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An analysis of hydrodynamic models and a proposal of cultural change based on predictions: the case of the Rio Grande do Sul flood, Brazil

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Abstract: The most severe extreme climate-crisis event in Brazil, the floods and inundations that struck the state of Rio Grande do Sul (RGS) in May 2024, has highlighted the urgent need to rethink urban infrastructure and research priorities within contexts marked by limited access to knowledge and disorganized territorial planning. The main objective of this study is to analyse the relationship between flood management and the implementation of structural and non-structural measures. Through a systematic literature review, solutions based on hydrodynamic models with application potential for preventing and mitigating floods in urban environments are identified. Likewise, a critical evaluation is carried out of the strategies deployed during the major flood in Rio Grande do Sul, and more effective and sustainable alternatives are proposed. Rio Grande do Sul also faces cultural-related problems with cascade effects: serious separatist attempts to break away from the rest of Brazil, together with persistent manifestations of machismo and racism that have caused multiple fatalities rooted in notions of superiority, all of which exert an impact on crisis management. Drawing on this perspective, the following research question is formulated: What role does culture play in knowledge management for floods and drainage, particularly with regard to the use of hydrodynamic models? This question motivates the proposal of an integrated model of Cultural Intelligence, Knowledge Management and Social Participation, intended to optimize the design and implementation of flood-control plans. Initially, following a comparative analysis of the CRESTv2.1, HEC-RAS, MIKE 21 and cGAN-Flood models, the Hydropol2D forecasting model was considered for application. Nevertheless, significant limitations were identified, such as its failure to account for the effects of agricultural activity on hydrological dynamics. Consequently, it is suggested that Hydropol2D be replaced by the SWAT+ (Soil and Water Assessment Tool) model combined with the groundwater module (GWFlow). This enables more accurate simulation of surface and subsurface hydrological processes. This integrated tool not only provides enhanced capacity for assessing the impacts of land-use patterns and agricultural practices but also improves accuracy when modelling urban-drainage scenarios.

Key words: cultural change; knowledge management, hydrodynamic models; organizational intelligence; SWAT+ GWFlow; urban planning

1 Introduction

Brazil, with its diverse geography and extensive river systems, is highly prone to hydrometeorological risks, including floods (Marengo et al., 2021, 2020). Over the years, the country has experienced numerous catastrophic floods that have played a significant role in shaping its disaster-management frameworks (Debortoli et al., 2017; Tompkins et al., 2008).

Webber et al. (2024) found that the state of Rio Grande do Sul (RGS) in Brazil underwent the worst climate crisis in its history in April-May 2024. Rainfall levels were extremely high, and both institutional and civil-society strategies proved insufficient to prevent highly destructive scenarios—a catastrophe that inflicted substantial societal damage (Ferreira, 2024).

The most severe and direct impact fell on the lives of people affected by urban and rural floods across certain areas of the state (Figure 1).

By late May 2024, the recorded death toll was close to 200, with numerous missing persons and more than 600,000 people displaced from their homes (Sun et al., 2024).

Figure 1. Flooding of Porto Alegre, on Lake Guaíba ---photograph by Douglas Rohers

Rio Grande do Sul, like the rest of Brazil, suffers greatly from a lack of knowledge in managing its vast natural resources. As a result, poorer populations endure frequent floods. Unlike other Latin-American countries such as Uruguay, Argentina, Chile and Portugal, Brazilians show little enthusiasm for reading. Among all South-American countries—a region already facing considerable deficiencies in knowledge, since its cultures place greater emphasis on verbal communication due to linguistic accessibility—Brazil is the country with the lowest reading volume, according to the International Reading Association (Conselho Brasil Sul, data from 2000). This partly explains its recurring flood disasters. Over the past 20 years, 4,255 people have died from environmental disasters in Brazil, and another 8 million have been left homeless, according to a study by the National Secretariat of Civil Defence and Civil Protection. The statistics represent average annual economic losses of R$ 24 billion together with 212 deaths per year.

The number of aircraft-related accidents is also relatively high (129 accidents since 1915).

According to 2000 data from the International Reading Association (Conselho Brasil Sul), Brazilians read an average of one book per year, while Chileans, Uruguayans and Argentines read four books over the same period. Compared with more-developed countries, Brazilian readership is even smaller: residents in developed countries read approximately 20 books per capita every year.

The Brazilian Book Chamber (CBL, 2024), in the sixth edition of its study *Retratos de la Lectura en Brasil*, reported a loss of 6.7 million readers in the previous four years. This means that 53 % of the population had not read even part of a book during the three-month period before the survey.

Lack of access to knowledge and lack of motivation to acquire it, compounded by abundant sources of distraction, the influence of coastal beaches—where Latin- Americans tend to open bars and restaurants rather than productive businesses — and the constant proliferation of information, hinder public understanding of real- world events. Accordingly, the OECD confirmed that Brazil ranks first among 21 countries in terms of belief in fake news (OECD, 2024).

According to IBGE (2020), approximately 30 million people in Brazil are functionally illiterate. It is striking that Brazil, the world's tenth- largest economy, has 62.5 million people (29.4 % of the Brazilian population) living in poverty; of these, 17.9 million (8.4 % of the population) live in extreme poverty (World Bank, 2021).

Several authors denounce the Brazilian government's indifference toward the poor and knowledge- deprived populations (Macedo, 2024; Silva e Silva, 2010; Menezes, 2019; Pitombeira e Oliveira, 2025; Souza, 2018; Libâneo, 2016). According to data released by the Instituto Trata Brasil, around 33 million Brazilians lack access to safe drinking water, and 100 million people are not served by sewage systems.

Turning to the failure of the flood- protection system in Porto Alegre, capital of RGS: flood impacts would have been mitigated if routine operation and maintenance had been carried out.

In fact, a document signed by more than 40 sanitation engineers and technicians states that Porto Alegre's flood- protection system failed owing to insufficient maintenance[1].

The system comprises multiple pumps and sluice gates; the failure of even one component can trigger system- wide collapse. Specifically, during the May 2024 event, according to the Municipal Department of Water and Drainage (DMAE), one sluice gate failed, and the electrical installation in the machine- room was not designed to operate under flooded conditions. To avoid the risk of electric shock, the entire pumping system was shut down, triggering a cascade effect.

In an interview, Nanci Giugno, Master in Urban and Regional Planning and engineer, explained that "the city has two systems: sluice gates and drainage. Both failed"[2].

Beyond system operation and maintenance, flood- forecasting models are highly valuable for flood management. With a 1- to 2- day forecast horizon, it is possible to predict flood impacts on cities with reasonable accuracy.

According to Nonnemacher and Fan (2023), every real invested in flood- prevention systems can save approximately R$ 40.00 by reducing potential flood- related damages in Rio Grande do Sul. Effective prevention requires new rainfall monitoring stations, a team equipped with relevant expertise in hydrology, agriculture and geography, and the production of actionable outputs.

For forecasting purposes, it is necessary to predict not only precipitation but also water levels, water depth across streets and city blocks, and conditions of the full urban infrastructure network. In cities without structural flood- protection works (i.e. dikes), forecasting and early warnings—especially for mobility- related decisions—are essential to reduce flood impacts. This requires accurate monitoring- station data together with suitable, fast- running models to project flood consequences. The ideal flood- management strategy consists of well- calibrated forecasts combined with proper monitoring of protective infrastructure.

