Hydrodynamic and Pollutant 2D Model - Manual Version 1.0

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About This File

This file was created for the benefit of all scientists that looks to enhance their hydrodynamic modeling knowledge. The entirety of the contents within this manual, were made with the purpose of being free for public use.

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SECTION 1

Introduction to HydroPol2D

Welcome to HydroPol2D Manual. The objective of this file is to provide a brief introduction to the *Hydrodynamic and Pollutant 2D Model* first developed in (Gomes Jr et al., 2023). This file is organized to present the rationale behind all modeling aspects, as well as examples of how to apply the model to real-world case studies. If you have any questions, please contact us at marcusnobrega.engcivil@gmail.com or luis.castillo@unah.hn.

HydroPol2D is a Matlab model that has most of its input data entered from Microsoft Excel spreadsheets. The model allows a variety of simulations with different boundary conditions, such as spatially-varied rainfall, inflow hydrographs at particular gauges, sattelite rainfall, rainfall derived from gauge interpolation, spatially-invariant design storms of alternated blocks or Huff, and user-defined spatially-invariant rainfall. In addition, the model allows the simulation of internal boundary conditions to represent dam-break scenarios or to control flood in reservoirs due to hydraulic devices such as weirs and orifices.

The model is designed to perform either CPU or GPU computations, which is an important feature when high resolution modeling is required. All computations are raster-based, therefore states are simulated per each cell of the rectangular grid of the domain.

HydroPol2D model was developed in a collaboration between the University of Sao Paulo - Sao Carlos School of Engineering and the University of Texas at San Antonio.

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- The San Antonio River Authority

A list of recent publications associated with the model are presented for reference as follows:

1. Gomes Jr, Marcus N., Vijay Jalihal, and Eduardo Mario Mendiondo. "Exploring the Impact of Rainfall Temporal Distribution and Critical Durations on Flood Hazard Modeling." (2024).

2. Ambrogi Ferreira do Lago, Cesar, Jose Artur Teixeira Brasil, Marcus Nóbrega Gomes, Eduardo Mario Mendiondo, and Marcio H. Giacomoni. "Improving pluvial flood mapping resolution of large coarse models with deep learning." Hydrological Sciences Journal (2024).

3. Rápalo, Luis, Marcus N. Gomes Jr, and Eduardo Mario Mendiondo. "Developing an Open-Source Flood Forecasting System Adapted to Data-Scarce Regions: A Digital Twin Coupled with Hydrologic-Hydrodynamic Simulations." Available at SSRN 4703477.

4. Rápalo, Luis, and Eduardo Mario Mendiondo. Towards establish a continental early warning system for flood preparedness: A study case of south america's data-scarce countries, in No. EGU24-13442. Copernicus Meetings, 2024

5. Gomes Jr, Marcus N., Marcio H. Giacomoni, Fabricio AR Navarro, and Eduardo M. Mendiondo. "Global Optimization-Based Calibration Algorithm for a 2D Distributed Hydrologic-Hydrodynamic and Water Quality Model." arXiv preprint arXiv:2308.16864 (2023).

6. Gomes Jr, Marcus Nóbrega, César Ambrogi Ferreira do Lago, Luis Miguel Castillo Rápalo, Paulo Tarso S. Oliveira, Marcio Hofheinz Giacomoni, and Eduardo Mario Mendiondo. "HydroPol2D—Distributed hydrodynamic and water quality model: Challenges and opportunities in poorly-gauged catchments." Journal of Hydrology (2023): 129982.

7. Sánchez, M.H., Nóbrega, M., de Andrade, M. and Mediondo, M.E., XXV SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS RIVER FLOW FORECASTING METHODS: A REVIEW.

8. de Sousa, Milena Rosa, Marcus Nóbrega Gomes Jr, Enrico de Oliveira Pavan, Luis Miguel, Castillo Rapalo, Fabricio Alonso Richmond Navarro, and Eduardo Mario Mendiondo. "MODELAGEM DISTRIBUÍDA FISICAMENTE BASEADA EM BACIAS URBANAS: MODELO HYDROPOL2D APLICADO À SÃO CARLOS (SP)."

9. Júnior, Marcus Nóbrega Gomes, Enrico de Oliveira Pavan, Luis Miguel Castillo Rapalo, Marcio Hofheinz Giacomoni, and Eduardo Mario Mendiondo. "Modelo Hidrodinâmico e de Qualidade da Água Bidirecional (2DCAWQ): Desafios de Modelagem em Bacias com Dados Escassos: Aplicação na Bacia do Tijuco Preto–São Carlos."

1.1

SUB-SECTION

How to get it

1.1.1 Downloading

The model files and input data used in the paper are found on Github and the link is shown (here). Files are organized in folders and can be easily accessed in Github.

1.1.2 Computational Requirements and Software Packages

HydroPol2D can run in single core computing or parallel mode.

The hardware requirements will vary according to the resolution and detail of each case study simulated. The study case extension is directly proportional to the memory requirements, since all matrices follow the domain size. We recommend a unit with the least 8 GB of RAM if a single core mode is used for the computations. On the another hand, we recommend a unit with GPU (NVIDIA) with at least 2 GB of VRAM and 3.5 of Compute Capability (see Nvidia GPUs) for the parallel mode.

The software requirements are related to Matlab license and the additional packages employed, according to the processing mode choose. Regular Matlab essentials license is required for both processing modes. For single core mode, the Mapping Toolbox is required (see Mapping Toolbox). For the parallel mode, the Mapping Toolbox and the Parallel Computing ToolBox (see Parallel Toolbox) are required.

1.1.3 Additional Software Required

Users need to have access to additional software for data preparation and post-processing activities:

- Microsoft Excel, this spreadsheet application will help to organize the input data required by the model, such as rainfall data, and land use and land cover characteristics, coordinates of points of interest, model's performance parameters, among others.
- QGIS or any GIS software tool that works with rasters to allow the user for preprocessing initial data requirements (see Sec. 1.1.6), and as a post-processing, such as visualization or any other process required by the user with the model outputs.

1.1.4 Input Data Files

In this section, we provide an overview of the input data. Here are described the input data files required and the overall information to run HydroPol2D. The data files required vary according to the model execution mode (Fig. 1). This figure has clickable buttons that bring the reader to the specific sections where the input is detailed. Also, the HP model button links to the GitHub website to download the model.

For HydroPol2D input data structure, we use .xlsx sheets to facilitate the procedure of assigning model parameters according to the user defined input data.

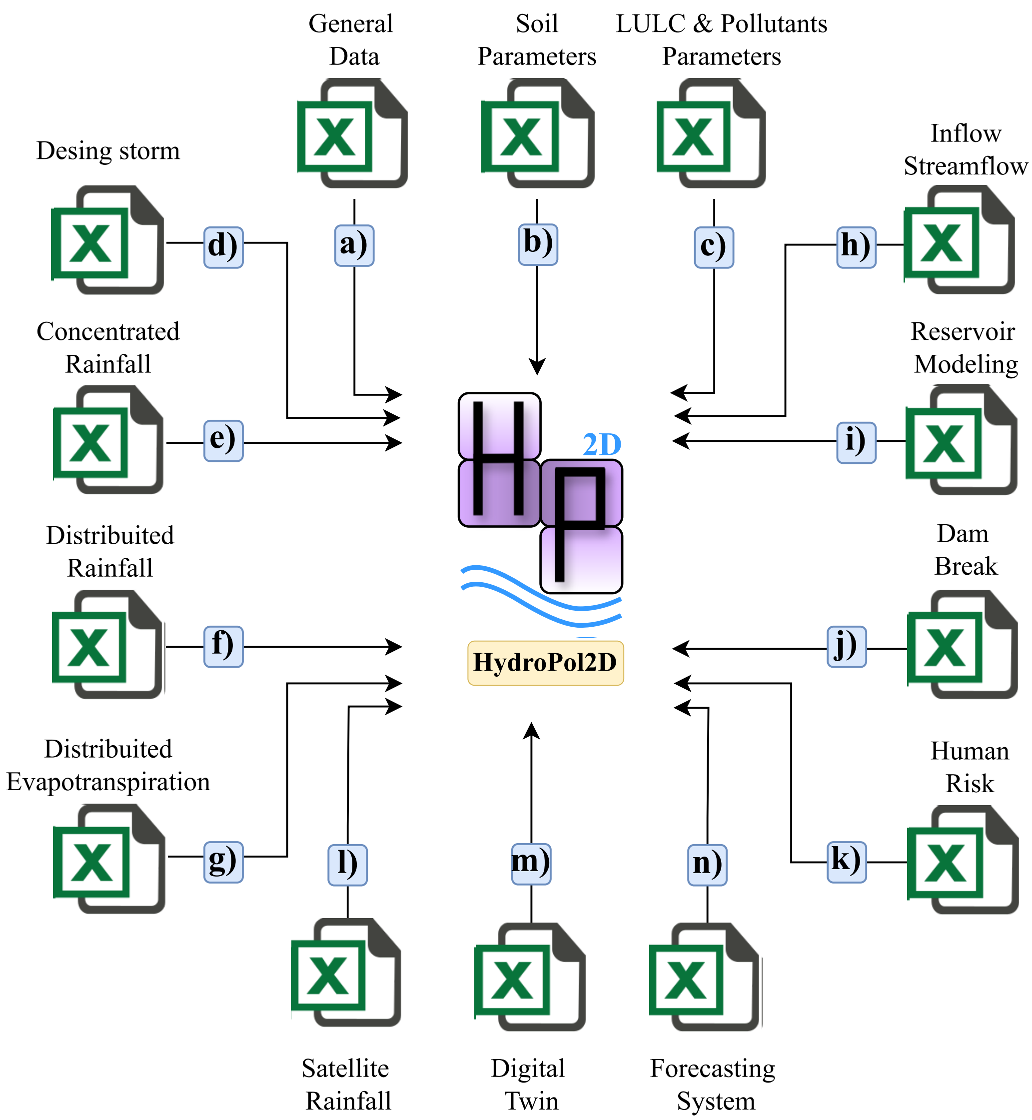


Figure 1: HydroPol2D - data input data structure according to the execution mode. "Clickable Icons".

1.1.5 Soil, Land Use and Land Cover, and Pollutants Parameters

This section consists of the input data required to HydroPol2D as a function of the LULC and soil classifications. Assigned parameters of the model vary with the rasters of LULC and Soil of the study area. We include some reference values for a first order approximation in Sec. 1.1.6. We also recommend that the rasters of LULC and Soil be in the Pseudo Mercator reference coordinate (EPGS:3857).

Related to land use and land cover, it is necessary to specify the name (for plotting results i.e., impervious, developed areas) and index for each class (e.g., 1, 2, ...). Parameters for the hydraulic and water quality behaviour are necessary, such as: manning roughness coefficient (n), initial abstraction (h_0), initial water depth condition (d_0), pollutant build-up and wash-off coefficients (C_1, C_2, C_3, C_4). In Fig. 2 are shown the structure for the LULC and pollutants parameters. Notice that there is an impervious index that has to be specified in order to impose zero infiltration in such areas. If you don't specify it, the model will assume that infiltration can occur in this area following the associated soil raster classification in the area.

2)

HydroPol2D - LULC Parameters

LC	Index	n ($m.s^{-1/3}$)	h0 (mm)	d0 (mm)	C_1	C_2	C_3	C_4	index_impervious
Water	0	0.0253	0	0	5.72	0.17	1200	1.2	6
Trees	1	0.0271	1.72	0	5.72	0.17	1200	1.2	
Grass	2	0.032	1.98	0	5.72	0.17	1200	1.2	
Flooded Vegetation	3	0.0323	2.08	0	5.72	0.17	1200	1.2	
Crops	4	0.0316	4.29	0	5.72	0.17	1200	1.2	
Shrub and Scrub	5	0.0332	7.33	0	5.72	0.17	1200	1.2	
Built Areas	6	0.0298	0.55	0	27	0.3	1200	1.2	
Bare Ground	7	0.0209	1.44	0	27	0.17	1200	1.2	
Snow and Ice	8	0.0325	0	0	27	0.17	1200	1.2	

Figure 2: HydroPol2D input data structure for LULC and pollutants.

Related to soil type, name of the soil, relative index, and hydraulic properties such as saturated conductivity (k_{sat}), suction head (ψ), initial water content (I_0), and water deficit (θ_{sat} - θ_i). Please note that the indexes used in these folders must match with information stored in the input rasters .TIF used when reading the general data.

3)

HydroPol2D - Soil Parameters

Soil_type	Index	k_{sat} (mm/h)	ψ (mm)	I_0 (mm)	θsat (cm3.cm-3)	θi (cm3.cm-3)
PHh	17012	0.55	300	10	0.35	0.1
NTu	17015	0.55	300	10	0.35	0.1
RGe	17036	10.9	110.1	10	0.412	0.1
CMd	17047	7.6	88.9	10	0.434	0.1
RGc	17049	10.9	110.1	10	0.412	0.1
FLe	17050	7.6	88.9	10	0.434	0.1
KSh	17087	1	208.8	10	0.432	0.1
KSh	17088	1	208.8	10	0.432	0.1
NTu	17089	0.55	300	10	0.35	0.1
GLu	17090	1	208.8	10	0.432	0.1
LPk	17091	7.6	88.9	10	0.434	0.1
PHh	17092	0.55	300	10	0.35	0.1

Figure 3: HydroPol2D input data structure for soil types.

1.1.6 Data Sources

The model requires static (i.e., they don't vary within the simulation) gridded maps of (i) land use land cover (LULC), (ii) digital elevation model, and (iii) soil data, and according to the modelling type (see Sec. 2) distributed rainfall and initial moisture condition could be required as input data.

Each of these maps, as mentioned in other sections, should be projected in the same coordinate system and must be entered either as a .TIFF file with the directories of these files specified in the General_Data sheet.

Since the HydroPol2D post-processing considers planar projections, we recommend the WGS84 as reference coordinate system, with the Mercator projection (EPSG:3857). According to the study cases explained on this manual (see Sec. 4), we recommend some data sources:

- The Land Use and Land Cover (LULC) is a categorical value, ranging from 0 up to the number of classes included in the input data. We recommend the Dynamic World data (Brown et al., 2022) with 10 meters of spatial resolution and 9 classes, see Dynamic World for more details. Notice that within the HydroPol2D, the user can reserve a value for impervious surfaces. With this consideration, we can create a mask and be able to neglect infiltration in impervious areas. Other product that could be considered for LULC are the yearly Dynamic Land Cover from Copernicus with 100 m of spatial resolution (See here), or MapBiomas with 30 m for Brazil (Souza and Azevedo, 2017).

- The soil data also is a categorical value, we recommend the version 2 of the Harmonized World Soil Database (Nachtergaele et al., 2009), see HWSD V2 for more details. This database provides soil characteristic data for hydrological modeling.

- The digital elevation model (DEM) can be either clipped or assessed in the whole rectangular grid. We recommend clipping the DEM using the catchment boundaries, unless the catchment is an exact rectangle. In the clipped case, the outside of the mask values are supposed to be negative, typically assumed as -9999. We recommend using the OpenTopography plugin for Qgis (here), the user must create an account in the OpenTopography official site in order to get a user key. This allows to download multiple DEM for multiple purposes.

SECTION

2 HydroPol2D Applications we are missing water quality

The HydroPo2D capabilities for both hydrological and hydrodynamic context is wide. A few examples of the application of this modeling approach are:

- Estimate hydrological processes in watersheds under discrete or continuous simulation
- Estimate floodplain maps and assess spatial-variability of infiltration e evapotranspiration
- Propagate flow in 2-D watershed domain with the diffusive-wave model coupled with cellular-automata approach.
- Simulate internal boundary condition to represent reservoir spillways and orifices.
- Perform one-at-the-time sensitivity analysis
- Simulate the effects of design storms in 2D modeling
- Simulate a plethora of boundary conditions such as spatially and temporally varied rainfall, rainfall interpolated from gauge stations, inflow hydrograph from gauge stations, etc.

Since the HydroPol2D is capable of multiple kind of applications, in the next sections, we describe how to set up each condition of modeling.

2.1

SUB-SECTION

General Set Up

In the General Input Data is set up all the execution model properties. In Fig. 4 is shown a general view of the general input data structure. Here, we explain those parameters and required input data that the model need despite the execution mode.

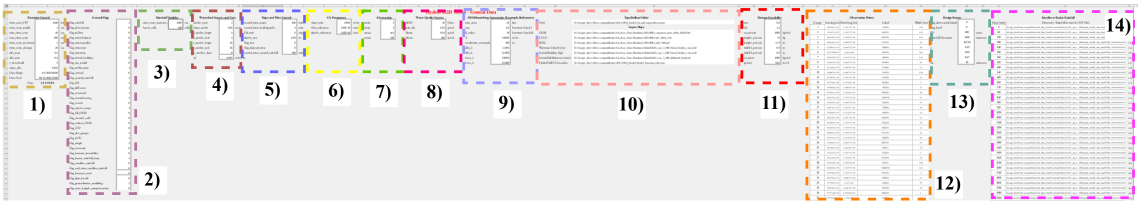


Figure 4: HydroPol2D - General data input data structure. Sections 1, 2, 3, 4, 5, 6, 10, 12 are always required to be entered while the remainder sections are optional and might be only act.

2.1.1 Running Control

In this sub-section, parameters such as the Date begin and Date end are necessary to inform the model how long the simulation will be. That information has the format of day/month/year hour:minutes:second. This condition will apply for Sec. 2.2, Sec. 2.3, and Sec. 2.4.

Related to the stability criteria parameters, we provide some recommendations to establish initial values according to the study case. lest assume that we are using a spatial discretization (resolution) of 10 meters in our DEM, then the user has to be aware of the relation between distance and flow velocity in order to warranty the numerical stability, or the Courant-Friedrichs–Lewy (*CFL*) stability criterion:

- **Time step model** All variables and matrices have to be preallocated to an initial certain size. If an adaptive time-stepping is used, the size of the matrices are unknown. To this end, the variable time-step-model defines the initial guess for the average time-stepping of the model just for creating the size of the arrays. Please notice, however, that if the time_step_change is large, let's assume 1-min for example, the model will run with the time_step_model time-step value up to the end of the first minute of the simulation. As an initial guess, 5-seconds is an estimate.
- **Min time step**, during the important hydraulic periods (high flow velocity) the model will required a little time discretization in order to ensure the numerical stability. A good starting

point for this value is dividing the resolution by the assumed maximum velocity that could happen within the system, times the Alpha coefficient. For our example, and assuming that our max velocity could be 9 m/s and alpha = 0.4, the Min time step will be $0.4(\frac{10}{9}) = 0.44$s.

- **Max time step** is the opposite case, and we have to assume the velocity that the base flow could have. For our example, and assuming that our base flow velocity could be 1 m/s and alpha = 0.4, the Max time step will be $0.4(\frac{10}{1}) = 4$s.

- **Time step increments**, for this parameter a good practice is to set equal to the Min time step. For our example, 0.44s.

- **Time step change**, this parameter considers how often the adaptive time step will change. A good starting point could be 30s.

- **Alpha max**, related to the *CFL* stability criterion, we recommend set as 0.5.

- **Alpha min**, related to the *CFL* stability criterion, we recommend set up to 0.3 if the user considers using an adaptive *CFL*. Nevertheless, if the user will employ a fixed *CFL*, we recommend setting the parameter value equals to Alpha max.

- **V threshold,** this indicates the limit of the flow velocity when the adaptive *CFL* criterion will be effective. We recommend to set as 3 m/s.

