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Flooding and drying simulation on floodplains using a 2D HEC-RAS model: a Sinos river case study

Simulação de inundação e secagem em planícies usando o modelo 2D HEC-RAS: estudo de caso do rio Sinos

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ABSTRACT

The HEC-RAS software reaches its 6.0.0 version in May of 2021, introducing new computational tools to its users. Among these new tools, HEC-RAS is capable of simulating spatially varied rain and evaporation data by grid, constant values or table format. A 2D Sinos river model was created with the intent of testing mainly these two new tools. The Sinos river is located in the state of Rio Grande do Sul, Brazil. The model was calibrated and validated before being used. This article focus mainly in describing floodplain drying, those in which are used for agricultural purpose.

Keywords: Drying; HEC-RAS; Model; Floodplain; 2D.

RESUMO

Após a atualização 6.0.0 do software HEC-RAS, o introduz novas capacidades computacionais aos usuários. Dentre estas novas ferramentas, o programa dispõe da possibilidade de interpolar espacialmente chuvas e simular dados de evaporação, seja com dados pontuais tabelados, constantes ou em forma de grid. Com a finalidade de testar especialmente essas duas novas funções, um modelo 2D do Rio dos Sinos, no Rio Grande do Sul, Brasil, foi criado, contemplando calibração, validação e simulação de séries históricas. O artigo se atenta majoritariamente às secagens das planícies com plantações localizadas nas proximidades da confluência do Rio dos Sinos com o Rio Jacuí.

Palavras-chave: Secagem; HEC-RAS; Modelo; Planícies; 2D.

INTRODUCTION

The River Analyses System HEC-RAS (United States Army Corps of Engineers, 2021a) is one of the most popular hydrodynamic modelling tools among the water resources community with several applications such as flood risk analyses, design of hydraulic structures and dam break analyses.

In may of 2021, HEC-RAS received an updated, reaching the 6.0.0 version (United States Army Corps of Engineers, 2021b). New computational tools were added as well as updating older tools already present from previous releases. Two newly added tools are explored in this work: The possibility to represent spatially variable rain and evaporation in 2D hydrodynamic models. Both of these tools were not present in previous releases, resulting in a new layer of hydrological detail models could now reach. A case study about the Sinos River and its floodplains is used to verify these tools potential.

Floodplains can be challenging to model, mainly those containing complex hydraulics behavior (Liu et al., 2019). Flood inundations areas are affected by roughness, hydraulic structures, computational parameters in both 1D and 2D modelling. Overall, 2D models achieve better results when simulating floodplains, but still can underestimate or overestimated the inundation area. This work demonstrates new possibilities by adding rain and evaporation data to these models.

The Sinos river locates in the Rio Grande do Sul state, Brasil (Rio Grande do Sul, 2020). It has around 190 km of length, starting at the Caraá city and it outlets at the Jacuí's river delta (Figure 1). The Sinos river watershed drains an area of 3694 km^2, mostly located in the northeastern portion of Rio Grande do Sul state.

The model's region takes into account the Sinos river and it's floodplains. The upstream delimitation locates north of Leopoldo Petri's street and downstream delimitation locates where the Sinos river meets the Jacuí river.

Floodplains are found in the last 10 km of Sinos river and are used for agriculture. The 2D model simulates the water cycle within these floodplains as the case study.

METHODOLOGY

This work uses HEC-RAS to mainly test the new spatially varied rain and evaporation tools present since the 6.0 release, in a case study about the Sinos river. The modeling process utilizes the correct overall 2D modelling guidelines (United States Army Corps of Engineers, 2021c) present in the software's manuals as well as numeric calculus theory.

