiltration, and water retention under certain conditions, potentially contributing to runoff attenuation. However, the review does not claim that rock dust has been empirically demonstrated to reduce flood damage at the watershed scale; rather, it identifies this as an important hypothesis for future modelling and field validation. A central contribution of this study is the development of an integrated socio-hydrological governance framework that connects hydrological modelling with adaptive decision-making, emergency planning, land-management strategies, and stakeholder participation. The findings suggest that effective flood resilience in Brazil requires not only improved simulation tools, but also stronger hydrometeorological monitoring, interdisciplinary collaboration, and closer integration between science, policy, and society. The proposed framework advances interdisciplinary understanding of flood resilience by integrating hydrological modelling, sustainable land management, and governance into a unified conceptual approach applicable to climate adaptation and watershed management in Brazil.

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1. Introduction

Flooding has become a persistent and increasingly severe challenge across Brazil, particularly in Rio Grande do Sul, which has emerged as one of the most vulnerable states, and recent extreme events have exposed the fragility of both structural protection systems and emergency response arrangements. In Porto Alegre, the May 2024 floods revealed serious operational weaknesses in the city's existing protection infrastructure. Although pumps and floodgates were designed to reduce inundation risk, their effectiveness depends on proper maintenance, operation, and resilience under extreme conditions. The failure of key system components contributed to a cascading breakdown that significantly intensified flood impacts. Short-lead flood forecasting substantially improves evacuation planning, emergency response, and infrastructure protection. However, forecasting alone cannot reduce disaster risk without adequate monitoring networks, hydrometeorological observations, technical capacity, land-use planning, and institutional coordination. An integrated strategy combining accurate monitoring and rapid forecasting is essential for effective flood management. A recent technical note by Paiva et al. (2024), titled Hydrological Criteria for Adaptation to Climate Change: Extreme Rainfall and Floods in the Southern Region of Brazil, emphasises that large-scale infrastructure projects must be designed to withstand extreme hydrometeorological conditions rather than relying solely on historical return periods. Traditionally, urban drainage infrastructure has been dimensioned according to return periods ranging from 10 to 25 years for micro-drainage systems and 50 to 100 years for macro-drainage systems. However, climate change and the alteration of vegetation cover in urban basins are increasing both the frequency and intensity of flood events, making these assumptions increasingly less reliable under non-stationary climatic conditions. As a result, the concept of tolerable risk in urban drainage planning must therefore be redefined in light of growing climate uncertainty.

Addressing current and future flood risks in Rio Grande do Sul requires more than isolated structural interventions. The 2024 flood disaster demonstrated that even well-established flood-protection infrastructure can be overwhelmed by unprecedented hydrometeorological conditions, exposing weaknesses in drainage systems, dams, and emergency management. Extreme rainfall, rapid runoff generation, and complex watershed interactions highlighted the need for integrated hydrological and hydraulic assessments that consider both catchment-scale processes and urban flood dynamics. While structural measures remain important, their effectiveness during extreme events is inherently limited without complementary non-structural approaches, including land-use planning, early warning systems, risk communication, and coordinated governance. These lessons emphasise the importance of combining advanced hydrological modelling with adaptive watershed management to strengthen long-term flood resilience under a changing climate. Although small reservoirs and related structural measures can help regulate runoff and reduce pollutant transport under moderate conditions, their effectiveness is limited during extreme hydrometeorological events because discharge volumes exceed capacity. Under such circumstances, structural measures alone may offer limited protection. Non-structural approaches, including land-use planning, risk communication, early warning systems, and institutional coordination, often provide more flexible and cost-effective pathways for reducing flood risk. Where structural interventions remain necessary, they must be supported by detailed technical, hydrological, and environmental studies to minimise unintended consequences and improve long-term resilience. In this context, integrated modelling frameworks are essential for linking physical hydrological processes with socio-institutional decision-making. Flood generation is shaped not only by rainfall intensity and hydraulic routing, but also by soil conditions, land use, groundwater behaviour, watershed management, and governance capacity. Accordingly, this study is structured into four analytical components: (1) a comparative assessment of HydroPol2D and SWAT+GWFlow for flood simulation and forecasting; (2) a review of hydrodynamic and coupled hydrological modelling approaches in flood-risk management; (3) an examination of emergency planning, and social participation mechanisms within flood governance systems; and (4) the development of a socio-hydrological governance framework aimed at improving adaptive capacity and resilience in flood-prone regions.

2. Research Gap and Study Contribution

Substantial advances have been made in flood modelling, agricultural soil management, and governance studies. Yet these areas are often addressed as separate research agendas. Urban flood models frequently provide detailed inundation maps but do not adequately represent groundwater behaviour, longer-term watershed responses, or the cumulative effects of land-management change. Conversely, agricultural studies on soil amendments rarely explore implications for flood resilience, runoff generation, or catchment hydrology. Governance studies, meanwhile, often acknowledge environmental uncertainty but do not consistently incorporate hydrological model outputs into institutional decision-making frameworks. This paper addresses that gap by integrating three traditionally separate research domains:

1. hydrodynamic and hydrological modelling for flood analysis;
2. sustainable soil management through rock dust applications; and
3. socio-hydrological governance systems.

The main contribution of this study is the development of an interdisciplinary framework for assessing the potential links between rock dust application, catchment hydrology, and flood resilience. Rather than establishing a direct causal relationship, the paper provides an integrative conceptual review with practical relevance for watershed management and flood resilience planning in Brazil.

