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A STUDY OF HYDROPOL2D AND SWAT+GWFLOW MODELS TO IMPROVE FLOOD FORECASTING: A CASE STUDY IN BRAZIL

Um estudo dos modelos HYDROPOL2D e SWAT+GWFLOW para melhorar a previsão de cheias: um estudo de caso no Brasil

Un estudio de los modelos HydroPol2D y SWAT+GWFlow para mejorar el pronóstico de inundaciones: un estudio de caso en Brasil

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ABSTRACT

Limited studies have assessed the effects of land management practices on hydrologic processes and agronomic responses in fully integrated stream-aquifer systems, considering the whole picture: hydrology - agroforestry systems - humans - biodiversity. As climate change intensifies and urban vegetation is increasingly altered, urban basins are experiencing more frequent and severe flood events. Hydrodynamic models are vital for understanding and managing these events, but they often rely on hydrometric station data that can be both scarce and inaccurate, especially during extreme weather. This research focuses on how combining structural strategies with non-structural approaches can improve flood resilience and emergency response planning. The central research question asks: *How does culture influence flood management systems (including hydrodynamic modeling) and drainage-related challenges like waterlogging?* A key outcome of the study is the identification of a Knowledge Management and Social Participation framework as a useful tool for creating an effective flood management plan using the HydroPol2D model. However, the limitations of HydroPol2D, particularly its lack of consideration for agricultural impacts on hydrology, lead to the recommendation of using the SWAT+ model alongside the GWFlow groundwater module to provide a more integrated and robust hydrological evaluation.

RESUMO

Estudos limitados avaliaram os efeitos das práticas de gestão do solo nos processos hidrológicos e nas respostas agronômicas em sistemas integrados de rios e aquíferos, considerando o panorama completo: hidrologia, sistemas agroflorestais, seres humanos e biodiversidade. Com a intensificação das mudanças climáticas e a crescente alteração da vegetação urbana, as bacias hidrográficas urbanas estão sofrendo eventos de inundação mais frequentes e severos. Os modelos hidrodinâmicos são vitais para a compreensão e gestão desses eventos, mas muitas vezes dependem de dados de estações hidrométricas que podem ser escassos e imprecisos, especialmente durante eventos climáticos extremos. Esta pesquisa concentra-se em como a combinação de estratégias estruturais com abordagens não estruturais pode melhorar a resiliência a inundações e o planejamento de resposta a emergências. A questão central da pesquisa é: como a cultura influencia os sistemas de gestão de inundações (incluindo a modelagem hidrodinâmica) e os desafios relacionados à drenagem, como o alagamento? Um resultado fundamental do estudo é a identificação de uma estrutura de Gestão do Conhecimento e Participação Social como uma ferramenta útil para a criação de um plano eficaz de gestão de inundações utilizando o modelo HydroPol2D. No entanto, as limitações do HydroPol2D, particularmente a falta de consideração dos impactos da agricultura na hidrologia, levam à recomendação de usar o modelo SWAT+ juntamente com o módulo de águas subterrâneas GWFlow para fornecer uma avaliação hidrológica mais integrada e robusta.

RESUMEN

Estudios limitados han evaluado los efectos de las prácticas de gestión del suelo en los procesos hidrológicos y las respuestas agronómicas en sistemas de agua y acuíferos totalmente integrados, considerando el panorama completo: hidrología - sistemas agroforestales - humanos - biodiversidad. A medida que el cambio climático se intensifica y la vegetación urbana se altera cada vez más, las cuencas urbanas experimentan inundaciones más frecuentes y severas. Los modelos hidrodinámicos son vitales para comprender y gestionar estos eventos, pero a menudo dependen de datos de estaciones hidrométricas que pueden ser escasos e inexactos, especialmente durante condiciones climáticas extremas. Esta investigación se centra en cómo la combinación de estrategias estructurales con enfoques no estructurales puede mejorar la resiliencia a las inundaciones y la planificación de la respuesta a emergencias. La pregunta central de la investigación es: ¿Cómo influye la cultura en los sistemas de gestión de inundaciones (incluido el modelado hidrodinámico) y los desafíos relacionados con el drenaje, como el anegamiento? Un resultado clave del estudio es la identificación de un marco de Gestión del Conocimiento y Participación Social como una herramienta útil para crear un plan eficaz de gestión de inundaciones utilizando el modelo HydroPol2D. Sin embargo, las limitaciones de HydroPol2D, en particular su falta de consideración de los impactos agrícolas en la hidrología, llevan a la recomendación de utilizar el modelo SWAT+ junto con el módulo de aguas subterráneas GWFlow para proporcionar una evaluación hidrológica más integrada y robusta.

INTRODUCTION

This study aims to demonstrate how the complementary use of the HydroPol2D and SWAT+GWFlow models can enhance flood forecasting accuracy and improve flood impact assessment. In addition, it seeks to highlight the influence of cultural factors on knowledge production and the application of intelligence in flood management. By doing so, it underscores the urgent need for improving communication and collaboration among universities (knowledge producers), government agencies, private entities, and civil society.

Flooding is a persistent and escalating issue across Brazil, particularly in Rio Grande do Sul, which has been identified by climate change models as one of the region's most vulnerable to severe future flood events. In Porto Alegre, recent floods in May 2024 revealed critical failures in the city's protection systems. While the infrastructure, comprised of pumps and floodgates, is designed to mitigate flooding, its effectiveness depends on proper maintenance and operation. In this event, the failure of a single floodgate and the vulnerability of the electrical system, which was not designed to function under inundation conditions, led to a full shutdown of the pumping system. The cascading failure significantly worsened the flooding impacts. These operational shortcomings highlight the need for both robust infrastructure and proactive emergency planning supported by accurate flood forecasting.