According to a technical note entitled *Hydrological criteria for climate- change adaptation: Extreme rainfall and floods in Southern Brazil*, recently published by Paiva et al. (2024), large- scale infrastructure and planning projects, which are commonly designed for return periods of 50 years or longer, must withstand the largest flood on record, regardless of

its estimated return period. By definition, a return period (TR) is a time interval, measured in years, over which a given flood event is expected to occur at least once on average.

Urban planning usually defines tolerable risk thresholds for such systems. Micro- drainage systems (i.e. storm- water galleries and urban storm drains) are designed for return periods of 10 to 25 years, whereas macro- drainage works —

large-scale rivers and canals — are typically dimensioned for return periods ranging from 50 to 100 years. Under climate change, the concept of tolerable risk for drainage projects needs to be revisited owing to the non-stationarity of precipitation. In other words, a major Urban Macro-Drainage Project is required to cope with flood-related hazard.

Conceptually, it is clear that the discharge of the four rivers feeding into the Guaíba Lake must be reduced. These rivers flow toward the six raw-water pumping stations EBAB (five located on the Guaíba and one on the Jacuí River), as well as the six dams (three in Bento Goncalves). To achieve this, detailed studies on the hydrological-hydraulic behaviour of each river basin must be prepared. Such studies should underpin an integrated approach to hydrological-basin planning, covering both surface-water and groundwater resources in particular.

Rathore et al. (2025) emphasize the critical need for integrated river-basin management and improved flood-forecasting systems to mitigate future flood risks.

There are eighteen dams in Rio Grande do Sul. In May 2024, six of them were under emergency status with imminent failure risk, and one had already suffered partial breach. Owing to the steep gradient within the Taquari-Antas River basin, large volumes of runoff rapidly reached the dam complex. This effect was amplified when heavy rainfall concentrated over the basin headwaters, exactly as observed during the May 2024 disaster. According to a recent technical report from the Institute of Hydraulic Research (IPH), several rain-gauge stations recorded total rainfall exceeding 1,000 mm within two weeks. Over this short window, precipitation totals exceeded 40 % of the region's average annual rainfall. Certain flood-release processes can be managed by small reservoirs distributed along the river. These reservoirs not only attenuate runoff volumes but also lower the high pollutant loads carried by surface runoff, thereby reducing adverse impacts on drinking-water treatment plants. Nevertheless, for an extreme flood such as the May 2024 event, structural solutions relying on reservoirs are practically unfeasible. An impractically huge storage capacity would be required to achieve meaningful mitigation effects. Non-structural measures may represent the more reasonable path forward. Where structural measures are considered, detailed studies must be conducted to prevent potential damage and adverse environmental impacts.

Accordingly, Rathore et al. (2025) highlight that growing intensity of extreme climate events, largely driven by anthropogenic climate change, has altered precipitation patterns. Such shifts contribute to higher frequency and greater severity of flood events (Meng et al., 2025; Mitchell et al., 2006; Wasko et al., 2021).

Chemical fertilizers represent one major source of greenhouse-gas emissions. This research proposes rock dust as an alternative, especially within the Gaucho farming system (Rio Grande do Sul), where local farmers show a strong tendency to use Russian-origin fertilizers.

This work is organized into four chapters. The first section provides a comparative analysis of hydrodynamic models. The second section examines Brazilian culture, with a focus on Gaucho culture (Rio Grande do Sul). Section 3 addresses the importance of standard emergency plans for risk management and social participation, grounded in Knowledge Management (KM) and Social Intelligence (SI) practices. Finally, Section 4 presents the Culture-Knowledge-Intelligence (CCI) model built upon the findings from the preceding sections.

2 Comparative analysis of hydrodynamic models

Rathore et al. (2025) identify the areas affected by the May 2024 floods in Porto Alegre, Brazil, using advanced remote-sensing and geospatial techniques. These datasets combine remote-sensing observations and auxiliary geospatial data. Each source delivers critical information for accurately mapping flood extent and assessing impacts, through integration of multispectral imagery from Sentinel-1 SAR, Sentinel-2 and PlanetScope, together with contours derived from the Copernicus DEM.

Chen et al. (2023) explain that the hydrological cycle is complex, and accurate hydrological models can improve our understanding of the hydrological cycle and support informed decision-making in water management.

According to Rennó and Suares (2022), a hydrological model may be defined as a mathematical representation of water flow and its components across a given area of the Earth's surface and-or subsurface. In this respect, hydrodynamic models, which solve the fundamental flow equations, can be applied to predict flood behaviour.

There is a close interrelationship among hydrological, biological and ecological modelling. Material transport by water is influenced by biological activities, which may either increase or decrease the concentration of such substances. Furthermore, the water-flow regime exerts impacts on multiple habitats.

Hydrodynamic models are built to analyse processes occurring during fluid flow. They cover not only laminar flow but also turbulent flow, such as those observed during major flood events.

Environmental hydrodynamic models constitute essential tools for the management and planning of interventions in natural water bodies, as they enable analysis of three key phenomena (Rossman, 2001):

- Turbulent Hydrodynamic Circulation: Evaluates changes in momentum (mass × velocity), which produce variations in water levels and currents.
- Water Quality: Examines the transport of substances that affect water composition and quality.
- Sedimentological Processes: Analyses erosion, transport and deposition cycles of sediments that govern morphology and morphodynamics.

The purpose of these models is to simulate water movements, transport processes, discharges and flows, together with its constituents (gases, salinity, nutrients, heat, sediments, among others).

Stokes Oceanografía (2023) breaks the modelling workflow into ten steps:

1) Development of a conceptual model for the phenomenon;

2) Collection of input data;

3) Definition of numerical-domain boundaries;

4) Digitization of the coastline or, for river-basin applications, use of terrain-elevation models;

5) Construction of a numerical mesh to discretise space into finite intervals;

6) Generation of bathymetry for rivers, channels and reservoirs;

7) Definition of simulation scenarios and boundary conditions;

8) Configuration and setup of simulation runs;

9) Analysis of outputs;

10) Iteration of the workflow until simulated results approximate observed measurements, followed by final result presentation.

In Brazil, the HidroWeb Portal is the most-widely-used data source for hydrological-hydrodynamic studies. This portal provides access to information compiled by the National Hydrometeorological Network (RHN), managed by the National Water Agency (ANA), including historical observed discharge time-series, bathymetry, among other datasets. Nevertheless, stream-flow observations are not the only input required for hydrological and hydrodynamic models. More comprehensive models are essential; they need to represent river-basin behaviour, soil-moisture content, topographic properties, land-use patterns, and datasets describing the spatial-temporal distribution of precipitation. These requirements further increase the complexity of the modelling workflow. In countries such as the United States, complete high-resolution national-scale maps and time-series are freely available, which simplifies the development of flood-prediction models.