3. Methodology

3.1. Review Design

This study adopts an integrative literature review to synthesise current knowledge on flood modelling, sustainable soil management, and socio-hydrological governance. Unlike systematic reviews that primarily evaluate evidence within a narrowly defined research question, an integrative review enables the combination of theoretical, empirical, and methodological studies from multiple disciplines to develop new conceptual understanding. This approach is particularly appropriate because flood resilience is influenced by interacting hydrological, environmental, agricultural, and institutional processes that cannot be adequately examined within a single disciplinary framework. The review therefore seeks to identify conceptual linkages between hydrodynamic flood modelling, watershed-scale hydrological processes, sustainable soil-management practices, and adaptive governance. These relationships are synthesised into an interdisciplinary framework intended to support future research and flood-management planning in Brazil.

3.2. Literature Search Strategy

The literature search was conducted using four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. Publications published between 2000 and 2025 were considered to capture both foundational developments in hydrological modelling and recent advances in integrated watershed management.

Searches combined keywords related to five principal themes:

- hydrodynamic modelling;
- flood forecasting;
- SWAT+GWFlow;
- HydroPol2D;
- rock dust, soil management, and socio-hydrology.

- Representative search strings included combinations such as:
- "HydroPol2D AND flood modelling";
- "SWAT+GWFlow";
- "rock dust AND soil hydrology";
- "flood resilience AND Brazil";
- "socio-hydrology AND governance".

Reference lists of highly cited review papers and recent journal articles were also examined to identify additional relevant studies.

3.3. Study Selection

Studies were included when they:

- were published in peer-reviewed journals or authoritative technical reports;
- addressed flood modelling, watershed hydrology, groundwater interactions, sustainable soil management, or flood governance;
- presented empirical results, numerical modelling, conceptual developments, or methodological innovations relevant to flood resilience.

Studies were excluded when they:

- lacked methodological transparency;
- focused exclusively on engineering applications unrelated to flood management;
- provided insufficient information for evaluating hydrological or governance implications.

3.4. Data Synthesis

The selected literature was analysed using a qualitative thematic synthesis to identify recurring concepts, methodological developments, and knowledge gaps across the fields of hydrological modelling, sustainable land management, and socio-hydrological governance. The review did not follow a formal systematic review protocol (e.g., PRISMA), as its primary objective was conceptual integration rather than quantitative evidence synthesis. Rather than statistically combining results, the review synthesised evidence from multiple disciplines to develop an interdisciplinary framework linking hydrological modelling, rock dust applications, and adaptive governance for flood-resilience planning.

The synthesis was organised into three interconnected themes:

1. hydrodynamic and hydrological modelling for flood analysis;

2. sustainable soil management and the potential hydrological effects of rock dust applications; and

3. socio-hydrological governance and adaptive flood-risk management.

These themes provided the basis for developing the interdisciplinary conceptual framework proposed in this study, which integrates physical watershed processes, land-management practices, numerical modelling, and institutional decision-making into a unified approach for improving flood resilience.

4. Hydrological and Hydrodynamic Modelling for Flood Management

4.1. Fundamentals of Hydrological and Hydrodynamic Modelling

According to Rennó and Soares (2022), hydrological models are mathematical representations of the movement and storage of water and its constituents within the Earth's surface and subsurface systems. These models provide a quantitative framework for simulating watershed processes and understanding the interactions among precipitation, infiltration, evapotranspiration, groundwater recharge, and streamflow across spatial and temporal scales. Hydrodynamic models, by contrast, solve the fundamental equations of fluid flow to simulate flood propagation, water levels, flow velocities, and inundation dynamics under different hydrological conditions. Whereas hydrological models primarily describe rainfall–runoff processes at the catchment scale, hydrodynamic models simulate the movement of floodwaters through river channels and floodplains, making them indispensable for flood forecasting, hazard assessment, infrastructure planning, and emergency management. Hydrological and hydrodynamic processes are closely interconnected with ecological systems and land-management practices because changes in vegetation cover, soil properties, agricultural activities, and groundwater conditions directly influence runoff generation, sediment transport, and river flow dynamics. Consequently, modern flood-risk assessments increasingly adopt integrated modelling approaches that combine physical hydrological processes with environmental and land-use information to better represent watershed behaviour under changing climatic conditions. Environmental hydrodynamic models play a central role in flood-risk assessment and water-resources management by simulating the movement of water, sediments, and dissolved substances throughout river systems. Beyond predicting flood extent and water depth, these models provide valuable insights into three key processes (Rossman, 2001):

- Hydrodynamic circulation, which describes variations in water levels, flow velocities, and current patterns resulting from changes in momentum.

- Water-quality processes, which simulate the transport, dispersion, and transformation of chemical and biological constituents within aquatic environments.

- Sediment transport, which evaluates erosion, transport, deposition, and channel morphodynamics that shape river morphology and floodplain evolution.

Together, these processes provide a comprehensive representation of river-basin dynamics and support integrated assessments of flood hazards, environmental quality, and watershed management.