Forecasting models with a 1-2-day lead time can provide essential information to anticipate flood impacts and support decision-making. Nonnemacher and Fan (2023) estimate that for every R$1 invested in flood prevention systems, approximately R$40 in potential damage can be avoided in Rio Grande do Sul. To be effective, flood forecasting systems require a dense network of rain gauge stations, skilled monitoring teams, real-time modeling, and reliable outputs. Beyond rainfall forecasts, predictions of water levels, street-level flood depths, and impacts on urban infrastructure are crucial, especially for cities lacking comprehensive protection systems like levees. In such contexts, early warnings and timely evacuation protocols can significantly reduce losses.

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", emphasizes that large-scale infrastructure projects must be able to withstand the most extreme recorded floods, regardless of return period estimates. Traditionally, flood infrastructure is designed based on return periods, 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 obsolete. The concept of "tolerable risk" in urban drainage planning must be redefined under non-stationary climate conditions.

To address current and future flood risks, a comprehensive Urban Macro drainage Project is urgently needed. This would involve hydrological and hydraulic studies of the four main rivers flowing into Lake Guaíba and their influence on six critical pumping stations (EBABs) and dams, including three located in Bento Gonçalves. These studies would provide a foundation for integrated watershed management, guiding both structural and non-structural interventions.

In May 2024, six of the eighteen dams in Rio Grande do Sul were in emergency condition, with one experiencing partial failure. The Taquari-Antas River basin, with its steep topography, rapidly channels runoff during heavy rainfall, particularly in upstream areas, as seen in the May event. According to the Institute of Hydraulic Research (IPH), rainfall totals exceeded 1,000 mm in some locations over two weeks, with some stations recording over 40% of the annual average precipitation in that short period.

While small reservoirs along river courses can help manage runoff and reduce pollutant concentrations affecting water treatment plants, they are not feasible for extreme events like the May 2024 flood due to the sheer volume of water involved. In such cases, structural measures may offer limited mitigation potential. Non-structural strategies, such as policy changes, risk mapping, public awareness, and emergency planning, are often more viable and cost-effective. However, when structural interventions are necessary, they must be based on detailed technical and environmental studies to avoid unintended consequences.

Thus, this work is structured into four chapters:
Comparative Analysis of Hydrodynamic Models. Examines the capabilities and limitations of HydroPol2D and SWAT+GWFlow for flood forecasting.

Literature Review. Provides an overview of the current state of hydrodynamic modeling and its application in flood risk management.

Emergency Planning and Social Participation. Discusses the development of Standard Emergency Plans and the role of collective governance and institutional organization.

Culture-Knowledge-Intelligence (CCI) Model. Proposes a new framework based on the integration of cultural context, knowledge sharing, and intelligence systems to improve flood resilience.

A Comparative Analysis of Hydrodynamic Models

According to Rennó and Suares (2022), a hydrological model is defined as a mathematical representation of the movement of water and its constituents across the Earth's surface and subsurface. These models play a crucial role in simulating the water cycle and understanding how water interacts with various components of the environment.

Hydrodynamic models solve fundamental fluid flow equations to predict flood behavior and water movement under different scenarios. Unlike models limited to laminar flow, hydrodynamic models are designed to simulate turbulent flows, which are typical in large flood events. This makes them essential tools for analyzing and managing high-intensity hydrological phenomena.

There is a strong interconnection between hydrological, biological, and ecological modeling, as water transport affects and is affected by biological processes. For example, the presence or absence of vegetation or microbial activity can significantly alter the quantity of nutrients or sediments transported by water. Similarly, flow regimes influence aquatic habitats and ecosystem structures.

Environmental hydrodynamic models are particularly valuable for planning and managing natural water bodies. They provide insights into three key phenomena (Rossman, 2001):
Hydrodynamic Circulation. Analyzes changes in momentum (mass × velocity), leading to variations in water levels and current patterns.

Water Quality. Tracks the transport of chemical and biological substances that affect water quality parameters.

Sedimentological Processes. Studies the erosion, transport, and deposition cycles of sediments, influencing river morphology and dynamics (morphodynamics).

The primary goal of these models is to simulate the movement and transport of water and its constituents, such as heat, salinity, nutrients, gases, and sediments, across time and space. According to Stokes Oceanography (2023), the modeling process typically involves the following ten steps: **Build a conceptual model of the phenomenon; Gather relevant input data; Define the numerical domain boundaries; Digitize coastlines or use digital elevation models (DEMs) for river basins; Create a numerical grid to discretize the area for solving conservation equations; Generate bathymetry (riverbed and reservoir depths); Define simulation scenarios and boundary conditions; Configure and execute the model runs; and Analyze simulation results**. Iterate the process until results closely align with observed data, then present findings.

In Brazil, one of the most widely used data sources for hydrological and hydrodynamic modeling is the HidroWeb Portal, operated by the National Water Agency (ANA). It provides access to historical series of river flows, bathymetric data, and other key parameters gathered through the National Hydrometeorological Network (RHN). However, flow data alone are insufficient. More comprehensive models require additional information, including **soil moisture conditions, topographic characteristics, land use and land cover data and Temporal and spatial rainfall distribution**. These additional layers significantly increase the complexity of modeling but are essential for accurate flood forecasting.