For instance, Rathore et al. (2025) employed daily satellite precipitation data from the GPM-IMERG Level 3 Late-Run collection (https://gpm.nasa.gov/data/directory/) with a spatial resolution of 10 km (Huffman et al., 2019) to investigate the extreme-precipitation events that triggered the floods in Rio Grande do Sul (RGS), Brazil, in early May 2024.

It is important to note that discharge time-series are not always available for a given river and time period. Small-sized rivers, for example, are not covered within the monitoring network operated by the National Water Agency (ANA). Nevertheless, such data can be obtained indirectly: through proportional calculations based on neighbouring catchment areas or by means of rainfall-runoff curves. These "regionalization" techniques allow discharge estimation for small rivers, yet they fail under extreme-event conditions.

Getirana et al. (2012) point out that open-water surfaces depend largely on river geometry and topography. River geometry governs the potential for river overbank flow, whereas topography defines the flooded area as a function of overflow volume. Nevertheless, both factors suffer from limitations originating from deficiencies in required input datasets. Errors within Digital Elevation Models (DEM) remain one of the major sources of uncertainty when modelling river-floodplain interactions. In particular, satellite-derived DEMs are not suitable for delivering accurate elevation profiles of alluvial floodplains. The "floodplain burning" approach, which draws upon detailed river and floodplain maps, has proven effective for gradually adjusting pixel elevations within inundated zones (Getirana et al., 2012).

Gomes Júnior et al. (2023) explain that hydrological, hydrodynamic and pollutant-transport models are essential for decision-making in flood mitigation and water-quality improvement (Fan & Collischonn, 2014). A wide range of models reported in the literature can quantify hydrodynamic processes across different temporal and spatial scales.

For fast-response events and urban catchments, the weighted-cellular-automaton two-dimensional model (WCA2D) (Guidolin et al., 2016) adopts a cellular-automaton approach to route runoff and generate surface flood-inundation maps. Thanks to its high computational efficiency and low memory demand, with only minor trade-offs in accuracy, WCA2D has proven suitable for large-scale flood simulation. It supports numerous simulation runs required for risk-analysis workflows. This two-dimensional overland-flood model couples with the one-dimensional CADDIES model for sewer networks developed by Austin et al. (2014), forming a simplified urban-drainage modelling framework for urban-flood investigations. Nevertheless, during major flood disasters, the influence of micro-scale drainage is greatly diminished when confronted with massive rainfall and runoff volumes.

A recent serious-game approach was proposed by Gomes Jr. (2024). He built a game to simulate dam-break scenarios, enabling users to perceive the magnitude of hydraulic forces arriving at urban areas, as well as flood-water depth and flow velocity. The game was applied to 21 dams, including the Brumadinho dam and the 14 de Julho dam. Furthermore, Gomes Júnior et al. (2023) highlight the HydroPol2D model. It advances hydrological-hydrodynamic modelling by supporting two-dimensional coupled simulation of flood propagation and water quality. It simulates momentum transfer over floodplains, computes spatially distributed infiltration and evapotranspiration, and reproduces the transport and fate of pollutants. These approaches yield a more integrated analysis of the hydrological behaviour of river catchments and improve understanding of the processes controlling river runoff.

HydroPol2D also advances hydroinformatics by providing a fully-explicit numerical model coupled with an adaptive time-stepping method to guarantee numerical stability for its water-quantity and water-quality modules. Furthermore, HydroPol2D supports Graphics Processing Unit (GPU) acceleration and has open-source releases for Matlab and Python (Gomes Junior et al., 2023).

The HEC-RAS software, developed by the United States Army Corps of Engineers, simulates two-dimensional flows through the numerical solution of shallow-water equations. The model accounts for multiple physical factors including inertia, pressure gradient, gravitational effects, friction, turbulence, and Coriolis effects, which describe the behaviour of water and air currents across different hemispheres. Nevertheless, one major limitation of HEC-RAS is its high computational cost, particularly for high-resolution flood simulations. Details of the formulations and numerical schemes adopted in model version 6.1.0 are documented in Brunner (2016).

To generate a composite topographic map, multiple datasets were merged. For the Amazon River reach and open-water zones within the alluvial floodplain, topography estimated by Fassoni-Andrade et al. (2020a) was adopted, with a spatial resolution of 30 meters (available at data.mendeley.com/datasets/vn599y9szb/1). This mapping product was produced by digitizing river nautical charts and applying the Flood2Topo method (Fassoni-Andrade et al., 2020) based on optical satellite data (Gomes Júnior et al., 2023).

Lago et al. (2024) assessed the performance of the HEC-RAS model against a proposed model that integrates cGAN-Flood for flood prediction across seven urban catchments in San Antonio and São Paulo. The results indicated that combining MAP with cGAN-Flood improved the accuracy of flood maps, enabling flooded-area delineation and water-depth estimation. Nevertheless, the model underestimated total flood volume (v_t) in several cases. Furthermore, cGAN-Flood cannot predict flow velocity, which constitutes a critical parameter for risk-map production. An additional limitation is that cGAN-Flood was trained exclusively for flood-extent prediction. This constrains its applicability under conditions of variable input data or when high-fidelity detailed flood forecasts are required.

Despite these limitations, cGAN-Flood was found to be 50-fold and 250-fold faster than the WCA2D and HEC-RAS models, respectively. Nevertheless, further research is needed to improve its applicability. Artificial intelligence tools, which often lack deep learning of the hydrological behaviour of river basins, should be used with caution due to the scarcity of high-quality observational data. Large-scale deployment of these techniques requires settings with abundant flood-monitoring datasets, where machine-learning models can be trained using reliable observational records of basin behaviour.

A study by Fassoni-Andrade et al. (2023) described that the HEC-RAS model employs an unstructured computational mesh, where cell orientation and size vary as a function of topography. This allows topographic breaks to be incorporated to set the orientation of computational cells. The researchers also introduced computation pauses to manually vectorize topographic contours along river banks. In alluvial-plain zones, isolines for flood-frequency thresholds of 90 % and 60 % were derived from the flood-frequency map produced by Fassoni-Andrade et al. (2020).

Errors in topographic mapping, downstream boundary-condition specifications, and insufficient representation of hydrological processes in alluvial plains (including local infiltration, precipitation, evaporation and groundwater flow) constitute sources of uncertainty when modelling flood extents. This is particularly significant during low-water periods (Fassoni-Andrade et al., 2023).

On the other hand, Long et al. (2023) improved flow simulations by coupling hydrological and hydrodynamic models. They built a hydrological model using the Soil and Water Assessment Tool (SWAT) for the Dongting Lake basin, which simulates real-time flow in data-scarce areas, and coupled it with the MIKE21 hydrodynamic system. MIKE21 can incorporate additional boundary conditions and adjust the characteristic scales of input datasets. This modelling approach proves useful when confronting data scarcity in certain regions.

A commonly-used procedure in modelling is regionalization (Arsenault et al., 2019) [2], which transfers hydrological information from gauged areas to data-sparse regions (Bao et al., 2012; Yang et al., 2020) [3][31]. Jillo et al. (2017) [19] applied a rainfall-runoff model in data-scarce observational sites and adopted this regionalization approach to estimate water yield in neighbouring zones. Nevertheless, the obtained results were not validated.