4.2. Data Requirements for Hydrological and Hydrodynamic Modelling

The reliability of hydrological and hydrodynamic models depends largely on the quality, spatial resolution, and temporal availability of input data. Accurate datasets are essential for model calibration, validation, and the reliable simulation of flood processes across different spatial scales. Although recent advances in remote sensing and geospatial technologies have improved data accessibility, many river basins continue to experience significant data limitations, particularly in developing countries such as Brazil. According to Stokes Oceanography (2023), the modelling process typically involves the following steps:

1. Build a conceptual model of the phenomenon.

2. Gather relevant input data.

3. Define the numerical domain boundaries.

4. Digitize coastlines or use Digital Elevation Models (DEMs) for river basins.

5. Create a numerical grid to discretize the study area for solving the governing conservation equations.

6. Generate bathymetry (riverbed and reservoir depths).

7. Define simulation scenarios and boundary conditions.

8. Configure and execute the model runs.

9. Analyse simulation results.

10. Iterate the process until simulated results closely reproduce observed conditions.

In Brazil, one of the most widely used data sources for hydrological and hydrodynamic modelling is the HidroWeb Portal, operated by the National Water Agency (ANA). It provides access to historical river-flow records, bathymetric information, and other hydrological observations collected through the National Hydrometeorological Network (RHN). These datasets constitute an important foundation for model development, calibration, and operational flood forecasting. However, flow observations alone are insufficient for reliable flood simulations. More comprehensive modelling approaches require additional datasets, including:

- Soil moisture conditions;
- Topographic characteristics (Digital Elevation Models);
- Land-use and land-cover information;
- Temporal and spatial rainfall distribution; and
- Groundwater observations, where available.

The integration of these datasets enables a more realistic representation of watershed processes, although it also increases computational complexity and data requirements. In countries such as the United States, nationwide availability of high-resolution topographic and hydrometeorological datasets has substantially facilitated hydrological modelling. In contrast, Brazil continues to face important monitoring limitations. Smaller rivers frequently lack direct observations within the ANA monitoring network, requiring indirect estimation methods such as regionalisation techniques or area-proportional calculations from neighbouring catchments. Although these approaches provide practical alternatives where observations are unavailable, they may introduce considerable uncertainty during extreme flood events, when local hydrological responses differ substantially from regional averages.

4.3. Sources of Uncertainty in Flood Modelling

Despite significant advances in hydrological and hydrodynamic modelling, the accuracy of flood simulations remains highly dependent on the quality of input data and the representation of key physical processes. Uncertainties associated with topography, river geometry, boundary conditions, and hydrometeorological observations can substantially influence model performance, particularly during extreme flood events when small errors may propagate through the simulation and affect flood-depth and inundation estimates. Getirana et al. (2012) emphasize that open water surface extent is heavily influenced by river geometry and topography. While geometry determines whether a river will overflow, topography defines the shape of the floodplain and therefore the extent of flooding for a given overflow volume. Yet, both parameters are often affected by limitations in available input data, which remain one of the principal sources of uncertainty in hydrodynamic modelling. Errors in Digital Elevation Models (DEMs) remain a major source of uncertainty in modeling the interactions between rivers and floodplains,commonly known as várzeas. Current satellite, derived DEMs often lack the resolution and accuracy needed to represent floodplain elevation profiles with sufficient precision. This poses significant challenges, especially when modeling flood dynamics in flat, low-lying regions, where even small elevation errors can substantially alter predicted inundation extent and flow pathways. To address this limitation, the "floodplain burning" technique, which modifies elevation pixels using river and floodplain map data, has been proposed as a method to better reflect actual terrain features. This gradual adjustment of elevations improves model performance in many cases. However, in extreme flood events, such simplified approaches may fail to capture the full complexity of hydrological behaviour, particularly where floodplain storage, groundwater interactions, and rapidly changing hydraulic conditions occur simultaneously. According to Getirana et al. (2012), the extent of open water surfaces depends closely on both river geometry and topography. While geometry influences whether river overflow will occur, topography determines how floodwaters spread across the floodplain. Unfortunately, limitations in input data, especially elevation data, can undermine the accuracy of such models, particularly in the simulation of overflow and inundation areas. These findings highlight the importance of high-quality topographic information and continuous improvements in remote-sensing technologies to reduce uncertainty in flood-risk assessments.