In countries like the United States, high-resolution data and maps are available nationwide, greatly facilitating model development. In contrast, Brazil still faces limitations. For instance, smaller rivers often lack direct monitoring data in ANA’s network. In such cases, indirect methods like area-proportional calculations from nearby watersheds or rainfall-runoff curve analyses (regionalization techniques) are used to estimate flow rates. However, these methods are unreliable for extreme events, where localized dynamics diverge significantly from averages.

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 can compromise the accuracy of hydrodynamic simulations.

Errors in Digital Elevation Models (DEMs) remain a major source of uncertainty in modeling the interactions between rivers and floodplains, commonly known as Várzea’s. 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.

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 the hydrological behavior.

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.

Hydrological and Hydrodynamic Models for Flood and Water Quality Management

As noted by Gomes Jr. 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 2D simulations with minimal loss in accuracy, particularly valuable for risk analysis involving multiple scenarios

The WCA2D model can also be integrated with the CADDIES 1D model (Austin et al., 2014), which simulates sewer network behavior, resulting in a simplified yet effective approach for urban drainage modeling. However, during large flood events, the impact of micro drainage systems becomes negligible compared to the overwhelming volume of surface runoff and precipitation.

Integrated Modeling Approaches

Gomes Junior et al. (2023) also emphasize the potential of the HydroPol2D model, which advances flood modeling by enabling 2D simulations of both flood dynamics and water quality. HydroPol2D incorporates key features such as: **Simulation of floodplain momentum transfer; Spatially distributed infiltration and evapotranspiration; Modeling of pollutant transport and fate.**

This integrated approach allows for a more comprehensive assessment of watershed hydrological behavior, 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 HEC-RAS software, developed by the United States Corps of Engineers, allows the representation of two-dimensional flows based on the numerical solution of the shallow-water equations. It represents the terms of inertia, pressure gradient and gravitational effects, friction, turbulence, and Coriolis effects (a curve that water and air currents have in different hemispheres). The major difficulty of the HEC-RAS model is its high computational cost for simulating floods at high resolution. Details of the formulations and numerical schemes used in the model (version 6.1.0) can be found in Brunner (2016).

A composite topographic map was produced by merging several databases. In the Amazon River and the open-water areas of the floodplain, the topography estimated by Fassoni-Andrade et al. (2020a) was used at a spatial resolution of 30 m (available at data.mendeley.com/datasets/vn599y9szb/1). This mapping was created by digitizing nautical charts of rivers and using the Flood2Topo method (Fassoni-Andrade et al., 2020) via optical satellite data (Gomes Júnior et al., 2023).

Lago et al. (2024) evaluated the performance of the proposed model against a 3-m resolution River Another disadvantage is that cGAN-Inflood cannot predict velocities, a critical parameter for creating risk maps. Furthermore, cGAN-Flood was only trained on flood expansions. Unfortunately, this limits its application to situations where data resolution varies or in scenarios requiring more detailed flood forecasts. Even so, cGAN-Flood was 50 and 250 times faster than WCA2D and HEC-RAS, respectively. However, cGAN-Flood has limitations, and future research is needed to improve its applicability. The use of artificial intelligence tools that typically lack deep learning about the hydrological behavior of river basins must be done with caution, given the scarcity of large volumes of observed data.

Large-scale application of these techniques requires a scenario with extensive flood monitoring data where it would be possible to train machine learning models with reliable observations of river basin behavior. According to Fassoni-Andrade et al. (2023), in a study to understand the dynamics of the complex hydrological systems of the Amazon and the flooding of riverside communities, the HEC-RAS model uses an unstructured computational grid in which the orientation and size of the cells can vary according to the topography, so that breaks can be included to define the orientation of the faces of the computational cells. The researchers add breaks considering a manual digitization of the topographic contours of the riverbanks. In the floodplain areas, the isolines formed by the 90% and 60% flood frequency thresholds from the flood frequency map prepared by Fassoni-Andrade et al. (2020) were used.

Errors in topographic mapping, downstream boundary conditions, and the lack of representation of hydrological processes in the floodplain, such as local infiltration, precipitation, evaporation, and groundwater flow, can be sources of uncertainty in mapping flood extent using the hydrodynamic model, especially during low-water periods. Some modeling errors may be related to model input and validation data, such as remotely sensed maps of water surface extent, and the lack of representation of hydrological processes, such as **local infiltration, precipitation, evaporation and groundwater flow** (Fassoni-Andrade et al., 2023).

Given the wide availability of models and numerical solutions, models capable of handling the often-recurring lack of data in large basins could be a quick solution for flood forecasting. In this sense, De Angelis and Gomes Jr. (2024) found that the HydroPol2D model can be a low-cost solution for predicting the hydrological-hydraulic behavior of river basins, particularly for estimating flood maps that contain water depths in streets, blocks, neighborhoods, canals, and, consequently, throughout the entire river basin.

Furthermore, recent research uses the HydroPol2D model to assess the risk of human entrapment, generating risk maps every 15 minutes that can be used to aid decision-making. However, the quality of the models' results could be improved with more available data. Currently, Rio Grande do Sul has 1,700 pluviometry stations (which measure rainfall in the river basin) and fluviometric stations (which measure river level and flow), but only 25% transmit data in real time. Only in this way can hydrodynamic models be fed, if they do not have data provided by the population itself sent through videos and photos (De Angelis &

Gomes Jr., 2024).