For the Amazon River basin and its alluvial plain zones, the 30- m- resolution topography estimated by Fassoni- Andrade et al. (2020) was adopted. This dataset is available via the Mendeley portal. The mapping dataset was generated by digitizing river nautical charts and implementing the Flood2Topo method. As for coupled models, a Chinese research team led by Yuannan Long also used the SWAT model for hydrological analysis in data- poor areas, and coupled it with the MIKE21 hydrodynamic system to improve flow- simulation performance.

De Angelis and Gomes Júnior (2024) found that the HydroPol2D model can serve as a low- cost solution for predicting the hydrological- hydraulic behaviour of river basins. This model generates flood- inundation maps with water- depth information for streets, neighbourhoods, channels and the entire watershed. Recent studies using HydroPol2D have also focused on producing risk maps every 15 minutes to support more effective decision- making. Nevertheless, output quality can be improved with additional input data. In the state of Rio Grande do Sul (Brazil), there are currently 1,700 rainfall and stream- gauging stations, yet only 25 % of them transmit real- time data. This limits the performance of hydrodynamic models, unless citizen- sourced data from videos and photographs are adopted (De Angelis & Gomes Júnior, 2024).

Another well- known hydrodynamic model is CRESTv2.1. This widely- used enhanced version delivers multiple improvements: (a) implementation of distributed parameters; (b) replacement of three soil layers with a single layer to reduce parameter requirements; (c) incorporation of impervious- area fraction; (d) introduction of a rainfall multiplier parameter to reduce precipitation- forcing bias; and (e) auto- calibration, among others (Shen et al., 2017; Xue et al., 2013, 2016). The CREST model is efficient and effective for flood- monitoring applications. However, several limitations remain to be addressed to achieve satisfactory simulation of both hydrological extremes. For instance, the hydrograph recession branches produced by CREST are much steeper than observed records (Chen et al., 2020). Its single- layer soil structure may trigger errors in soil- moisture estimation. Moreover, the absence of groundwater storage and routing routines may lead to water- volume underestimation in long- term hydrological simulations (Kan et al., 2017). Furthermore, for sustainable water- resources management, especially in regions with temporally variable precipitation, groundwater simulation can no longer be regarded as a negligible component (Asrie & Sebhat, 2016; Massuel et al., 2017).

Lastly, Le Li et al. (2021) offer new insights into the complex nonlinear interactions between hydrological processes and environmental changes. Developed by the United States Department of Agriculture (USDA), the SWAT model remains one of the most widely applied tools for simulating sediment and nutrient dynamics across macro-, meso- and micro- scale basins (Arnold et al., 1998).

The SWAT model has proven to be a valuable tool for identifying the main hydrological processes influencing nitrate loads in study areas, especially during dry seasons. Key input datasets required for its setup include the digital elevation model (DEM), land- use maps, soil- type maps, daily meteorological data, water- quality records and agricultural management practices. In this study, a 30- m- resolution DEM (Asmat V2) obtained from the USGS website (http://www.usgs.gov) was used for watershed delineation (Le Li et al., 2021). Nevertheless, Castellanos- Osorio (2025) and Sánchez- Gómez (2024, 2025) point out that the representation of groundwater in the base SWAT+ model is regarded as an important limitation. According to Yimer et al. (2023), agricultural drainage systems are essential for evacuating excess groundwater and maintaining adequate oxygen levels for crop growth. However, these systems also produce considerable environmental and hydrological impacts, such as the reduction of groundwater volume and increased pollutant transport downstream.

To assess such effects, researchers have adopted more advanced hydrological- modelling tools, such as the SWAT+

model coupled with the GWFlow groundwater- flow module. This approach enables analysis of how agricultural drainage may deplete water- table levels and alter natural hydrological processes. Building model scenarios with and without agricultural- drainage systems facilitates the evaluation of drainage impacts on geohydrology.

Future research should focus on measuring drainage flows and calibrating geohydrological models to improve understanding of the dynamics between groundwater and agricultural drainage. These efforts will help reduce uncertainties in dry- season flow predictions and other water- balance components. Accurate quantification of drained water is essential for assessing its environmental impacts.

Yimer et al. (2023) found that agricultural drainage is a common practice for improving crop productivity, as it optimizes soil moisture and keeps the root zone adequately aerated. Agricultural drainage can substantially lower groundwater levels and alter watershed hydrology. Therefore, building model scenarios with and without this feature can reveal adverse impacts on geohydrological processes. The standalone Soil Water Assessment Tool (SWAT+) was originally developed to simulate discharge at the outlet of the Kleine Nete watershed. Afterwards, a physically- based, spatially- distributed groundwater module (GWFlow) was integrated into SWAT+, and calibrated against outlet discharge records (Yimer et al., 2023).

In the reviewed case studies, SWAT+ coupled with GWFlow exhibited better performance compared with the standalone SWAT+ version (Arnold, 1998). Furthermore, Bailey et al. (2023) developed an advanced GWFlow variant. This physically- based module is spatially integrated with SWAT+, enabling watershed- scale simulation of both surface and subsurface flow, with agricultural- drainage processes explicitly represented within its structure.

Sánchez- Gómez et al. (2025) found that among watershed- scale hydrological models, the Soil and Water Assessment Tool (SWAT) is one of the most widely used (Arnold et al., 2012; Fu et al., 2019; Gassman et al., 2014). SWAT is able to simulate certain management practices (i.e., reservoir release, water transfer, irrigation), albeit in a simplistic and limited fashion (Neitsch et al., 2009). For this reason, it is frequently coupled with other software tools (e.g., Ashraf et al., 2017; Ayele et al., 2022; Dash et al., 2022; Phung et al., 2022; Zhang et al., 2023).

A fully restructured version of the model, SWAT+, was released several years ago with new capabilities (Bieger et al., 2017). The model's flexibility for simulating water- management operations has been greatly improved in SWAT+. Reservoir simulation was the most challenging task in this work due to multiple contributing factors (model calibration, implementation of water transfers, upstream reservoirs, reliability of observed data), as well as decision tables. The constructed release- decision tables enabled multiple scenario analyses and achieved accurate simulation results for most of the modelled reservoirs. The addition of release- decision tables in SWAT+ has enhanced flexibility for simulating these key components of water- resources management. Reservoir simulation using SWAT has been addressed in numerous studies (e.g., Liu et al., 2019; Marak et al., 2020; Zhang et al., 2012). Nevertheless, limitations in older SWAT versions have prompted researchers either to modify the source code (e.g., Jordan et al., 2022; Kim et al., 2021; Wang et al., 2023) or to couple the model with other external software (Anand et al., 2018).

SWAT+ was also applied to simulate reservoir operations by Wu et al. (2020), who documented SWAT+ reservoir routines and developed and implemented numerous release- decision tables for the United States, together with a calibration procedure for these decision tables (Sánchez- Gómez et al., 2025). Sánchez- Gómez (2024) notes that hydrological models are widely used to support water- resources management, including scenario- impact assessment (Hakala et al., 2019; Molina- Navarro et al., 2018). Process representation, model limitations, modeller- defined assumptions, and calibration procedures all contribute to uncertainty within model predictions (Goderniaux et al., 2015; Hakala et al., 2019; Karlsson et al., 2016; Mendoza et al., 2015; Smerdon, 2017).