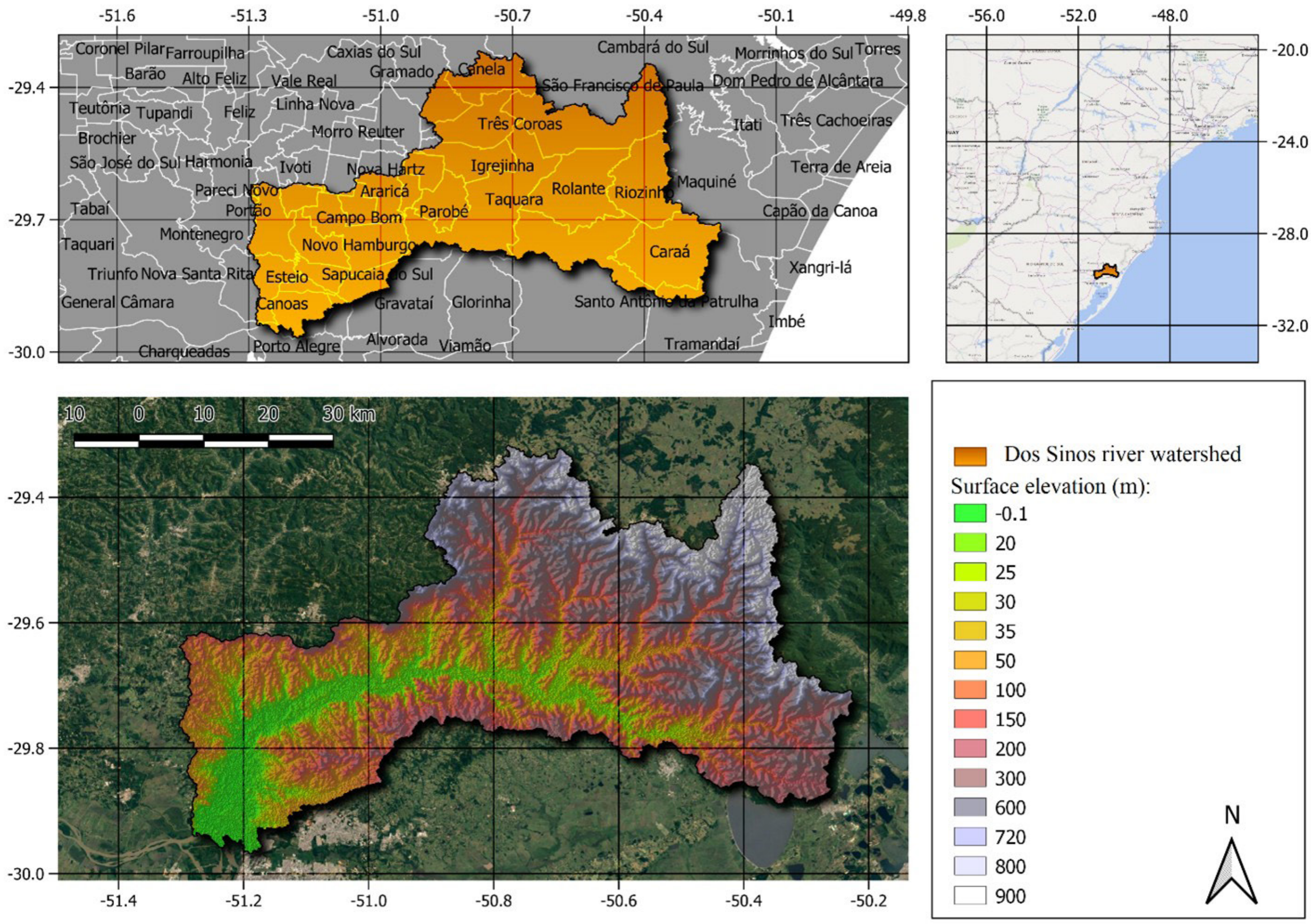

Figure 1. Sinos river watershed location (Google, 2020).

Spatially varied rain and evaporation time series are input in a simulation when locating gauges with their coordinates inside the meteorological tab on the unsteady flow data button and enabling this data type (Figure 2). The data can have a GRID format, be manually entered in table format or even a constant value. The interpolation method is also selected in this tab.

The model's calibration and validation are done by using discharge and stage data from a gauge. Observed values are then compared to simulated values. The quality obtained from the calibration and validation processes are judged by statistic parameters like the determination coefficient (Glantz & Slinker, 1990) and nash-sutcliffe (Nash & Sutcliffe, 1970).

Both spatially varied rain and evaporation are displayed using a side by side view with control simulations, where these tools were not applied. This methodology allows for a clear view on the effects and detailing that the model could achieve by implementing these tools. Water flow inside irrigations channels were detected while simulating, even though there is no direct relationship with the new tools being tested, this adds veracity to the river-floodplain representation and is talked more in detail later in this case study.

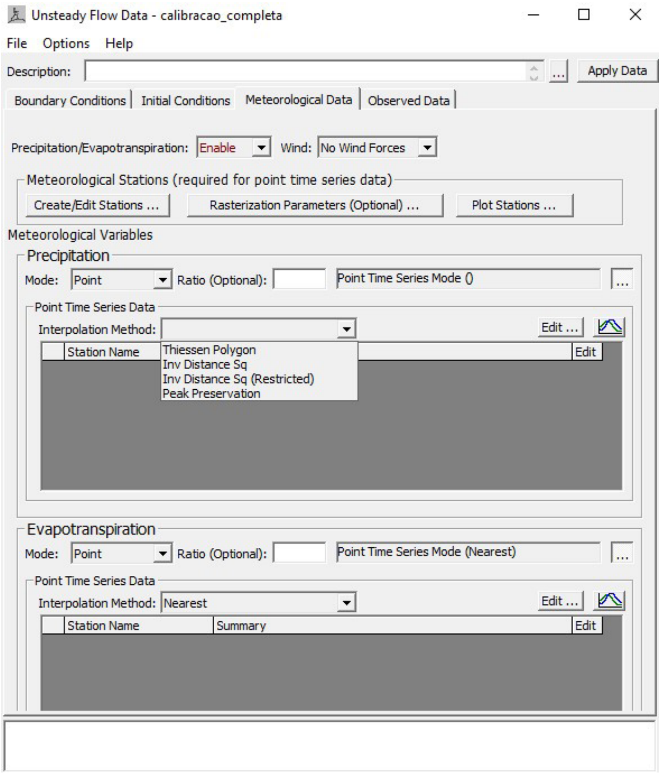

Figure 2. HEC-RAS interface for rain and evaporation data input.

MODEL DEVELOPMENT

Terrain

The terrain data used is a digital surface model (DSM) (Infraestrutura Estadual de Dados Espaciais, 2021). Critical analysis of the model shows that this DSM is satisfactory for what the study achieved by testing the new rain and evaporation tools. The model's usage for flood control is not recommended. This topic is revisited in detail during the conclusion section. The DSM resolution is 2.5 meters.

Bathymetry

Bathymetry is not usually found in digital elevation models because the data acquisition methods can't collect information under water surface. Therefore, a Sinos river bathymetric study (Fundação Estadual de Planejamento Metropolitano e Regional, 2017) was used to digitalize 186 cross sections within the model.

2D Mesh

HEC-RAS' way of interpreting terrain data is through it's geometry, in this case a 2D mesh (United States Army Corps of Engineers, 2021f).

While creating a 2D simulation, computational cells must be generated over the digital elevation model. This cells are part of a mesh and it's dimensions are specified by the user. The software gets the terrain data from the faces of each cell. A good modeling practice is to place these faces over important hydraulic entities like banklines by using breaklines. This increases the simulation's quality (Figure 3).

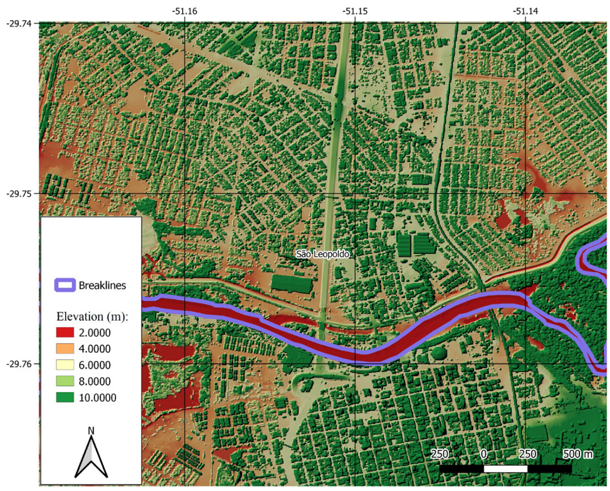

Figure 3. Breaklines being used to increase model veracity.