4.4. Major Hydrodynamic Models for Flood Simulation

Hydrological and hydrodynamic models for flood and water-quality management have become essential tools for supporting flood forecasting, emergency planning, and river-basin management. Different models have been developed to address specific hydrological processes, spatial scales, and management objectives, ranging from rapid urban flood simulations to large-scale watershed analyses. As noted by Gomes Junior et al. (2023), hydrological, hydrodynamic, and pollutant transport models are essential tools for decision-making in flood mitigation and water-quality management. A variety of models exist to quantify hydrodynamic processes across different temporal and spatial scales. At finer scales, such as urban watersheds and rapid-response events, the WCA2D model (Guidolin et al., 2016) applies a cellular automata approach to simulate surface runoff and generate flood maps efficiently. This model offers high computational performance and low memory requirements, enabling large-scale two-dimensional simulations with minimal loss of accuracy, making it particularly suitable for real-time flood forecasting and scenario analysis in urban environments. The WCA2D model can also be integrated with the CADDIES 1D model (Austin et al., 2014), which simulates sewer-network behaviour, resulting in a simplified yet effective approach for urban drainage modelling. However, during large flood events, the impact of micro-drainage systems becomes negligible compared with the overwhelming volume of surface runoff and precipitation. Consequently, additional hydrodynamic processes must be represented to accurately simulate large-scale flood propagation. The HEC-RAS software, developed by the United States Army Corps of Engineers, allows the simulation of two-dimensional flows through the numerical solution of the shallow-water equations. It explicitly represents inertia, pressure gradients, gravitational forces, friction, turbulence, and Coriolis effects. These capabilities have made HEC-RAS one of the most widely adopted hydrodynamic models for floodplain mapping, river engineering, and hydraulic infrastructure assessment. However, the model's major limitation is its high computational cost when high-resolution flood simulations are required. Details of the formulations and numerical schemes implemented in Version 6.1 are presented by Brunner (2016). Recent advances have also introduced artificial intelligence (AI) techniques into flood modelling. Lago et al. (2024) evaluated the performance of the cGAN-Flood model, demonstrating that AI-based approaches can substantially reduce computational time compared with conventional hydrodynamic models. The study reported that cGAN-Flood was approximately 50 times faster than WCA2D and 250 times faster than HEC-RAS, highlighting its potential for rapid flood prediction. Despite these computational advantages, cGAN-Flood presents important limitations. The model cannot predict flow velocities, which are essential for producing reliable flood-risk maps, and it was trained primarily on flood-expansion datasets. Consequently, its applicability remains limited in situations involving varying spatial resolutions or where detailed hydraulic information is required. Furthermore, AI models depend on extensive high-quality observational datasets for training and validation, which remain unavailable in many river basins, particularly within developing countries. Large-scale implementation of AI-based flood models therefore requires extensive hydrometeorological monitoring networks capable of providing reliable observations of watershed behaviour. Without sufficient observational data, physically based hydrodynamic models continue to provide the most robust framework for understanding flood processes and supporting flood-risk management.

4.5. HydroPol2D: Capabilities and Limitations

Gomes Junior et al. (2023) emphasize the potential of the HydroPol2D model, which advances flood modelling by enabling two-dimensional simulations of both flood dynamics and water-quality processes. Unlike conventional hydrodynamic models that focus primarily on flood extent, HydroPol2D integrates hydraulic and environmental processes within a single modelling framework, allowing a more comprehensive assessment of watershed behaviour during flood events. HydroPol2D incorporates key features such as:

- Simulation of floodplain momentum transfer;
- Spatially distributed infiltration and evapotranspiration; and
- Modelling of pollutant transport and fate.

This integrated approach allows for a more comprehensive assessment of watershed hydrological behaviour, especially in scenarios involving both high runoff and contamination risks. By combining flood prediction with water-quality analysis, such models support more effective, cross-disciplinary decision-making for river-basin management and disaster resilience. The ability to simultaneously evaluate hydraulic processes and pollutant transport represents an important advantage for urban flood management, where floodwaters often mobilise contaminants from industrial, agricultural, and residential areas. Given the wide availability of models and numerical solutions, models capable of handling the often-recurring lack of data in large basins could provide a practical solution for flood forecasting. In this sense, De Angelis and Gomes Júnior (2024) found that the HydroPol2D model provides a cost-effective solution for predicting the hydrological–hydraulic behaviour of river basins, particularly for estimating flood maps containing water depths in streets, blocks, neighbourhoods, canals, and, consequently, throughout the entire river basin. Its computational efficiency makes the model particularly attractive for operational flood forecasting, especially where computational resources are limited. Furthermore, recent research uses the HydroPol2D model to assess the risk of human entrapment, generating flood-risk maps at 15-minute intervals that can be used to support emergency decision-making. These high-temporal-resolution simulations provide emergency managers with timely information that can improve evacuation planning, infrastructure protection, and disaster response during rapidly evolving flood events. However, the quality of the model outputs depends strongly on the availability of accurate hydrometeorological observations. Currently, Rio Grande do Sul has approximately 1,700 pluviometric stations, which measure rainfall, and fluviometric stations, which measure river level and discharge. However, only about 25% transmit data in real time. Only in this way can hydrodynamic models be effectively updated, if they do not rely on supplementary information provided by the population through photographs and videos (De Angelis & Gomes Júnior, 2024). This limitation highlights that improvements in monitoring infrastructure are as important as advances in numerical modelling for increasing the reliability of flood forecasts. Despite its considerable advantages, HydroPol2D provides a simplified representation of groundwater dynamics and long-term watershed processes. The model is primarily designed to simulate surface-water dynamics during flood events and therefore does not explicitly represent groundwater recharge, subsurface flow, agricultural drainage, or long-term land-management effects. These limitations justify the integration of HydroPol2D with watershed-scale hydrological models capable of representing coupled surface–groundwater interactions.