- **Slope alpha**, this indicates the ratio of how the *CFL* will change. We recommend to set as 0.225.

1)

	A	B	C
2	**Running Control**		
3	Time_save_ETP	1440	min
4	Time_step_model	5	sec
5	Min_time_step	0.00001	sec
6	Max_time_step	5	sec
7	Time_step_increments	0.01	sec
8	Time_step_change	30	sec
9	Alpha_max	0.4	
10	Alpha_min	0.4	
11	V_threshold	5	
12	Slope_alfa	0.225	
13	Date Begin	1/1/2011 0:00	
14	Date End	1/1/2011 2:00	
15	Days	**0.0833**	

Figure 5: Running Control Sub-section.

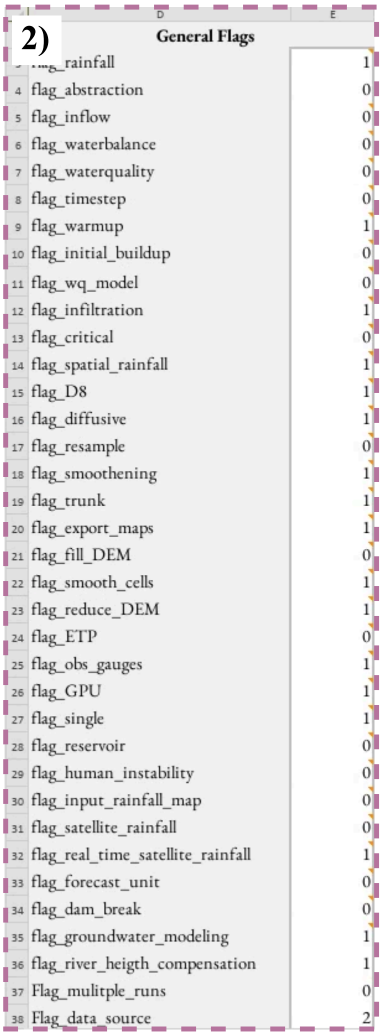
2.1.2 General Flags

This sub-section defines the model execution mode options allowed in HydroPol2D. Each value equals 1 indicates that a condition is applied in the model (e.g., flag_rainfall = 1 means that rainfall is being model, whereas flag_rainfall = 0 indicates that no precipitation is modeled). The user can define the modeling conditions, e.g., rainfall (lumped, distributed, Design storm or satellite rainfall), model hydrodynamic structure (kinematic or diffusive), consideration of ETP calculation, among others. Notice that some flags can also include multiple options when they are activated, e.g., Human instability risk have four flags option: 0 = deactivated; 1 = method 1; 2 = method 2; and 3 = method 3. Here we explain the flags included within the model:

- **Flag rainfall**, 1 we are modeling rainfall, 0 we neglect it.
- **Flag abstraction**, 1 we are modeling initial abstractions, 0 we neglect it.
- **Flag inflow**, 1 means we have inflow hydrograph boundary condition, 0 otherwise.
- **Flag waterbalance**, 1 we correct the truncation and numerical problems altering the mass balance by redistributing this value in the cells that receive the inflow hydrograph. 0 we don't correct the water balance.
- **Flag waterquality**, 1 means we are modeling water quality. To this end, make sure that the parameter entered the LULC are correct (see Sec. 2.9).
- **Flag timestep**, 0 we use the Courant method for adapting time-steps.
- **Flag warmup**, 1 we enter a map of initial warmup, which is a .TIF map with initial water surface depths in m and initial soil moisture in mm. 0 we don't input it, and we assume d_0 in (mm) and I_0 (mm) in the LULC parameters sheet.
- **Flag initial buildup**, 1 we enter a map of initial pollutant warmup, which is a .TIF map with initial pollutant mass in kg for each pixel. 0 we don't input it, and we assume the initial mass by the parameters of build-up and wash-off entered later (see Sec 2.1.7).
- **Flag wq model**, 1 we are using the build-up and wash-off with rating curves and changing it according to B_{min}, B_{max} values. Otherwise, we are modeling with traditional exponential wash-off model in terms of Bt.
- **Flag infiltration**, 1 we are modeling infiltration. 0 we are neglecting infiltration in all areas.
- **Flag critical**, 1 we limit 2-D velocities to the critical flow. Otherwise, we don't include this limitation in the CA model.
- **Flag spatial rainfall**, 1 means that rainfall will be spatially variable. In this case, see the manual to check how to enter the rainfall maps. 0 means we will use another method for rainfall.
- **Flag D8**, 1 we are modeling using an 8-D diffusive wave approximation. 0 we use a 4-D diffusive approximation.
- **Flag diffusive**, 1 we solve diffusive-wave model, otherwise we solve kinematic wave model. In this case, it is recommended to impose a minimum slope (see Sec. 2.1.4).
- **Flag resample**, 1 we resample the maps and change the pixel size to the selected pixel size in the Resample section, see Sec. 2.1.8 for more details.
- **Flag smoothening**, 1 we smooth streams, otherwise we don't do any smoothening, see Sec. 2.1.8.

- **Flag trunk**, 1 we only smooth the main channel, otherwise we smooth all channels defined by the flow accumulation threshold network created automatically, see Sec. 2.1.8.
- **Flag export maps**, 1 we export .TIF maps, otherwise we don't export maps, see Sec. 2.1.5.
- **Flag fill DEM**, 1 we fill all sinks in the DEM, otherwise 0.
- **Flag smooth cells**, 1 we smooth the DEM raster using a Gaussian filter.
- **Flag reduce DEM**, 1 we reduce elevation of flow cells to represent the real bottom elevation.
- **Flag ETP**, 1 we model Penman-Monteith Model. To this end, you need to enter climatological data, see Sec. 3.4. Also, please make sure you enter dates according to Date Begin and Date End, entered in the Running Control section (Sec. 2.1.1).
- **Flag obs gauges**, 1 means we are observing some particular points and retrieving depths, flows, and other important states, see Sec. 2.1.10.
- **Flag GPU**, 1 we run the model in parallel model with Graphic Unit Process (GPU), otherwise the model run within the Central Unit Process (CPU).
- **Flag single**, 1 the model convert all arrays to single precision, 0 the model run all arrays in double precision. This affects the calculation precision.
- **Flag reservoir**, 1 we consider the gates in reservoirs as internal boundary conditions. See Sec. 2.8 for more details.
- **Flag human instability**, 1 we solve human instability with theoretical approach by Jonkman and Penning-Rowsell (2008), 2 empirical approach by Postacchini et al. (2021); 3 Theoretical approach by Milanesi et al. (2015). 0 the model does not assess human instability.
- **Flag input rainfall map**, 1 we use known maps of rainfall intensity in mm/h. See Sec. 2.5 for more details.
- **Flag satellite rainfall**, 1 we run PERSIANN satellite rainfall from the Date Begin to Date End. See Sec. 2.5 for more details.
- **Flag real time satellite rainfall**, 1, we run PERSIANN satellite rainfall from the Date Begin up to near real time data that is being automatically received in the FTP procedure (a digital twin). See Sec. 2.12 for more details.
- **Flag forecast unit**, 1 we run the model as secondary machine just for forecasting, local connection between computers is required. See Sec. 2.13 for more details.
- **Flag dam break**, 1 is considered a hypothetical dam break scenario, observed gauges points are required to indicate with coordinates to represent a dam structure. See Sec. 2.10 for more details.
- **Flag groundwater modeling**, 1 we are modeling groundwater lateral flux per unit of river. To this end, you need to enter the lateral contribution ql at the watershed inputs. See Sec. 2.1.4.

- **Flag river height compensation**, 1 the model employs a water depth compensation according to the river width for fair comparison of water levels between simulated and observer data. This is commonly used with the Digital Twin and Forecast system.
- **Flag multiple runs**, 1 the model will run for multiple rainfall. An especial sheet is required for this procedure. working on this
- **Flag data source**, 1 the model will gather gauge stations information from the Hydrometeorological Automated Data System (HADS), or 2 the model will gather gauge stations information from the Brazilian National Agency of Water (ANA).



2)

	D	E
	General Flags	
	flag_rainfall	1
4	flag_abstraction	0
5	flag_inflow	0
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	2

Figure 6: General Flags Sub-section

2.1.3 Matricial Variables

This is used if and only if an inflow hydrograph is used and allows the model to use a different one to avoid calculation in large matrices. Therefore, the model change the size of the matrices according to the wet cells that were derived from the inflow hydrograph propagation.

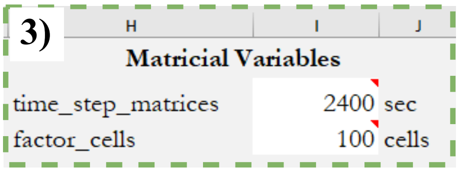


Figure 7: Matricial Variables Sub-section.

2.1.4 Watershed Inputs and Cuts

Definition of the outlet conditions. The outlet type defines which outlet boundary condition is used, that is, normal flow or critical flow.

- **Outlet type** if 0 we use a critical outlet boundary condition, otherwise we use a gradient boundary condition and the slope outlet must be specified.
- **Slope outlet** is the magnitude of the slope as boundary condition. Must be m/m units.
- **N outlet data** is the number of extra outlets that the model will consider when assess the discharge that flow through the basin outlet. Notice that the model automatically identify the outlet location according to the lower elevation in the DEM. For example, this condition will be necessary in the case when the outlet (a pixel with 1 meter of resolution) is in the middle of a river with 10 meters of width, then, the user must need 9 extra pixels to set the boundary conditions.
- **Ql** is an average of lateral contribution of groundwater per meter of river. A good start point of this parameter is 0.035m$^3/s/m$.

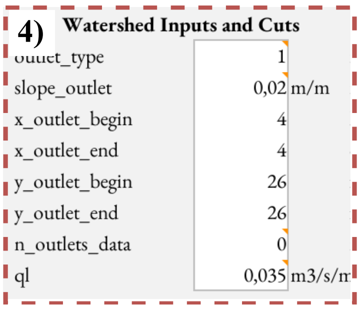


Figure 8: Watershed Inputs and Cuts Sub-section.

2.1.5 Maps and Plots Control

In this sub-section, we define the time that the spatial and source variables are recorded. Users must be aware about memory and processing requirements by the model. High temporal discretization, to save maps, will generate a great quantity of output information. It is recommended to define these thresholds to save the maps as the same as the temporal discretization of the input data. Here, we explain the usage of each variable:

- **Record time maps** are related to the time interval to save information about water depths and water pollutants or Human risk if is simulated. Here, the user has to consider the time interval from the rainfall records (Sec. 2.2, Sec. 2.3, Sec. 2.4, Sec. 2.5) or inflow (Sec. 2.7). The user can set up the outputs' frequency save as same as the input data frequency. Lower or higher values of frequency can be employed; however, the user must be aware about the memory storage on the system that the model will require. For example, consider a simulation with satellite rainfall with data for every 60 minutes, and the user set to save maps every 360 minutes, then, the model will export maps of water depths and rainfall every six hours, making an aggregation of all the six maps on that interval. If the user set the frequency to save maps for every 60 minutes, the model will export all the maps with no aggregation because it's not required.

- **Record time hydrographs** is just the interval time of how the plots related to the hydrographs will be exported. This interval must not be higher than the simulation time.
- **Pol min** is the minimum pollutant concentration threshold that the model will consider exporting the outputs. For example, if this value is 0.1 mg/L, all the output exported will be higher than this threshold.
- **Depth wse** is the minimum water depth threshold that the model will consider exporting the outputs. For example, if this value is 0.05 m, all the maps exported will be higher than this threshold.
- **Flag wse** is to save wse maps (1), otherwise we save depth (0).
- **Flag elapsed time**, if 1, we plot maps, charts and all animations will be performed using Elapsed Time (for example: 0-10-20-30... and so on). Otherwise, we the time values will be using the date information given in the Running Control section (the format of day/month/year hour:minutes:second).
- **Record time spatial rainfall**, if the satellite information is employed, either with pre-downloaded tiles or automatic downloading (see Sec. **??**, this value should be equal to the input time interval (1 hour for PDIR-Now) or higher. Lower values will result in an error within the model. If higher values are set, the model will make an average of the inputs' rainfall maps that belong to that interval of time. Note that larger values than the resolution of the rainfall data will be recorded as time averages.

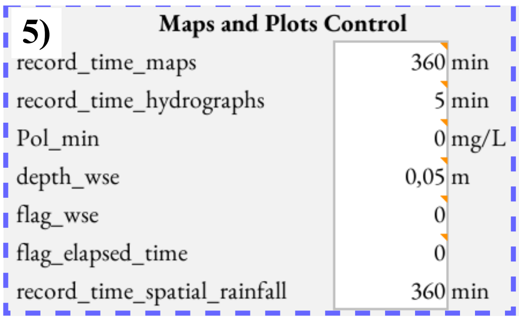


Figure 9: Record Time Maps Sub-section.

2.1.6 Celular Automata Parameters

Definition of some thresholds for cellular automata according to specific modeling circumstances.

- **Slope min** is the minimum wse slope to consider in the calculations within the diffusive model. We recommend a value of 0.001 m/m.

- **Flow tolerance** is to avoid numerical instability during the simulation. Flows smaller than this value are neglected. We recommend a value of 1.00E−10.

- **Depth tolerance** similarly to flow tolerance, this value is to avoid numerical instability during the simulation. depths smaller than this value are neglected. We recommend a value of 1.00E−16

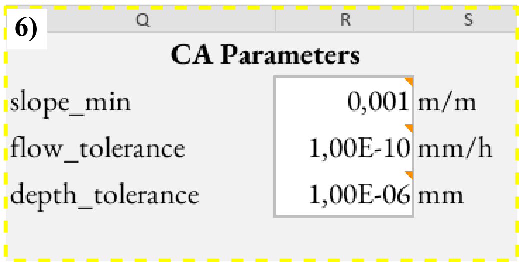


Figure 10: Celular Automata Parameters Sub-section.

2.1.7 Water Quality Inputs

Here are defined the water quality model parameters. marcus, your turn.

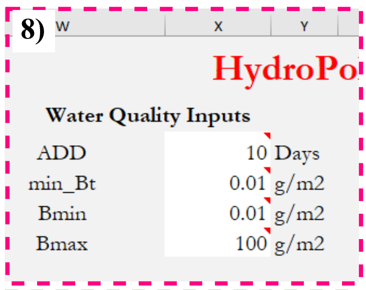


Figure 11: Water Quality Input Sub-section.

2.1.8 DEM Smoothing, Imposemin, Resample, Bathymetry

Optional procedures to treat the used digital elevation model.

- **Min area** is the threshold for defining creeks. According to the size of the study area, this value could vary. Values too little tends to generate a dense hydrography on the modelling, affecting the groundwater contribution (Q_l) with too much base flow. The unit parameter is km^2.

- **Tau** is a unitless value to smoothening the digital elevation model. Between 0 and 1.

- **K value** is a unitless value to smoothening the digital elevation model. Between 0 and 1.

- **sl** is the minimum slope for the impose min algorithm used when diffusive modeling is applied or flag_difussive = 1.

- **Resolution resample** is used when the user desire to run a less spatial discretized model. For example, if all the spatial input data (Sec. 1.1.6) is 30 meters of resolution, through a bicubic interpolation the user could resample the information (500 meters for example). For this, the resample flag must be active (flag_resample = 1). Moreover, we recommend the use of the D8 flow directions (flag_D8 = 1) because the resampling will generate a "noise" DEM and the D8 flow will avoid flow accumulations.

- **Alpha 1, 2 and beta 1 and 2** This are the raster-based DEM filter parameters used to smooth the DEM, later explained in Sec. 3.9

9)

AA	AB	AC
Model - General Data		
DEM Smoothing, Imposemin, Resample, Bathymetry		
min_area	0.5	km^2
tau	0.2	between 0 and 1
K_value	10	between 0 and 20
sl	0.0001	m/m
resolution_resample	500	m
alfa_1	1.4351	
alfa_2	0.1901	
beta_1	0.8054	
beta_2	0.5289	

Figure 12: DEM Smoothing, Imposemin, Resample, Bathymetry Sub-section.

2.1.9 Directories

Here are defined the directories for the DEM, land use and land cover, soil type, warm-up depths (if apply), Initial Build-up), Initial Soil Moisture (if apply). Additionally, the TopoToolBox (Schwanghart and Scherler, 2014), and all the HydroPol2D function directories must be informed. Please note that Matlab must have access to these folders, so if you store the files in a protected folder, the model might crash.

10)

AD	AE
TopoToolbox Folder	
Path	H:\...\topotoolbox-master
Input Maps	
DEM	H:\...\DEM.tif
LULC	H:\...\Land_Cover_Data.tif
SOIL	H:\...\SOIL.tif
Warmup Depth (m)	H:\...\Warmup_Depths.tif
Initial Buildup (kg)	H:\...\Soil_500.tif
Initial Soil Moisture (mm)	H:\...\Evento3_I.tif
HydroPol2D Functions	H:\...\Model_Functions_Directory

Figure 13: Directories Sub-section.

2.1.10 Observation Points

In this section are defined the coordinates for all the relevant stream gauges within the study area that the user wants to extract modeling results for post-processing or to be displayed during the modeling status. Results such as water stages and discharges can be retrieved for all coordinates entered in this section. Please notice that the model will estimate the cell in which the entered coordinate falls, using the rater resolution. For example, if you resample the DEM, you might alter the river or creek coordinate and the retrieve data might be outside the stream domain. Moreover, the width of the river is informed in case of water depth compensation were required. see Sec.?? for more details about water depth compensation due to the river width.

12) **Observation Points**

Gauge	Easting (m)	Northing (m)	Label	Width (m)
1	-9818216,95	1701737,96	CHIH3	100
2	-9781716,95	1722737,96	SANH3	105
3	-9819216,95	1726237,96	RCHH3	109
4	-9864216,95	1682237,96	POSH3	60
5	-9598716,95	1644737,96	FRAH3	68

Figure 14: Observation Points Sub-section.

2.2

SUB-SECTION

Synthetic Design Storms

The HydroPol2D model allows running with user-defined synthetic storms with varied return periods, durations, and time intervals, once defined the intensity-duration-frequency Sherman-type parameters. The current version allows simulating with the Alternated Blocks Method and with the Huff Hyetographs.

The user have to choose between the two methods available. In the general data flag (Fig. 15/2), the user must set all flags related to rainfall equal to zero such as: flag_rainfall = 0, flag_spatial rainfall = 0, flag_satellite rainfall = 0. Then, the user must activate the flag_alternated block = 1 or flag_huff = 1. Finally, parameters such as Return Period (Rp), rainfall duration, and those related to the IDF curves, have to be setted up (Fig. 15/13).

