10.18605/2175-7275/cereus.v16n3p449-464

<< Recebido em: 12/08/2024 Aceito em: 13/09/2024. >>

ARTIGO ORIGINAL

REVISTA CEREUS
ISSN: 2175-7275

Development of a Digital Twin for the Muriaé river watershed/Brazil

Desenvolvimento de Digital Twin para bacia hidrográfica do rio Muriaé/Brasil

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RESUMO

Desastres ambientais, como as inundações, vêm ocorrendo com maior frequência em diversas cidades, tornando-se um desafio aos gestores públicos e à população. A representação do ciclo hidrológico por meio de Digital Twin é uma forma de contribuir para a tomada de decisões do poder público em medidas de redução de riscos de desastres. Por meio de cenários hipotéticos, é possível pensar estratégias de mitigação de problemas e impactos ambientais e sociais que possam ser evitados, neutralizados ou reduzidos. O objetivo desse trabalho é detalhar o processo de calibração e validação de Digital Twin aplicado em bacia hidrográfica do rio Muriaé. As simulações foram realizadas na plataforma MOHID. A metodologia de avaliação dos resultados incluiu análise de hidrograma e de métricas estatísticas. Essa análise constatou que a alternativa que mesclou duas fontes de dados apresentou melhores resultados para validação do modelo por melhor representar a vazão do canal modelado em relação aos dados observados em estações fluviométricas.

Palavras-chave: Modelagem computacional. MOHID. Validação. Métricas estatísticas.

ABSTRACT

Environmental disasters, such as floods, are occurring more frequently in various cities, posing a challenge to public managers and the population. Representing the hydrological cycle through Digital Twin technology is a way to contribute to the decision making process of public authorities in disaster risk reduction measures. By exploring hypothetical scenarios, strategies for mitigating problems and environmental and social impacts that can be avoided, neutralized, or reduced can be devised. The aim of this study is to detail the calibration and validation process of a Digital Twin applied to the Muriaé river watershed. Simulations were performed using the MOHID platform. The methodology for evaluating the results included analysis of hydrographs and statistical metrics. This analysis allowed to find out that combining data from two sources yielded better results for model validation by more accurately representing the flow of the modeled channel compared to observed data from river gauging stations.

Keywords: Computational modelling. MOHID. Validation. Statistical metrics.

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1. INTRODUTION

The natural environment is a complex system under pressure from climate change, pushing the field of environmental science to undergo changes as its scientists are increasingly called upon to address significant questions arising from this complexity and associated uncertainties (BLAIR, 2021). The rise in extreme weather events leads to environmental disasters, considered one of the major challenges faced by public officials in Brazil, as they can threaten city infrastructure and leave parts of the population vulnerable (SALES, 2023).

Humanity creates cities, and consequently, aspects of daily life contribute to detrimental effects on the environment. Issues such as urbanization, irregular occupation of riparian areas, and environmental degradation alter the permeability and roughness of a watershed. All these factors can lead to situations where problems propagate downstream, often exporting issues to neighboring municipalities. Therefore, it is imperative to consider pathways for climate resilience and sustainable development, viewing the watershed as a holistic entity (CHIN *et al*., 2017).

One of the challenges is analyzing hydrological processes at the scale of large watersheds. Understanding the behavior of infiltration capacity and runoff in small-meter areas, where each variable's behavior can be observed, differs from observing the behavior resulting from the combination of all processes defining river runoff. This is because certain elements vary as the watershed scale changes (COLLISCHONN & TUCCI, 2001).

Digitally or virtually representing anthropogenic changes in the hydrological cycle in a realistic manner can contribute to public decision-making aimed at disaster risk reduction measures. Thus, Digital Twins, initially used in engineering, now contribute to the field of environmental science. These hydrological models capture the current understanding of the environment, encoding it into mathematical models capable of representing the desired structure and its behavior, thereby reproducing hypothetical scenarios of interest (BLAIR, 2021).

Hydrological Digital Twins can be developed using various software tools, such as the Hydrologic Engineering Center's River Analysis System (HEC-RAS), the Storm Water Management Model (SWMM), and the Hydrodynamic Model (MOHID). Among the primary applications of hydrological modeling, one can mention: forecasting streamflow, predicting future changes in ecosystems, and understanding the impact of land use changes (ALMEIDA & SERRA, 2017).

To represent the processes of the hydrological cycle, it is necessary to provide input data such as elevation data, rainfall data, Manning coefficient, some of which are associated with known variables like land use classes, vegetation cover, or soil types. However, one of the major challenges researchers face is the absence of data series for the modeled watersheds (COLLISCHONN & TUCCI, 2001).

Two processes are essential to ensure better results in simulations: calibration and validation of the hydrological model. Due to potential discrepancies between measured values and initial model outputs, comparing these results with real data becomes indispensable (BLAINSKI *et al*., 2017). The calibration process allows adjusting the simulated results to match the observed field data, thereby improving the representation of watershed behavior in the model and reducing potential errors in simulations. Calibration can be conducted manually or automatically. In manual calibration, adjustments to input parameters identified through sensitivity analysis as having the greatest influence on the simulated variable are made in an iterative trial-and-error process (SILVEIRA *et al*., 2022).

During the validation stage, the model is run using the parameter values determined during calibration on a different dataset from the one used in calibration. If the model meets minimum quality criteria, it can be considered suitable for simulating the watershed. One method of evaluating simulation results is by comparing the generated hydrograph with observed data, aiming for a close match to the observed hydrograph with good accuracy (BLAINSKI *et al*., 2017).