To reduce simulation uncertainty, multiple output variables should be analyzed to ensure the modelled watershed and its properties are reproduced as realistically as possible (i.e., water balance, flow components and other key hydrological variables) (Arnold et al., 2015). A recommended workflow to ensure a model performs well for a given variable (e.g., discharge) for physically correct reasons (e.g., realistic contributions from surface and groundwater flow) is soft-calibration (SC). Under this approach, model parameters are constrained using soft information prior to hard-calibration (HC) (Chawanda et al., 2020; Sánchez-Gómez et al., 2025).

Castellanos-Osorio (2025) draws similar conclusions: coupling SWAT+ with the new GWFLOW module improves surface-groundwater interaction simulation. A flow-duration-curve (FDC)-based calibration approach helps accurately reproduce baseflow. Calibration for both (1) SWAT+ and (2) SWAT+-GWFLOW focused on low-flow adjustment, improving daily-flow accuracy for environmental-flow estimation. Furthermore, one major challenge is the requirement for piezometric data to better define initial boundary conditions, alongside complete geohydrological information for the study area, which can vary greatly. Accurate hydrological simulation depends heavily on these datasets. The coupled SWAT+-GWFLOW delivered better performance across the whole hydrograph. It captured high, medium and low-flow conditions more reliably than the standalone model. Representing groundwater dynamics via the GWFLOW module greatly enhanced baseflow simulation and yielded realistic watershed-water-balance outputs. Accordingly, SWAT+-GWFLOW is an effective tool not only for environmental-flow assessment but also for hydrological planning and decision-making in watersheds where groundwater processes are critical (Castellanos-Osorio, 2025).

Yimer et al. (2023) found that the SWAT+GWFLOW model satisfactorily reproduces well discharge across most of the Escalda watershed. Gridded datasets performed well when forcing the geo-hydrological model, indicating their suitability for regional-scale studies. Finally, accurate simulation of discharge and hydraulic head was achieved using freely available global datasets. This opens opportunities for applying this coupled model in data-scarce regions lacking geological surveys and aquifer-property measurements.

In practical application, the coupled SWAT+GWFLOW model should be integrated with Agricultural and Hydraulic Knowledge Management, covering knowledge sharing, knowledge generation and practical implementation, for instance a holistic understanding of agricultural-drainage systems including surface and subsurface hydrological processes. All these knowledge-based practices are heavily shaped by culture, as will be discussed throughout the paper. Accordingly, where a culture is highly insular and struggles with these three knowledge-related processes, it is important to build cultural intelligence: the capacity to understand, adapt to, and selectively retain beneficial values, assumptions, traditions and beliefs from other cultural contexts. Structural measures (e.g., hydraulic infrastructure) and non-structural strategies (e.g., education and knowledge-transfer programmes) rely on the willingness of both public and private sectors, in terms both of institutional learning and financial investment. Such willingness may be absent. Investments in these measures can yield relatively low political returns. Resources may instead be diverted toward electoral-driven projects aimed at influencing public-opinion shapers, rather than benefiting poor riparian communities who lack access to technical knowledge.

Many residents live very close to water bodies, sometimes even in violation of regulations. It is therefore necessary to better manage urbanization and soil imperviousness. In addition, public-authority outreach to citizens is insufficient: residents are not adequately instructed on risk-reduction measures and appropriate behaviour under hazard conditions. A culture of prevention and forecasting is essential, yet this requires training for all stakeholders together with government-led public-awareness campaigns to shift societal attitudes. Silveira and Dewes (1993) report that one of the earliest integrated water-resources-management initiatives in Rio Grande do Sul dates back to 1971 under CEEIBG (Executive Committee for Integrated Studies of the Guaíba Watershed). CEEIBG aimed to improve the environmental condition of the Guaíba River basin, reconciling activities of federal, regional, state and municipal bodies with integrated water-resource utilization and water-quality conservation. Subsequently, State Law No. 10.350 of 30 December 1994 established the State Water-Resources System, regulating Article 171 of the Rio Grande do Sul State Constitution. It was amended by Law No. 11.560 (22 December 2000) and Law No. 11.685 (8 November 2001). Later, the State Water-Resources Plan (PERH) was enacted. This management instrument, mandated under both state and federal water legislation (State Law 10.350/1994; Federal Law 9.433/1997), guides water-policy implementation and water governance by defining state-level objectives, principles and guidelines. Nevertheless, the most recent drought report available on the SEMA portal is from 2021. It contains only meteorological analysis and forecasts plus selected hydrographs for major rivers across Rio Grande do Sul. Created in 1999, SEMA (State Secretariat for Environment and Infrastructure) serves as the central body of the State Environmental-Protection System (Sisepra), in charge of environmental-policy governance for Rio Grande do Sul.

3 The concerning separatist movement in Rio Grande do Sul and the impacts of the state-scale major flood

The Movimento por la Independencia de la Pampa (MIP, Pampa Independence Movement) was founded in 1990 by Irton Marx. It advocates the secession of Rio Grande do Sul from the rest of Brazil and has collected more than one million signatures in support[1]. The most prominent group is the Movimento Gaucho Tradicionalista (MTG, Gaucho Traditionalist Movement). Its participants regard Gaucho traditionalism as the-largest-popular-cultural movement worldwide at present. Drawing on folklorist-traditionalist Lessa (1985), Oliven (2006) reports two-million direct participants in MTG; its official website records 1,400 affiliated traditionalist associations. According to traditionalists, reverence for Gaucho traditions exists in New York, Lisbon, Paris and Tokyo. This stems from the "diaspora" of Gaucho-origin populations migrating out of Rio Grande do Sul across Brazil and the globe (Kaiser, 1999). Sociologist Luvizotto (2009) investigated ethnicity and separatism within Gaucho culture, analyzing their interplay inside the movement striving for Rio Grande do Sul's emancipation from Brazil. From the Gaucho perspective, the "Brazilian" stands as the other: an outsider-stranger excluded from local social space and social bonds. This "other" may be discussed openly, subject to criticism, accusation and stereotyping: "The 'Brazilian' is slow-witted, mischievous and lazy" (Luvizotto, 2009). This originates from deeply-rooted local traditions in Rio Grande do Sul. Local communities believe these traditions foster greater honesty compared with the rest of Brazil. Lourenção et al. (2019) identify personality traits attributed to other Brazilians: sensual, shrewd, cheerful, creative, hospitable, friendly and cordial. Buarque de Holanda (1936), in *Raízes de Brasil* (Roots of Brazil), observed that superficial politeness may mask intellectual deficiency. This thesis is corroborated by Gylberto Freire (2010, 2015) and Caio Junior (1945). Several Brazilian scholars have recognized culture's behavioural influence. Though acknowledging Brazil's diverse, heterogeneous culture, Freitas (1997) summarizes national traits relevant for organizational-culture analysis: hierarchy-orientation, personalism, cunning, sensuality and an adventurous spirit. Buarque de Holanda (1975) portrayed the archetypal Brazilian as a symmetrical counterpoint to ascetic North-American Protestant values. Key traits include personal-centred individualism, pursuit of immediate gratification, and disregard for communal bonds and long-term ideals.