For the river main pathway, the chosen cell resolution is 15 meters, while 200 meters was determined for the floodplain. Cell resolution changes are linear and not instant between the floodplain and river.

Two lines were placed within the model as boundary conditions to add discharge data upstream and stage data on the outlet.

The outlet gauge had some missing data, therefore another data point, 6 km downstream, is used as a replacement. The gauge code is 87450005. Because of the proximity and flat surface, no level corrections were done.

A Manning's 'n' layer was manually created and added to HEC-RAS. The values used to represent the different types of roughness within the model (Table 1) were chosen based on the specialized literature guidelines (Arcement & Schneider, 1989). The following table gives insight on the values used after the calibration was done and what kind of terrain they are related to:

Modeling hydraulic structures, like bridges, was judged unnecessary because of the objectives of this study.

Calibration

In order to guarantee the model's capability to represent the Sinos river reality to a decent degree, a calibration process was done.

Table 1. Manning's values and the terrain profile.

Terrain	Manning's 'n'
Concrete and urbanized areas	0.0120
Main river	0.0360
Low vegetation floodplain	0.0400
High vegetation floodplain	0.0600
Dense forest	0.0700

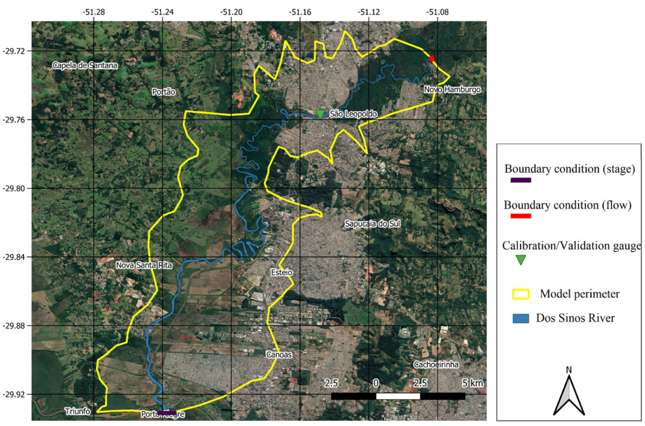

Figure 4. Calibration and validation gauge location (Google, 2020).

To achieve this, an intermediate gauge with stage data was used to compare observed data with simulated values. The simulation representation success is measured with determination coefficient and also nash-sutcliffe.

The chosen gauge is found in São Leopoldo city and it's code is 87382000 (Figure 4). The data series used is from 402 days, going from 6 of july of 2012 to 11 of august of 2013. Before each data series simulation, two days of warm up were simulated with constant discharge and stage values, therefore the river is properly filled with water. This guideline is followed in all simulations, even those that aren't about calibration.

The computational parameters used in the simulation deserve special attention, mainly the Courant number (United States Army Corps of Engineers, 2021d) and the hydraulic equation. By using 5 minutes as the time interval with the possibility of dynamically reducing this interval during the simulation, the Courant number is kept under 1, maintaining computational stability. There was no need for the complete momentum equations because the diffusion wave equation (United States Army Corps of Engineers, 2021e) resulted in both good calibration and validation values and also was enough to test the new HEC-RAS precipitation and evaporation tools.

Equation 1 – diffusion wave:

$$\frac{\partial h}{\partial t} = \nabla.\left(\beta \nabla z_s\right) + q \tag{1}$$

where $\beta = -\dfrac{R^{2/3} h}{n\,|\nabla z_s|^{1/2}}$; $V = -\dfrac{R^{\frac{2}{3}}}{n} \dfrac{\nabla z_s}{|\nabla z_s|^{\frac{1}{2}}}$; $\dfrac{n^2}{R^{4/3}} |V| V = -\nabla z_s$; V is the velocity vector; R is the hydraulic radius; ∇z_s is the water stage gradient; n is Manning's rugosity coefficient.

Finishing the calibration process (Table 2; Figure 5), the results found are the following.

The determination coefficient (R^2) was 0.98 while the nash-sutcliffe was 0.96 for the calibration simulation. The volume error was under 0.003%.

Discharge range performance

After the successful calibration process, the model was tested in three simulations (Figure 6), involving low, average and high discharge data (Table 3).

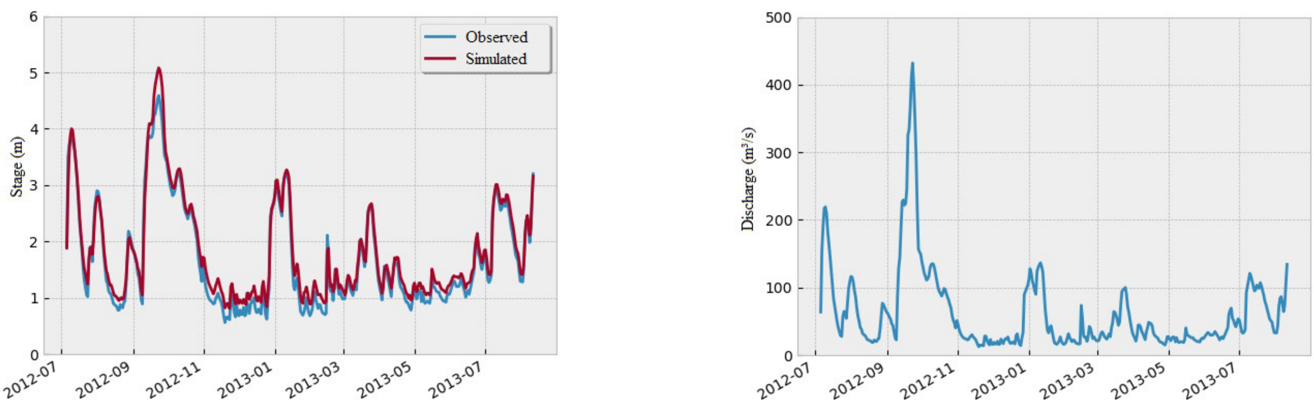

Figure 5. Calibration performance shown in graphical form.