With ongoing climate change, most experts predict an increase in extreme weather events (IPCC, 2014). Due to the impact of agriculture on hydrology, alternative models have emerged, although only a few are designed to predict and control these effects. Le Li et al. (2021) provide new insights into the complex, nonlinear interactions between hydrological processes and environmental change. One widely adopted model is the Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture (USDA). This model can simulate the daily dynamics of sediment and nutrients in watersheds from the mesoscale to the macroscale (Arnold et al., 1998).

The SWAT model is particularly valuable for identifying the key hydrological processes that affect nitrate loads in study areas, especially during dry seasons. Key inputs for SWAT modeling include a digital elevation modErrors in Digital Elevation Models (DEMs) remain a major source of uncertainty in modeling the interactions between rivers and floodplains, commonly known as Várzea's. 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.

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 the hydrological behavior.

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.

Emerging Trends: AI and Visualization Tools

A recent trend in flood modeling is the application of artificial intelligence (AI), especially for rapid predictions where physically based hydrological-hydraulic models are too computationally expensive. Lago et al. (2024) highlight the use of deep learning models (e.g., MAP), which show promising results for small urban catchments (areas under 500 hectares). For larger catchments, however, traditional modeling methods (e.g., 1D hydrodynamic models) are still recommended, despite the higher investment in data collection and model development.

One such model is HydroHP-1D, which, as described by Gomes Jr. et al. (2023), supports both steady-state and transient flow simulations in one-dimensional channels. Its outputs can be visualized through animations, videos, and GIFs, resources increasingly used to communicate risks and raise public awareness. An online repository of these visualizations is available in Gomes Jr. (2024).

The visual communication of risk through media such as maps, videos, and animations is becoming a key strategy for public engagement. One innovative example includes the development of "serious games", which allow users, particularly those in at-risk areas, to interactively experience the impacts of hazardous events. In a notable case, Gomes Jr. (2024) created a serious game simulating dam failure scenario, enabling users to understand the height, force, and speed of incoming floodwaters. The tool has been applied to 21 dams, including the Brumadinho and 14 de Julho Dam.

Integrated Modeling Approaches

Gomes Jr. et al. (2023) also emphasize the potential of the HydroPol2D model, which advances flood modeling by enabling 2D simulations of both flood dynamics and water quality. HydroPol2D incorporates key features such as: **Simulation of floodplain momentum transfer; Spatially distributed infiltration and evapotranspiration; Modeling of pollutant transport and fate**

This integrated approach allows for a more comprehensive assessment of watershed hydrological behavior, 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.el (DEM), land use maps, soil maps, daily meteorological data, water quality data, and agricultural management practices.

The DEM used (ASMAT V2, 30 m resolution) was sourced from the USGS website (http://www.usgs.gov) to delineate the watersheds (Le Li et al., 2021). Yimer et al. (2023) found that agricultural drainage systems are essential for removing excess groundwater and ensuring sufficient oxygen for crops. However, these drainage systems have environmental and hydrological impacts, particularly by reducing groundwater volume and transporting contaminants downstream. To better understand these impacts, researchers turned to advanced modeling tools such as the SWAT+ model with the integrated groundwater module (GWFlow).

Agricultural drainage can significantly deplete groundwater levels, adversely affecting hydrological processes. Developing models with and without these drainage features provides valuable insights into their effects on geohydrology. Future research should prioritize measuring drainage flows and calibrating geohydrological models to better understand groundwater and drainage dynamics. Such efforts can reduce uncertainties in predicting dry-season streamflow and other components of the water balance. Quantifying drainage water is essential to assessing its environmental impact.

The coupled SWAT+ GWFlow model proved more suitable than the stand-alone SWAT+ model for these case studies (Arnold, 1998). Bailey et al. (2023) also developed an advanced GWFlow module that is physically based and spatially integrated with SWAT+. This coupled model simulates surface and subsurface water flow at catchment scales and explicitly incorporates agricultural drainage into the model structure. The GWFlow module also allows model calibration and validation using observed groundwater margin data and groundwater discharge time series, increasing its reliability for hydrological studies (https://www.dov.vlaanderen.be/) (Table 1).

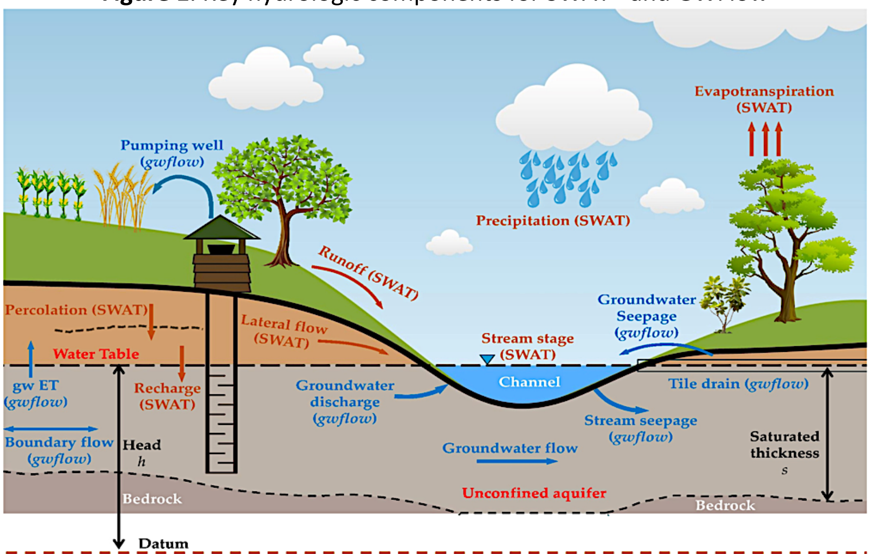
Table 1. Summarizes an evaluation of the hydrodynamic models studied in this work