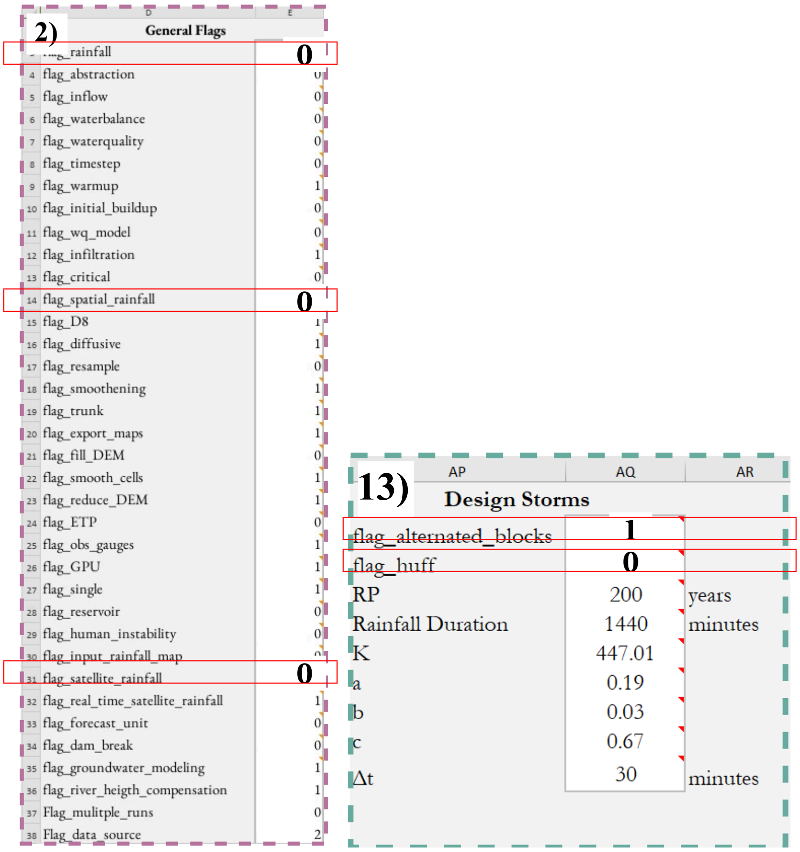


Figure 15: Synthetic Design Storms Set Up.

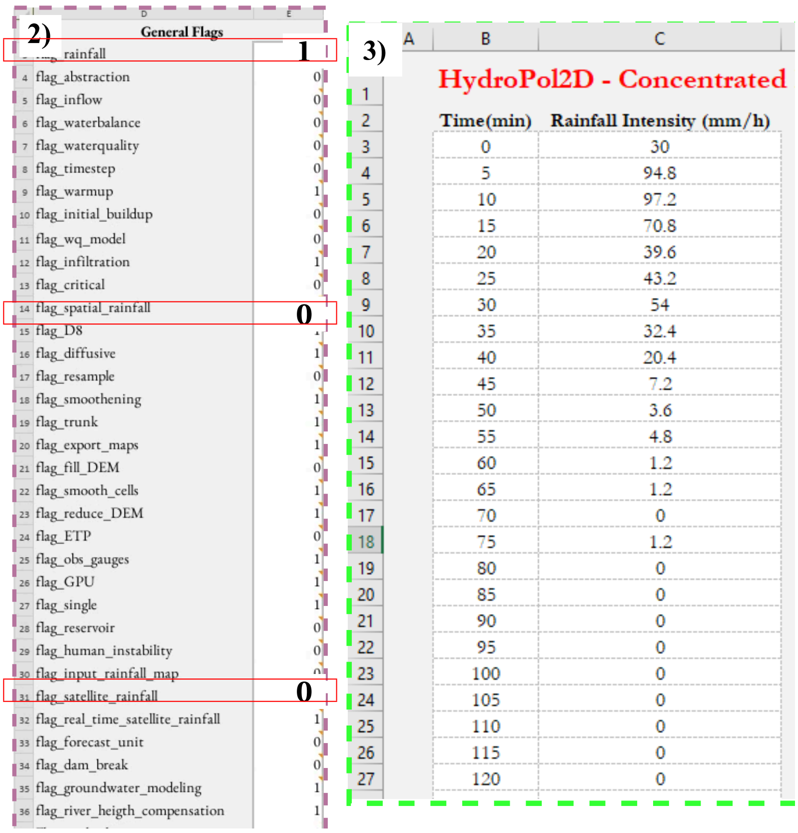
2.3

SUB-SECTION

Concentrated Rainfall

The user have to activate the rainfall as flag_rainfall = 1 (Fig. 16/2), this flags is general to simulate rainfall and the HydroPo2D by default assume it as concentrated. Moreover, the remaining flags must be zero, such as: flag_spatial rainfall = 0, flag_satellite rainfall = 0, flag_alternated block = 0, and flag_huff = 0.

Once the concentrated rainfall is active, the data input is also needed (Fig. 16/3). Notice that the input data related to the time should be in sequence and with equal intervals in minutes, for example, 0–10-20-30 and so on. Additionally, the rainfall should be expressed in intensities (mm/hr).



Time(min)	Rainfall Intensity (mm/h)
0	30
5	94.8
10	97.2
15	70.8
20	39.6
25	43.2
30	54
35	32.4
40	20.4
45	7.2
50	3.6
55	4.8
60	1.2
65	1.2
70	0
75	1.2
80	0
85	0
90	0
95	0
100	0
105	0
110	0
115	0
120	0

Figure 16: Concentrated Rainfall Set Up.

2.4

SUB-SECTION

Spatial Rainfall

The user have to activate the rainfall modeling as flag_rainfall = 1 (Fig. 17/2), this flags is general to simulate rainfall and the HydroPo2D by default assume it as concentrated; nevertheless, to simulate the distributed rainfall as flag_spatial rainfall = 1, the model will ignore the concentrated rainfall modeling and will perform as distributed. The remaining flags must be zero, such as: flag_satellite rainfall = 0, flag_alternated block = 0, and flag_huff = 0.

Once the spatial rainfall is active, the data input is also needed (Fig. 17/1). Notice that the input data related to the time should be in sequence and with equal intervals in minutes, for example, 0–10-20-30 and so on. Additionally, the rainfall should be expressed in intensities (mm/hr). Notice that the coordinates and the index also are required for the inverse-distance-weighting (IDW) interpolation.

2)

	D	E
	General Flags	
3	flag_rainfall	1
4	flag_abstraction	0
5	flag_inflow	0
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	2

1)

Index	1	2	3	4	5	6
Rain Gauge	A709	A712	A713	A726	A701	A705
Easting [m]	209164.1101	849618.4546	848951.7014	846940.2355	947510.2963	702974.9245
Northing [m]	7531185.042	7267004.737	7405171.529	7485402.431	7394699.729	7526212.36
Date (min)	Rainfall Intensity (mm/h)	Rainfall Intensity (mm/h)	Rainfall Intensity (mm/h)	Rainfall Intensity (mm/h)	Rainfall Intensity (mm/h)	Rainfall Intensity (mm/h)
0	0	0	0	0	0	0
180	0	0.933333333	0	0	0	0
360	0	0.066666667	0	0	0	0
540	0	0.133333333	0	0	0	0
720	0	0.133333333	0	0	0	0
900	0	0	0	0	0	0
1080	0	0	0	0	0	0
1260	0	0	0		0.8	0

Figure 17: Spatial Rainfall Set Up.

2.5

SUB-SECTION

Satellite Rainfall

For the satellite rainfall, the HydroPol2D employs the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) products, specifically the Dynamic Infrared–Rain rate (PDIR-Now) (Nguyen et al., 2020). There are two ways to use this data: A) with the tiles pre-downloaded, or B) automatic download within the model through a Transfer File Protocol with The Center for Hydrometeorology and Remote Sensing (CHRS, 2023).

2.5.1 Usage with Pre-donwloaded Tiles

The user have to activate the rainfall as flag_rainfall = 1 and flag_spatial_rainfall = 1 (Fig. 18/2), this flags is general to simulate rainfall and the HydroPo2D by default assume it as concentrated. Then, the input rainfall maps must be activated as flag_input rainfall maps = 1. Moreover, the remaining flags must be zero, such as: flag_satellite rainfall = 0, flag_alternated block = 0, and flag_huff = 0.

Once that input rainfall maps are active, it is necessary to inform the path of each rainfall tile in sequence. For this, we provide a "command windows script" (CMD or PowerShell) to identify all the paths within a folder and copy into the clipboard. The tiles should be storage within a folder in .tif format, then, the script provided with the user information must be executed. Finally, the paths should be pasted on the general data (Fig. 18/14). The HydroPol2D when read the information will set the coordinate system as WGS84 (EPGS:3857).

Related to the simulation time, the user must inform the Date Begin and Date end in the Running Control in the general data (Fig. 4/1). Notice that The dates should be in concordance with the data of tiles provided.

Algorithm 1: Script for copy path from all rainfall tiles within a folder.

```
input: User input information within blue colour.
$driveLetter = "C:"
$folderPath = "...\folder with the data pre-downloaded"
$fullPath = Join-Path -Path $driveLetter -ChildPath $folderPath
$fileList = Get-ChildItem -Path $fullPath -File | Sort-Object
$paths = $fileList.FullName -join "‘r‘n"
$paths | Set-Clipboard
Write-Host "Full paths copied to clipboard."
output: all the paths in sequence copied into the clipboard.
```

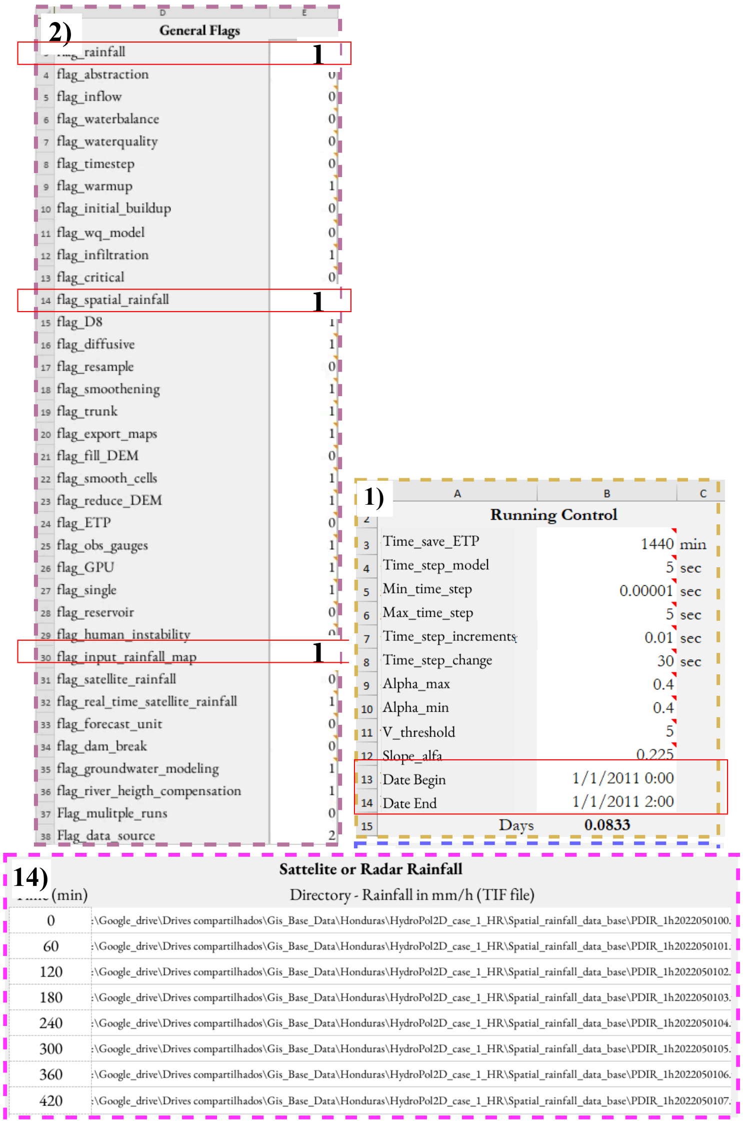


Figure 18: Pre-download Rainfall Tiles Set Up.

2.5.2 Usage with automatic tiles downloading

For the automatic download of the tiles through the FTP, the user has to activate the rainfall as flag_rainfall = 1 (Fig. 19/2), this flags is general to simulate rainfall and the HydroPo2D by default assume it as concentrated. Then, spatial rainfall must be activated as flag_spatial rainfall = 1. Moreover, the remaining flags must be zero, such as: flag_satellite rainfall = 0, flag_alternated block = 0, and flag_huff = 0, and flag_input rainfall maps = 0.

Related to the simulation time, the user must inform the Date Begin and Date end in the Running Control in the general data (Fig. 19/1). Here, we remind the user about the hourly timescale of the PDIR-Now data, and the model considers a time zone corrections to start the simulation (according to an average of the longitudes obtained from the digital elevation model of the study area). The PERSIANN data upload has as reference the UTC=0 and the user must be aware about this when set the time simulation interval. For example, if the user tries to simulate a discrete event from 1/1/2011 17:00 to 2/1/2011 12:00 in Honduras, Central America (UTC-6), the model will gather the tiles from 1/1/2011 11:00 to 2/1/2011 6:00 to simulate.

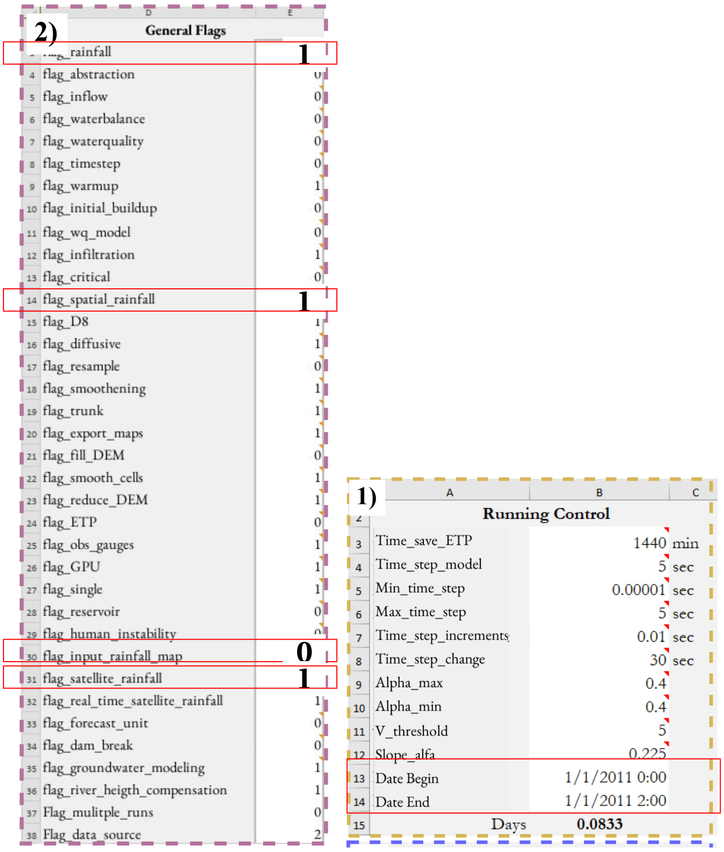


Figure 19: Automatic Download Rainfall Tiles Set Up.

2.6

SUB-SECTION

Evapotranspiration

Evapotranspiration is the portion of the water balance in the watershed that is characterized as the volume of water that returns to the atmosphere, which represents the sum of evaporation (soil) and transpiration (plants). For daily quantification, we use the Penman-Monteith method, which is suggested worldwide by the Food and Agriculture Organization of the United Nations (FAO) and nationally suggested by the Brazilian Agricultural Research Corporation (Embrapa).

The user have to activate the evapotranspiration flag as flag_ETP = 1 (Fig. 20/2). Once the evapotranspiration is active, the data input is also needed (Fig. 20/2). Notice that the input data related to the time should be in sequence and with equal intervals in minutes, for example, 0–10-20-30 and so on. The model requires the input of spatially distributed data, for this we can use a single value for all pixels comprised in the watershed or, if we have two or more weather stations, use the (IDW) method to interpolate the data represented below.

- Relative humidity (%)
- Net radiation at the crop surface (MJm^{-2}day^{-1});
- Soil heat flux density (MJm^{-2}day^{-1});
- Mean daily air temperature at 2 meters height (°C);
- Wind speed at 2 meters height (ms^{-1});
- Saturation vapor pressure (kPa);
- Actual vapor pressure (kPa);
- Slope vapor pressure curve (kPa°C^{-1});
- psychrometric constant (kPa°C^{-1}).

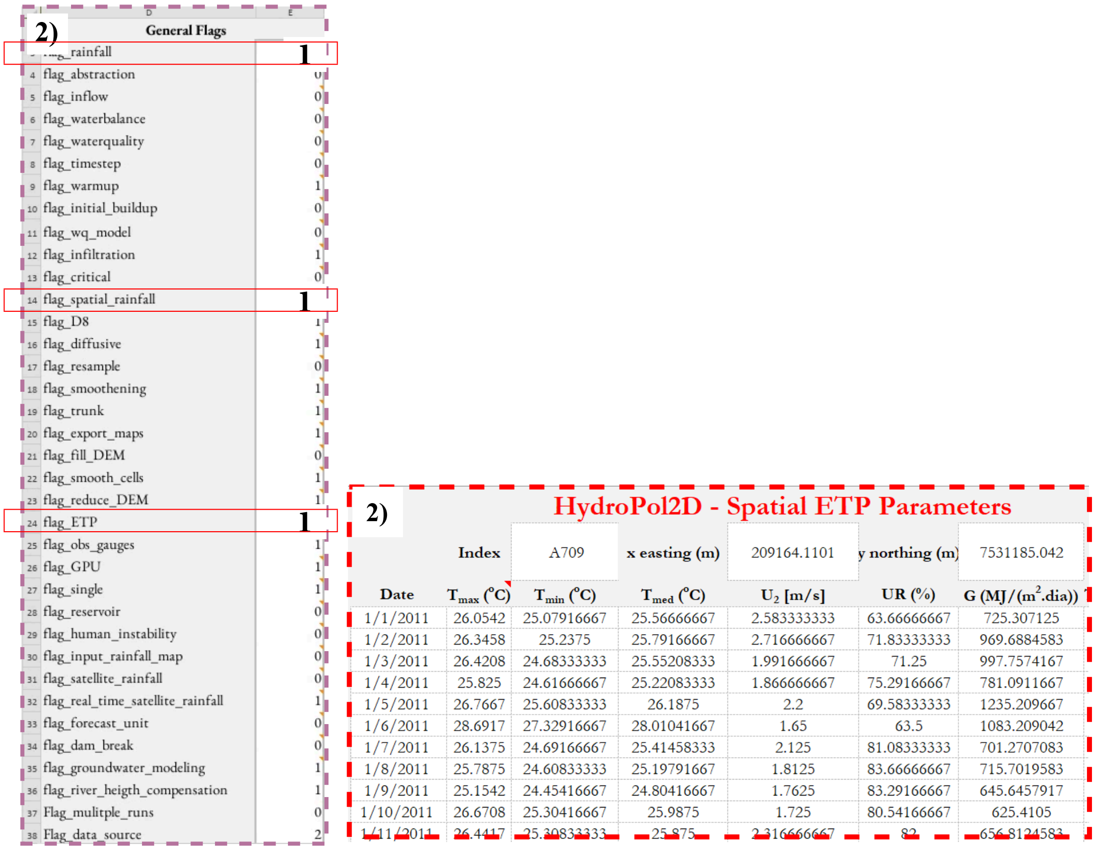


Figure 20: Evapotranspiration Set Up.

Due to the particularities, some parameters may not be available in the meteorological stations considered, for this, it is highlighted some simplifications that can be performed in order to reduce the number of parameters required for input to the model. In a first step, some EMBRAPA recommendations were implemented in this model, mainly regarding applications in Brazilian territory. Reducing the input parameters to:

- Maximum temperature (°C)
- Minimum temperature (°C)
- Mean temperature (°C)
- Altitude ($meters$)
- Latitude (rad)

In other regions, similar simplifications can be implemented, but we suggest that the coefficients be checked according to the characteristics of the simulation area.