Although this has changed somewhat over the past two decades, Brazil has historically lacked integration with other nations in the region, both culturally and economically. Many Brazilians would not even identify themselves as Latin-American. For more than a century, Brazil competed for hegemony across South America. Nevertheless, following the 2014 FIFA World Cup and the 2016 Olympic Games, Brazil and Peru became economic and social partners amid widespread corruption linked to Brazil's largest corporation. The Odebrecht scandal in Brazil ranks among the largest corporate-corruption cases in history. *The Mechanism* is a Brazilian political-drama television series created by José Padilha and Elena Soarez (2018). Loosely based on real-world events, it depicts a corruption scandal that unfolds in Brazil during investigations into alleged governmental corruption involving oil-industry and construction firms. José Padilha had to flee the country, as his work also exposed how the government armed favela groups to prevent unified social pushback against the state. Neves Costa, Ferreira & Pontes de Campos (2024) describe the "Car Wash" operation led by Judge Sergio Moro. Brazil's largest anti-corruption investigation began in early 2014 and ended in 2021. It is comparable only to Italy's "Mani Pulite" (Clean Hands) operation, partly owing to many cultural parallels between the two countries (Bertonha, 2010). A huge, intricate corruption network was progressively uncovered, shaking Brazil's fragile democracy to its foundations (Neves Costa, Ferreira & Pontes de Campos, 2024).

In 2021, the Federal Supreme Court ruled that then-judge Sérgio Moro had acted with bias when trying former-president Lula. This ruling invalidated evidence collected under his leadership within the Car-Wash investigation and brought the operation to an end.

4 The culture–knowledge–intelligence (CCI) model and knowledge management in disaster contexts

Roland (2000) provided practical explanations regarding the formation of cultures and the relationship among the state, knowledge, and intelligence. Various studies have linked historical and ecological factors to the evolution of collectivist or individualist cultures. Fincher et al. (2008) and Murray and Schaller (2010) found that countries with a high prevalence of pathogens before the 20th century tended to develop more collectivist cultures. The underlying logic is that, in contexts of high pathogen load, collectivist norms—characterized by the control of individual behavior and a more closed attitude toward outsiders—offer adaptive advantages by limiting the spread of disease. Other explanations regarding the origins of collectivism and individualism include agricultural and ecological factors. For instance, Talhelm et al. (2014) argue that societies based on rice cultivation, which requires greater coordination and collective labor, develop a more collectivist orientation, in contrast to wheat-farming cultures. Likewise, Buggle (2015), drawing on the ideas of Wittfogel (1957), suggests that the historical need for extensive irrigation systems favored the emergence of more centralized and collectivist social structures. Conversely, Knudsen (2017) found that a strong historical dependence on fishing is more closely associated with individualist cultures, given that this activity promotes autonomy.

Roland (2000) also proposed that geography influenced whether societies developed under state-led or market-based systems. Countries that today require stronger state governance tend to possess more collectivist cultures, whereas regions where market systems flourished gave rise to more individualist cultures. In South America, for example, legal frameworks tend to center on disputes between individuals, such as conflicts over property, which reflects an individualist cultural orientation. From an anthropological perspective, Edward Tylor was the first to define culture in his work *Primitive Culture* (1871), regarding it as a natural phenomenon that can be studied scientifically. Tylor maintained that culture follows regular patterns and causes, which allows for the formulation of laws governing its evolution. Kroeber, for his part, understood culture as a cumulative process resulting from the historical experiences of previous generations. This process, according to him, shapes or constrains individual creativity. Both Kroeber and Felix Keesing agreed that there is no genetic relationship with culture: any person can adopt the culture of the place where they grow up, regardless of their biological origin. Kroeber even argued that culture is what truly distinguishes human beings from animals, as it enables them to transcend their biological limitations.

Five key principles emerge from these ideas:

1. Culture, together with genetic heritage, determines human behaviour and human achievements.

2. Human beings act according to cultural norms; their instincts have been modulated by a long evolutionary process.

3. Through cultural acquisition, learning overrides the influence of genetically-determined behaviours.

4. As has been recognized since the Enlightenment, it is learning —whether through socialization or enculturation— that determines human behaviour and capacities.

5. Culture is a cumulative process that can both stimulate and restrict individual creativity.

In terms of economic development, multiple scholars agree that governments should place science at the heart of their economic growth and recovery strategies. Science generates knowledge, which in turn drives innovation, improves quality of life, strengthens democracy, fuels economic growth and delivers solutions to complex problems. Nevertheless, Rothberg and Erickson (2004) warn that knowledge by itself is static and only acquires value when it is applied.

In 1989, Richard Ackoff proposed a widely-accepted taxonomy in the field of Knowledge Management (KM), which distinguishes among data, information, knowledge and intelligence. According to Davenport and Prusak (1998), data are objective, discrete records of events; within organizations, they usually consist of structured transactions. Information, by contrast, is understood as a message —in the form of documents, visual or auditory communication— that has a sender and a receiver.

Knowledge goes further: it is a dynamic combination of experience, values, contextual information and technical know-how that enables the interpretation and application of new information. This knowledge is formed in individuals' minds and is inherently complex, structured and intuitive; hence it cannot always be articulated in a clear or logical manner (Davenport et al., 1998).

The transformation of knowledge into intelligence involves a human process of interpretation, analysis, integration, prediction and action. Information is contextualized according to the values and criteria of the decision-maker, who then applies this knowledge in concrete situations to generate intelligence. Rothberg and Erickson (2004) emphasize that knowledge is socially constructed through collaboration, yet it holds no value if it remains unused. In short, knowledge constitutes the foundation of intelligence, whereas intelligence represents knowledge-in-action for solving problems.

Choo (2002) defines intelligence as a continuous cycle of activities including environmental perception, knowledge construction and meaning-making through interpretation, all supported by the memory of past experiences.

Based on these theoretical foundations, the Culture-Knowledge-Intelligence (CCI) model is constructed, as illustrated in Figure 1.

The fundamental premises of the CCI model are: (i) Culture consists of the beliefs, values, assumptions and traditions of a society (Schein, 1985). (ii) For education to fulfil its transformative function, the curriculum must be reorganized around the four pillars of learning: learning to know, learning to do, learning to live together and learning to be (Nan-Zhao, 2000). (iii) Intelligence rests on three fundamental pillars: prediction, strategy and action (Rothberg and Erickson, 2004).