Hydrodynamic Models	Evaluation Model
Digital Elevation Models - DEM	Are not suitable for providing accurate elevation profiles of floodplains in addition to problems with the required input data
WCA2D model integrated to 1D CADDIES model	in large flood events, the effect of micro drainage is reduced in relation to the large volumes of precipitation and runoff generated
HEC-RAS	The model's greatest difficulty is its high computational cost for simulating floods in high resolution
cGAN-flood	Despite its advantages over the above models, it can underestimate the total flood volume to be distributed (vt). Another disadvantage is that it cannot predict velocities, a critical parameter for creating risk maps. It also limits its application in situations where data resolution varies or in scenarios that require more detailed flood forecasts
HydroPol2D model	It allows for a more integrated analysis of the hydrological behavior of river basins that contribute to river runoff, but it does not consider agricultural data such as the amount of water the soil can retain
the Soil and Water Assessment (SWAT)+ model with the integrated groundwater module (GWFlow)	This coupled model simulates surface and groundwater flow at the watershed scale and explicitly incorporates agricultural drainage into its structure. The GWFlow module also allows for calibration and validation of the model using observed groundwater margin data and groundwater flow time series, increasing its reliability for hydrological studies

SWAT+ GwFlow allows for a more integrated analysis of the hydrological behavior of river basins that contribute to river runoff. However, it does not consider agricultural data, such as the amount of water the soil can retain. This coupled model simulates surface and groundwater flow at the river basin scale and explicitly incorporates agricultural drainage into its structure. The GWFlow module also allows model calibration and validation using observed groundwater margin data and groundwater flow time series, increasing its reliability for hydrological studies.

This has an implication for the general hydrological modeling community to pay close attention to drained water as it affects the different water balance components and the environment (Yimer et al., 2023). Agricultural water drainage can significantly lower groundwater levels and affect catchment hydrology (Yimer et al., 2023a). In few words, SWAT + GWFlow model is the better representation of surface-groundwater interactions (Figure 1. Predict catchment dynamics and assess the streamflow response).

Figure 1. Key hydrologic components for SWAT+ and GWFlow



Abbas et al. (2025). Orange arrows represent fluxes simulated by SWAT+ while blue arrows indicate those simulated by GWFlow.

Important to notice that the model is calibrated for stream discharge at the catchment outlet, and for both streamflow and groundwater head. The most important conclusions are:

1. The soil surface endures repeated instances of waterlogging; thus, drainage systems are often applied (Oosterbaan, 1994).

2. Parameters such as aquifer hydraulic conductivity, available water capacity, and percolation coefficient are the primary drivers of groundwater boundary flow.

3. After the SWAT+ model was set up for all the catchments, the GWFlow inputs were prepared using a Python script (https://swat.tamu.edu/). This starts with discretizing the catchments into square-sized grid cells.

Rock Dust as a Bio-Dynamic Fertilizer

Carbon is no longer stored solely by trees but is instead absorbed and stored directly by the soil. Therefore, properly managed ground rock intensifies the natural process through what is called accelerated weathering, a process that benefits from Brazil's tropical climate, where there are intense solar radiation and high rainfall. Accelerated weathering, therefore, occurs when this natural process is technologically applied on a controlled and intensified scale to capture carbon. Rather than waiting for minerals such as olivine, basalt, or serpentinite to slowly react with atmospheric CO_2, the technique seeks to increase the contact surface (by crushing rocks), spread them over agricultural soils or coastal areas, and create favorable conditions for the chemical reaction to occur more quickly. This approach is seen as a long-term carbon removal solution, as it transforms CO_2 into stable minerals.

Bauwhede (2024) highlights that the definition of rock dust has evolved over time, with varying interpretations among different authors. At present, the most widely accepted definition refers to rock dust as a fine powder produced from rocks such as basalt, granite, dolerite, and sandstone, which contain essential minerals and trace elements. This material, typically graded below 200 mesh (75 µm), is primarily used to improve soil quality and enhance plant growth. Numerous studies have demonstrated its ability to stimulate microbial activity in the soil, leading to improved plant growth, increased productivity, and better nutrient cycling.

In addition to its primary benefits, rock dust has been shown to increase the cation exchange capacity (Anda et al., 2015) and water-holding capacity of sandy soils (Kahnt et al., 1986). However, some types of rock dust are either inefficient or contain potentially harmful elements in high concentrations. Therefore, the effectiveness of applying ground rock powders to tropical soils depends largely on the chemical and mineralogical composition of the rocks, the soil's specific deficiencies, and the needs of the crops being cultivated (van Straaten, 2017).