4.6. SWAT+GWFlow: Integrating Surface and Groundwater Processes

With ongoing climate change, most experts predict an increase in the frequency and intensity of extreme weather events (IPCC, 2014). These changes are expected to alter watershed hydrology through shifts in precipitation patterns, increased surface runoff, modified groundwater recharge, and changes in soil-moisture dynamics. Consequently, hydrological models capable of representing both surface-water and groundwater processes have become increasingly important for long-term flood-risk assessment and watershed management. Because land use and agricultural management strongly influence watershed hydrology, process-based models capable of representing these interactions have become increasingly important. Le Li et al. (2021) highlight the complex, nonlinear relationships between hydrological processes and environmental change, emphasising the need for modelling approaches that integrate both natural watershed dynamics and human activities. Among the most widely applied process-based models is the Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture (USDA). SWAT simulates the daily dynamics of streamflow, sediment transport, nutrients, and other watershed processes across meso- to macro-scale river basins (Arnold et al., 1998). Its process-based structure enables the assessment of natural hydrological processes together with the impacts of land-use change, agricultural management, and climate variability on watershed behaviour. The SWAT model is particularly valuable for identifying the key hydrological processes affecting sediment and nutrient transport within river basins, especially during dry seasons. Unlike purely hydrodynamic models, SWAT represents long-term watershed behaviour by simulating precipitation, evapotranspiration, infiltration, surface runoff, groundwater recharge, lateral flow, and river discharge within an integrated framework. Key inputs for SWAT modelling include Digital Elevation Models (DEMs), land-use and land-cover data, soil characteristics, and meteorological observations. Although SWAT has been widely applied for watershed management and water-quality assessment, its traditional groundwater component represents aquifer processes using simplified conceptual approaches. This limitation has led to the development of SWAT+GWFlow, which couples SWAT with a physically based groundwater-flow model to improve the representation of groundwater dynamics and surface–groundwater interactions.

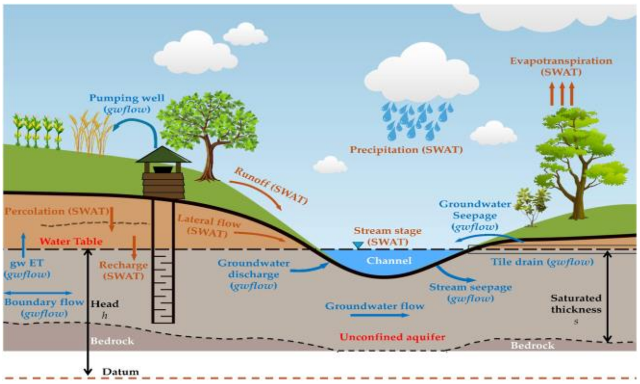

Figure 1: Conceptual representation of the coupled SWAT+GWFlow model illustrating the interactions among precipitation, surface runoff, infiltration, groundwater recharge, lateral flow, evapotranspiration, and groundwater–surface water exchanges within a watershed. The coupled framework enables explicit simulation of surface–groundwater interactions and

agricultural drainage processes, providing a comprehensive representation of watershed hydrology.

As illustrated in Figure 1, SWAT+GWFlow explicitly represents the major hydrological pathways controlling watershed behaviour. Unlike conventional watershed models, the coupled framework simulates groundwater flow and river–aquifer interactions, allowing a more realistic assessment of long-term hydrological responses to land-use change and soil-management practices. SWAT+GWFlow explicitly simulates groundwater recharge, groundwater flow, river–aquifer exchanges, and groundwater storage while maintaining SWAT's ability to represent land-use change, agricultural practices, and watershed hydrology. As a result, the coupled model provides a more comprehensive understanding of how land-management interventions influence streamflow generation, baseflow, and flood responses over long temporal scales. For this reason, SWAT+GWFlow complements rather than replaces hydrodynamic models such as HydroPol2D. Whereas HydroPol2D provides high-resolution simulations of flood propagation and inundation during individual flood events, SWAT+GWFlow evaluates the longer-term hydrological processes that control runoff generation, groundwater behaviour, and watershed response. The integration of these complementary modelling approaches therefore offers a more complete framework for flood-risk assessment, climate-change adaptation, and sustainable watershed management.

4.7. Comparative Assessment of HydroPol2D and SWAT+GWFlow

The review demonstrates that HydroPol2D and SWAT+GWFlow address different but complementary aspects of flood modelling. HydroPol2D is particularly effective for high-resolution simulation of flood propagation, inundation depth, water quality, and emergency-response applications in urban environments. Its computational efficiency also makes it suitable for operational flood forecasting where rapid decision-making is required. In contrast, SWAT+GWFlow provides a watershed-scale representation of hydrological processes by explicitly simulating surface runoff, infiltration, groundwater recharge, subsurface flow, river–aquifer interactions, and the hydrological impacts of land-use change. These capabilities enable the assessment of long-term watershed responses that cannot be represented by event-based hydrodynamic models alone. The complementary strengths of these models form the conceptual foundation of this review. HydroPol2D provides detailed flood-hazard information during individual events, whereas SWAT+GWFlow explains the watershed processes that generate those events and evaluates how changes in land management may influence future flood behaviour. Because these models operate at complementary spatial and temporal scales, they provide different but highly compatible perspectives on flood processes. Their integration therefore offers a more holistic approach to flood-risk assessment by linking short-term flood forecasting with long-term watershed management. This integrated perspective is particularly relevant to the objectives of the present study because it establishes the scientific basis for evaluating how sustainable soil-management practices, including rock dust applications, may influence infiltration, groundwater recharge, runoff generation, and ultimately flood resilience. The following section therefore examines the potential role of rock dust as a nature-based strategy for improving watershed hydrological function and supporting adaptive flood management.

Table 1: Comparison of hydrological and hydrodynamic modelling approaches used in flood-risk assessment.