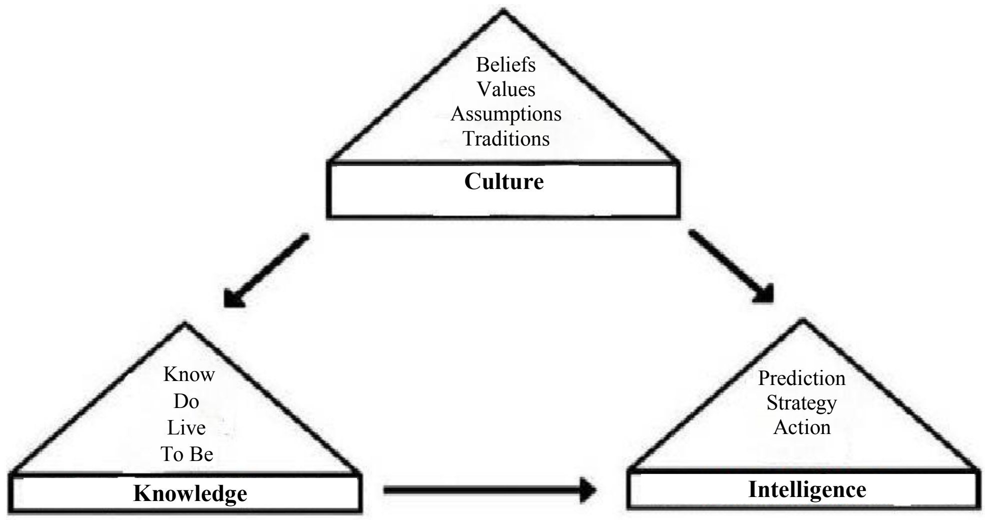


Figure 2. The Culture- Knowledge- Intelligence (CCI) model (adapted from Choo, 1998)

The CCI model is grounded on three- key hypotheses (Table 1).

Table I. Hypotheses in the CCI model

Hypotheses	Sources	Results
Culture has a positive impact on knowledge.	The successful implementation of a knowledge management system depends closely on a critical analysis of the existing organizational culture (de Ré et al., 2017).	Supported
Cultural change has a positive impact on intelligence.	Culture affects organizational and social behaviours, how people will act in a given situation, as well as thinking and decision- making (Schein, 1985).	Supported
Knowledge (KM) exerts a positive impact on intelligence.	Rothberg and Erickson (2004) clarify that knowledge without application is ineffective. In short, knowledge is the foundation of intelligence, since intelligence is knowledge- in- action for solving problems.	Supported

The Culture- Knowledge- Intelligence (CCI) model demonstrates how culture influences both the production of knowledge and the capacity to generate practical intelligence. In the case of the recent floods in Rio Grande do Sul, it became evident that a culture characterized by short- term urgency and lack of long- term planning —including the absence of investment in preventive works that yield no immediate electoral return— exerted a negative impact on the generation and application of knowledge, especially tacit knowledge. This type of knowledge, built on practical experience, is difficult to codify and share, as it relies on trust, commitment and the social identity of technical communities.

The lack of effective mechanisms to translate the accumulated experience of technicians and academics into concrete actions, both before and after critical events (such as flooding of machinery rooms and dam overtopping), reflects how operational intelligence was also limited by the prevailing institutional culture.

The practical application of the CCI model, especially for the great floods of May 2024, can be illustrated, for instance, by the communication difficulties identified between the university and government, between government and society, and between the university and society. The Special Rapporteurship on Economic, Social, Cultural and Environmental Rights (REDESCA) of the Inter- American Commission on Human Rights (CIDH) publishes the report *Impacts of the floods in*

Rio Grande do Sul: *observations and recommendations for the guarantee of economic, social, cultural and environmental rights*. The report highlights the disproportionate impacts on the most-vulnerable groups, including girls and women, Afro-descendant peoples, indigenous peoples and traditional communities, persons with disabilities, older persons, the LGBTQIA+ population, migrants and refugees, as well as rural and informal-sector workers. Furthermore, based on information gathered during the visit and analysis of available data, the report identifies structural failures that may have contributed to the scale of impacts upon DESCA rights: environmental degradation, agribusiness expansion, weakening of environmental legislation, lack of maintenance for flood-containment systems, and urban growth with low environmental resilience.

5 Knowledge management and communities of practice (CoP)

Knowledge management (KM) seeks to systematize, codify and redistribute tacit knowledge within organizations to convert it into explicit knowledge (Rothberg and Erickson, 2004). Given the interdisciplinary nature of flood-related challenges, high-quality public spaces must be created to foster collaboration among researchers, decision-makers and communities. Social awareness of climate change and its consequences should be strengthened through active citizen participation, ensuring that solutions are culturally appropriate and socially accepted.

A key tool for this knowledge integration is the Cutter Social Vulnerability Index (Cutter, Boruff & Shirley, 2012), which makes it possible to anticipate impacts, assess needs and design more-effective early-warning systems.

As a practical tool for applying KM in this study, Communities of Practice (CoP), or community forums, are proposed.

Morgado da Silva and Araújo (2019) [23] point out that Community Forums can contribute significantly to the construction of citizenship by providing a democratic space where ethical and social conflicts are debated and transformed. Communities of Practice (CoPs) are based on the management of socially distributed knowledge, but they require expert mediation to avoid misinterpretation or information overload.

Oliveira and Villardi (2014), following Gherardi (2003), emphasize that emotions, desires, and personal identities profoundly affect how knowledge is produced and shared. People seek knowledge not only for its practical utility but also as an end in itself. Nevertheless, Moura (2009) notes that CoPs have been understudied from a critical perspective.

Lave and Wenger (1991) and Wenger (2000) acknowledge that CoPs are not neutral: they can be spaces of learning and creativity, but also of exclusion or institutional rigidity. Participating in them entails engaging in dialogue, sharing experiences, constructing meanings, and contributing to collective processes of reflection, which fosters organizational learning (Souza-Silva and Davel, 2007).

An effective CoP must have three key elements (Wenger, 2006):

1. Domain: A shared area of knowledge that gives the group its identity, with committed members who value one another's experience and competences.

2. Community: A collaborative setting where experiences are exchanged, problems are solved, and learning-based relationships are built.

3. Practice: The shared repertoire of experiences, tools, stories and methods that underpin collective action.

Progressive participation, also known as Legitimate Peripheral Participation (Gherardi et al., 1998), enables new members to learn through informal interaction and acquire legitimacy within the group.

6 Proposal: Create a CoP for flood prevention

It is proposed to establish a Community of Practice aimed at sharing best practices and lessons learned for flood mitigation, with specialists assigned by thematic area. These experts would facilitate debates, analyse proposals and channel concrete recommendations towards decision-making. One of the expected outcomes of this dynamic is institutional cultural transformation.

According to De Angelis (2023), there are three fundamental challenges to achieve this:

1. Foster a culture of knowledge- sharing inside and outside the public sector.

2. Deploy intelligent digital tools that transform information into contextualized knowledge and applied wisdom.

3. Strengthen the active participation of citizens, public officials and enterprises in the production of new knowledge, supported by expert systems that analyze and facilitate the collaborative process.

7 Emergency plans and applied technology

Cultural change promoted through knowledge management and the development of organizational intelligence is key to designing more effective emergency plans. According to De Angelis (2024), such plans should combine structural measures (e.g., hydraulic works) with non- structural strategies (e.g., educational and knowledge- transfer programmes).

Technological tools such as the HAZUS software developed by FEMA (USA) enable estimation of potential damages caused by dam failures and support cost- benefit analysis, thereby facilitating infrastructure planning and rezoning in vulnerable areas (De Angelis & Gomes Júnior, 2024).