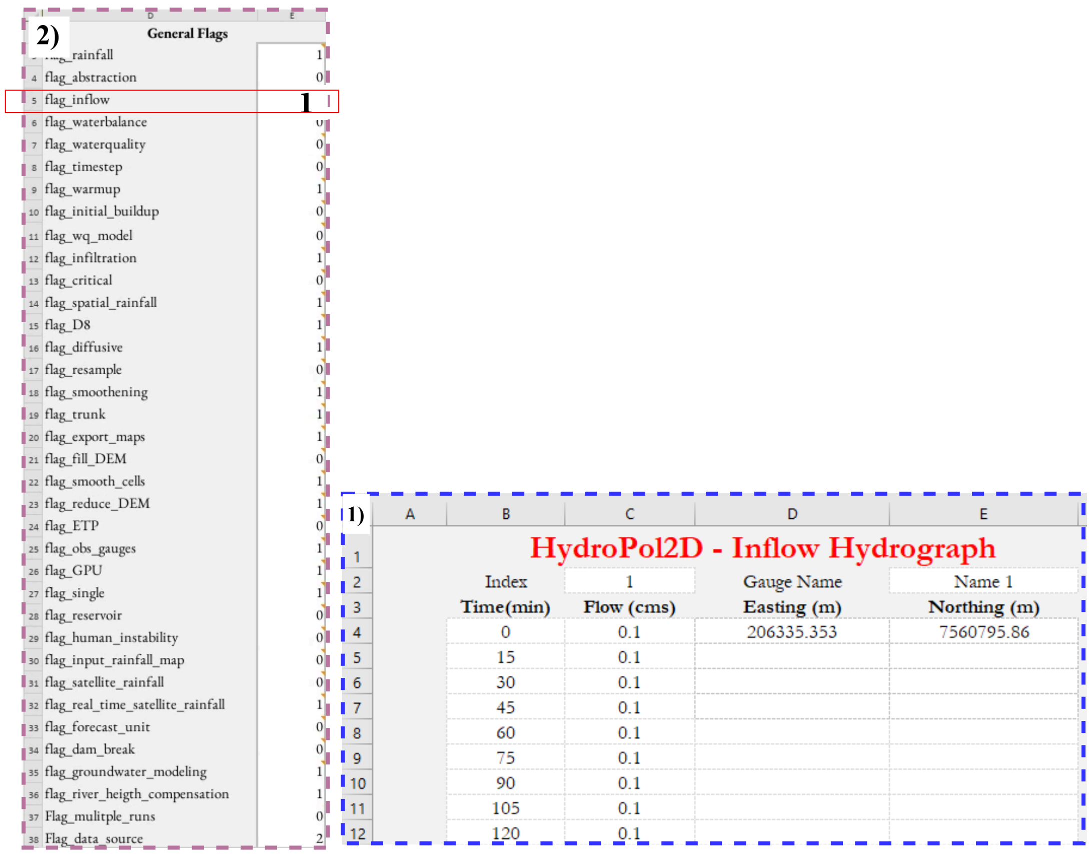
2.7

SUB-SECTION

Inflow Boundary Condition

For the inflow data, the inflow flag must be activated as flag_inflow = 1. It is necessary to specify the hydrograph and coordinates from where the stream flow is entered as a boundary condition. Please notice that you can specify more than one cell per inflow gauge. The flow discharge is distributed to the number of cells of the gauge. In software such as HEC-RAS, users can define a line where the boundary condition can be entered. Similarly, we can do the same by allowing users to enter the required number of cells to distribute the flow discharge.

A good practice for this boundary condition is to avoid just select few elements (pixels) to distribute the flow, in order to avoid flow accumulation due to the flow velocity and time-step. The inflow discharge units is on cubic meters per second (m^3/s).



2)

	D	E
	General Flags	
3	flag_rainfall	1
4	flag_abstraction	0
5	flag_inflow	1
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	2

1)

	A	B	C	D	E
1		HydroPol2D - Inflow Hydrograph			
2		Index	1	Gauge Name	Name 1
3		Time(min)	Flow (cms)	Easting (m)	Northing (m)
4		0	0.1	206335.353	7560795.86
5		15	0.1		
6		30	0.1		
7		45	0.1		
8		60	0.1		
9		75	0.1		
10		90	0.1		
11		105	0.1		
12		120	0.1		

Figure 21: Inflow Boundary Conditions.

2.8

SUB-SECTION

Reservoir Modeling

For the reservoir operation modeling, the reservoir flag must be activated as flag_reservoir = 1. In Fig. 22 are shown the variables that will represent the geometrical characteristics for the spillways and orifices. For each element, coordinates should also be informed with their respective index.

HydroPol2D - Reservoir Data

Index	x(m)	y(m)	L(m)	A(m^2)	Dir	Hv (m)	Ho (m)	Cd	C	Qf (m^3/s)
1	-5167173.995	-2703950.299	0	1	9	0	4.874	0	0.68	1
2	-5167154.053	-2703929.141	13.2	0	9	0.5	0	1.6	0	1
3	-5168893.2	-2704260.582	0	1.21	9	0	3.55	0	0.68	1

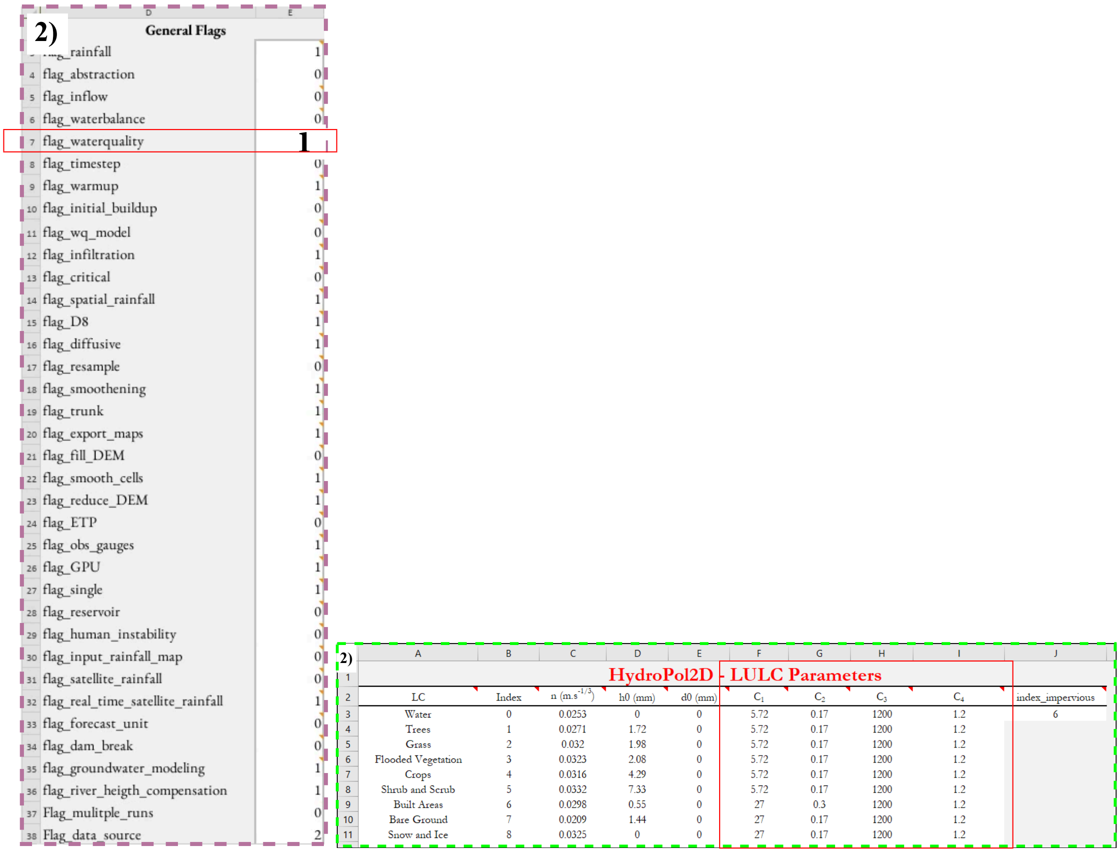
Figure 22: HydroPol2D - Reservoirs input data. This figure should be replaced in the final version. The parameters might have changed.

2.9

SUB-SECTION

Water Quality

Marcus In Fig. 23



2)

	D	E
	General Flags	
3	flag_rainfall	1
4	flag_abstraction	0
5	flag_inflow	0
6	flag_waterbalance	0
7	flag_waterquality	1
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	2

2)

	A	B	C	D	E	F	G	H	I	J
1	HydroPol2D - LULC Parameters									
2	LC	Index	n (m.s$^{-1/3}$)	h0 (mm)	d0 (mm)	C_1	C_2	C_3	C_4	index_impervious
3	Water	0	0.0253	0	0	5.72	0.17	1200	1.2	6
4	Trees	1	0.0271	1.72	0	5.72	0.17	1200	1.2	
5	Grass	2	0.032	1.98	0	5.72	0.17	1200	1.2	
6	Flooded Vegetation	3	0.0323	2.08	0	5.72	0.17	1200	1.2	
7	Crops	4	0.0316	4.29	0	5.72	0.17	1200	1.2	
8	Shrub and Scrub	5	0.0332	7.33	0	5.72	0.17	1200	1.2	
9	Built Areas	6	0.0298	0.55	0	27	0.3	1200	1.2	
10	Bare Ground	7	0.0209	1.44	0	27	0.17	1200	1.2	
11	Snow and Ice	8	0.0325	0	0	27	0.17	1200	1.2	

Figure 23: Water Quality Set Up.

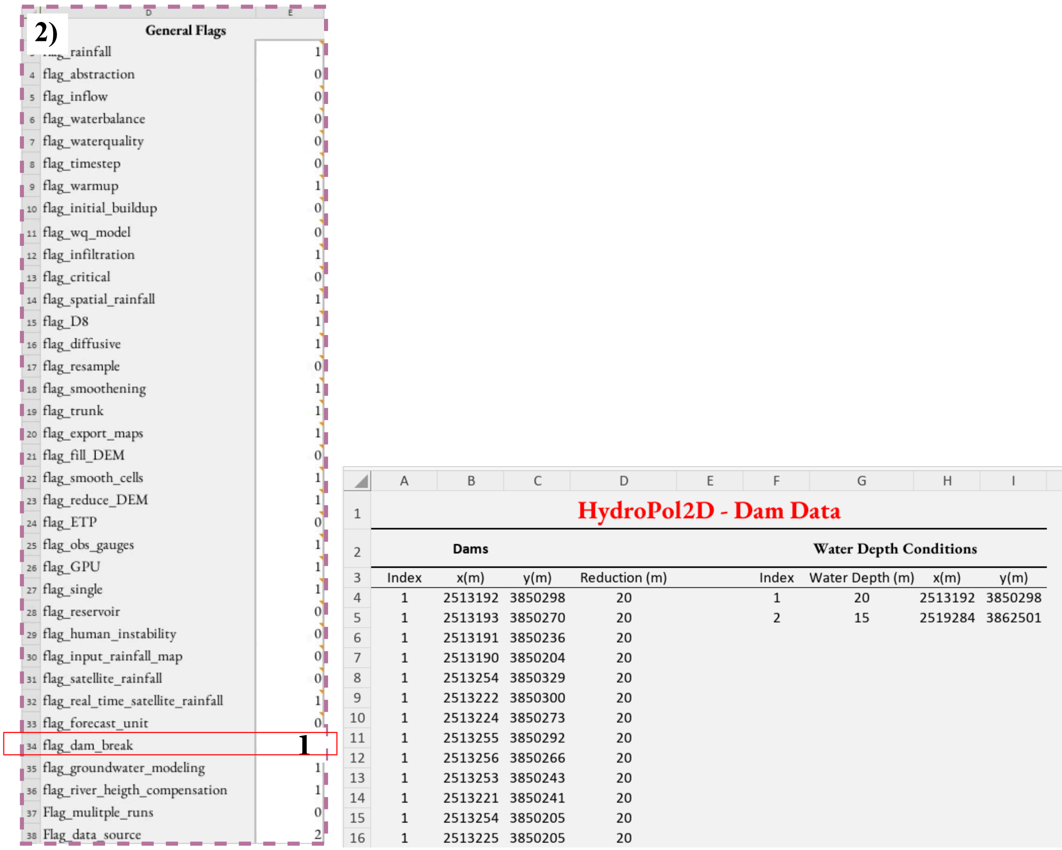
2.10

SUB-SECTION

Dam Break

To model a hypothetical Dam break, the dam break flag must be activated as flag_dam break = 1, (Fig. 24/2). The user must inform the coordinates from the digital elevation model of the desired structure, how much these coordinates will change after the dam failure and the water depth condition within the reservoir that cause the failure. During the modeling processing, when the water depth condition is reached, the HydroPol2D will modify or "burn" the DEM values from the desired structure according to the reduction values (see. Fig. 24), this will simulate the dam break, then, there will not structure that contains the store water, allowing it to flow downstream. Here, for each dam there is a water depth condition (indicated by the index), which also required their coordinates to assess the water level of the dam.

In Fig. 24 notice that according to the grid size employed, all the cells that represent the dam structure should be informed, or at least, the side of the structure to represent the failure.



2)

	General Flags	
3	flag_rainfall	1
4	flag_abstraction	0
5	flag_inflow	0
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	1
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	2

HydroPol2D - Dam Data

	A	B	C	D	E	F	G	H	I
2		Dams					Water Depth Conditions		
3	Index	x(m)	y(m)	Reduction (m)		Index	Water Depth (m)	x(m)	y(m)
4	1	2513192	3850298	20		1	20	2513192	3850298
5	1	2513193	3850270	20		2	15	2519284	3862501
6	1	2513191	3850236	20					
7	1	2513190	3850204	20					
8	1	2513254	3850329	20					
9	1	2513222	3850300	20					
10	1	2513224	3850273	20					
11	1	2513255	3850292	20					
12	1	2513256	3850266	20					
13	1	2513253	3850243	20					
14	1	2513221	3850241	20					
15	1	2513254	3850205	20					
16	1	2513225	3850205	20					

Figure 24: Hypothetical Dam Break Set Up.

2.11

SUB-SECTION

Human Instability Risk

For the human risk assessment, the human instability flag must be activated as flag_human instability > 0, (Fig. 25/2). Fig. 25 shows that there are three procedures options implemented within the HydroPol2D: 1) Theoretical approach by Jonkman and Penning-Rowsell (2008); 2) Empirical approach by Postacchini et al. (2021); 3) Theoretical approach by Milanesi et al. (2015), then, the user must specify which method will use. Values related to the fluid characteristics and pedestrian physiognomy are required according to the type of methods chosen.

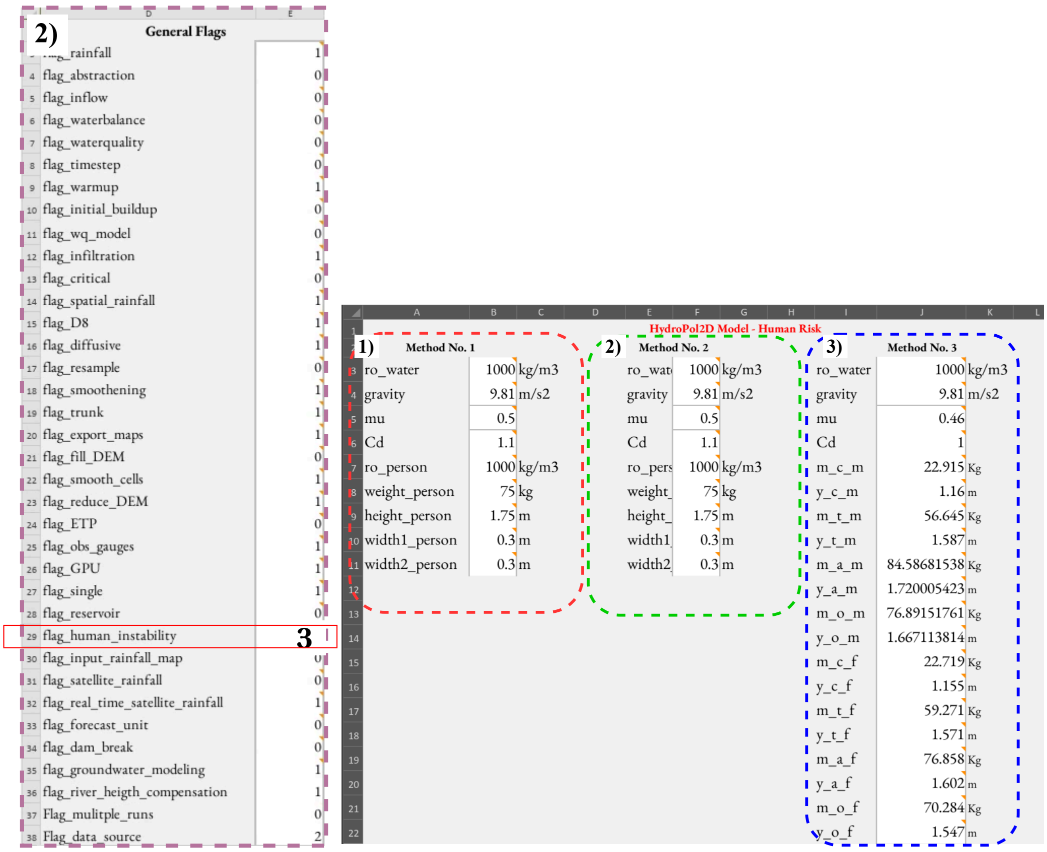


Figure 25: HydroPol2D - Human Instability Risk Set Up.

2.12

SUB-SECTION

Digital Twin Capability

The HydroPol2D is capable to run in an endless loop in order to keep a real-time simulation, which can be considered as a hydrodynamic Digital-Twin within basin scale. In this execution mode, the satellite rainfall with automatic download is employed (see Sec. 2.5). Flags such as flag_real time satellite rainfall = 1 and flag_rainfall = 1 must be activated, see Fig. 26/2. Notice that the model will display a graphical interface to aid the monitoring procedure, see Rápalo et al. for more details.

Information from land gauge station is also gathered in real-time for this execution mode. The user must specify (flag_data source = 1 or 2) between the Hydrometeorological Automated Data System (HADS), 1, or the Brazilian National Agency of Water (ANA), 2. Here, in the observation points sub-section (Fig. 26/12), the user must specify which gauge stations from the system chosen will employ on the Digital Twin.

2.12.1 HADS Source

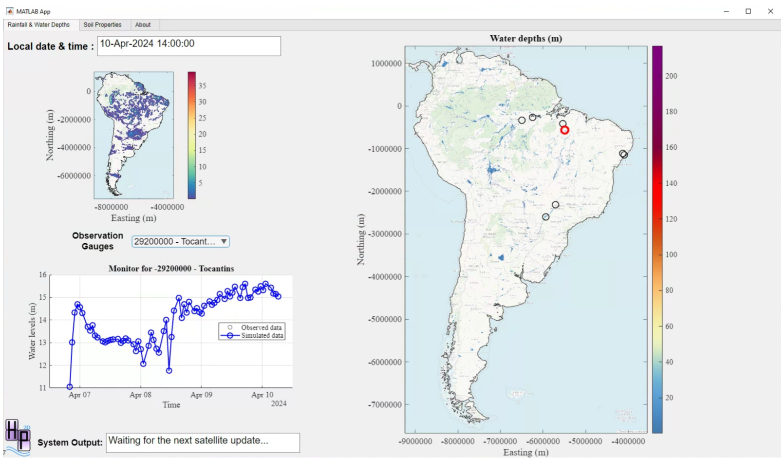
For this case, the system will link the label from the observation point with the HADS database, then, it is important to notice that names of the station have to match between the model and the HADS system. For example, for the station in the ULUA river near to CHINDA in Honduras, the label is "CHIH3" from the NWSLI. See HADS DCPs for the full list. Moreover, gauge index and coordinates must be informed.