Model/Approach	**Primary application**	**Main strengths**	**Main limitations**
DEM	Terrain representation	Essential topographic input	Elevation uncertainty in floodplains
WCA2D	Urban flood simulation	Fast and computationally efficient	Limited during extreme flood events
WCA2D + CADDIES	Urban drainage	Surface–sewer interaction	Limited influence during major floods
HEC-RAS	Hydraulic modelling	Accurate physical representation	High computational cost
cGAN-Flood	AI flood prediction	Extremely fast	Cannot simulate velocity; requires extensive training data
HydroPol2D	Flood dynamics and water quality	High-resolution flood simulation; infiltration and pollutant transport	Limited groundwater representation
SWAT+GWFlow	Watershed hydrology	Surface–groundwater interactions; land-use and agricultural processes	Lower spatial detail for urban inundation

Table 1 demonstrates that no single modelling approach adequately represents all processes relevant to flood-risk assessment. Hydrodynamic models such as HydroPol2D provide detailed simulations of flood propagation and inundation dynamics, whereas watershed-scale models such as SWAT+GWFlow better represent groundwater interactions, land-use change, and long-term hydrological responses. Consequently, these models should be regarded as complementary rather than competing approaches, providing the conceptual basis for the integrated socio-hydrological framework proposed in this study.

5. Rock Dust and Sustainable Soil Management

Sustainable land-management practices have gained increasing attention as complementary strategies for reducing flood risk while improving soil health and ecosystem resilience. Although structural flood-control measures remain essential, nature-based solutions are increasingly recognised for their potential to modify watershed hydrological processes by enhancing infiltration, increasing soil-water storage, reducing surface runoff, and improving groundwater recharge. Among these approaches, rock dust application has emerged as a promising soil-management practice because of its potential to improve both agricultural productivity and soil physical properties.

While most research has focused on the agronomic and geochemical benefits of rock dust, relatively little attention has been given to its potential influence on watershed hydrology and flood resilience. This section therefore reviews the current understanding of rock dust applications, their effects on soil hydraulic properties, and their possible contribution to sustainable flood-risk management.

5.1. Rock Dust as a Sustainable Soil Amendment

Rock dust has traditionally been applied as a soil amendment to improve soil fertility, increase nutrient availability, and enhance agricultural productivity. More recently, interest has expanded beyond crop production to include its potential role in carbon sequestration through enhanced rock weathering, making it an increasingly important nature-based solution for climate-change mitigation.

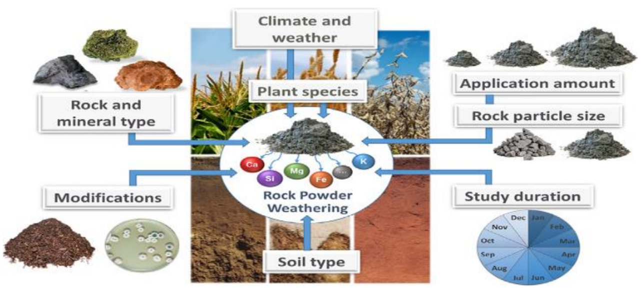

Figure 2: Major factors influencing the effectiveness of rock dust weathering, including mineral composition, climatic conditions, soil characteristics, plant species, application rate, particle size, and treatment duration. These interacting factors determine nutrient release, weathering rates, and potential changes in soil hydraulic properties.

Figure 2 demonstrates that the effectiveness of rock dust depends on multiple interacting environmental and management factors rather than a single controlling variable. Consequently, any assessment of its hydrological influence must consider both soil characteristics and local climatic conditions.

Depending on its mineralogical composition, rock dust gradually releases essential nutrients into the soil while modifying soil structure and influencing physical, chemical, and biological processes. These characteristics have attracted growing attention within sustainable agriculture and environmental management because they may provide long-term improvements in soil function without relying exclusively on conventional chemical fertilisers.

5.2. Hydrological Effects of Rock Dust

Although rock dust has primarily been investigated for its agronomic benefits, its influence on soil hydraulic properties may also have important implications for watershed hydrology. Improvements in soil aggregation, porosity, and water-holding capacity have the potential to increase infiltration rates, reduce surface runoff, and enhance groundwater recharge under suitable environmental conditions. These hydrological processes are directly relevant to flood generation because they influence the partitioning of rainfall between infiltration and overland flow. Consequently, changes in soil physical properties resulting from rock dust application may alter watershed responses to rainfall events, particularly where agricultural land occupies a substantial proportion of the catchment. However, the magnitude of these effects remains uncertain and depends on multiple factors, including rock type, particle size, application rate, soil characteristics, land management, climate, and rainfall intensity.

5.3. Rock Dust and Flood Resilience

Despite increasing interest in rock dust as a sustainable agricultural practice, its potential contribution to flood resilience remains largely unexplored. Most published studies evaluate crop productivity, soil fertility, carbon sequestration, or enhanced weathering, whereas relatively few examine how rock dust applications may influence runoff generation or catchment-scale flood dynamics. From a hydrological perspective, improvements in infiltration and soil-water storage could contribute to reducing peak runoff during rainfall events. Nevertheless, existing evidence remains insufficient to establish a direct causal relationship between rock dust application and flood mitigation at the watershed scale. Accordingly, rock dust should currently be regarded as a promising hypothesis rather than a demonstrated flood-control measure. Its hydrological effects require further investigation through field experiments and physically based watershed modelling, particularly using integrated frameworks such as SWAT+GWFlow.