As previously discussed, understanding and simulating the hydrological cycle are crucial for quantitatively assessing water risk and managing watersheds, especially given the numerous anthropogenic alterations affecting the hydrological cycle, particularly in the context of climate change. In this regard, this study aims to detail the calibration and validation process of a Digital Twin applied to the Muriaé river watershed. To achieve this, statistical metrics were employed, including the Pearson correlation coefficient and the Nash-Sutcliffe efficiency coefficient, to evaluate which strategy best represented the flow of the modeled channel compared to data observed at river gauging stations.

2. MATERIALS AND METHODS

In this section, the study watershed where the Digital Twin was applied will be presented, as well as the methodological procedures for the construction and validation of the model.

2.1 Study area

The study area belongs to the Muriaé river sub-basin, located in the Lower Paraíba do Sul and Itabapoana Hydrographic Region (RH-IX). The focus of analysis includes the four municipalities along the Muriaé river in the Northern and Northwestern regions of the State of Rio de Janeiro, which frequently experience flooding. The study area encompasses the urban areas of these four municipalities of interest: Cardoso Moreira, Italva, Itaperuna, and Laje do Muriaé, covering a total area of 7298 km².

These municipalities are characterized by low population density, as observed in the 2022 Census data from the Instituto Brasileiro de Geografia e Estatística (IBGE): Laje do Muriaé has a density of 28.94 inhabitants per square kilometer (hab/km²); Itaperuna has 91.3 hab/km²; Italva has 48.33 hab/km²; and Cardoso Moreira has 24.8 hab/km² (IBGE, 2023). Historical series data from these four municipalities, provided by the Agência Nacional de Águas e Saneamento Básico (ANA) through the HidroWeb portal, show years with higher precipitation and consequently longer recurrence intervals, such as 1942, 1957, 1961, 1979, and 2011, all with recorded rainfall exceeding 450 mm (HIDROWEB, 2023).

The Muriaé river, one of the main tributaries of the Paraíba do Sul river on its left bank, stretches for 300 km. It flows through a predominantly flat region with topographic amplitude generally less than 100 meters in its surroundings, which contributes to the formation of floodplains during major floods (AGEVAP, 2017; DANTAS, 2000). Therefore, this region deserves attention due to the damages occurring during extreme precipitation events. In Figure 1 the location of the study area is represented.

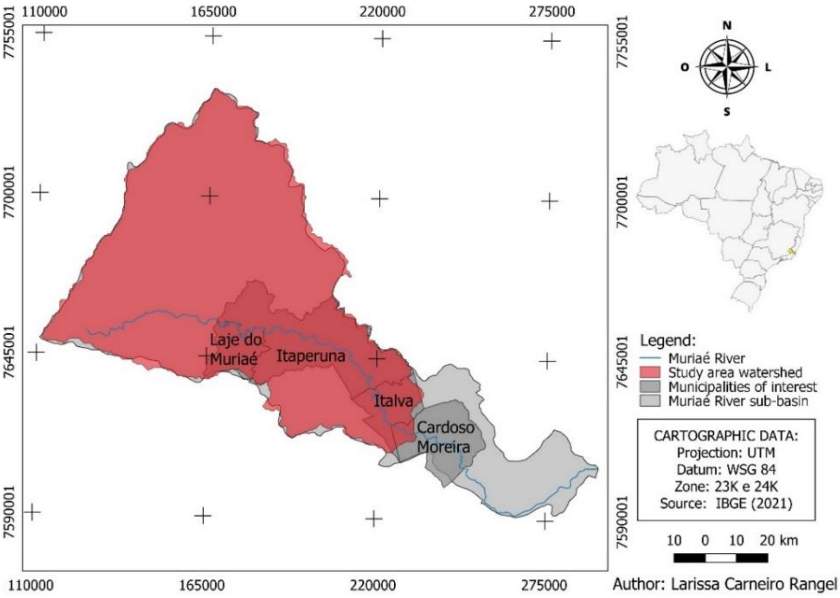

Figure 1. Study Area Location.

2.2 Methodological procedures

The MOHID platform was used for the flow simulations in this study using the Bentley-owned graphical interface known as OpenFlows FLOOD, more specifically by employing the MOHID Land numerical tool. The MOHID platform was developed by the Marine, Environment and Technology Center (MARETEC) at the School of Engineering of the Universidade Técnica de Lisboa, originated in 1985. It is programmed in the ANSI FORTRAN 95 language and has been continuously updated since then (MOHID, 2012).

Data collection regarding river characterization, topographic characteristics of the region, soil types, land use, and extreme precipitation events is essential for constructing the Digital Terrain Model (DTM) and configuring simulation properties. Therefore, it is necessary to define the time period for these activities. The chosen interval spans from January 2012 to June 2015, divided into three phases: warm-up period (January 2012 to June 2012), calibration (July 2012 to June 2013), and validation (July 2013 to June 2015). This period shows high flow peaks, allowing for the assessment of the representativeness of the simulated data compared to the observed data, not only in base flow but also during these peaks.

The Digital Terrain Model (DTM) was developed by importing xyz files of the study region into the program, containing topographic data obtained from TOPODATA of the Instituto Brasileiro de Pesquisas Espaciais (INPE). These files were interpolated using a regular mesh grid with cells of 500m resolution. Smoothing of grid data and removal of depressions in the DTM were performed to ensure that the digital terrain resembles the physical environment accurately. Next, the watershed for this study was delineated, along with its drainage network, starting from an outlet defined downstream of the urban area of Cardoso Moreira.

For a clearer visualization of the stages conducted in this study, in Fig. 2 are presented the steps from defining the study area, gathering necessary data, constructing the Digital Terrain Model (DTM) and delineating the study watershed, configuring simulation properties, running the simulations, and the methodology used for analyzing the results. The configuration phase of simulation properties will be detailed next, focusing on the following aspects adjusted within the platform: drainage network, rainfall, surface runoff, and water percolation in the soil.