It is possible to observe that the model reaches the best performance with average discharge input and moderate stage oscillation. Flood and drought situations had worse validation, thus the model is not suitable to be used for such studies.

The digital surface model used guarantees that neither calibration nor validation processes are ideal. However, because the point of this work is to use the new evaporation and precipitation tools in HEC-RAS, the model is considered validated enough to be used on the next simulations in this state.

RAIN AND EVAPORATION TOOLS

Choosing precipitation gauges and data series

The data series selected must contain precipitation data in all gauges as well discharge and stage data for boundary conditions.

Table 2. Coefficient performance for each simulation.

	R^2	NSE
Low discharge	0.91	0.36
Average discharge	0.98	0.91
High discharge	0.90	0.64

Table 3. Water covered surface for each simulation.

Simulation \ Date	19/06/1996	05/07/1996	28/07/1996
Discharge only (km^2)	**4.2**	**25.6**	**10.0**
Discharge + rain (km^2)	**61.5**	**66.7**	**31.1**
Discharge + evaporation (km^2)	**3.9**	**25.3**	**6.5**

Five rain gauges were selected (Figure 7) and the data series used for precipitation, discharge and stage were from 12 of july to 6 of august, in 1996.

The used hydrological data, discharge in m^3/s and rain in incremental mm, can be better understood in the following mosaic (Figure 8).

Rain representation in HEC-RAS

The spatially diverse rain was simulated using the squared distance as the interpolation rule. When using this interpolation method, 'eyes' like shapes develop on the HEC-RAS interface displaying rain height (Figure 9). Each cell in the 2D mesh gets rain input based on its location.

Evaporation tools in HEC-RAS

For evaporation data, the adopted value was 100 mm/month (Instituto Nacional de Metereologia, 2021). Being constant for the entire model, each cell inputs this data during the simulation.

Comparing discharge, rain and evaporation simulations

By simulating only discharge data, then discharge plus rain and finally discharge plus evaporation, there is the possibility to clearly see each component and their effect on the hydrological

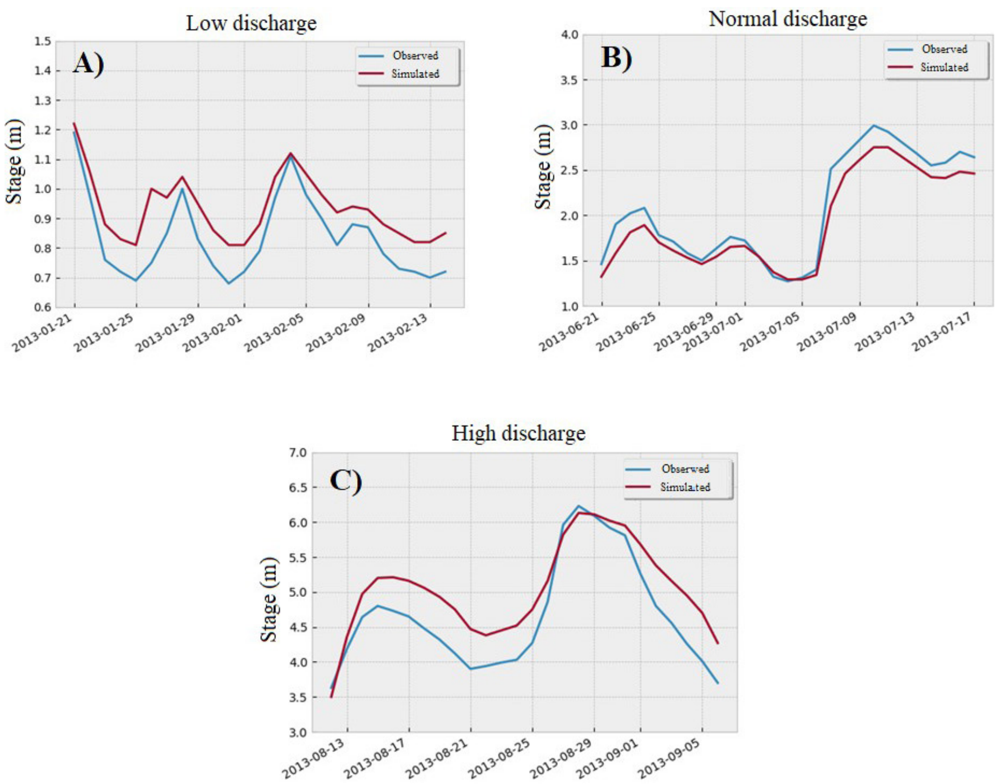

Figure 6. (A) Low discharge data (B) Average discharge data (C) High discharge data.