5.4. Current Knowledge Gaps

Current evidence demonstrates considerable progress in the fields of flood modelling, sustainable soil management, and enhanced rock weathering. However, these disciplines have largely developed independently, resulting in limited understanding of how land-management interventions influence watershed hydrology and flood resilience simultaneously. Few studies have integrated process-based hydrological models with soil-management scenarios to evaluate the potential impacts of rock dust on runoff generation, groundwater recharge, and flood behaviour. This knowledge gap provides the primary motivation for the interdisciplinary framework proposed in the present study, which combines hydrodynamic modelling, watershed-scale hydrology, sustainable soil management, and socio-hydrological governance into a unified approach for adaptive flood-risk management.

6. An Integrated Socio-Hydrological Framework for Flood Resilience

6.1. Rationale for an Integrated Framework

Flood resilience cannot be achieved through hydrological modelling, engineering infrastructure, or land-management interventions alone. Flood generation results from complex interactions among climatic conditions, watershed characteristics, land use, soil properties, groundwater dynamics, and institutional decision-making. Consequently, effective flood-risk management requires an interdisciplinary framework capable of integrating physical, environmental, and socio-economic processes within a unified decision-support system. Although considerable advances have been made in hydrodynamic flood modelling, watershed hydrology, sustainable soil management, and governance, these disciplines have generally evolved independently. As discussed in the previous sections, hydrodynamic models such as HydroPol2D provide detailed information on flood propagation and inundation dynamics, whereas watershed models such as SWAT+GWFlow represent the long-term hydrological processes controlling runoff generation and groundwater recharge. Similarly, studies on rock dust primarily focus on soil fertility and carbon sequestration, while governance research often examines institutional capacity without explicitly incorporating hydrological model outputs into decision-making. This fragmentation limits the development of comprehensive flood-management strategies. Therefore, this study proposes an integrated socio-hydrological framework that links hydrological modelling, sustainable soil management, and adaptive governance to improve watershed resilience under changing climatic conditions.

6.2. Components of the Proposed Framework

The proposed framework consists of four interconnected components, each representing a critical dimension of flood-risk management. The first component comprises the physical watershed system, including precipitation, topography, land use, soil properties, river networks, groundwater systems, and hydrological processes that control runoff generation and flood propagation. The second component focuses on modelling and simulation. HydroPol2D provides high-resolution simulations of flood inundation, water depth, and hydraulic behaviour during individual flood events, while SWAT+GWFlow represents watershed-scale processes such as infiltration, groundwater recharge, subsurface flow, and the hydrological impacts of land-management practices. The third component addresses sustainable land management, with particular emphasis on rock dust application as a potential nature-based intervention. Although current evidence does not demonstrate a direct causal relationship between rock dust application and flood mitigation, improvements in soil structure, infiltration, and water-holding capacity may influence watershed hydrology and therefore warrant further investigation through integrated modelling approaches. The fourth component represents adaptive governance, including emergency planning, stakeholder participation, early warning systems, institutional coordination, and evidence-based decision-making. This component ensures that scientific knowledge generated through hydrological modelling is translated into practical flood-risk management policies and climate-adaptation strategies.

6.3. Interactions Between Framework Components

The proposed framework recognises that flood resilience emerges from continuous interactions among natural processes, land-management practices, modelling tools, and governance systems. Changes in land use or soil management influence infiltration, evapotranspiration, groundwater recharge, and runoff generation, which subsequently affect flood magnitude and inundation patterns. These hydrological responses can be simulated using SWAT+GWFlow at the watershed scale and translated into detailed flood-hazard maps through HydroPol2D. The resulting model outputs provide scientific evidence that can support emergency planning, infrastructure design, land-use regulation, and community preparedness. At the same time, governance decisions influence future land-management practices and monitoring investments, creating continuous feedback between environmental processes and institutional responses. This socio-hydrological perspective recognises flood management as a dynamic and adaptive process rather than a purely engineering problem. Consequently, flood resilience depends not only on improving model accuracy but also on strengthening monitoring networks, interdisciplinary collaboration, stakeholder engagement, and the integration of science into policy development.