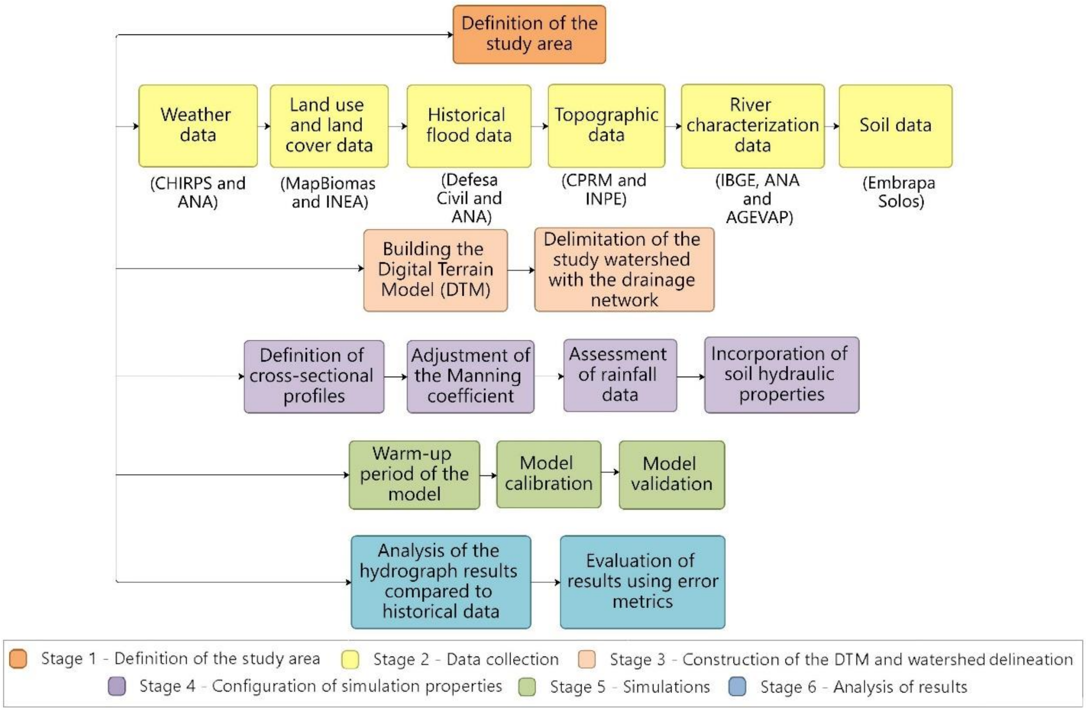

Figure 2. Schematic diagram of the stages for model validation.

2.2.1 Drainage network

The definition of cross-sections for the drainage network can be done using two methods provided in the MOHID platform: based on Strahler stream order or based on drained area. Initially, the Strahler order method was used, with trapezoidal sections divided into 3 orders. The values for these sections were defined using data obtained from river gauging stations and estimates from satellite imagery analysis.

The initial simulations revealed that the model was highly sensitive to changes in the values of the cross-sections. To ensure better model effectiveness, the method for defining cross-sections was switched to be based on drainage area. Following tests conducted during the calibration phase, the following values for cross-sections per drained area were determined, as shown in Tab. 1.

Table 1. Cross-section data defined by drainage area.

Drainage area (km²)	Major base (m)	Minor base (m)	Height (m)	Cross-sectional area (m²)
50.0	10.0	5.0	2.0	15.0
300.0	10.0	5.0	2.0	15.0
500.0	20.0	15.0	2.0	35.0
2200.0	40.0	30.0	2.5	87.5
3000.0	100.0	60.0	3.5	280.0
5633.0	198.0	120.0	4.5	715.5
7298.0	198.0	120.0	4.5	715.5

2.2.2 Surface runoff

The Manning equation is commonly used in runoff propagation models to represent the resistance to flow caused by bed roughness. The roughness of the watershed can be defined using literature values corresponding to predominant land use and vegetation. However, the channel roughness, although it can be initially based on recommended literature values, is typically adjusted through calibration of this coefficient (PAZ, 2010).

Therefore, the values of the channel roughness coefficient were adjusted based on the model calibration results, resulting in a value of 0.05. The coefficient related to the watershed also underwent adjustments throughout the calibration process, and the final values are presented in Tab. 2. These values were associated with the land use and land cover of the region extracted from MapBiomas (2024).

Table 2. Values of the Manning coefficient based on land use and land cover.

Land use and land cover	Percentage of the total area of the watershed	Manning coefficient
Continental water body	0.45%	0.05
Urbanized area	0.81%	0.03
Mining	0.04%	0.09
Uncovered area	0.20%	0.10
Forest vegetation	17.18%	0.30
Grassland vegetation	0.004%	0.25
Silviculture	0.71%	0.28
Pasture	66.40%	0.15
Permanent crops	2.83%	0.20
Other agricultural areas	11.38%	0.20

2.2.3 Precipitation

Precipitation in the MOHID platform can be defined either with a constant value across the grid or using a data file to initialize variable values in space and time, as was the case in the simulations generated in this study. The simulations began using data extracted from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which is a publicly available dataset of nearly global precipitation from 1981 to the present time. CHIRPS interpolates satellite imagery at a resolution of 0.05° with gauge station data to create temporal series of precipitation (FUNK, 2015). These data are provided in NetCDF format, requiring conversion to the HDF5 format used by the MOHID platform.

However, after conducting several simulations, discrepancies were identified between simulated results using CHIRPS data and observed data from weather stations monitored by ANA. Consequently, it was decided to evaluate two sources of precipitation information during the validation process: one based solely on CHIRPS data and another corrected using data from ANA's meteorological stations.