2.12.2 ANA Source

For the ANA source case, similarly with the HADS conditions, the user must fill basic information relation index, coordinates and labels. The latter, will consider the first 8 digits of the label since we employ the available web service from the ANA, and the model, need the gauge station code. For example, for the station Itacoatiara in the Solimões-Amazonas river in Brazil, the label could be "16030000 - Itacoatiara". See ANA stations for the full telemetry list.

2)

	General Flags	
3	rainfall	1
4	flag_abstraction	0
5	flag_inflow	0
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	1
15	flag_D8	1
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	0
30	flag_input_rainfall_map	0
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1
37	Flag_mulitple_runs	0
38	Flag_data_source	1



12)

Observation Points				
Gauge	Easting (m)	Northing (m)	Label	Width (m)
1	-9818216,95	1701737,96	CHIH3	100
2	-9781716,95	1722737,96	SANH3	105
3	-9819216,95	1726237,96	RCHH3	109
4	-9864216,95	1682237,96	POSH3	60
5	-9598716,95	1644737,96	FRAH3	68

Figure 26: Digital Twin Set Up data source flag.

2.13

SUB-SECTION

Forecasting System

Similarly, as made in the Digital Twin mode, the forecast system is an endless loop of modeling within the HydroPol2D. Here, this execution mode requires a Digital Twin running in order to get initial condition from, and then, forecast the hydrodynamic conditions. This means that a first unit will be running the Digital Twin (Sec. 2.12), and a second unit will forecast with information from the Global Forecast System (GFS), see Rápalo et al. for more details. For this case, the forecast flag must be activated (flag_forecast = 1). Additionally, notice that the model will display a graphical interface to aid the monitoring procedure.

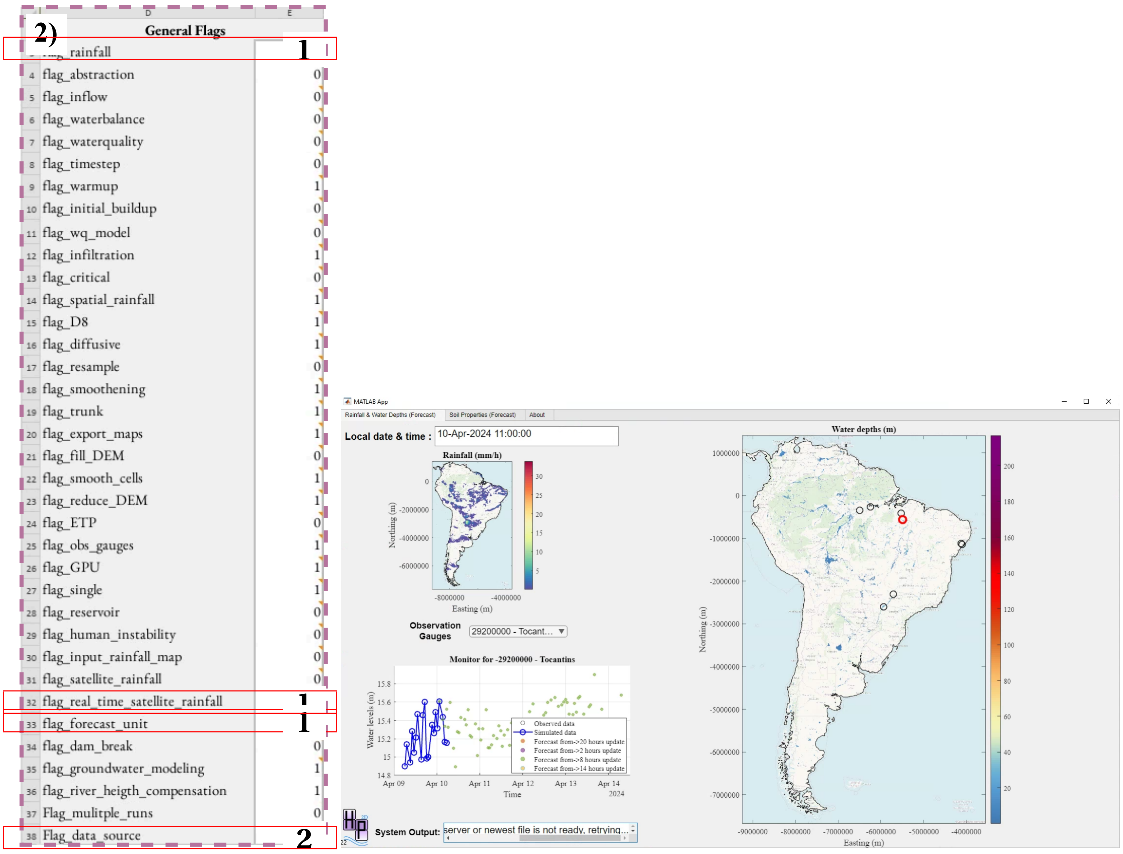


Figure 27: Forecast System Set Up.

3

SECTION

Mathematical Details of HydroPol2D

HydroPol2D is a numerical hydrodynamic and pollutant transport and fate model. Some of the mathematical algorithms and equations are detailed presented in this chapter. The mathematical definitions and notations are defined by:

Italicized, boldface upper and lower case characters in boldface represent matrices and column vectors: a is a scalar, $\boldsymbol{a}$ is a vector, and $\boldsymbol{A}$ is a matrix. Matrix $\boldsymbol{I}_n$ denotes an identity square matrix of dimension n-by-n, while $\boldsymbol{O}_{m\times n}$ and $\mathbf{1}_{m\times n}$ denotes a zero and one matrix of size m-by-n, respectively. The notations $\mathbb{R}$ and $\mathbb{R}_{++}$ denote the set of real and positive real numbers. The notations $\mathbb{R}^n$ and $\mathbb{R}^{m\times n}$ denote a column vector with n elements and an m-by-n matrix in $\mathbb{R}$. The element-wise product or Hadamard product is defined as $\boldsymbol{x}\circ\boldsymbol{y} := [x_1 y_1, x_2 y_2, \ldots, x_n y_n]^T$ multiplications. Similarly, the element-wise division or Hadamard is defined as $\boldsymbol{x}\oslash\boldsymbol{y} := [\frac{x_1}{y_1}, \frac{x_2}{y_n}, \ldots, \frac{x_n}{y_n}]^T$. The element-wise p power of a matrix $\boldsymbol{A}$, $(\boldsymbol{A}^{\circ p})$, with $\boldsymbol{A}\in\mathbb{R}^{m\times n}$ and $p\in\mathbb{R}$ is given by $a_{i,j}^p$ for $i\in\mathbb{N}_{++}$, and $j\in\mathbb{N}_{++}$.

3.1

SUB-SECTION

Matrixwise Stormwater Runoff Mass Balance Equation

A pseudo-code of the model is presented in Algorithm 2. The mass balance equation can be written as follows:

$$\frac{\mathrm{d}\boldsymbol{H}(t)}{\mathrm{d}t} = \boldsymbol{B}_i \circ \boldsymbol{I}(t) + \frac{1}{A}\boldsymbol{B}_Q \circ \boldsymbol{Q}(t) - \boldsymbol{F}(\boldsymbol{H}(t), \boldsymbol{F}_d(t)) - \boldsymbol{E}_{TR}(t) + \sum_{i=1}^{m}\left(\overbrace{\boldsymbol{B}_d(\boldsymbol{H}(t))\boldsymbol{Q}_{out}(\boldsymbol{H}(t))}^{\boldsymbol{Q}_{in}(\boldsymbol{H}(t))} - \boldsymbol{Q}_{out}(\boldsymbol{H}(t))\right) \tag{1}$$

where $\boldsymbol{B}_i$ and $\boldsymbol{B}_Q \in \mathbb{R}^{n\times p}$ are boolean time invariant matrices representing cells that receive rainfall and inflow, respectively, $\boldsymbol{B}_d(\boldsymbol{H}(t)) \in \mathbb{R}^{n\times p}$ is the flow distribution time-variant matrix function derived from the celullar automata rules, $\boldsymbol{H}(t) \in \mathbb{R}^{n\times p}$ is the water surface depths, $\boldsymbol{I}(t) \in \mathbb{R}^{n\times p}$ is the rainfall intensity, $\boldsymbol{F}(\boldsymbol{H}(t), \boldsymbol{F}(t)) \in \mathbb{R}^{n\times p}$ is the infiltration rate, $\boldsymbol{F}_d \in \mathbb{R}^{n\times p}$ is the accumulated infiltration depth, $\boldsymbol{E}_{TR}(t) \in \mathbb{R}^{n\times p}$ is the evapotranspiration rate, $\boldsymbol{Q}_{in}(t)$ and $\boldsymbol{Q}_{out}(t) \in \mathbb{R}^{n\times p}$ are inflows and outflows from each cell, assuming a Von-Neumann squared grid, m is the the number of neighbor cells from a given cell, n and p represents the number of cells in Cartesian coordinates in the domain and t is a time index.

Expanding Eq. (1) by a 1^{st} order Taylor's approximation, we can derive an explicit numerical solution for the water surface due to overland flow problem neglecting high order, such that:

$$\begin{aligned}\boldsymbol{H}(t+\Delta t) = {} & \overbrace{\boldsymbol{H}(t) + \Delta t\left(\boldsymbol{B}_i \boldsymbol{I}(t) + \frac{1}{A}\boldsymbol{B}_Q \boldsymbol{Q}(t) - \boldsymbol{F}(\boldsymbol{H}(t), \boldsymbol{F}_d(t), \boldsymbol{E}_{TR}) - \boldsymbol{E}_{TR}(t)\right)}^{\boldsymbol{H}_{ef}(t)} + \\ & \Delta t \sum_{i=1}^{m}\left(\boldsymbol{Q}^i_{in}(\boldsymbol{H}(t)) - \boldsymbol{Q}^i_{out}(\boldsymbol{H}(t))\right)\end{aligned} \tag{2}$$

where $\boldsymbol{H}_{ef}(t) \in \mathbb{R}^{n\times p}$ is the effective depth for overland flow routing. To solve Eq. (2), we develop a weighted cellular automata approach using Manning's equation to estimate matrix $\boldsymbol{Q}_{out}$, and using topological relationships between cells, we derive $\boldsymbol{Q}_{in}(t)$ in terms of $\boldsymbol{Q}_{out}(t)$ by calculating $\boldsymbol{B}_d(\boldsymbol{H}(t))$. Details of how to solve the WCA2D model can be found in **?** and (**?**) and are described later in Algorithm 3.

Table 1: Variable definitions, dimensions, and units, where n and p define the domain, and m represent the number of boundary cells per cell.

Class	Symbol	Description	Dimension	Units
Input Matrices and Data	$\boldsymbol{I}(t)$	Rainfall intensity	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{LT^{-1}}$
	$\boldsymbol{E}_{TR}(t)$	Evapotranspiration rate	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{LT^{-1}}$
	$\boldsymbol{Q}(t)$	Inflow hydrograph	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3T^{-1}}$
	ω	Cell area	$\mathbb{R}$	$\mathrm{L^2}$
	$\mathbb{C}$	Set of cells	N.A	N.A
	$\mathbb{O}$	Set of outlet cells	N.A	N.A
	$\mathbb{B}$	Set of domain borders	N.A	N.A
	Δx	Average cell width	$\mathbb{R}$	L
	Δt	Model time-step	$\mathbb{R}$	T
	α_1	Time-step coefficient for water quantity	$\mathbb{R}$	T
	α_2	Time-step coefficient for water quality	$\mathbb{R}$	T
	σ	Slope tolerance	$\mathbb{R}$	$\mathrm{LL^{-1}}$
Infiltration model	$\boldsymbol{F}(t)$	Infiltration rate	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{LT^{-1}}$
	$\boldsymbol{F}_d(t)$	Infiltrated depth	$\mathbb{R}^{\mathrm{n \times p}}$	L
Flood routing model	$\boldsymbol{H}(t)$	Water surface depth	a	L
	$\boldsymbol{B}_i$	Rainfall incidence matrix	$\mathbb{R}^{\mathrm{n \times p}}$	N.A
	$\boldsymbol{B}_q$	Inflow hydrograph incidence matrix	$\mathbb{R}^{\mathrm{n \times p}}$	N.A
	$\boldsymbol{B}_d(H(t))$	Flow distribution matrix	$\mathbb{R}^{\mathrm{n \times p}}$	N.A
	$\boldsymbol{Q}_{in}(t)$	Inflows in each cell	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3T^{-1}}$
	$\boldsymbol{Q}_{out}(t)$	Outflows in each cell	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3T^{-1}}$
	$\boldsymbol{H}_{ef}(t)$	Effective depth for overland flow	$\mathbb{R}^{\mathrm{n \times p}}$	L
Cellular Automata	$\mathbf{WSE}$	Water surface elevation	$\mathbb{R}^{\mathrm{n \times p}}$	L
	s_0^b	Outlet slope boundary condition	$\mathbb{R}$	L.L-1
	g	Gravity acceleration	$\mathbb{R}$	$\mathrm{L^3T^{-2}}$
	$\boldsymbol{N}$	Manning's roughness coefficient	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{TL^{-1/3}}$
	Δh_{min}	Minimum assumed water level difference	$\mathbb{R}$	L
	$\Delta \boldsymbol{V}$	Available free volume within boundary cells	$\mathbb{R}^{\mathrm{n \times p \times (m+1)}}$	$\mathrm{L^3}$
	$\Delta \boldsymbol{H}_{ef}$	Available water depth within boundary cells	$\mathbb{R}^{\mathrm{n \times p \times (m+1)}}$	L
	$\Delta \boldsymbol{V}_{min}$	Minimum intercell volume transfer	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3}$
	$\Delta \boldsymbol{V}_{max}$	Maximum intercell volume transfer	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3}$
	$\boldsymbol{\Omega}$	Weights for each direction	$\mathbb{R}^{\mathrm{n \times p} \times m}$	N.A
	$\boldsymbol{V}_m$	Maximum outflow velocity per each cell	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{LT^{-1}}$
	$\boldsymbol{I}_{tot}^*$	Total intercell volume	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3}$
	$\boldsymbol{V}_{min}$	Minimum intercell transferable volume	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{L^3}$
Build-up and wash-off	$\boldsymbol{\Phi}$	Wash-off rate	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{MT^{-1}}$
	$\boldsymbol{C}_1$	Build-up coefficient	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{ML^{-2}}$
	$\boldsymbol{C}_2$	Build-up exponent	$\mathbb{R}^{n \times p}$	$\mathrm{T^{-1}}$
	$\boldsymbol{C}_3$	Wash-off coefficient	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{(LT^{-1})}^{C_4}\mathrm{T^{-1}}$
	$\boldsymbol{C}_4$	Wash-off exponent	$\mathbb{R}^{\mathrm{n \times p}}$	N.A
	$\boldsymbol{B}_{out}^i$	Mass of pollutant washed for direction i	$\mathbb{R}^{\mathrm{n \times p}}$	M
	$\boldsymbol{W}_{out}^{tot}$	Sum of washed pollutant for all directions	$\mathbb{R}^{\mathrm{n \times p}}$	M
	$\boldsymbol{B}$	Available mass of pollutant in each cell	$\mathbb{R}^{\mathrm{n \times p}}$	M
	$\boldsymbol{C}(t)$	Instantaneous pollutant concentration	$\mathbb{R}^{\mathrm{n \times p}}$	$\mathrm{ML^{-3'}}$

Algorithm 2: Main Algorithm, where $\boldsymbol{\gamma}, \boldsymbol{\tau}, \boldsymbol{\theta}$, and $\boldsymbol{\beta}$ are time vectors and $\boldsymbol{F}_d$ is the accumulated infiltration depth. The details of all input data are described in Table S1 in the supplemental material section.

input: Input maps and parameters from .tif and .xlsx files (i.e., Digital Elevation Model, Land Use and Land Cover Map) time, minimum and maximum time-step, stability method, outlet boundary cells, cells receiving rainfall, cells receiving inflow hydrograph, recording times for maps and for hydrographs, outlet boundary condition type, outlet boundary condition slope, flag to correct water balance, flag to simulate water quality, antecedent dry days, flag do correct time-step
set: Hydrologic, Hydrodynamic, and Water Quality distributed parameters according to input maps
while $t <$ *Routing Time* **do**
  compute: Infiltration Capacity through Green-Ampt Model
  compute: Inflow Rate from rainfall, inflow hydrograph and neighbor cells outflow
  compute: Infiltration Rate = min(Infiltration Capacity, Inflow Rate)
  compute: Cellular Automata Weighted System from Algorithm 3 and find $\boldsymbol{Q}_{out}, \boldsymbol{H}_{ef}, \boldsymbol{I}^*_{tot}$
  compute: Build-up and Wash-off problem and determine spatial washed mass of pollutant and concentration
  if $t \in \boldsymbol{\gamma}$ **then**
    Check stability criteria and refresh time-step
  end if
  compute: Disaggregation of inflow and rainfall to the time-step used
  if $t \in \boldsymbol{\tau}$ **then**
    Resize all state matrices to the new coordinate system
  end if
  compute: 2-D discretized solution of the mass balance of stormwater runoff and pollutant mass
  compute: Water Balance Error
  if *Water Balance Error* $>$ *Tolerance* **then**
    Redistribute water balance error in the inflow cells
  end if
  if $t \in \boldsymbol{\theta}$ **then**
    Save maps of water surface depths and pollutant concentration
  end if
  if $t \in \boldsymbol{\beta}$ **then**
    Save hydrographs and pollutugraphs at the outlet
  end if
end while
output: Export Hydrographs, Pollutographs, .TIFF maps, and GIFs of water surface elevations and pollutant distributions over time

Algorithm 3: Cellular automata pseudocode

input: Cell elevations, initial surface water depths, $\boldsymbol{N}$, $\boldsymbol{H}_0$, Δt, Δx, s_0^b, c, Velocity to the steepest direction $\boldsymbol{V}_m$, Intercell Volume $\boldsymbol{I}_{tot}$ previous outflow volumes, Minimum water depth Δh_{min} Set of cells $\mathbb{C}$, Outlet cells $\mathscr{O}$, Domain borders $\mathbb{B}$

for *i = 1 to m* **do**

  compute: $\Delta \boldsymbol{H}_{ef,i} = \mathbf{WSE} - \mathbf{WSE}_i,\ \Delta \boldsymbol{H}_{ef} \in \mathbb{R}^{n \times p \times (m+1)}, \mathbf{WSE} \in \mathbb{R}^{n \times p}$

end for

if *Outlet Type = 1* **then**

  compute: $\Delta \boldsymbol{H}_{ef,m+1} = s_0^b \Delta x\ \forall\ \mathbb{C} \in \mathbb{O}$

else

  compute: $\Delta \boldsymbol{H}_{ef,m+1} = \boldsymbol{H}_{ef}^{\circ -1/6} g^{0.5} \circ \boldsymbol{N}\ \forall\ \mathbb{C} \in \mathbb{O}$

end if

$\boldsymbol{H}_{ef,m+1} \leftarrow 0\ \forall\ \mathbb{C} \in \mathbb{B}$

$\boldsymbol{\Delta H}_{ef} \leftarrow 0\ \forall\ \Delta \boldsymbol{H}_{ef} \leq \Delta h_{min}$

compute: $\Delta \boldsymbol{V} = A \Delta \boldsymbol{H}_{ef},\ \Delta \boldsymbol{V} \in \mathbb{R}^{n \times p \times (m+1)}$