Araújo (2024) [1] warns that according to FEMA data, 40 % of businesses do not reopen after disasters, and an additional 25 % close within one year. This highlights the urgency of interventions such as the dredging of the Taquari River basin, a need that has been debated for more than four decades.

8 Technological innovation and sustainable energy

Regarding sustainability, Wendland et al. (2023) highlight the role of advanced synthetic materials in improving the efficiency of energy production, storage and utilization. Technologies such as solar cells, advanced batteries and efficient catalysts can reduce dependence on fossil fuels and mitigate climate change.

With regard to transport, particularly public transport —a significant source of CO_2 emissions—green hydrogen represents a promising alternative. Although its production cost still exceeds that of hydrogen derived from fossil- fuel sources, this cost gap is expected to narrow soon. Renewable hydrogen is produced via electrolysis using electricity from sustainable sources (solar, wind, hydroelectric, geothermal, tidal), or through biogas or the biochemical conversion of biomass, provided that sustainability criteria are met.

9 Biodynamic- Hydrodynamic model

Biodynamic agriculture, which employs rock dust to reduce heavy reliance on chemical fertilizers, has the potential to improve climatic and hydrological indicators.

As noted earlier, chemical fertilizers, besides polluting water bodies, increase soil carbon sequestration, which contributes to rising temperatures and, consequently, changes in precipitation.

Hydrodynamic models are applied in flood- related studies to predict water density near spillways and develop an optimal flood- release plan.

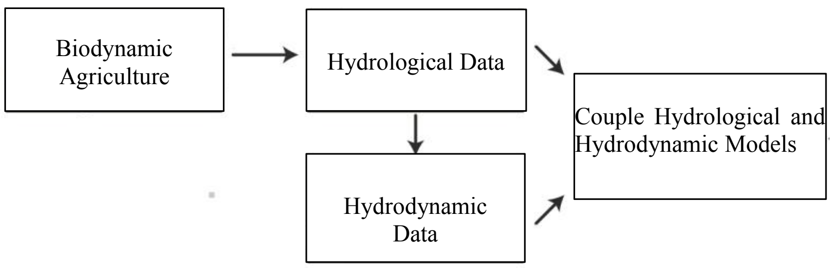
As Angelis (2014) found, an emergency plan depends on the variability of hydraulic and hydrological properties, since hydraulic indicators are affected by land- use patterns and subsequently by climate change.

This paper proposes establishing Communities of Practice around the following themes to share knowledge and experiences and improve the decision- making process:

1- Agriculture and Climate Change
2- Hydrodynamic models and required data
3- Improvement of flood forecasting
4- Emergency plans and public engagement

5- Electrical structures of machine rooms.

Based on this literature review, a relationship model between the Biodynamic Agriculture model and the Hydrodynamic Model is constructed:



It is important to highlight within this model that improvements in agricultural data enhanced hydrological and hydrodynamic data, given the links to climate change as well as environmental-protection considerations.

10 Results and discussion

The main finding of this literature review is that the Hydropol2D model serves as a low-cost solution for predicting the hydraulic-hydrological behaviour of the Rio Grande do Sul basin. Specifically, it can produce flood-inundation maps showing water depths across streets, city blocks, neighbourhoods and channels, and thus for the entire basin.

Furthermore, as discussed above, the Hydropol2D model can assess the risk of people being swept away by floodwaters. It generates risk maps every 15 minutes to support decision-making.

Nevertheless, this paper highlights the requirement for rainfall data and fluviometric station observations. It proposes optimizing the configuration of existing stations, as well as constructing new stations by public authorities.

It should be borne in mind that cultural change is even more important than the Hydropol2D model itself. During the 2023 and 2024 flood events, only palliative, stop-gap measures were adopted, which aggravated the crisis and resulted in 151 deaths, more than 100 missing persons and over 600 displaced people.

Meteorological alerts for heavy rainfall were issued approximately five days in advance. Existing flood-protection structures, including dikes, sluice gates and drainage pumps, received no maintenance, so the system collapsed before reaching the 6-metre flood-water-level threshold. As noted earlier, the submerged drainage pumps failed to pump water out of the city, because they could not operate under excessive water inundation.

There was also an obvious lack of multidisciplinary teamwork for better management of urbanization and soil sealing, especially for communities living adjacent to flood-prone zones.

In the absence of a Knowledge Management and Organizational Intelligence plan, public authorities failed to communicate effectively to instruct the public on risk-reduction measures and emergency-response procedures.

11 Conclusion

This paper presents two research models that feed back into one another: the Culture-Knowledge-Intelligence (CCI) model and the social-participatory risk-management model. The first model illustrates the importance of learning from other cultures and building cultural intelligence. Flooding is a global problem, which creates the need for knowledge-and-experience exchange with other countries, in particular Argentina.

Climate-change impacts combined with the occupation of flood-prone zones will make events such as the May 2024 floods increasingly frequent. Nevertheless, current mathematical capabilities of forecasting models allow flood-impact prediction with reasonable accuracy within a lead-time of several days, which provides support for emergency-response plans. This requires collecting elevation, precipitation, bathymetry and other datasets as input for forecasting models. States such as Santa Catarina and Pernambuco already possess such datasets. Researchers from the Hydraulic Research Institute put forward these and other measures at the end of 2023 after the November floods; however, the responsible public authorities failed to implement them.

Researchers also point out governmental deficiencies in the maintenance of flood-control works (containment dikes and flood barriers). Protection systems, especially in Porto Alegre, require large-scale deployment of qualified operators to guarantee proper operation of sluice gates and machine rooms. Public memory of the unprecedented impacts of the 2024 floods should not only serve as a warning to the population, but also translate into regular, appropriate operation-and-maintenance actions for flood-protection infrastructure.

Paiva et al. (2024) recommend that infrastructure projects and planning should be adaptive and flexible. Designs shall facilitate, rather than block, future expansion (e.g. bridge widths, culvert sections, crest elevations of dams and dikes). This makes it possible to accommodate future increases in reference design values given the risks associated with extreme hydrological events.

Building permanent teams for regular management of flood-protection systems—instead of teams activated only during flood crises—should be a priority. This work aims to identify solution-oriented guidelines, rather than assign blame. Affected populations suffer the most, being displaced from formerly stable residential areas. This highlights two core pillars of intelligence:

1. Prediction (delivered by hydrodynamic models)
2. Strategy and action (delivered by social-participatory emergency planning).

As analyzed in this paper, better collaboration between universities, government and the public is required. Stakeholders with knowledge and practical experience can generate improved hydrological datasets, including not only rainfall records but also water-level observations across urban infrastructure, to feed prediction, strategy and action models. Furthermore, a standard state-wide emergency plan should be developed for replication across Brazil, together with public risk-education programmes, especially for riparian communities.

12. Suggestions for future studies

According to Gomes Junior et al. (2023), future studies should incorporate the spatial variability of precipitation and evapotranspiration within large-scale hydrological catchments, especially for modelling compound scenarios featuring persistent droughts followed by unprecedented floods. Future research ought to integrate socioeconomic datasets with geospatial analyses, to better understand the cascading impacts of floods on vulnerable populations and underpin equitable resilience-building strategies.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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