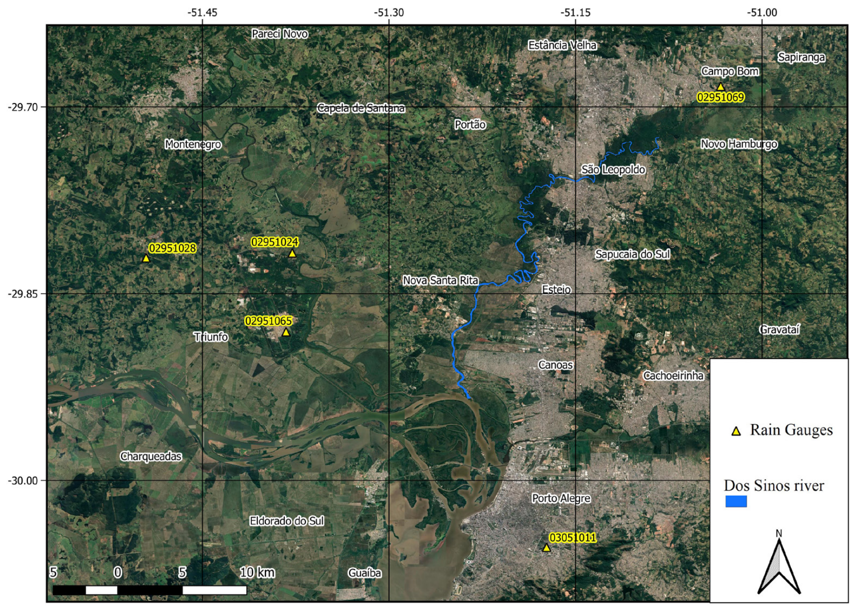

Figure 7. Sinos river and rain gauges' locations (Google, 2020).

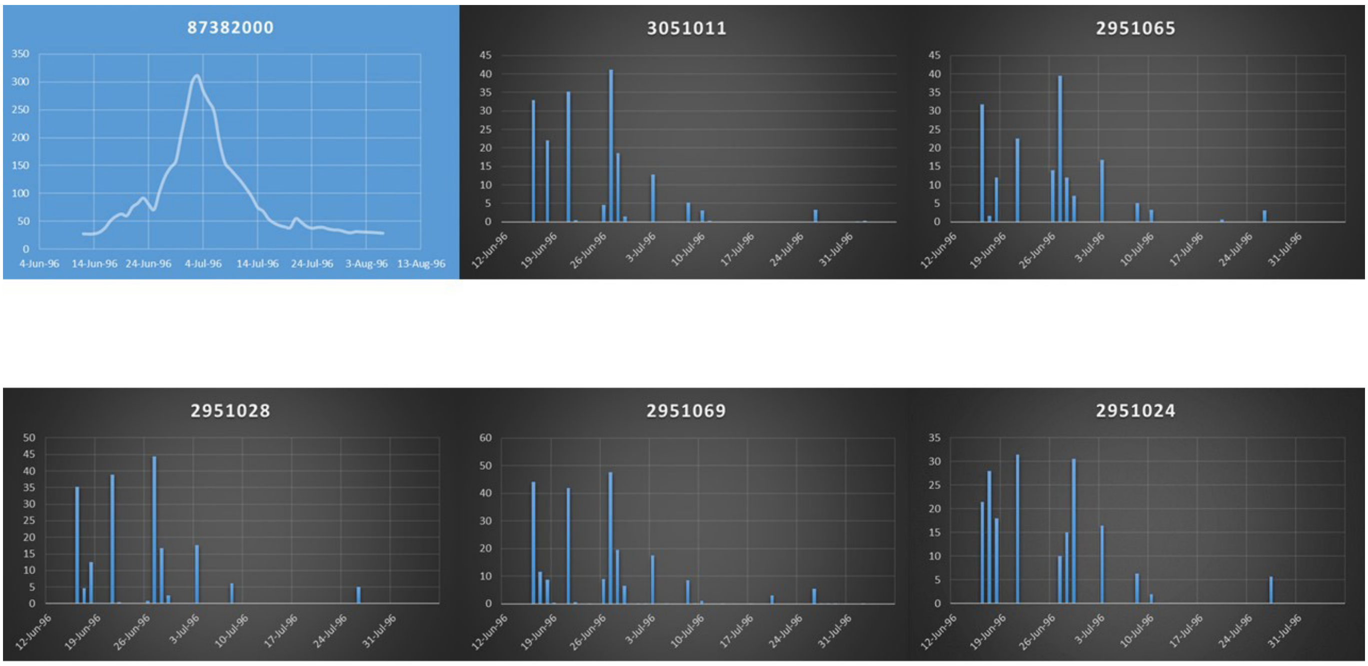

Figure 8. Discharge and rain data series for each gauge.

model (Figure 10). The timestamps chosen to be used in this comparison were 19/06/1996, 05/07/1996 and 28/07/1996.

Rain input is displayed having a large impact on water covered surface when viewed side by side with the discharge data alone. The evaporation effects are better visualized in the third row, when river discharge decreases, leaving water on floodplains to dry out.

Another way to help visualize the different effects between each case is by overlapping the water covered surface without satellite data. The next panel (Figure 11) uses the color red to represent discharge + evaporation data, green to represent discharge only and blue to represent discharge + rain data.

Simulating both rain and evaporation

Finishing off with the last simulation (Figure 12) of this work, every hydrological and climate data are simulated together, displaying what would be the complete usage of the news tools in a HEC-RAS model. The data series starts in 12 of july and ends 06 of august, year 1996.

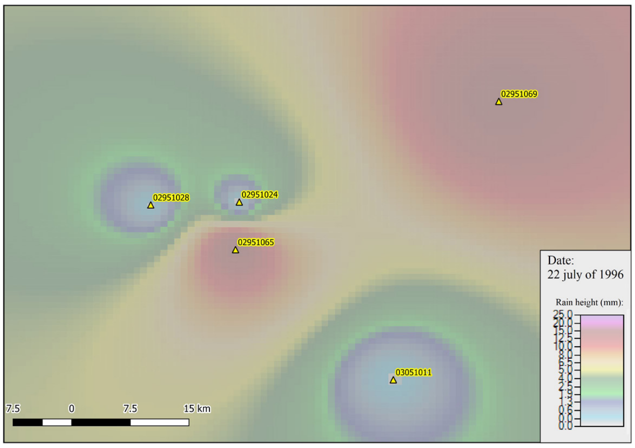

Figure 9. Graphical rain representation as seem in HEC-RAS interface.