Costa *et al*. (2019) conducted a validation of precipitation data estimated by CHIRPS for Brazil, comparing it with data from meteorological stations within the dataset from the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) of the INPE and the Instituto Nacional de Meteorologia (INMET). In this study, they found that the monthly average of CHIRPS data showed overestimated values with a mean error compared to station data. These annual average precipitation values were calibrated using regional regressions applied to CHIRPS data, resulting in significant improvement in comparison accuracy.

In this work, we used CHIRPS data during periods when the comparison of results with observed streamflows was satisfactory, correcting values with larger differences using data from meteorological stations. To perform this correction, precipitation data from stations in the region were incorporated into the corresponding module using multiple temporal series distributed across the watershed based on Voronoi polygons. The simulation was rerun for the respective month to apply the correction. In Figure 3, these polygons and the locations of the rain gauge stations used can be observed. This data correction occurred in December 2013 and 2014, as well as from January to June 2015.

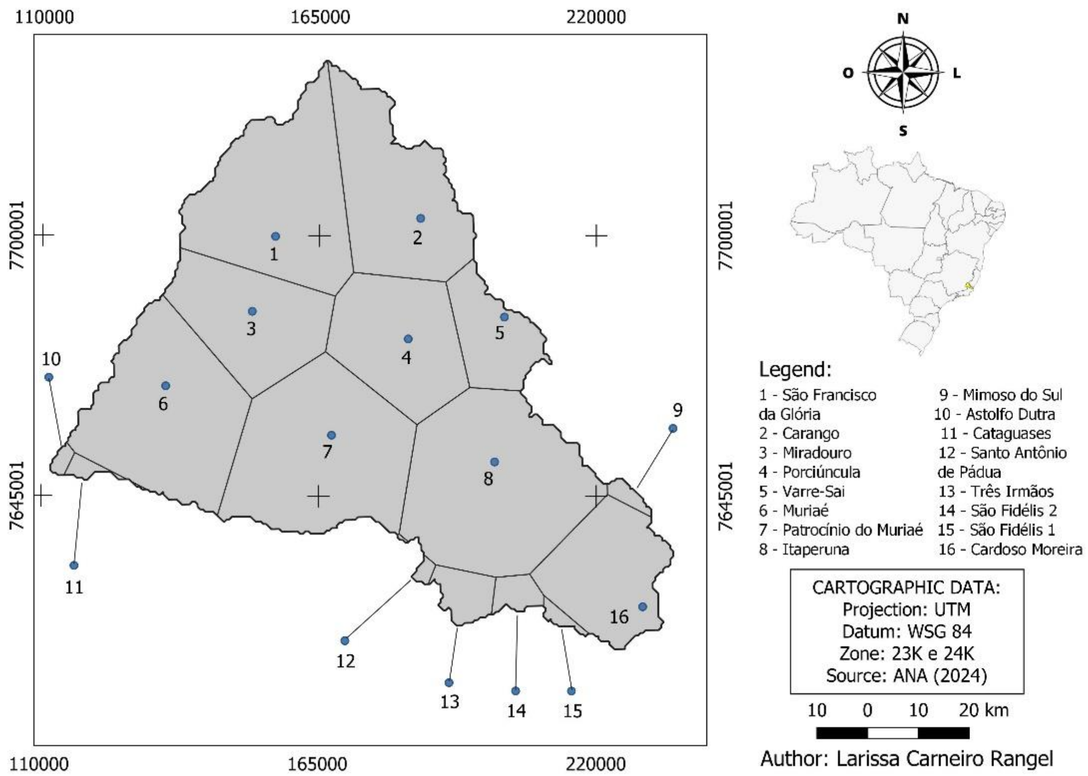

Figure 3. Polygons and respective locations of the rain gauge stations.

2.2.4 Water percolation in the soil

In relation to the permeability of the watershed, a constant value of 0.1 was used for the impermeable fraction. The soil was defined by five layers with the following thicknesses (in meters): 2.0 - 1.0 - 0.4 - 0.3 - 0.3. The hydraulic properties of each soil layer, characterized by the percentage of sand, silt, and clay, were obtained using the MOHID SOIL TOOL. This tool facilitates the processing and preparation of input data for the MOHID platform, importing and processing these soil texture parameters to calculate hydraulic properties for each soil type in the watershed of interest, and generating input files for use in the platform (SALES *et al*., 2024b).

The study region presents seven different soil types, considering the first three categorical levels of the Brazilian Soil Classification System. Regarding the first categorical level, the region contains soils from the orders of Argissolo, Cambissolo and Latossolo (EMBRAPA, 2006). The distribution of soils in the study area is shown in Fig. 4, as provided in the Soil Map of Brazil by Embrapa (2011).