One of the main advantages of rock dust compared to chemical fertilizers is its suitability for highly weathered tropical soils, where soluble fertilizers may be costly or scarce (Swoboda, Döring & Hamer, 2022). In their analysis of 48 crop trials, Swoboda, Döring and Hamer (2022) found that rock dust can serve as a viable alternative source of potassium (K) and a multi-nutrient soil amendment for tropical soils, although its effectiveness in temperate climates remains uncertain. The most promising results were seen with basalts and rocks containing nepheline or glauconite. Basalt powder stands out due to its high magnesium (Mg) and iron (Fe) silicates and basic pH, providing essential nutrients like phosphorus (P), potassium (K), calcium (Ca), and micronutrients (Swoboda, Döring & Hamer, 2022).

Viana, Caetano and Pontes (2021) discuss a technique that combines intermediate amounts of basalt powder with larger doses of cattle manure. This combination proved to be the most effective method for improving soil fertility, although various other approaches are also used.

Da Silva et al. (2017) emphasize that pairing rock powders with organic materials can enhance biological activity, influencing the mineral weathering process. However, further research is needed to understand how these materials interact with rock powders, particularly basalt.

Research by Nogueira et al. (2024) indicates that animal grazing plays a crucial role in potassium recycling within ecosystems, with animal excreta contributing significantly to potassium levels in the soil, which is essential for crop nutrition. Nevertheless, Nogueira et al. (2024) note that rock dust is not a viable long-term solution for potassium supply due to its low solubility. However, the addition of organic compounds can stimulate "bio-weathering" processes, enhance the dissolution of rock dust and provide potassium to crops (Machado et al., 2016; Basak et al., 2021).

Composting plays a key role in nitrogen cycling, impacting compost quality (Hoang et al., 2022). Some researchers, however, present findings without adequate testing, such as lab trials or field applications. Ramos et al. (2022) suggest that combining organic fertilizers with rock dust can fulfill both macro and micronutrient needs at a significantly lower cost (<60%) and with long-term soil fertility benefits. For example, corn and beans grown in basalt-enriched soils yielded up to five times more than those without basalt dust (Conceição et al., 2022).

Bauwhede et al. (2024) also report that rock dust can reduce nutrient leaching, providing a slow, sustained nutrient release into the soil. However, nutrient release depends on rock mineralogy, soil acidity, and testing methodologies. Grecco et al. (2016) stress that low processing costs and the need for alternative fertilizers make rock dust a viable option, although the nutrient release rate varies by rock type and weathering conditions.

Dos Santos et al. (2016) explain that rock dust has a slower nutrient release compared to chemical fertilizers. While this slow release can be beneficial in some cases, it may also be a disadvantage, as it requires larger quantities of material and extends the process.

Lopes-Assad et al. (2006) found that the fungus *Aspergillus niger* is effective in solubilizing phosphate rocks, with increased acidity promoting higher potassium solubilization. However, when treating alkaline ultramafic rocks with *Aspergillus niger*, the acidity decreased, reducing potassium solubilization.

To counteract soil acidity, liming with calcium or magnesium carbonates (e.g., calcite and dolomite) is commonly practiced. These minerals neutralize hydrogen ions and mitigate aluminum toxicity in the soil (Goulding, 2016). The application of rock dust must be tailored to the specific crop being grown. For example, lettuce, which has high nutrient demands in a short period, may not benefit from basalt dust due to its low nutrient content.

Hanish et al. (2024) found that applying up to 100g of basalt powder did not significantly increase lettuce yields, with yields from untreated soil being nearly four times smaller than those with soluble fertilizers. Lettuce's short production cycle requires high doses of soluble nutrients, which basalt dust cannot provide.

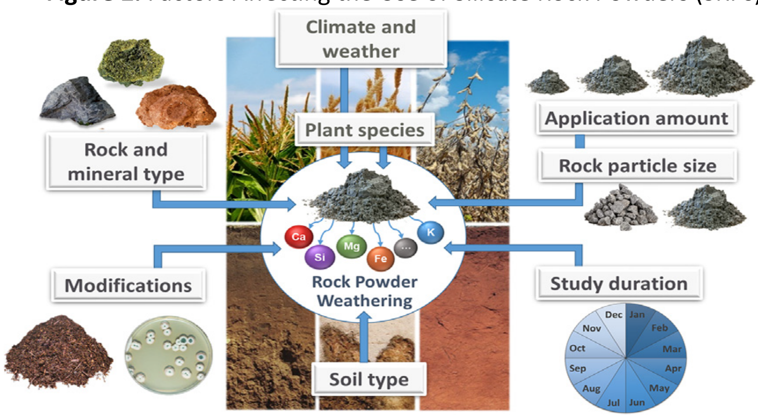
Guimarães et al. (2020) found that banana orchards fertilized with mineral sources produced higher yields than those using organic-mineral mixes. However, the latter improved soil conditions, increasing phosphorus (P) and potassium (K) availability. Excessive potassium can lead to nutritional imbalances, which could reduce plant productivity. More research is needed to refine banana fertilization strategies.

Viana, Caetano and Pontes (2021) advise caution in overestimating the effectiveness of rock dust as a fertilizer in Brazil. Although rock dust holds potential, more research is needed to assess its agronomic benefits, especially when combined with animal manure (Viana et al., 2021).

Swoboda, Döring and Hamer (2020) found that various modifications to rock powders can significantly enhance the agronomic effectiveness of silicate rock powders (SRPs). Enhanced weathering of SRPs has the potential to sequester large amounts of CO_2 from the atmosphere, while the addition of silicon (Si) can improve plants' resistance to a wide range of biotic and abiotic stresses.