$\Delta \boldsymbol{V} \leftarrow c,\ \forall\ \Delta \boldsymbol{V} = 0$

compute: $\Delta \boldsymbol{V}_{max} = \max(\Delta \boldsymbol{V}),\ \Delta \boldsymbol{V}_{max} \in \mathbb{R}^{n \times p}$

compute: $\Delta \boldsymbol{H}_{ef,max} = \max(\Delta \boldsymbol{H}_{ef}),\ \Delta \boldsymbol{H}_{ef,max} \in \mathbb{R}^{n \times p}$

compute: $\Delta \boldsymbol{V}_{min} = \min(\Delta \boldsymbol{V}),\ \Delta \boldsymbol{V}_{min} \in \mathbb{R}^{n \times p}$

compute: $\boldsymbol{\Omega} = (\Delta \boldsymbol{V}_{tot} + \Delta \boldsymbol{V}_{min}) \oslash \Delta \boldsymbol{V},\ \boldsymbol{\Omega} \in \mathbb{R}^{n \times p \times (m+1)}$

compute: $\boldsymbol{\Omega}_{max} = \max(\boldsymbol{\Omega}),\ \boldsymbol{\Omega}_{max} \in \mathbb{R}^{n \times p}$

compute:
$\boldsymbol{V}_m = \min(\sqrt{g} \boldsymbol{H}_{ef}^{\circ 0.5}, \boldsymbol{N} \oslash \max(\boldsymbol{H}_{ef} - \boldsymbol{H}_0)^{\circ 2/3} \circ (\boldsymbol{H}_{ef,max}(1/\Delta x))^{\circ 0.5}),\ \boldsymbol{V}_m \in \mathbb{R}^{n \times p}$

compute: $\boldsymbol{I}_{tot}^{*} = \min(\omega \boldsymbol{H}_{ef}, (\Delta x / \Delta t) \boldsymbol{V}_m \circ \boldsymbol{H}_{ef}, \boldsymbol{I}_{tot}^{p} + \Delta \boldsymbol{V}_{min}),\ \boldsymbol{I}_{tot}^{*} \in \mathbb{R}^{n \times p}$

compute: $\boldsymbol{I}_{tot}^{*} \leftarrow \mathrm{sum}_3(\boldsymbol{\Omega} \circ \boldsymbol{I}_{tot}^{*})$

compute: $\boldsymbol{Q}_{out} = 1/(\Delta t A) \boldsymbol{I}_{tot}^{*},\ \boldsymbol{Q}_{out} \in \mathbb{R}^{n \times p \times m}$

compute: $\boldsymbol{H}_{ef} \leftarrow \boldsymbol{H}_{ef} - (1/\omega) \boldsymbol{I}_{tot}^{*}$

output: $\boldsymbol{Q}_{out},\ ,\boldsymbol{H}_{ef},\ \boldsymbol{I}_{tot}^{*}$

3.2

SUB-SECTION

Design Storms

The design storms are entered as spatially-invariant rainfall data at all cells of the computational domain.

3.2.1 ABM - Chicago Hyetograph

The method assumes that the rainfall volume obtained by the IDF curve distributes following a peak factor γ, such that if $\gamma = 0.5$, the maximum intensity value of rainfall would be centered. The Chicago method hence equals the ABM if $\gamma = 0.5$ (Gomes Jr et al., 2024).

$$i(t) = \frac{KRP^{a}(\frac{t_1}{\gamma}(1-c)+b)}{(\frac{t_1}{\gamma}+b)^{1+c}} \text{ for } t = t_1 \leq \gamma t_{\mathrm{d}} \tag{3a}$$

$$i(t) = \frac{KRP^{a}(\frac{t_2}{\gamma}(1-c)+b)}{(\frac{t_1}{1-\gamma}+b)^{1+c}} \text{ for } t = t_2 > \gamma t_{\mathrm{d}} \tag{3b}$$

where γ is a peak factor assumed as 0.5 to represent the rainfall peak at 50% of the storm duration and Eqs. (3a) and (3b) represent equations for durations before peak and after peak.

3.2.2 Huff Hyetographs

The polynomial equations used in the model to represent the Huff temporal distribution are presented as follows (**?**):

$$P(t) = 0.2558\left(\frac{t}{t_{\mathrm{d}}}\right)^4 + 1.5586\left(\frac{t}{t_{\mathrm{d}}}\right)^3 - 4.346\left(\frac{t}{t_{\mathrm{d}}}\right)^2 + 3.603\left(\frac{t}{t_{\mathrm{d}}}\right) - 0.0579 \tag{4a}$$

$$P(t) = 6.1888\left(\frac{t}{t_{\mathrm{d}}}\right)^4 - 14.996\left(\frac{t}{t_{\mathrm{d}}}\right)^3 + 10.861\left(\frac{t}{t_{\mathrm{d}}}\right)^2 - 1.0758\left(\frac{t}{t_{\mathrm{d}}}\right) + 0.0235 \tag{4b}$$

$$P(t) = 71.986\left(\frac{t}{t_{\mathrm{d}}}\right)^6 + 206.68\left(\frac{t}{t_{\mathrm{d}}}\right)^5 - 211.78\left(\frac{t}{t_{\mathrm{d}}}\right)^4 - 92.488\left(\frac{t}{t_{\mathrm{d}}}\right)^3 + 16.973\left(\frac{t}{t_{\mathrm{d}}}\right)^2 - 0.5697\left(\frac{t}{t_{\mathrm{d}}}\right) + 0.0041 \tag{4c}$$

$$P(t) = -58.036\left(\frac{t}{t_{\mathrm{d}}}\right)^6 + 154.96\left(\frac{t}{t_{\mathrm{d}}}\right)^5 - 151.59\left(\frac{t}{t_{\mathrm{d}}}\right)^4 + 68.269\left(\frac{t}{t_{\mathrm{d}}}\right)^3 - 13.978\left(\frac{t}{t_{\mathrm{d}}}\right)^2 + 1.3842\left(\frac{t}{t_{\mathrm{d}}}\right) - 0.008 \tag{4d}$$

where Eqs (4a), (4b), (4c), and (4d) represent polynomial equations for Huff's 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} quartiles, respectively. Variables t and t_d are the time and the rainfall duration.

3.3

SUB-SECTION

Warm-Up Process and Initial Values for Modeling

Before starting the hydrodynamic simulations, a warm-up process is generally performed to ensure proper initial values in the model domain

One way to do that is to run the model with a constant inflow hydrograph at specific gauges, or to input a rainfall that is representative of the initial conditions.

Often, rivers and creeks have minimum water flow to maintain living ecosystems. Alternatively, a regulated flow from a dam-regulation control can maintain a constant flow at the creeks.

For water quality initial parameters of build-up in cells, one alternative is to run a frequent storm (i.e., RP of approximately a month) with an initial dry days of 10-15 days and allow the model to distribute the build-up following the hydrodynamics.

Can you please find a map of a catchment where you have the initial water surface depth to illustrate this idea here?

3.4

SUB-SECTION

Evapotranspiration Modeling

Although not often considered in rapid and intense flood modeling, evapotranspiration (ET) is important in continuous simulation models. ET is the process of evaporation in the soil-plant system transferring water to the atmosphere (Sentelhas et al., 2010). Several models are available to estimate the reference evapotranspiration (E_{to}) flux in monthly (?), daily (Hargreaves and Samani, 1985), or even sub-daily scale (Allen et al., 1989). The input data required to simulate it varies, and the proper selection of the model should be done according to data availability at the catchment. In this paper, we use the Penman-Monteith model, which requires spatialized data of wind speed at 2m from surface, relative humidity, temperature, and radiation. However, the latter can be indirectly estimated using the method presented as follows. Let (i, j) collect the central coordinates of a specific cell. The rate of evapotranspiration can be estimated as:

$$e_{to}^{i,j} = \frac{0.408 \times \Delta^{i,j}(r_n^{i,j} - g^{i,j}) + \gamma^{i,j} \times \frac{900}{t^{i,j}+273} \times u_2^{i,j} \times (e_s^{i,j} - e_a^{i,j})}{\Delta^{i,j} + \gamma^{i,j} \times (1 + 0.34 \times u_2^{i,j})} \tag{5}$$

where $\Delta^{i,j}$ = slope vapor pressure curve (kPa°C^{-1}), $\mathrm{r_n^{i,j}}$ = net radiation at the crop surface (MJm^{-2}day^{-1}), $g^{i,j}$ = soil heat flux density (MJm^{-2}day^{-1}), $\gamma^{i,j}$ = psychrometric constant constant (kPa°C^{-1}), $t^{i,j}$ = mean daily air temperature at 2 m height in (°C), $u_2^{i,j}$ = wind speed at 2 m height (ms^{-1}), $e_s^{i,j}$ = saturation vapor pressure (kPa) and $e_a^{i,j}$ = actual vapor pressure (kPa).

This model is programmed to be implemented with all the inputs required in Penman Monteith ($\Delta^{\mathrm{i,j}}$, $\mathrm{r_n^{i,j}}$, $\mathrm{g^{i,j}}$, $\gamma^{\mathrm{i,j}}$, $\mathrm{u_2^{i,j}}$, $\mathrm{e_s^{i,j}}$, $\mathrm{e_a^{i,j}}$ and $\mathrm{t^{i,j}}$), but due to the lack of sub-day data in several regions, we applied methods to simplify the database and reduce the number of input data. To this end, parameters such as $\gamma^{\mathrm{i,j}}$, $\mathrm{r_n^{i,j}}$, $\mathrm{e_s^{i,j}}$ and $\mathrm{e_a^{i,j}}$ can be estimated with the input of spatially referenced areas, altitudes, temperatures for each watershed cell and, considering, some coefficients according to the location and the day of the year (Allen et al., 1998; Conceição, 2006). The $\gamma^{\mathrm{i,j}}$ variable can be quantified by establishing a relationship with atmospheric pressure (6), which will only require the altitude data extracted from the digital elevation model ($\mathrm{z^{i,j}}$) (7).

$$\gamma^{i,j} = 0.665 \times 10^{-3} \times p_{atm}^{i,j} \tag{6}$$

$$p_{atm}^{i,j} = 101.3 \times \left(\frac{293 - 0.0065 \times \mathrm{z^{i,j}}}{293}\right)^{5.26} \tag{7}$$

where $p^{i,j}_{atm}$ = atmospheric pressure (kPa) and $z^{i,j}$ = altitude (meters).

The simplifications made for $e^{i,j}_{s}$ (kPa) (8), $e^{i,j}_{a}$ (kPa) (9), $\Delta^{i,j}$ (kPa$°C^{-1}$) (10), and $r^{i,j}_{n}$ ($MJm^{-2}day^{-1}$) (11) are presented below. The only input required for them is $g^{i,j}$ ($MJm^{-2}day^{-1}$), day of the year (d) (1 to 366 $\in \mathbb{N}_{++}$), latitude ($\phi^{i,j}$) (rad) and maximum ($t^{i,j}_{max}$) ($°C$), minimum ($t^{i,j}_{min}$) ($°C$) and average temperatures ($t^{i,j}$) ($°C$).

$$e_s^{i,j} = 0.6108 \times \exp\left[\frac{17.27 \times t^{i,j}}{t^{i,j} + 237.3}\right] \tag{8}$$

$$e_a^{i,j} = 0.61 \times \left(\frac{17.27 \times t_{min}^{i,j}}{t_{\mathrm{min}}^{i,j} + 237.3}\right) \tag{9}$$

$$\Delta^{i,j} = \frac{4098 \times \left[0.6108 \times \exp\left(\frac{17.2 \times t^{i,j}}{t^{i,j}+237.3}\right)\right]^2}{t^{i,j} + 237.3} \tag{10}$$

$$r_n^{i,j} = r_{ns}^{i,j} - r_{nl}^{i,j} \tag{11}$$

where $r^{i,j}_{ns}$ = short-wave radiation ($MJm^{-2}day^{-1}$), expressed in following equation (12) and $r^{i,j}_{nl}$ = long-wave radiation ($MJm^{-2}day^{-1}$), later detailed in (18).

$$r_{ns}^{i,j} = (1-\alpha) \times r_s^{i,j} \tag{12}$$

where $r^{i,j}_{s}$ = incident solar radiation ($MJm^{-2}day^{-1}$) (13) and α = 0.23, albedo coefficient for the culture referee (grass). Note that α can change according to the land cover in the watershed. Therefore, r_s can be calculated as:

$$r_s^{i,j} = k_{rs} \times r_a^{i,j} \times \sqrt{(t_{max}^{i,j} - t_{min}^{i,j})} \tag{13}$$

where $r^{i,j}_{a}$ = solar radiation at the top of the atmosphere ($MJm^{-2}day^{-1}$) (14) and k_{rs} = coefficient of 0.16 for continental areas and 0.19 to coastal areas. The solar radiation, however, is a periodic function of ϕ and is related to the relative distance between the sun and the surface, such that:

$$r_a^{i,j} = \frac{118.08}{\pi} \times d_r^{i,j} \times \left[w_s^{i,j} \times \sin(\phi^{i,j}) \times \sin(\delta^{i,j}) + \cos(\phi^{i,j}) \times \cos(\delta^{i,j}) \times \sin(w_s^{i,j})\right] \tag{14}$$

where $d^{i,j}_{r}$ = inverse relative distance between Earth and Sun (rad) (15), $w^{i,j}_{s}$ = sunrise angle (rad) (16) and $\delta^{i,j}$ = solar declination (rad) (17). We can estimate d_r as a periodic function of d, such that:

$$d_r^{i,j} = 1 + 0.33 \times \cos\left(\frac{2 \times \pi}{365} \times \mathrm{d}\right) \tag{15}$$

Moreover, w_s from (14) is a function of the latitude and δ, such that:

$$w_s^{i,j} = \frac{\pi}{2} - \text{arctg} \times \left[\frac{-\tan(\phi^{i,j}) \times \tan(\delta^{i,j})}{(1 - [\tan(\phi^{i,j})]^2 \times [\tan(\delta^{i,j})]^2)^{0.5}} \right] \tag{16}$$

if $(1 - [\tan(\phi^{\mathrm{i,j}})]^2 \times [\tan(\delta^{\mathrm{i,j}})]^2) \leq 0$, we use $1\mathrm{e}-5$. Variable δ can be estimated as:

$$\delta^{i,j} = 0.409 \times \sin\left(\frac{2}{\pi} \times \mathrm{d} - 1.39\right) \tag{17}$$

$$r_{nl}^{i,j} = \sigma \times \left[\frac{(t_{max}^{i,j} + 273.16)^4 + (t_{min}^{i,j} + 273.16)^4}{2} \right] \times (0.34 - 0.14 \times \sqrt{(e_a^{i,j})}) \times \left(1.35 \times \frac{r_s^{i,j}}{r_{so}^{i,j}} - 0.35\right) \tag{18}$$

where $\sigma = 4.903 \times 10^{-9}$ ($\mathrm{MJm^{-2}day^{-1}}$) and $\mathrm{r_{so}^{i,j}}$ = incident solar radiation without clouds ($\mathrm{MJm^{-2}day^{-1}}$), resulting in:

$$r_{so}^{i,j} = (0.75 + 2 \times 10^{-5} \times \mathrm{z^{i,j}}) \times r_a^{i,j} \tag{19}$$

More background and rationale of these methods can be found in Conceição (2006).

3.5

SUB-SECTION

Soil Recover and Groundwater Replenishing

Three hydrological processes are assumed to occur in the soil media. The evapotranspiration and sub-surface drainage reduce the water content in the media, whereas infiltration from the upper zone increases it. We focus here on the methods to estimate sub-surface exfiltration rate (f_g), which depends on the replenishing rate k_r and on the uppermost layer depth l_u, written as (**?**):

$$k_r = \frac{\sqrt{k_{sat}/25.4}}{75} \tag{20}$$

$$t_r = \frac{4.5}{\sqrt{k_{sat}/25.4}} \tag{21}$$

$$l_u = 4\sqrt{k_{sat}/25.4} \tag{22}$$

where k_r = replenishing rate (1/h), t_r = recovery time (h), and l_u = uppermost layer depth (m).

From previous equations, we can infer that the sub-surface exfiltration rate is given by:

$$f_g = (\theta_{sat} - \theta_i) k_r l_u 1000 \tag{23}$$

where f_g = sub-surface exfiltration rate (mm/h), θ_{sat} = saturated soil content (−), and θ_i = initial soil content (−). Therefore, f_g is a constant sub-surface exfiltration rate applied in the water balance equation.

3.6

SUB-SECTION

Hydrograph Separation with Eckhart Filter

The Eckhart digital filter allows separation of surface runoff from the baseflow using observed streamflow data and can be used in HydroPol2D to estimate groundwater fluxes. Therefore, observed streamflow data is required. Usually, this data is derived from fitted rain curves using daily stage observations that ultimately convert the stage into discharges. By considering a filter that separates runoff (i.e., rapid response) from the baseflow (i.e., slow reservoir), one can estimate the proportion of observed hydrograph that corresponds to each flow clasification.

Therefore, it is possible to obtain daily flow and baseflow hydrographs. The total observed stream flow is composed by the runoff and baseflow, given by Eq. (24a). The baseflow-index, which is the long-term ratio between the baseflow and the total volume, depends on the aquifer porosity properties and can be estimated by a regression made for several brazilian watersheds as a function of the 90th and 50th percentile discharges (Collischonn and Fan, 2013) as shown in Eq. (24b). During periods of hydrograph recession, the decay in the hydrograph is assumed by the releasing of the aquifer water from the groundwater linear reservoir. The aquifer decay coefficient k can be calculated by defining two points on the recession curve and solving Eq. (24c). The solution of the digital filter using the signal processing theory require another paramter a, that is given by Eq. (24d) and the baseflow for a time t can be estimated in Eq. (24e).

$$Q_{\mathrm{obs}}(t) = Q_{\mathrm{r}}(t) + b(t) \tag{24a}$$

$$\mathrm{BFI}_{\max} = 0.8344\frac{Q_{90}}{Q_{50}} + 0.2146 \tag{24b}$$

$$k = \frac{-\Delta t^d}{\ln\left(\frac{Q_{\mathrm{obs}}(t+\Delta t^d)}{Q_{\mathrm{obs}}(t)}\right)} \tag{24c}$$

$$a = e^{\frac{-\Delta t^b}{k}} \tag{24d}$$

$$b(t) = \frac{(1-\mathrm{BFI}_{\max})\,ab(t-\Delta t^b) + (1-a)\mathrm{BFI}_{\max}Q_{\mathrm{obs}}(t)}{1-a\mathrm{BFI}_{\max}} \tag{24e}$$

where $b(t)$ is the baseflow, Δt^b is the baseflow time-step, Δt^d is a time-step where two points of the recession curve are obtained, Q_{r} is the runoff discharge, Δt^d is a drought time-step, Q_{obs} is the total observed streamflow, $\mathrm{BFI}_{\max}$ is the baseflow index, k is the aquifer decay constant, Q_{90} is the 90th percentile of exceedance of stream flow, and Q_{50} is the streamflow of the 50th percentile.