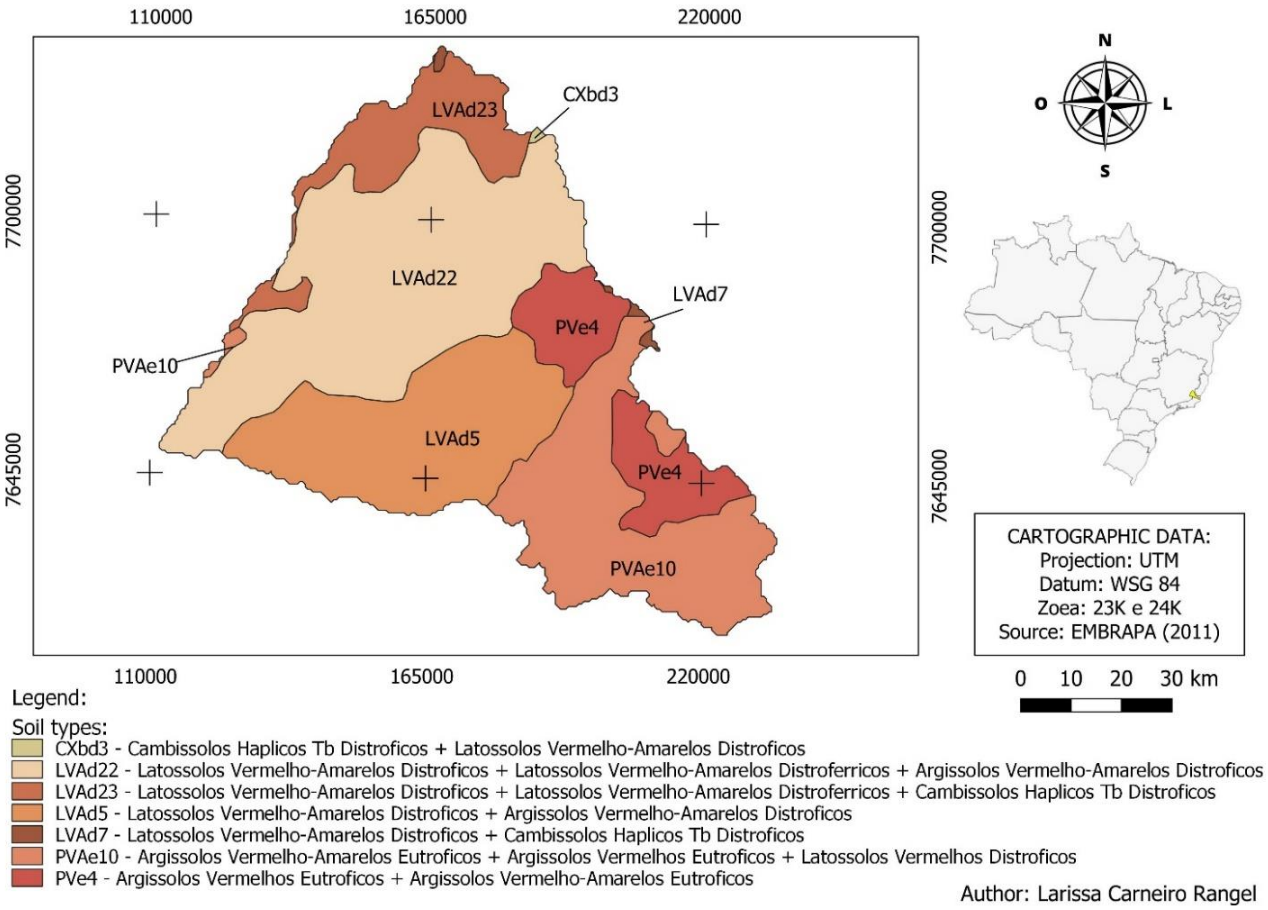

Figure 4. Soil types present in the study area.

With all these adjustments made, it was possible to run the validation phase simulations and analyze their results. For outputting the results, two nodes were created at the locations of the river stations in Itaperuna and Cardoso Moreira, as these are the two stations in the municipalities of interest for which ANA provides flow data. The hydrographs generated allowed for comparing the observed data with the data generated in the simulations, as will be demonstrated in the following section.

Additionally, in the following section, the process of analyzing the results through error metrics BIAS, Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), as well as the Pearson correlation coefficient (R), coefficient of determination (R^2), and Nash-Sutcliffe efficiency coefficient (NSE) are reported. The values were determined using the Timeseries Error and Uncertainty Analyzer tool (SALES *et al.*, 2024a). Both the hydrographs and this analysis were conducted for the two sources of precipitation information processed, based solely on CHIRPS and with data corrections based on the stations. Thus, model validation was achieved.

3. RESULTS AND DISCUSSION

The visual analysis of the hydrograph at the two outlet nodes in Itaperuna, RJ, and Cardoso Moreira, RJ, allows us to observe the model warming-up period and the representation of simulated discharge compared to observed discharge during the calibration phase, as shown in Fig. 4.

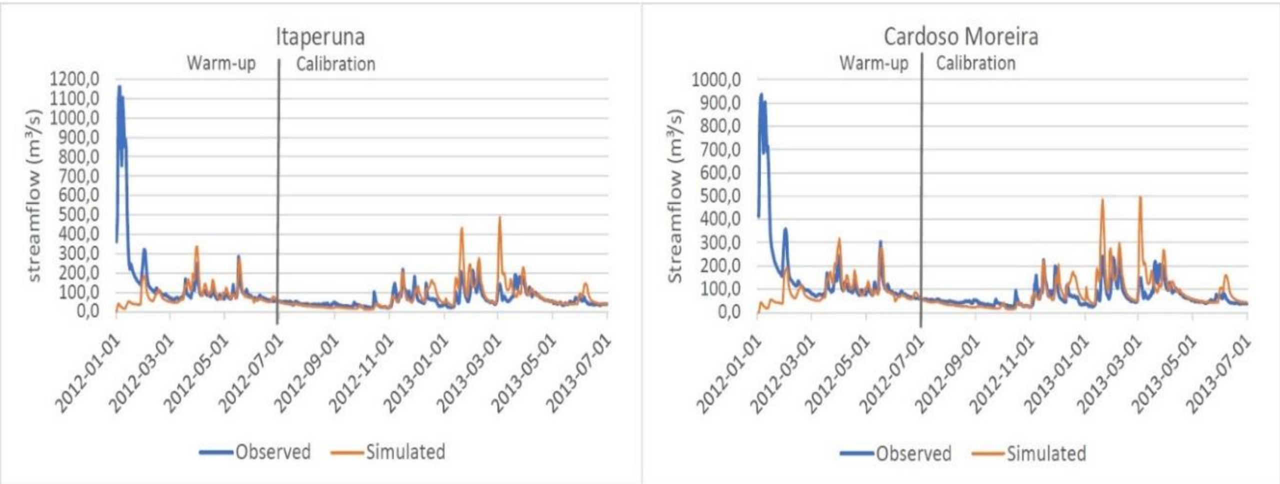

Figure 4. Warm-up period and calibration.