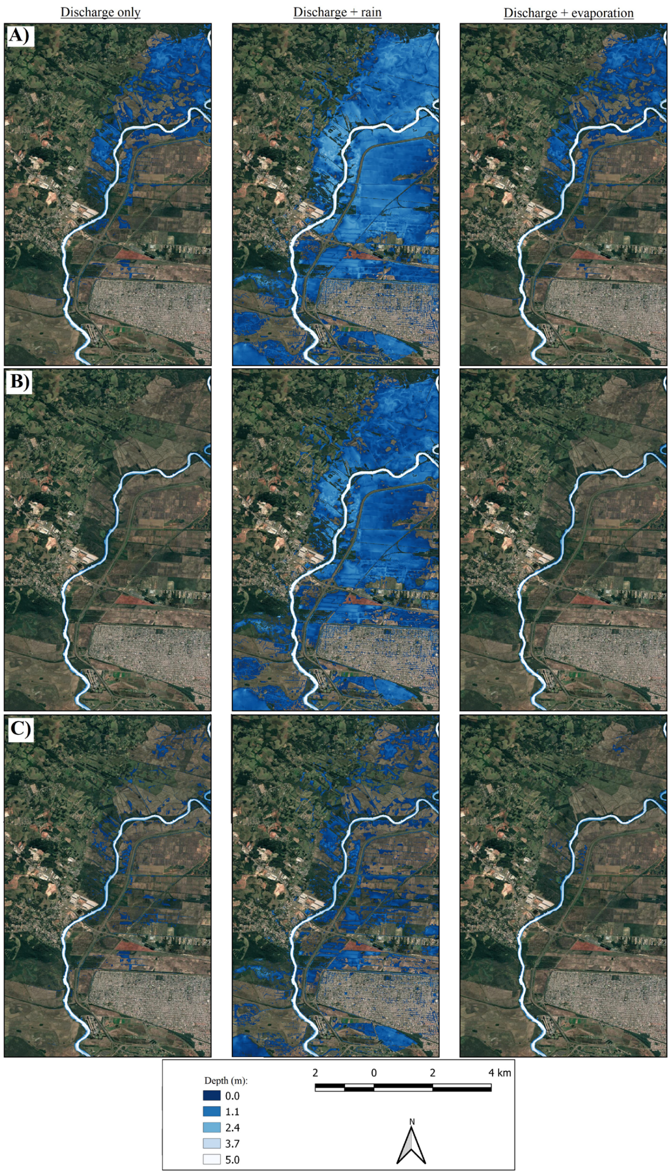

Figure 10. (A) 19/06/1996 (B) 05/07/1996 (C) 28/07/1996. Map source: Google (2020).

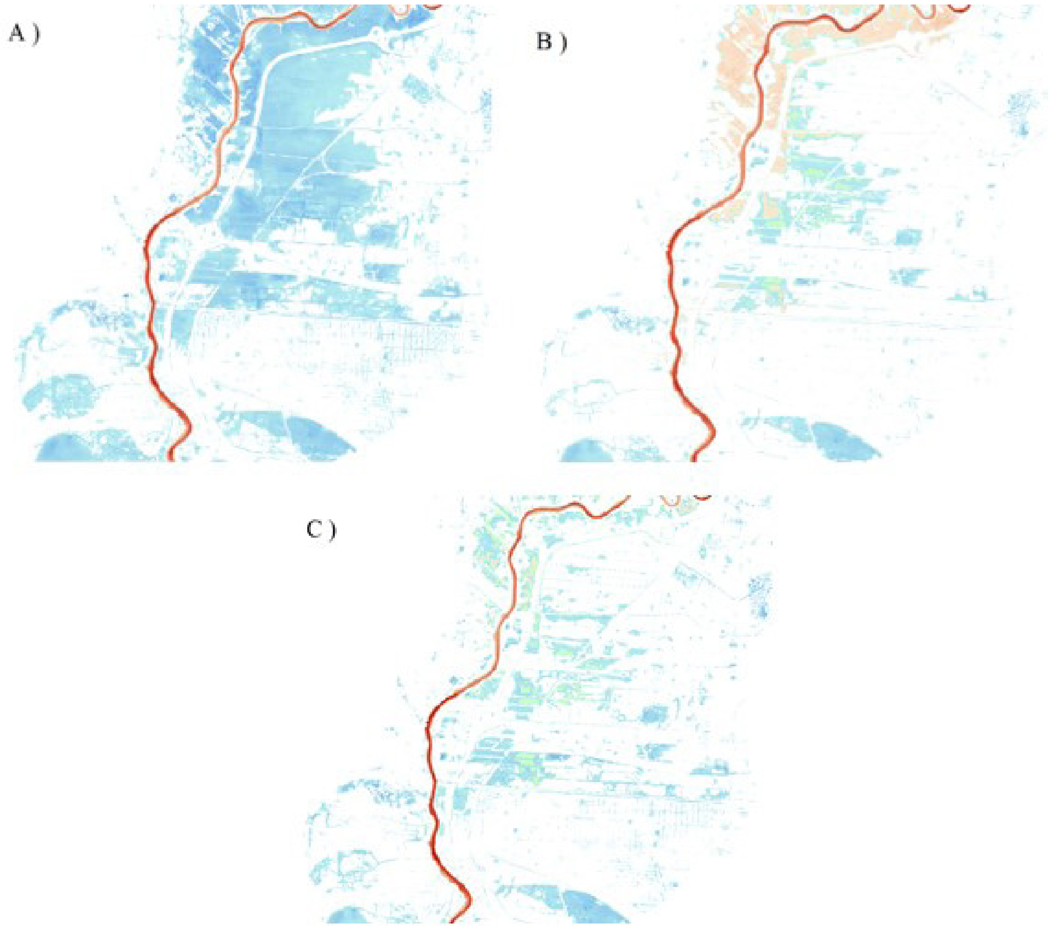

Figure 11. (A) 19/06/1996 (B) 05/07/1996 (C) 28/07/1996. Color legend as described in text.