7. Discussion

7.1. Implications of Integrating Hydrological Modelling and Sustainable Land Management

This review demonstrates that flood resilience cannot be achieved through advances in hydrodynamic modelling alone. Although models such as HydroPol2D provide detailed simulations of flood propagation, inundation extent, and water quality, they do not explicitly represent long-term watershed processes, groundwater dynamics, or the cumulative effects of land-management interventions. Conversely, watershed-scale models such as SWAT+GWFlow provide valuable information on infiltration, groundwater recharge, and runoff generation but do not simulate high-resolution flood propagation during individual flood events. These findings suggest that neither modelling approach independently provides a complete representation of flood processes. Instead, their complementary capabilities offer an opportunity to develop integrated modelling frameworks capable of supporting both operational flood forecasting and long-term watershed management. The review further indicates that sustainable land-management practices may play a more important role in flood-risk reduction than has traditionally been recognised. While rock dust has primarily been investigated for improving soil fertility and enhancing carbon sequestration, its potential influence on infiltration, soil-water storage, and runoff generation suggests that it may also contribute indirectly to flood resilience. However, available evidence remains insufficient to establish a direct causal relationship between rock dust application and reductions in flood magnitude or damage. Vê lêkolînê delîlên zanistî yên berfireh pêşkêş kirin derbarê hebûn, cudahiya biyolojîk û feydeyên tenduristiyê yên potansiyel ên cureyên *Lactobacillus* de ku di berhemên şîrî yên gelek bajarên Herêma Cizîrê de hatine dîtin. Di maweyek sê salan de, zêdetirî sed nimûne, ku şîr, mast û penîr di nav wan de bûn, bi awayekî rêkûpêk hatin komkirin û bi rêbazên mîkrobiyolojîk, biyokîmyayî û molekular (PCR) hatin analîzkirin. Ev encam têgihiştina me derbarê bakteriyên probiyotîk ên xwezayî ku di berhemên şîrî yên kevneşopî û pîşesazî de li herêmê hene, bi awayekî berbiçav pêşxist. Her wiha, encamên lêkolînê diyar kirin ku mast çavkaniya herî berdewam û herî dewlemend a cureyên *Lactobacillus* e, di dema ku di penîr û hin nimûneyên taybet ên şîrê de astên van bakteriyan kêm an jî gelek sînordar bûn. Ceribandinên laboratuwarî her wiha nîşan dan ku izolatanên *Lactobacillus* xwedî çalakiya dijî-bakterî ya berbiçav in û dikarin mezinbûna hem bakteriyên patojen ên Gram-erênî (Gram-positive) û hem jî Gram-neerênî (Gram-negative) asteng bikin. Ev taybetmendiyên dijî-mîkrobî bi awayekî hêzdar pêşniyar dikin ku van bakteriyan di zêdekirina parastina pergala berxwedana rûvî (gut immunity), vegerandina hevsengiya mîkrobiyota rûvî û pêşîlêgirtina dagirkirina rûviyan ji aliyê mîkroorganîzmayên zirardar ve rolek girîng heye. Ji ber vê yekê, cureyên *Lactobacillus* yên ku di berhemên şîrî yên herêmê de hatine veqetandin dikarin wekî çavkaniyên probiyotîk ên xwezayî û bi feyde werin nirxandin, û potansiyela wan heye ku di pêşxistina berhemên fonksiyonel û stratejiyên nû yên pêşîlêgirtin û alîkariya dermankirina nexweşiyên têkildar bi pergala helandinê de werin bikaranîn.

7.2. Scientific and Practical Implications

The interdisciplinary framework proposed in this study provides a conceptual basis for integrating hydrological modelling, sustainable soil management, and adaptive governance within a single decision-support framework. By combining HydroPol2D with SWAT+GWFlow, researchers and practitioners can evaluate both the immediate hydraulic consequences of flood events and the long-term hydrological impacts of land-management interventions. From a practical perspective, this integrated approach has important implications for flood-risk management in Brazil. It supports more informed land-use planning, improved emergency preparedness, enhanced watershed management, and stronger coordination between scientific institutions and public authorities. Rather than relying exclusively on structural flood-control measures, decision-makers may benefit from combining engineering solutions with nature-based interventions and adaptive governance strategies. The proposed framework may also assist in prioritising investments in hydrometeorological monitoring, remote sensing, and numerical modelling. Improved observational datasets would enhance model calibration and validation while increasing confidence in flood forecasts and climate-adaptation planning.

7.3. Limitations and Future Research

Several limitations should be acknowledged. First, this study represents an integrative conceptual review rather than an empirical modelling investigation. Consequently, the proposed framework has not yet been validated through field observations or numerical experiments. Second, although the review identifies plausible hydrological mechanisms through which rock dust application may influence flood generation, the available literature does not currently provide sufficient empirical evidence to quantify these effects at the watershed scale. Future research should therefore combine controlled field experiments with integrated hydrological modelling to evaluate how changes in soil hydraulic properties influence runoff generation, groundwater recharge, and flood behaviour under different climatic and land-use conditions. Future studies should also investigate the coupling of HydroPol2D and SWAT+GWFlow within unified modelling workflows, uncertainty analysis, remote-sensing data assimilation, and the application of artificial intelligence to improve flood forecasting while maintaining physically based process representation. Such research would provide stronger scientific evidence for integrating sustainable land-management practices into adaptive flood-risk management.

8. Conclusions

Flood risk in Brazil is increasing as a result of climate change, land-use transformation, and growing pressure on watershed systems. Addressing these challenges requires interdisciplinary approaches that integrate hydrological science, sustainable land management, and adaptive governance rather than relying on isolated engineering or policy solutions. This review has demonstrated the complementary roles of HydroPol2D and SWAT+GWFlow in flood-risk assessment. HydroPol2D provides detailed simulations of flood propagation and inundation dynamics, whereas SWAT+GWFlow represents watershed-scale hydrological processes, including groundwater interactions and land-management effects. Their integration offers a more comprehensive understanding of flood generation and watershed response than either modelling approach can provide independently. The review also identified rock dust as a promising nature-based intervention that may improve soil hydraulic properties and contribute indirectly to flood resilience. However, current evidence remains insufficient to establish a direct causal relationship between rock dust application and flood mitigation. Instead, this study proposes an interdisciplinary conceptual framework through which these potential relationships can be systematically investigated using integrated modelling approaches. The principal contribution of this study is the development of a socio-hydrological framework that links hydrological modelling, sustainable soil management, and adaptive governance into a unified approach for flood-risk management. This framework provides a foundation for future empirical research, supports climate-adaptation planning, and contributes to the development of more resilient watershed-management strategies in Brazil and other regions facing increasing flood risk under changing climatic conditions. Ultimately, strengthening flood resilience under changing climatic conditions will require the integration of physically based hydrological modelling, sustainable land-management practices, and adaptive governance within a unified socio-hydrological framework capable of supporting evidence-based decision-making.

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