For model validation, we chose to assess the correction of some rainfall data based on meteorological stations. Thus, we compared the hydrograph of simulated discharge using only CHIRPS data with discharge when station data were substituted. The difference in these results can be seen in Fig. 5 for December 2013 and 2014, as well as for the months of 2015 when rainfall data changes were made.

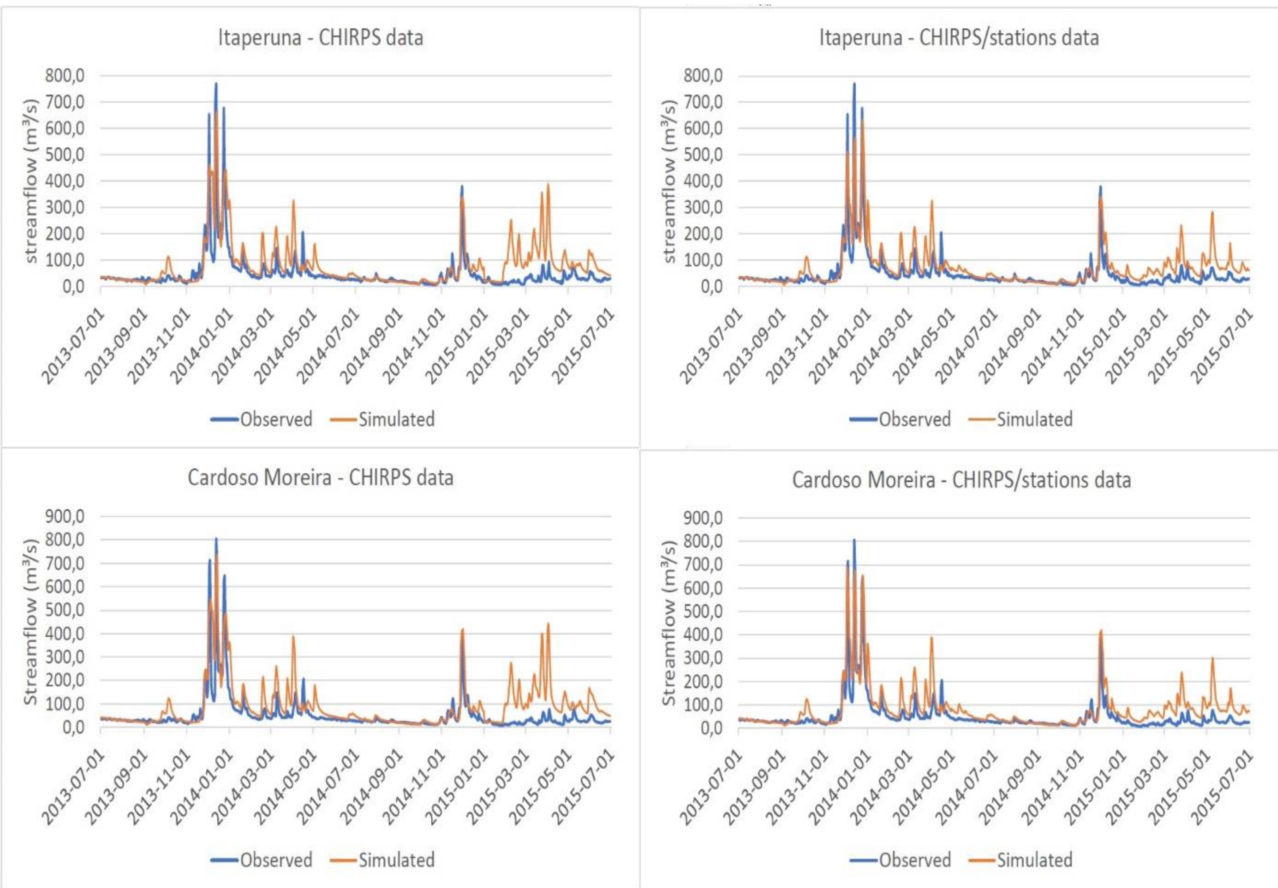

Figure 5. Validation with CHIRPS rainfall data vs. CHIRPS/Station data.

The analysis of the results was conducted, in addition to observing the hydrograph, using statistical metrics including: BIAS, MAE, MAPE, RMSE, R, R^2, and NSE. Schober *et al*. (2018) and Eryani *et al*. (2022) present an approach to interpreting the values of the correction coefficient and the Nash-Sutcliffe efficiency coefficient, respectively. These interpretations of the coefficients are presented in Tab. 3 and 4.

Table 3. Conventional approach for interpreting the Absolute Magnitude of Pearson correlation coefficient.

Absolute Magnitude of Correlation Coefficient - | R |	Interpretation
0.00–0.10	Insignificant correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

Source: Adapted from SCHOBER *et al*., 2018.

Table 4. Conventional approach for interpreting the Nash-Sutcliffe efficiency coefficient.

Nash-Sutcliffe efficiency coefficient - NSE	Interpretation
NSE<0.35	Less satisfactory efficiency
0.36–0.75	Satisfactory efficiency
0.76–1.00	Good efficiency

Source: Adapted from ERYANI *et al*., 2022.