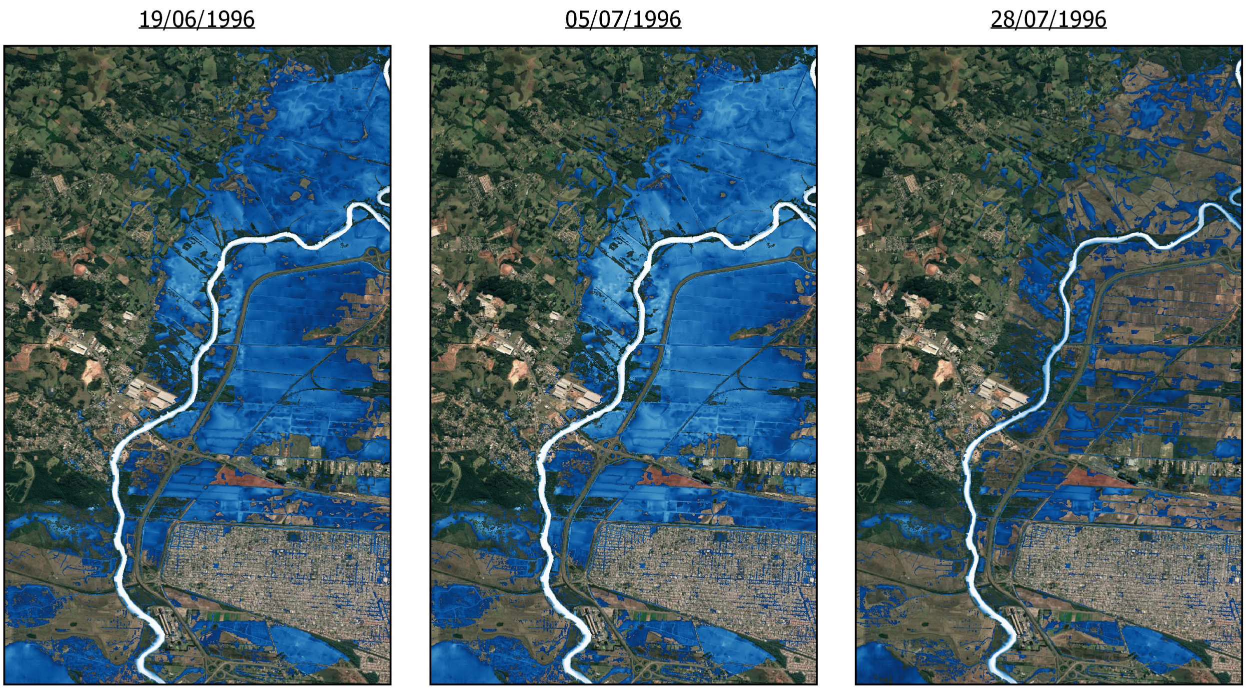

Figure 12. Complete simulation with discharge, rain and evaporation input. (Google, 2020).

Complete floodplain drying

One useful case to study in a hydrological model capable of representing evaporation is the time do fully dry and floodplain, be it after a flood or for agricultural purpose.

To illustrate this event, the previous simulation time was artificially extended without rain data and constant discharge values. It is observed that all entities on the floodplain (even natural depressions) reach complete drought (Figure 13) at 14 of september of 1996. Low depth water surface reaches drought by around half a month.

IRRIGATION CHANNELS OPERATION

One consequence of the high resolution used in the DSM is the possibility to see the irrigation channels working within the floodplain (Figures 14 and 15). These channels were already detailed in the original terrain data. Water flows from Sinos river

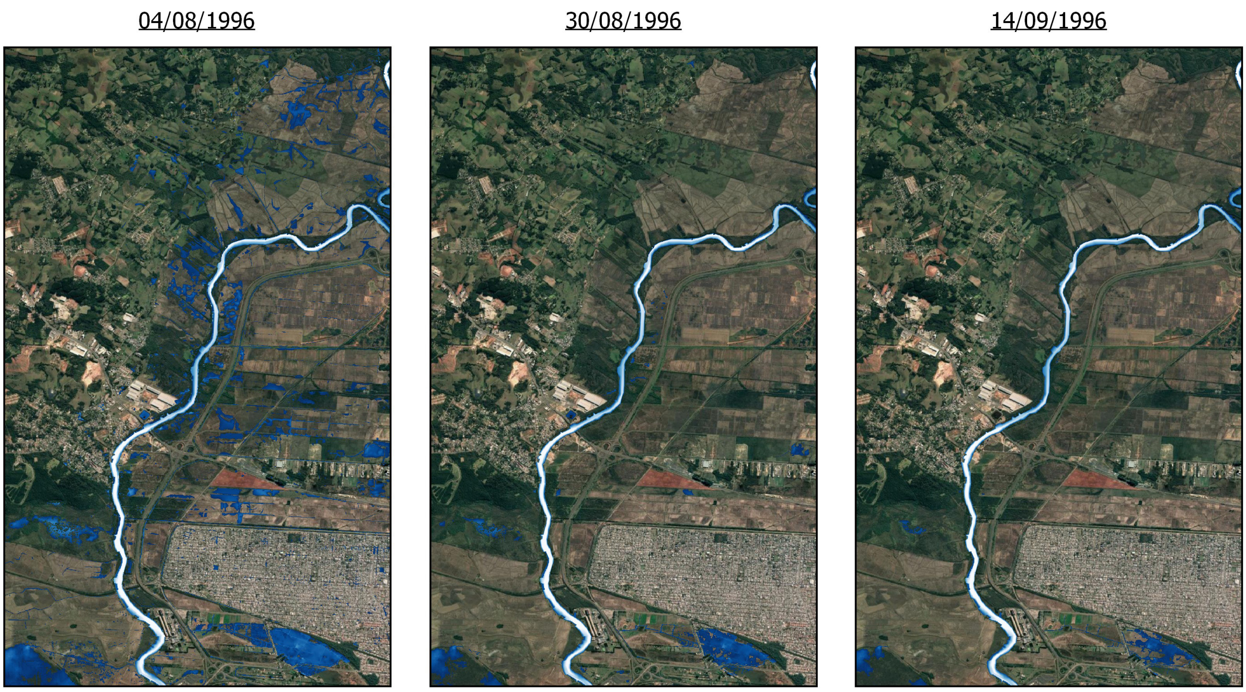

Figure 13. Complete drying of floodplain (Google, 2020).