We perform hydrograph separation for all stream gauges and calculate the specific average daily baseflow and average lateral ground flux as follows:

$$\bar{q_A}^i = \frac{1}{A^i n \Delta t^b} \sum_{j=1}^{n} b_j \tag{25a}$$

$$\bar{q_L}^i = \frac{1}{L^i n \Delta t^b} \sum_{j=1}^{n} b_j \tag{25b}$$

where q_A is the specific baseflow per unit of superficial drainage area, q_L is the specific baseflow per unit of stream, n is the number of time-steps, L is the streamflow length, A is the upstream drainage area, n is the number of observations, and i is the location of the stream gauge.

In this paper, to allow for a simple conceptualization of groundwater flux, we average all lateral stream fluxes such that the dependency of sub-catchments is disregarded by an assumption of a single average lateral groundflux, such that:

$$\bar{q}_L = \frac{1}{n_g} \sum_{i=1}^{n_g} \bar{q}_L^i \tag{26}$$

where $\bar{q}_L$ is the average lateral groundflux calculated from all observed streamgauges in the watershed, and n_g is the number of streamgauges.

HydroPol2D is a sub-hourly rainfall-runoff model that is typically solved with relatively smaller time-steps. To this end, the baseflow hydrograph can be incorporated into the mass balance by a lateral flux that enters the streamlines, such that a lateral groundwater flux $\bar{q}_l$ calculated from Eq. (26) changes the mass balance equation such that (Gomes Jr et al., 2023):

$$\frac{\partial d^{i,j}(t)}{\partial t} = \Big[\sum_{\mathcal{N}^{i,j}} I^{i,j}(t) - \sum_{\mathcal{N}^{i,j}} O^{i,j}(t) + i^{i,j}(t) - f^{i,j}\Big(d^{i,j}(t), F_d^{i,j}(t)\Big) - e_{\mathrm{T}}^{i,j}(t) - \bar{q}_L \Delta x \Big] \tag{27}$$

where $d^{i,j}(t)$ is the water surface depth (m), $I^{i,j}(t)$ is the inflow rate (LT^{-1}), $O^{i,j}(t)$ is the outflow rate (LT^{-1}), $i^{i,j}(t)$ is the rainfall intensity (LT^{-1}), $f^{i,j}(t)$ is the infiltration rate (LT^{-1}), $F_d(t)$ is the infiltrated depth of water into the soil (L), and $e_T^{i,j}(t)$ is the evapotranspiration rate (LT^{-1}).

The previous equation is solved using a forward Euler discretization and gives states from $t + \Delta t$ in terms of inputs and states from t.

3.7

SUB-SECTION

HydroPol2D Reservoir Modeling Routine

To simulate reservoir control in a 2D fashion, we imply a boundary condition at the reservoir dam, such that flow is limited to the available volume of water in the upstream cell and the spillway capacity. Let (i_g, j_g) be the gate location coordinates in the domain. The spillway capacity can be modeled through a Francis-type spillway equation such that:

$$Q^{i_g,j_g}(t) = \max\left(Cd^{i_g,j_g} L_{ef}^{i_g,j_g}(z^u + d^u(t) - p^{i_g,j_g})^{3/2}, \frac{\Delta x^2 d^u(t)}{\Delta t}\right), \ \forall \text{ gates} \tag{28}$$

where $(z^u + d^u)$ is the water surface elevation of the upstream cell connected to the gate cell, C_d is the spillway discharge coefficient, L_{ef} is the effective spillway length, p is the spillway elevation, Δx is the cell length, and Δt is the computational time-step.

The gate is then categorized by the effective length of the spillway, its discharge coefficient, its height, and the downstream cell ($i = 1, 2, \ldots m$, such that 1 = rightwards, 2 = leftwards, 3 = upwards, 4 = downwards for a Von-Neuman grid. Knowing the downstream cell of a gate allows us to define the upstream cell, which is assumed to be the diametral opposite cell to the downstream one.

Although the boundary condition described is designed for reservoir gates, it can represent channels and other hydraulic structures that follow a power relationship with the water depth.

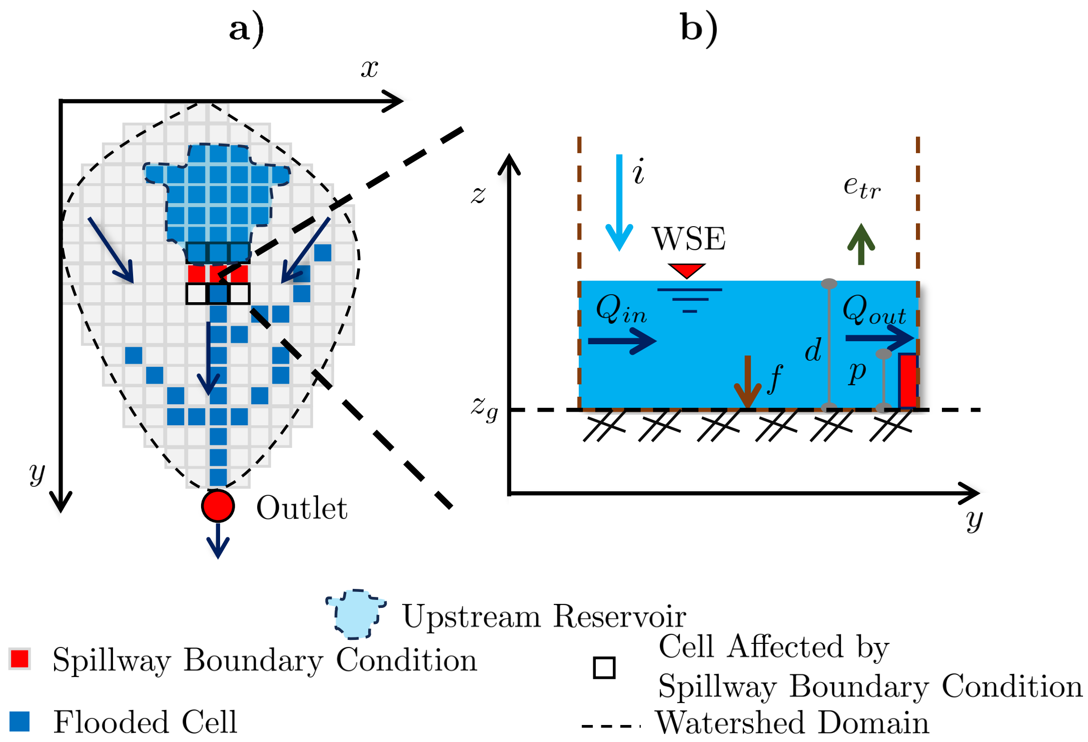


Figure 28: Effect of a reservoir in a 2D meshgrid of HydroPol2D. Part a) shows the flooded cells, the cells with spillway boundary conditions, and the cells affected to this boundary conditions. Part b) shows how the flow is confined in the upstream reservoir. Hydrological variables i = rainfall intensity, f = infiltration rate, d = water surface depth, WSE = water surface elevation, Q_{in} = inflow discharge are used to estimate the spillway boundary condition expressed by Q_{out}.

3.8

SUB-SECTION

Interpolation of Rainfall ETP and Climatological Forcing

HydroPol2D allows interpolating spatially distributed input data using the Inverse-Distance-Weightning method (Bartier and Keller, 1996), which is calculated as follows. Given a n_s number of stations with recorded values, we store the station values for a given time t in $\boldsymbol{z}_s(t) = [z_s^1(t),\ z_s^2(t), \ldots z_s^{n_s}(t)]^T$. The stations are located at known projected coordinates x and y described by vectors $\boldsymbol{x}_s$ and $\boldsymbol{y}_s$, respectively. We apply the IDW method (Bartier and Keller, 1996) by calculating the p-norm (i.e., projected distance for a euclidean norm) between each point of the meshgrid and the stations.

$$\hat{z}(\mathbf{x_s}, \mathbf{y_s}) = \frac{\sum_i^{n_c} w_i z_s^i}{\sum_i^{n} w_i}, \ w_i = \left|\left|(\mathbf{x_s}, \mathbf{y_s}) - (\mathbf{x_i}, \mathbf{y_i})\right|\right|_2^{-\beta} \tag{29}$$

where n_c is the number of cells in the catchment, β is the weighting factor and is typically assumed equals 2 to represent the Euclidean distance.

3.9

SUB-SECTION

Flow Accumulation-Based Filter

Let $\boldsymbol{F}_a$ be the flow accumulation matrix that indicates the number of pixels that drain to a particular cell (i,j) in the domain. Let $\boldsymbol{R}$ be a mask matrix defining the pixels that are considered as streams, that is, pixels that have a flow accumulation larger than a pre-defined threshold τ. As shown in **?**, the width of the river $\boldsymbol{B}$ and height $\boldsymbol{H}$ can be written as:

$$\boldsymbol{B} = \alpha_1 \boldsymbol{F}_a^{\circ\alpha_2} \boldsymbol{R} \tag{30}$$

$$\boldsymbol{H} = \beta_1 \boldsymbol{F}_a^{\circ\beta_2} \tag{31}$$

where parameters α_1, α_2, β_1, and β_2 are derived from fitting regression models in cross-section data.

Therefore, the estimated cross-section area under normal flow conditions is:

$$\boldsymbol{A} = \boldsymbol{B} \circ \boldsymbol{H} \tag{32}$$

If we impose that this area needs to be connected to only one pixel, we can calculate the DEM depth reduction (H_r) as follows:

$$\boldsymbol{H}_r = \frac{1}{\Delta x} \boldsymbol{A} \tag{33}$$

where Δx is the pixel resolution in meters.

Finally, a raster operation is performed in the $\boldsymbol{D}EM$, such that:

$$\mathrm{DEM} = \mathrm{DEM} - \boldsymbol{H}_r \tag{34}$$

3.10

SUB-SECTION

Constrained Regularized Smoothing of the Channel Length Profile

A detailed definition of the algorithm is presented in Schwanghart and Scherler (2017). For smoothing the streams, we assume $K = 10$ and $\sigma = 0.2$. The parameter K dictates the degree of smoothing.

3.11

SUB-SECTION

Watershed Geometrical Indicators

3.11.1 Compactness Coefficient

The compactness coefficient relates the perimeter of the catchment and a perimeter of a circle with the same area such that:

$$k_c = \frac{0,28P}{\sqrt{A}} \tag{35}$$

where P is the perimeter of the catchment and A is its area.

3.11.2 Form Factor

It is the relationship between the average width of the catchment (W) and the length of the catchment axis (L) (from the mouth to the farthest point in the area). The average width of the basin is typically determined by geoprocessing software. However, in the developed model, this width is estimated as follows:

$$\bar{L} = \sqrt{W^2 + H^2} \tag{36}$$

where W and H are the largest $x - x$ length, and $y - y$ length in the 2-D spatial domain, respectively.

Therefore, the factor form is given by:

$$K_f = \frac{A}{\bar{L}} \tag{37}$$

3.11.3 Circularity Index

The circularity index is the ratio between the catchment area and the correspondent perimeter of a circle with the same perimeter such that:

$$IC = 12,57\frac{A}{P^2} \tag{38}$$

3.12

SUB-SECTION

Water Quality Modeling

The descriptions of the HydroPol2D presented in this manual are adapted from the publication presented in Gomes Jr et al. (2023).

The mathematical framework utilized for evaluating the movement and destiny of pollutants is grounded in the build-up and wash-off model (Deletic, 1998; Rossman and Huber, 2016). The concept of build-up pertains to the accumulation of pollutants within the catchment during dry periods, while wash-off involves the flushing and conveyance of these pollutants during wet events (Rossman and Huber, 2016). Various mathematical representations of this model have been proposed, with this paper adopting an adaptation of the exponential build-up and wash-off model. Moreover, the escalation of pollutants (ΔB) within the catchment during dry weather periods is assumed to be contingent solely on the number of consecutive dry days (ADD), as delineated in Eq. (39):

$$\Delta B^{i,j} l = 10^{-4} A_c \left[C1, l^{i,j} \exp\left\{ -C_{2,l}^{i,j} \mathrm{ADD} \right\} \right] \pm R_l(\mathrm{ADD}) \tag{39}$$

where C_1 signifies the build-up coefficient, which is influenced by land use and land cover (kgha^{-1}), C_2 represents the daily build-up accumulation rate (day^{-1}), ADD stands for the antecedent dry days (days), A_c denotes the area (m^2), l denotes the land use classification (e.g., pervious or impervious areas), and a source term R is introduced to accommodate the modeling of a non-conservative mass balance due to self-degradation or chemical reaction, which varies for each land use and land cover (kgha^{-1}).

The equation (39) applies during dry spells and computes the increase in build-up, which when combined with the initial build-up, signifies the quantity of mass available in each cell after the passage of ADD time (Deletic, 1998). Typically, for total suspended solids, the contribution R can be disregarded. The original formulation of the exponential wash-off model, which influences the variation in build-up during wet weather periods, can be expressed as follows in Eq. (40).

The equation (40) describes the rate of change of pollutant mass in terms of time (t) as a function of the outflow ($W_{out}(t)$), where:

$$\frac{\mathrm{d}B(t)}{\mathrm{d}t} = -W_{out}(t) = 10^{-4} A_c \left(-C_3^* q(t)^{C_4^*} B(t) \right) \tag{40}$$

Here, C_3 and C_4 denote the wash-off coefficients in terms of specific flow rates (i.e., flow divided by catchment area) rather than flow discharges in each cell. The variable $q(t)$ represents the flow rate, usually expressed in ($\mathrm{mmh^{-1}}$) or ($\mathrm{inh^{-1}}$), and can be deduced by dividing the outlet flow by the catchment area in a concentrated model (**?**). The units of C_3 depend on the units of $q(t)$, and this is factored into the conversion factor of C_4 to ensure that the wash-off rate W has units of mass per time (e.g., $\mathrm{kgh^{-1}}$). In essence, for the International System of Units, C_3 has dimensions of $(\mathrm{LT^{-1}})^{C_4}\mathrm{T^{-1}}$, contingent on $q(t)$ Rossman and Huber (2016).

This equation, Eq. (40), is utilized in SWMM software and is implemented in a concentrated hydrologic conceptual model, assuming a single representative value for the entire sub-catchment. To simulate the wash-off process, a modification of the exponential wash-off model previously discussed has been employed (**????**). The adaptation made in HydroPol2D is as follows: instead of modeling wash-off using functions dependent on specific flow rates (equivalent depth per unit of time), the model computes the transport of pollutants, i.e., the rate at which pollution is washed away, as a function of the flow discharges leaving each cell and the available mass to be washed. Another significant deviation is that pollutants enter and exit cells simultaneously during wet weather periods. This characteristic alters the mass balance equation so that the equation for the rate of change of pollutant mass can be expressed as a combination of inputs and outputs of pollutant mass. This is illustrated in the equation:

$$\frac{\partial B^{i,j}(t)}{\partial t} = \sum_{\forall\ \mathrm{dir}} W^{i,j}_{\mathrm{in,dir}}(t) - \sum_{\forall\ \mathrm{dir}} \overbrace{C_3\Big(Q^{i,j}_{\mathrm{dir}}(t)\Big)^{C_4} f\Big(B(t)\Big)}^{W^{i,j}_{\mathrm{out,dir}}(t)}, \tag{41}$$

In this context, W represents the wash-off load ($\mathrm{kgh^{-1}}$), where the sub-indices *in* and *out* denote the inlet and outlet of the cells, respectively. The sub-index dir signifies the flow direction, which varies among leftwards, rightwards, upwards, and downwards, respectively, following the Cartesian directions. $W_{\mathrm{in,dir}}(t)$ represents the rate of pollutant inflow in the direction dir, and the term $\sum_{\forall\ \mathrm{dir}} W^{i,j}\mathrm{in,dir}(t)$ computes the pollutant inflow rate, contingent upon the problem's topology. $Q\mathrm{dir}$ stands for the outflow discharge ($\mathrm{m^3s^{-1}}$) in the direction dir, and $f(B(t))$ is further elaborated upon.

By discretizing Eq. (41) utilizing a forward Euler scheme, we obtain:

$$B^{i,j}(t+\Delta t) = B^{i,j}(t) + \Delta t\overbrace{\Big(\sum_{\forall\ \mathrm{dir}} W^{i,j}_{\mathrm{in,dir}} - \sum_{\forall\ \mathrm{dir}} W^{i,j}_{\mathrm{out,dir}}(t)\Big)}^{\Delta W^{i,j}(t)} \tag{42}$$

The function $f(B(t))$ adjusts the pollutant washing equation based on the mass accumulated in the cells. When $B(t)$ falls below B_{min}, the pollutant flux is assumed to be zero. This scenario typically occurs with pollutants firmly fixed on the soil and surface, making them difficult to wash off. When $B(t)$ exceeds B_{min} but remains below a threshold B_{r}, which is dependent on the type of pollutant, the washing rate follows a sediment rating curve independent of the accumulated mass. Hence, washing becomes solely dependent on the rating curve coefficients, which are equivalent to the wash-off coefficients. It's worth noting that B_r can be assumed to be equal to B_min, effectively neglecting the influence of the rating curve. In cases where the available mass falls between B_r and B_m, where B_m serves as an upper limit, the wash rate is adjusted by the mass of pollutants in the cell, adhering to the typical exponential wash-off model (**?**). If $B(t)$ surpasses B_m, the maximum output rate is capped at the representative value of B_m. These conditions are expressed in Eq. (43) as follows:

$$f\Big(B(t)\Big) = \begin{cases} 0, \text{ if } B(t) \le B_\mathrm{min} \\ 1, \text{ if } B_\mathrm{min} \le B(t) \le B_\mathrm{r} \\ (1 + \ B(t) - B_\mathrm{r}), \text{ if } B_\mathrm{r} \le B(t) \ge B_\mathrm{m} \\ (1 + B_\mathrm{m} - B_\mathrm{r}), \text{ if } B(t) \ge B_\mathrm{m}. \end{cases} \tag{43}$$

Introducing a minimum value B_min for the pollutant washing rate significantly enhances the computational efficiency of the model by circumventing computations in cells where the accumulated mass tends toward zero, thereby preventing the minimum time-step from approaching zero. Additionally, setting the limit B_r proves effective as it ensures that pollutants adhere to a rating curve model for relatively low accumulated masses but above a minimum threshold B_r. Without this adjustment, utilizing the conventional wash-off model (Eq. (40)) could lead to non-realistic outcomes, particularly when considering a scenario where a relatively low available pollutant mass is washed by a high flow rate, resulting in minimal wash-off due to $B(t)$ approaching zero.

Previous modeling outcomes suggest that for Total Suspended Solids (TSS), B_min is set to 1 $\mathrm{gm^{-2}}$, B_r to 10 $\mathrm{gm^{-2}}$, and B_m to 100 $\mathrm{gm^{-2}}$, which aligns with TSS modeling in urban regions. These values are adaptable and can be calibrated for different pollutants.

SECTION 4

Applications - Study Cases

- Case Study No.1 - Franquinho Watershed (Concentrated Rainfall + Inflow + Human Instability).
- Case Study No.2 -
- Case Study No.3 -
- Case Study No.4 -
- Case Study No.5 -
- Case Study No.6 -
- Case Study No.7 - Satellite Rainfall + Digital Twin + Forecast System.
- Case Study No.8 -
- Case Study No.9 -
- Case Study No.10 -
- Case Study No.11 -
- Case Study No.12 -

4.1

SUB-SECTION

Case Study No.1 - Franquinho Watershed

Here we simulate the Franquinhos Watershed (FW), São Paulo, Brazil. This is a highly urbanized watershed, with around 7.3 km^2 of drainage area. The modeling consist in concentrated rainfall (Sec. 2.3), inflow modeling (Sec. 2.7), and assess human instability with the Milanesi et al. (2015) approach (Sec. 2.11).