NSE (Eq. 1) has been widely used to evaluate the performance of hydrological models, where NSE=1 indicates a perfect fit between simulated and observed data (DUC & SAWADA, 2023).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(o_i - s_i)^2}{\sum_{i=1}^{n}(o_i - \mu_o)^2} \qquad (1)$$

where s_i and o_i denote simulations and observations, respectively, and μ_o is the observed mean.

In Table 5, the values of the statistical metrics for the two precipitation sources are presented. This comparison allows us to observe improvements in error values when replacing periods with the greatest differences between simulated and observed data. These replacement periods were identified initially, and it was later confirmed that the precipitation data provided by CHIRPS on certain days during these months differed from the data from meteorological stations in the region.

Table 5. Comparison of error metrics between validation using CHIRPS precipitation data and CHIRPS/stations in Itaperuna/RJ and Cardoso Moreira/RJ.

Simulations performed in MOHID Land		BIAS	MAE	MAPE	RMSE	R	R^2	NSE
Itaperuna	CHIRPS	34.64	42.61	42.75	73.62	0.71	0.50	-0.05
	CHIRPS/stations	24.86	32.25	40.89	52.11	0.83	0.69	0.48
Cardoso Moreira	CHIRPS	42.42	49.24	42.86	83.57	0.72	0.52	-0.09
	CHIRPS/stations	31.54	36.76	40.93	57.93	0.86	0.74	0.48

The Pearson correlation coefficient and Nash-Sutcliffe efficiency coefficient also showed significant improvement after replacing the previously mentioned months. While the initial strategy already classified as having strong correlation based on R, the NSE value saw a substantial improvement from less satisfactory efficiency to satisfactory efficiency.

Finally, this analysis includes a scatter plot of simulated discharge versus observed discharge for the two precipitation data strategies used. In Figure 6, we observe the improvement in results when using precipitation data from two sources, CHIRPS and local meteorological stations. Based on these analyses, the model was validated, with potential for future adjustments to enhance it in subsequent work.

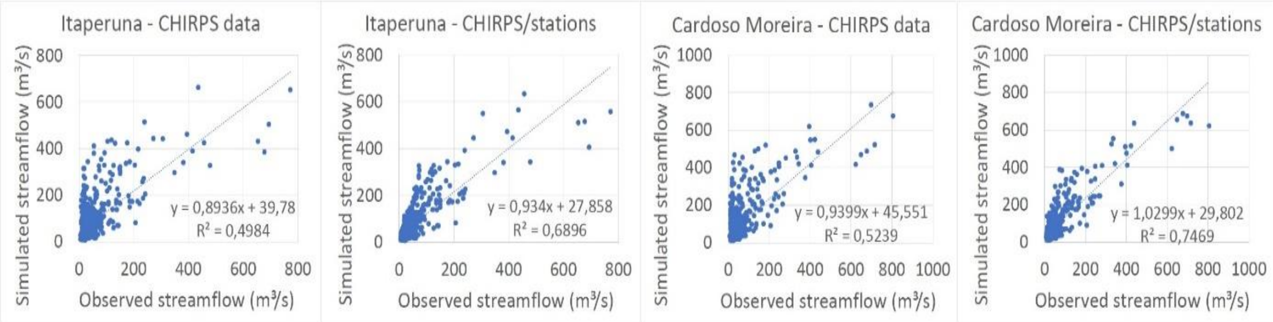

Figure 6. Scatter plot of simulated discharge vs. observed discharge for CHIRPS precipitation data vs. CHIRPS/stations.

4. FINAL CONSIDERATIONS

Hydrological modeling plays a crucial role in urban planning due to its ability to predict scenarios where alternative strategies can be discussed to mitigate the environmental disasters cities are facing. Seeking adaptation strategies to address the challenges posed by climate change can contribute to reduce the risk of these disasters.

Therefore, integrating Digital Twin technology into water resources management can assist municipal managers in decision-making processes aimed at mitigating environmental and social impacts that could be prevented, neutralized, or reduced. For this purpose, public policies should consider integrated strategies that move beyond ideological and utopian planning and instead focus on practical implementation. This approach should be associated with efficient and participatory management capable of addressing the various challenges ahead.

The developed model presented two alternatives for precipitation data sources. Comparing the simulation results through analysis of the generated hydrograph and evaluation of statistical metrics allowed for model calibration and validation. It was found that the alternative combining two data sources yielded better results. The model validation confirms that it should perform well in representing the region during other periods of interest, although evaluation of the precipitation data used as input remains necessary.

As future work, simulations can be conducted to assist in investigating the areas of the basin that have the most impact on flooding occurrences, as well as studying mitigation scenario proposals related to this frequent disaster in the region. The validated Digital Twin enables scenario evaluation through a spatial and temporal multiscale view of the region, providing results with high representativeness.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from the Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) – Funding Code 001.

REFERENCES

AGEVAP. Associação Pró-Gestão das Águas da Bacia Hidrográfica do Rio Paraíba do Sul. **Relatório de Situação da Região Hidrográfica do Baixo Paraíba do Sul e Itabapoana**. Rio de Janeiro, 2017.

ALMEIDA, L.; SERRA, J. C. V. Modelos hidrológicos, tipos e aplicações mais utilizadas. **Revista FAE**, Curitiba, v. 20, n. 1, p. 129 - 137, jan./jun. 2017. Available at: <https://revistafae.fae.edu/revistafae/article/view/113>. Accessed on: March 15, 2024.

BLAINSKI, E.; ACOSTA, E.; NOGUEIRA, P. C. P. Calibração e validação do modelo SWAT para simulação hidrológica em uma bacia hidrográfica do litoral norte catarinense. **Revista Ambiente e Água**. v. 12, n. 2, Taubaté – mar. / abr. 2017.