The specific type of Rock Dust (RD) used was shown to affect both growth improvements and foliar nutrition, highlighting the importance of conducting a thorough soil and/or foliar analysis to identify deficiencies before selecting the appropriate RD. Once these deficiencies are identified, the RD can be chosen more effectively through a cost-efficient commercial soil test. To assess the RD's effectiveness, we recommend conducting a lime-calibrated soil-RD suspension test over one to two months, followed by the measurement of exchangeable cations (eCEC) in the RD-treated soil (Ciesielski & Sterckeman, 1997; Van Der Bauwhede et al., 2024). However, further research is needed to fully explore the use of SRPs in combination with limestone, chemical fertilizers, or animal manure. Future studies should focus on the type of rock, soil characteristics, crop requirements, and the application rate (Figure 2).

Figure 2. Factors Affecting the Use of Silicate Rock Powders (SRPs)



Swoboda, Döring and Hamer (2022)

Studies have shown that different types of rock dust and application rates can lead to varying results, primarily due to the diverse mineral compositions of the dust and the existing nutrient profile of the soil (Ramezanian et al., 2015). In essence, the effectiveness of rock dust applications is influenced by several key factors, including the soil's physical and chemical properties, pollutant concentrations, crop species, regional climate conditions, microbial presence, and the specific type of rock dust used along with its mineral content (Der Bauwhede et al., 2024).

Bergmann and Holanda (2014) argue that when evaluating rocks for use as soil remineralizers, a thorough investigation through petrographic analysis is crucial. This method allows for the identification of mineral content, texture, crystallization order, grain size, and structural integrity. Additionally, any materials introduced to the soil must meet strict guidelines to avoid the inclusion of harmful elements, such as toxic heavy metals, or substances that could cause soil salinization or degrade the soil's physical structure, such as sodium or quartz compounds.

The potential of rock dust in remediating contaminated soils has attracted increasing attention, as it can both improve soil quality and support plant growth. This technique also helps with waste management, as rock dust can be derived from discarded rocks, providing an eco-friendly solution for soil restoration. While the potential is promising, there is still limited research, and further studies are necessary to assess the broader applicability of rock dust. A study found that after 120 days of treatment with rock dust, seed dry mass increased by 21 ± 9%, with no harmful elements being taken up from basalt rock dust (Der Bauwhede et al., 2024).

Chakraborty, Singh, and Hazra (2023) observed that in multiple countries, powdered mine waste (or spoils) has been used for soil remediation and remineralization (Hensel, 1894; OldBeld, 1996; Dumitru et al., 1999; Jakubowski et al., 2013; Li & Dong, 2013; Ramos et al., 2015; 2017; 2020; Basak et al., 2021; Burbano et al., 2022). This highlights the importance of studying the physical, chemical, and biological properties of soils near coal mines and evaluating overburden materials for potential soil remediation. Soil pollution is an increasingly urgent issue, especially around coal mining regions, as documented by global research (Niu et al., 2015; Masto et al., 2015; Maya et al., 2015; Pandey et al., 2016; Raj et al., 2017; Jiya et al., 2019; Wang et al., 2019; Siddique et al., 2020; Khan et al., 2020; Fang et al., 2021).

One of the major advantages of rock dust is its ability to boost the soil's potential for carbon sequestration (Szmidt & Ferguson, 2004). Studies (Kohler et al., 2010; Renforth et al., 2011; Manning et al., 2013; Rau et al., 2013) have explored how various silicate rock dusts can aid in CO2 reduction through carbon sequestration. The main mechanism behind this process is the weathering and precipitation of calcium (Ca) and magnesium (Mg) carbonates. Applying powdered olivine or pulverized basalt rock dust to soils can speed up weathering, sequester large amounts of CO2, and reduce the effects of acid rain (Schuiling & Krijgsman, 2006). However, further research is necessary to determine the best methods, cost-efficiency, and environmental impact for large-scale implementation of these strategies, especially in high CO2-emitting countries like Brazil.

Swoboda, Döring and Hamer (2020) observed that specific modifications to silicate rock powders (SRPs) can significantly improve their agronomic efficiency. Furthermore, enhanced weathering of SRPs may contribute to atmospheric CO_2 sequestration, while the silicon supplied through these amendments can bolster plant resilience to both biotic and abiotic stressors.

Thus, more research is needed to understand the use of silicate rock powders (SRPs) associated with limestone, or with a chemical fertilizer or with animal manure, and in particular the importance of the type of rock related to the type of soil and crop, in addition to the quantity

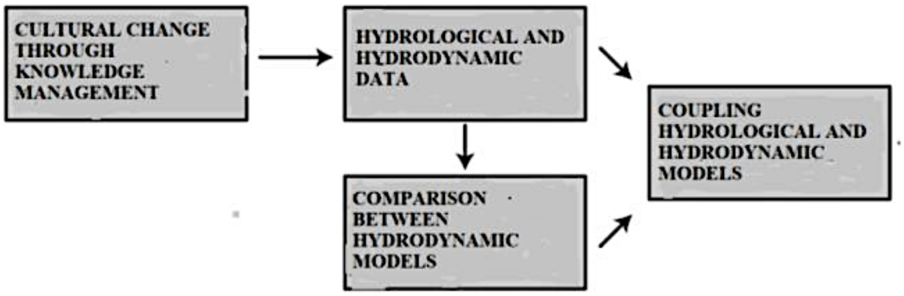
METHODOLOGY

The chosen methodology is a literature review and an exploratory analysis of the largest flood in Rio Grande do Sul. Snyder (2019) emphasizes that the literature review as a research method is more relevant than ever. Traditional literature reviews often lack thoroughness and rigor and are conducted ad hoc, rather than following a specific methodology. This work conducts an integrative literature review. Integration occurs not only in the literature review itself, where the intersection between these concepts is demonstrated through different sources, but also through the research model, in which all constructs are present.