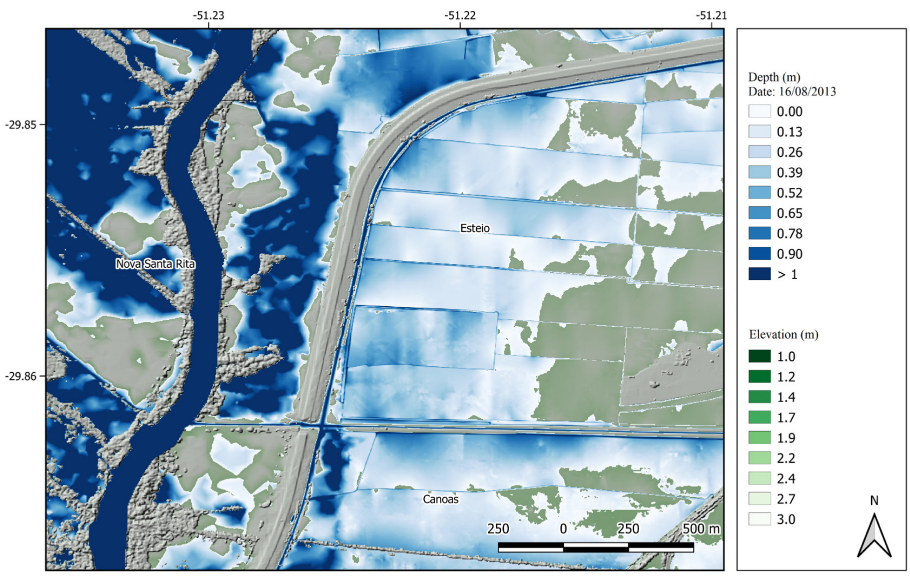

Figure 14. Irrigation channels as seem on HEC-RAS.

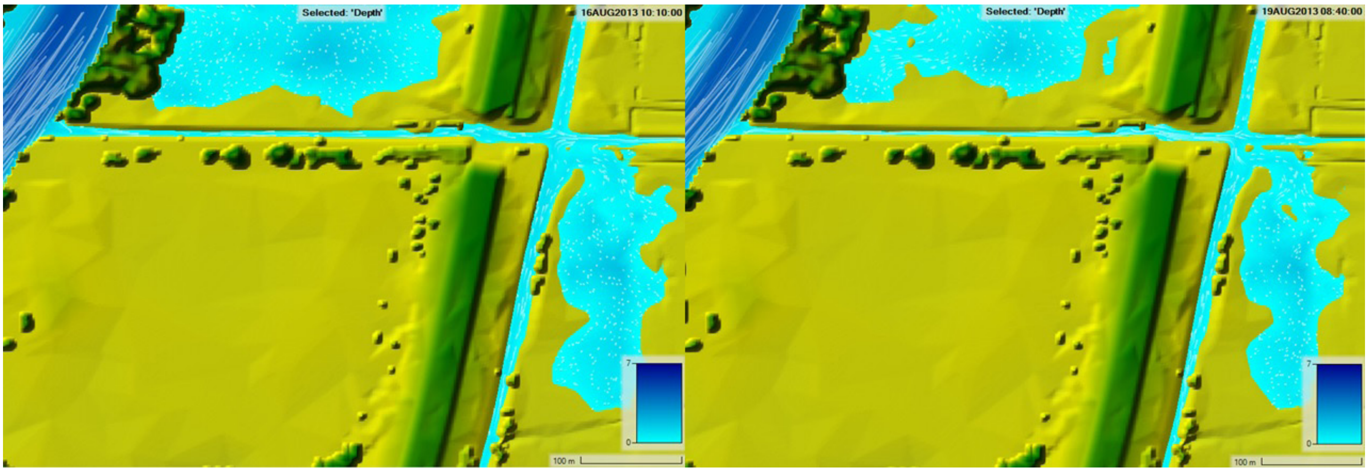

Figure 15. Irrigation channels with tracing particles turned on. Left image: irrigation channel inflow. Right image: irrigarion channel outflow.

to floodplains when discharge values are elevated and also drains back to it when discharge lowers.

CONCLUSION

This study was mainly to test out new possibilities within HEC-RAS. The addition of spatially varied rain and evaporation data in a model was proven useful in representing the hydrological cycle more realistically. The interface was clear to use and the gauge's data was successfully added in the simulations. Sinos river's floodplains dries as low discharge and no rain events take place. Locations affected by rain are dependent on how close they are to a rain gauge, as result of spatial interpolation.

Irrigation channels workings could be observed as result from a hydrodynamic simulation using high resolution DEM, this could lead to new possibilities around agriculture when paired with rain and evaporation input.

The users must be aware about the many spatial interpolations options available for rain as well as evaporation and properly choose one to suit their model. This adds a layer of complexity to the model and makes the sensibility analyses and validation more challenging.

Another challenge when using rain and evaporation data is the lack of information to validate the model outside river channels. Rain and evaporation data are found easier than discharge or water level in these regions. High complexity models could be left validated with only images from satellites.

Rain simulations take a lot of computational power, thus modelling the perimeter to only use as many cells as needed for the model is recommended.

The usage of a surface model wasn't ideal, however it was clear after calibrating and validating the model that the performance reached was enough to argue in favor of its use for this type of study.

This case study was done using floodplains with agricultural purposes, however some other applications could benefit greatly from varied evaporation and rain data. Some examples are reservoirs, detailed drainage systems and ocean affected regions.

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Authors contributions

André Luís Tonin: Conceptualization. Data curation. Investigation. Methodology. Software. Validation. Visualization Writing.

Rodrigo Cauduro Dias de Paiva: Conceptualization. Funding acquisition. Project administration. Writing.

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