BLAIR, G. S. Digital twins of the natural environment. **Patterns** 2, v. 2, 2021. Available at: <https://www.sciencedirect.com/science/article/pii/S266638992100221X>. Accessed on: January 11, 2024.

CHIN, A.; LUZZADDER-BEACH, S.; SOLECKI, W. D. Challenges of the “Anthropocene”. **Anthropocene**, v. 20, 2017, p 1–3.

COLLISCHONN, W.; TUCCI, C. E. M. Simulação Hidrológica de Grandes Bacias. **Revista Brasileira de Recursos Hídricos**, v. 6, n.1, jan/mar 2001, p 95-118.

COSTA, J.; PEREIRA, G.; SIQUEIRA, M. A.; CARDOZO, F.; SILVA, V. V. Validação dos dados de precipitação estimados pelo CHIRPS para o Brasil. **Revista Brasileira de Climatologia**, ano 15 – vol. 24, 2019.

DANTAS, M. E. **Estudo Geoambiental do Estado do Rio de Janeiro - Geomorfologia do Estado do Rio de Janeiro**. CPRM – Serviço Geológico do Brasil. BRASÍLIA, 2000.

DUC, L.; SAWADA, Y. A signal-processing-based interpretation of the Nash–Sutcliffe efficiency. **Hydrology and Earth System Science**, 27, p.1827–1839, 2023.

EMBRAPA. Centro Nacional de Pesquisa de Solos. **Sistema Brasileiro de Classificação de Solos**. 2 ed. Rio de Janeiro: Embrapa Solos, 2006. Available at: <https://www.agrolink.com.br/downloads/sistema-brasileiro-de-classificacao-dos-solos2006.pdf>. Accessed on: August 14, 2024.

EMBRAPA. **Mapa de Solos do Brasil**. 2011. Available at: <https://geoinfo.cnps.embrapa.br/layers/geonode%3Abrasil_solos_5m_20201104>. Accessed on: June 10, 2024.

ERYANI, I G. A. P.; JAYANTARI, M. W., WIJAYA, I K. M. Sensitivity Analysis in Parameter Calibration of the WEAP Model for Integrated Water Resources Management in Unda Watershed. **Civil Engineering and Architecture**, v. 10, n. 2, p. 455-469, 2022.

FUNK, C.; PETERSON, P.; LANDSFELD, M.; PEDREROS, D.; VERDIN, J.; SHUKLA, S.; HUSAK, G.; ROWLAND, J.; HARRISON, L.; HOELL, A.; MICHAELSEN, J. The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. **Nature - Scientific Data**, 2015.

HIDROWEB. **Sistema Nacional de Informações sobre Recursos Hídricos**. Available at: <https://www.snirh.gov.br/hidroweb/serieshistoricas>. Accessed on: May 20, 2023.

IBGE - Instituto Brasileiro de Geografia e Estatística. **Manual Técnico de Uso da Terra**. Manuais técnicos em geociências – número 7, Rio de Janeiro, 3ª edição, 2013.

IBGE - Instituto Brasileiro de Geografia e Estatística. **Censo 2022: População e Domicílios - Primeiros Resultados**. Available at: <https://censo2022.ibge.gov.br/panorama/>. Accessed on: June 29, 2023.

MAPBIOMAS. **Projeto MapBiomas – Coleção 8 da Série Anual de Mapas de Cobertura e Uso da Terra do Brasil**. Available at: <https://brasil.mapbiomas.org/>. Accessed on: May 1, 2024.

MOHID. **Descrição do MOHID**. MARETEC, Instituto Superior Técnico, Universidade Técnica de Lisboa. Translation: RODRIGUES, P. P. G. W.; translation review: NASCIMENTO, E. C.; technical review: JUNIOR, J. L. Essentia Editora: Campos dos Goytacazes, 2012.

PAZ, A. R. **Simulação hidrológica de rios com grandes planícies de inundação**. 2010. Tese (Doutorado em Recursos Hídricos e Saneamento Ambiental) – Instituto de Pesquisas Hidráulicas da Universidade Federal do Rio Grande do Sul, Porto Alegre, 2010.

SALES, C. B. Governança Ambiental e Gestão de Riscos e de Desastres (GRD): avanços e desafios da agenda de adaptação em nível local no Brasil. **Revista Política e Planejamento Regional**, v. 10, n. 2, p. 104 – 122, mai./ago. 2023.

SALES, D. S.; LUGON JUNIOR, J.; COSTA, D. A.; SILVA NETO, A. J. **MOHID SOIL TOOL - Computational Tool for Determining Soil Water Percolation Parameters** (Version 2.0.0) [Computer software], 2024a. Available at: <https://github.com/dhiegosales/MOHID_SOIL_TOOL>. Accessed on: May 15, 2024.

SALES, D. S.; LUGON JUNIOR, J.; COSTA, D. A.; SILVA NETO, A. J. **Timeseries Error and Uncertainty Analyzer** (Version 1.0.0) [Computer software], 2024b. Available at: <https://github.com/dhiegosales/Error-and-Uncertainty-Series-Analyzer>. Accessed on: May 30, 2024.

SCHOBER, P.; BOER, C.; SCHWARTE, L. A. Correlation coefficients: appropriate use and interpretation. **Anesthesia & Analgesia**, v. 126, n. 5, p. 1763-1768, 2018.

SILVEIRA, A.; CAVALCANTI, A. A.; MENEZES FILHO, F. C. M.; SEVERINO, M. F. Calibração do modelo hidrológico SWMM para a bacia do ribeirão vai e volta - Poços de Caldas, Minas Gerais. **Eng Sanit Ambient**, v.27, n.1, p. 55-65, jan/feb 2022.