The Biodynamic-Hydrodynamic Model

Hydrodynamic models are used in flooding situations to predict water density near the spillway and create an ideal flood discharge plan. As Angelis (2014) found, an emergency plan depends on the variability in hydraulic and hydrological properties, since hydraulic indicators are impacted by land use and, consequently, climate change. This work suggests the following Communities of Practice for sharing knowledge and experiences to improve the decision-making process: 1- Agriculture and Climate Change; 2- Hydrodynamic models and necessary data; 3- Improved forecasting in cases of floods; 4- Emergency Plans and relationship with the population; 5- Electrical structures of machine rooms based on this literature review, the relationship model between the Biodynamic Agriculture model and the Hydrodynamic Model is constructed (Figure 2).

Figure 2. Hydrodynamic model



Source: Author.

It is important to note that improvements in agricultural data have improved hydrological and hydrodynamic data in this model, given their relationship with climate change and even environmental impact.

RESULTS AND DISCUSSION

The main result of this literature review was to identify the HydroPol2D model as a low-cost solution for predicting the hydrological-hydraulic behavior of Rio Grande do Sul's river basins, specifically for estimating flood maps that contain water depths in streets, blocks, neighborhoods, canals, and, consequently, throughout the entire river basin. And not only that.

As we have seen, the HydroPol2D model can be used to assess the risk of human entrapment, generating risk maps every 15 minutes that can be used to aid decision-making. However, this work highlights the need for data from rainfall and fluviometric stations and suggests better infrastructure for these stations, as well as the construction of new ones by the government. It's important to note that the issue of cultural change is even more important than the HydroPol2D model itself. This is because the use of palliative solutions was observed in both the 2023 and 2024 floods, which worsened the situation, leaving 151 dead, more than 100 missing, and over 600 displaced.

It became clear that the University failed to communicate with the public, neither before the tragedy to collect data to feed the hydrodynamic models, nor during the flood to explain the path of the water and its causes and consequences, nor even post-flood to improve the university's forecasting capabilities, strategy, and action in partnership with public officials. Weather warnings of impending heavy rains were issued about five days in advance. There was no maintenance on existing flood protection structures, including dikes, floodgates, and pumps, so much so that the system collapsed before reaching the 6-meter flood limit. As we have seen, the flooded pumps were unable to pump water out of the city due to their inability to handle excess water.

Clearly, there was also a lack of multidisciplinary teamwork to better manage urbanization and soil waterproofing, particularly in communities living near flood zones. Without a Knowledge Management and Organizational Intelligence plan, there was a lack of effective communication by the government to educate the population on how to reduce risks and respond in emergency situations.

CONCLUSION

The article presented two research models that feed off each other: the Culture-Knowledge-Intelligence (CCI) model and the risk management model with social participation. The first model demonstrates the importance of learning from other cultures, cultural intelligence, given that the issue of floods is a global problem and therefore the need to exchange knowledge and experiences with other countries, particularly Argentina.

The effects of climate change, coupled with the occupation of flood-prone areas, mean that events like the one in May 2024 could become increasingly frequent. However, the current mathematical capabilities of forecasting models allow for a reasonable forecast of the impact of floods, on the order of a few days, and serve as a basis for emergency action plans. This requires a survey of elevation, rainfall, bathymetry, and other data to serve as input for forecasting models. States such as Santa Catarina and Pernambuco have such information. These and other measures were suggested by researchers at the Institute of Hydraulic Research in late 2023 after the November floods; however, they were not implemented by the responsible public agencies. Researchers also report the government's responsibility for maintaining the works (containment dikes and flood barriers).

Protection systems, especially in Porto Alegre, require intensive mobilization of trained personnel for the correct operation of floodgates and engine rooms. Preserving public awareness of the unprecedented impacts of the 2024 flood should not only serve as a warning to the population but also result in adequate and frequent operation and maintenance of protection systems.

Paiva et al. (2024) recommend that infrastructure projects and planning be adaptable and flexible, facilitating or preventing their expansion (e.g., bridge widths, culvert sections, dam and dike crest heights), thus enabling future increases in reference values, given the risk associated with extreme hydrological events. Training teams responsible for managing protection systems frequently, not only during flood events, should be a priority. This work aims to seek guidelines for a solution without necessarily assigning blame.

The affected population suffers the most, as they must move from previously stable areas, thus highlighting the importance of intelligence and its three pillars: 1. forecasting (the responsibility of the hydrodynamic model), 2. strategy and action (the responsibility of the emergency plan with social participation). As discussed in this paper, a better relationship between universities and the government is needed, with public participation. This ensures that those with knowledge and experience can access better hydrological data, not only rainfall but also water levels throughout the city's infrastructure system, to inform their forecasting, strategy, and action models. Furthermore, a standard state-wide emergency plan is needed that can be replicated throughout Brazil, considering the education of the population, particularly those living along rivers and rivers.

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