4.1.1 GIS Data - LULC, DEM, Soil

For the LULC classification, we used data from "Husqvarna Urban Green Space Index". For São Paulo city, the HUGSI project indicates that 37% of the LULC belongs to green space (Husqvarna-Group, b). The data is divided into 4 classes: trees (vegetation higher than 1 meter), grass (vegetation lower than 1 meter), water bodies, and other (such as houses, roads, hard-made surfaces, etc.); for more details about how data are processed, see Husqvarna-Group (a). Notice that this information used is different from that recommended to use in Sec. 1.1.6, because HUGSI data better depicts the spatial distribution within this urban area, when compared with the Dynamic World data (Brown et al., 2022).

Related to the digital elevation data, we used the airborne LiDAR DEM with 1 meter spatial resolution, freely available for download at the GeoSampa portal (PMSP, 2017). Data were re-sampled at 10 meters of spatial resolution using the "lidR" package (Roussel et al., 2020), to maintain the same spatial resolution of the Land Use and Land Cover (LULC) data. Finally, for the soil type, there is only red-yellow dystrophic clay according to the Harmonized World Soil Database, see Sec. 1.1.6.

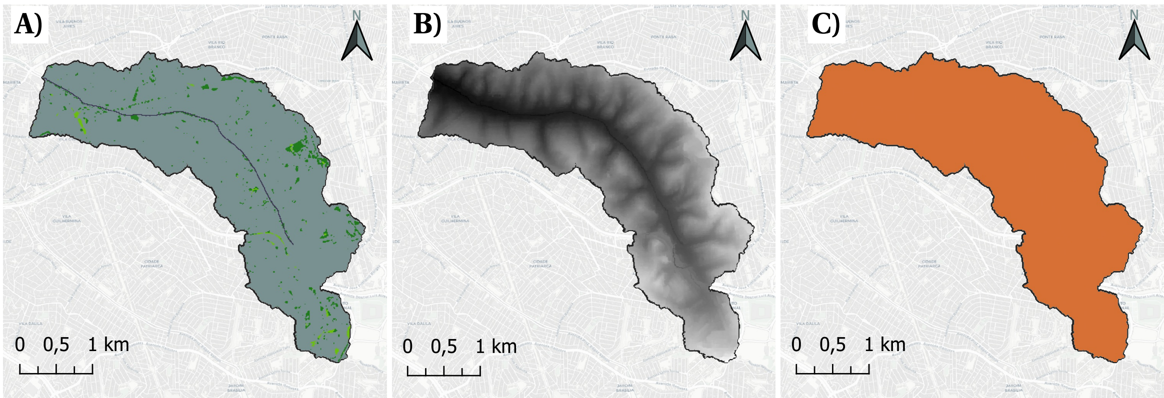


Figure 29: Franquinho Watershed Spatial Input. A) is the Land Use and Land Cover from Husqvarna-Group (b), B) is the Digital Elevation Model, and C) is the Soil Type which is red-yellow dystrophic clay.

4.1.2 Input Data

Besides to activate the necessary flags to simulate concentrated rainfall (Sec. 2.3), and human instability risk (Sec. 2.11), we show the final parameters used for the modeling in Fig. 30/1. Moreover, we remind the user about the good practices to set these parameters, see Sec. 2.1.

For the employed resolution (10m) and with the min and max time step set (0.01 and 20s), the flow velocity could vary from > 100 and 0.3 m/s due to the dynamic courant values from alpha 0.6 to 0.2. Notice that flow velocities higher than 100 m/s are not physically possible for this context; however, for the example purpose, we set this superior limit to avoid flow accumulation due to lower velocities during important hydraulic periods because flow needs to be faster. Moreover, we set the date begin and date end according to the observed event on february 10 in 2020. As explained in Sec. 2.3 and Sec. 2.7, we fill the input rainfall and inflow data with temporal discretization of 10 minutes. The rainfall data was obtained from The rainfall and water level gauge station 591 of São Paulo's Department of Water and Electrical Energy (DAEE). On the other hand, the inflow was estimated based on observations from that gauge stations for the base flow. Notice that the inflow duration has to be the same with the rainfall event.

2)

	D	E
	General Flags	
3	rainfall	**1**
4	flag_abstraction	0
5	flag_inflow	**1**
6	flag_waterbalance	0
7	flag_waterquality	0
8	flag_timestep	0
9	flag_warmup	1
10	flag_initial_buildup	0
11	flag_wq_model	0
12	flag_infiltration	1
13	flag_critical	0
14	flag_spatial_rainfall	**0**
15	flag_D8	[illegible]
16	flag_diffusive	1
17	flag_resample	0
18	flag_smoothening	1
19	flag_trunk	1
20	flag_export_maps	1
21	flag_fill_DEM	0
22	flag_smooth_cells	1
23	flag_reduce_DEM	1
24	flag_ETP	0
25	flag_obs_gauges	1
26	flag_GPU	1
27	flag_single	1
28	flag_reservoir	0
29	flag_human_instability	**3**
30	flag_input_rainfall_map	[illegible]
31	flag_satellite_rainfall	0
32	flag_real_time_satellite_rainfall	1
33	flag_forecast_unit	0
34	flag_dam_break	0
35	flag_groundwater_modeling	1
36	flag_river_heigth_compensation	1

1)

	A	B	C
	Running Control		
3	Time_save_ETP	1440	min
4	Time_step_model	**1**	sec
5	Min_time_step	**0.01**	sec
6	Max_time_step	**20**	sec
7	Time_step_increments	**0.1**	sec
8	Time_step_change	**20**	sec
9	Alpha_max	**0.6**	
10	Alpha_min	**0.2**	
11	V_threshold	**3.1**	
12	Slope_alfa	**0.18**	
13	Date Begin	**09/02/2020 19:00**	
14	Date End	**11/02/2020 16:00**	
15	Days	**1.91 Days**	

Figure 30: Franquinho Watershed Model Set Up.

Related to the LULC and Soil parameters, In Fig. 31 are show the calibrated values. Here, we highlight that the manning coefficient (n) are one of the sensitives parameters. Moreover, lower values tend to produce high velocities during simulation. For example, for the built areas, 0.01 of manning tends to generate high flows and could not be the best value to represent that LULC. According to the study purposes, enhanced calibration procedures could be required for this example.

Related to the soil type, according to the soil texture, it can be used to estimate key hydraulic parameters including saturated conductivity (K_{sat}), soil suction head (ψ), and moisture deficit ($\Delta\theta = \theta_{sat} - \theta_i$). We employed values from Rawls et al. (1983, 1982) as reference.

HydroPol2D - LULC Parameters

LC	Index	n ($m.s^{-1/3}$)	h0 (mm)	d0 (mm)	C_1	C_2	C_3	C_4	index_impervious
Built Areas	1	0,01	0	0	0	0	0	1,2	1
Grass	2	0,023	4	0	0	0	0	1,2	
Trees	3	0,025	6	0	0	0	0	1,2	
Main Channel	4	0,015	0	0	0	0	0	0	

HydroPol2D - Soil Parameters

Soil_type	Index	k_{sat} (mm/h)	ψ (mm)	I_0 (mm)	θsat (cm3.cm-3)	θi (cm3.cm-3)
1	1	0,30	250,00	6	0,49	0,1

Figure 31: Franquinho Watershed LULC and Soil Parameters.

For the Human instability data, we gathered physiological characteristics' data from the Food and Nutrition Surveillance System (SISVAN) program in Brazil, conducted by the Ministry of Health (SISVAN, 2022). The data was filtered for the São Paulo region. In Fig. 32 we show the parameters employed for this study case.

3)	Method No. 3	
ro_water	1000	kg/m3
gravity	9.81	m/s2
mu	0.46	
Cd	1	
m_c_m	22.915	Kg
y_c_m	1.16	m
m_t_m	56.645	Kg
y_t_m	1.587	m
m_a_m	84.58681538	Kg
y_a_m	1.720005423	m
m_o_m	76.89151761	Kg
y_o_m	1.667113814	m
m_c_f	22.719	Kg
y_c_f	1.155	m
m_t_f	59.271	Kg
y_t_f	1.571	m
m_a_f	76.858	Kg
y_a_f	1.602	m
m_o_f	70.284	Kg
y_o_f	1.547	m

Figure 32: Franquinho Watershed Human Instability Risk Parameters.

4.1.3 Running the Model

Before staring the simulation, we recommend some good practices for this study case. Flags such as D8, GPU and single must be considered to be employed.

- **Flag D8**, the user must consider allowing diagonal flow movement in order to avoid accumulation due to irregularities within the DEM. The latter is a typical issue when orthogonal flow is employed (D4); however, D8 flow required more memory usage and takes more time to be processed.

- **Flag GPU**, the user has to know the quantity of elements (pixels) that the study area have (number of rows times columns within the DEM), because the parallel processing could improve the model performance. The study case have around 300,000 elements, then parallel processing is recommended. Notice that for simulation with less than 100,000 elements, it is not recommended to use parallel processing since GPU architecture tends to be inefficient with few elements.

- **Flag Single**, when the user has RAM or VRAM memory limitations, we recommend activating the single precision in order to make the calculation with less accuracy (less decimal units in float numbers). On the another hand, for dam break simulation, single precision is not recommended.

To execute the model, within the folder created for the study case, the user has to execute the "HydroPol2D$_V$.m". This file has the task to read the "General_Data_HydroPol2D.xlsx" (Sec. 2.1), and call the HydroPol2D functions. Since the model is running, the sub-section windows of Matlab will display some variables values of the current simulation in real-time, see Fig. **??**. dont forget this

4.1.4 Simulation Results

The HydroPol2D model will generate multiple output, according to the model set up made (see the map and plots control sub-section in Sec. 2.1). For the outlet basin, in Fig. 33 is shown the input rainfall, the inflow discharge and the resultant discharge for the 10/02/2020 event. Moreover, in Fig. 34 are shown the multiple degrees of human instability (children, teenagers, adults and elderly persons), indicating streets that could represent potential risk for pedestrians.

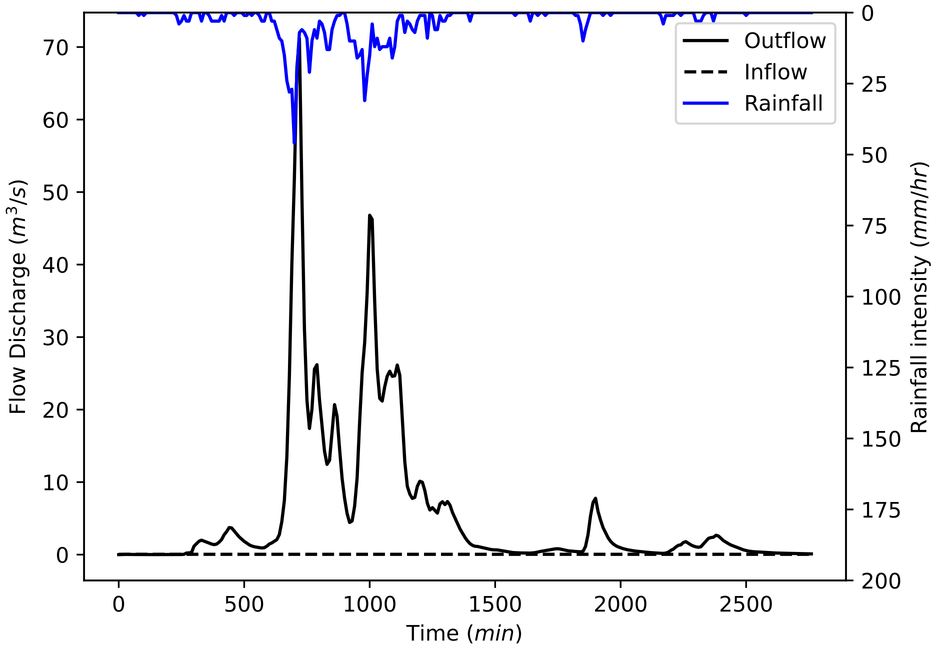


Figure 33: Franquinho Watershed Outlet results.

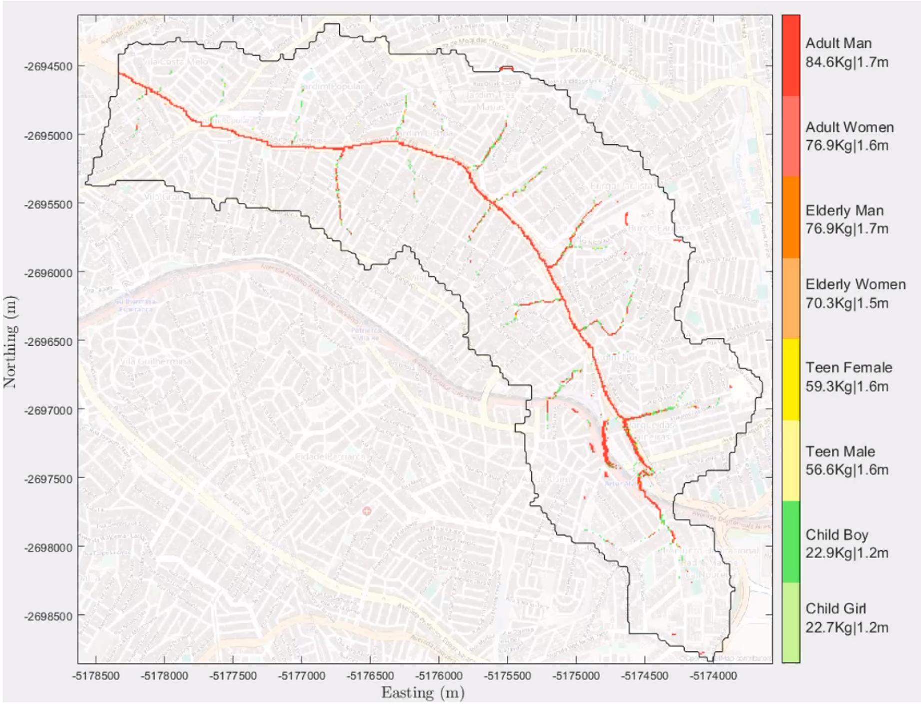


Figure 34: Franquinho Watershed Human Instability results.

4.1.5 Considerations

As early mentioned, the result here presented comes from calibrated parameters. The user must perform calibration procedures for their study area, changing parameters values of LULC, Soil and the model time steps.

For the calibration procedure, we recommend some good practices:

- The digital elevation model has to be free of hydraulic discontinuities, this mean that a pre-processing is required in order to "burn" the DEM. The latter is to remove bridges or trees that are within the river or channel, which the LiDAr survey captured. If these discontinuities are present, the resultant discharge will be affected because some discharge will be contained upstream within the basin. Then, changing model parameters will not help for the calibration in this case.
- The calibration should start with parameters found in literature that have some physical similarity with those in the study area.
- The user must start simulations with bigger time steps in order to see an initial hydraulic behaviour of the basin.

4.2

SUB-SECTION

Case Study 2 - Gregorio

4.2.1 QGIS - Data

4.2.2 Input Data

4.2.3 Running the Model

4.2.4 Extracting Results

4.2.5 Analyzing Results

4.3

SUB-SECTION

Case Study 3 - Aricanduva

4.3.1 QGIS - Data

4.3.2 Input Data

4.3.3 Running the Model

4.3.4 Extracting Results

4.3.5 Analyzing Results

4.4

SUB-SECTION

Case Study 4 - Reservoirs

4.4.1 QGIS - Data

4.4.2 Input Data

4.4.3 Running the Model

4.4.4 Extracting Results

4.4.5 Analyzing Results

4.5

SUB-SECTION

Case Study 5 - Spatial Rainfall

4.5.1 QGIS - Data

4.5.2 Input Data

4.5.3 Running the Model

4.5.4 Extracting Results

4.5.5 Analyzing Results

4.6

SUB-SECTION

Case Study 6 - Aricanduva (ETR Modeling)

4.6.1 QGIS - Data

4.6.2 Input Data

4.6.3 Running the Model

4.6.4 Extracting Results

4.6.5 Analyzing Results

4.7

SUB-SECTION

Case Study No.7 - Satellite Rainfall + Digital Twin + Forecast System

Here we simulate for a big scale in an endless loop the South American Continent. The modeling consist of near-real time simulation (digital twin, sec. 2.12), with satellite rainfall (PERSIANN PDIR-Now, sec. 2.5), and a forecast system with 5 days of lead time (sec. 2.13). We highlight that this model is not calibrated, and parameters might change in the future.

4.7.1 QGIS - Data

For the LULC classification, we used data from the Dynamic World (Brown et al., 2022). For this database there are 9 LULC classes: Water, Tress, Grass, Crops, Shrub and Scrub, flooded vegetation, built-up areas, bare ground, snow and ice. Notice that this information used is that recommended in Sec. 1.1.6, because it is word wide available. Related to the digital elevation data, we used the SRTM of 90m, freely available for download in the OpenTopography platform. Finally, for the soil type, we employed the Harmonized World Soil Database, see Sec. 1.1.6.

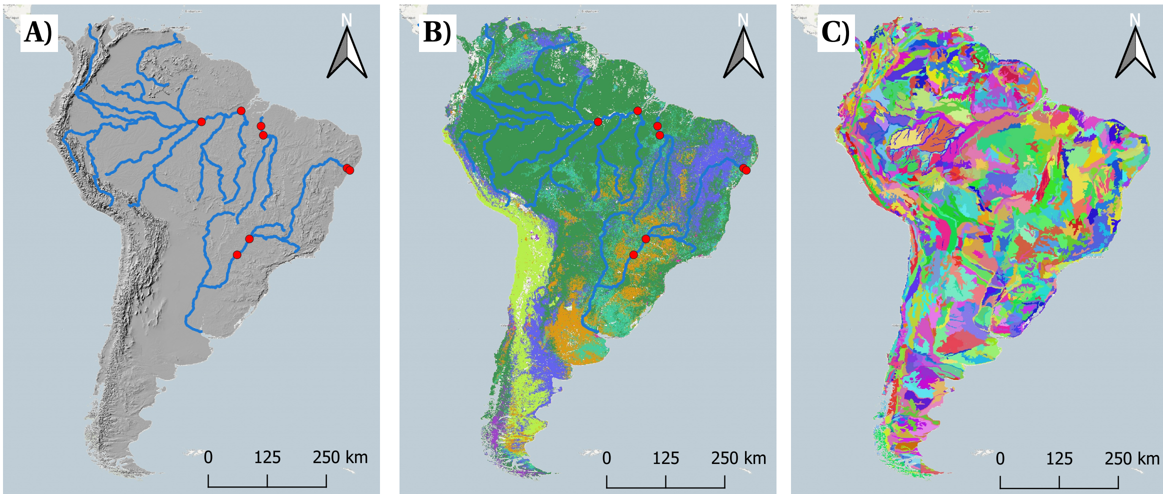


Figure 35: South America Spatial Input. A) is the Land Use and Land Cover from Brown et al. (2022), B) is the Digital Elevation Model, and C) is the Soil Type from the HWSD v2 (Nachtergaele et al., 2009).

4.7.2 Input Data - LULC, DEM, Soil

For this simulation, we employ the resample flag in order to reduce the spatial resolution of the DEM, LULC and SOIL. With a resample of 5 kilometres (as shown in Sec. 2.1.8) the spatial information will reduce their space in memory. For this configuration, the study area has around

2 million elements and took over 5 Gb of VRAM because we employed parallel processing. Notice that all parameters related to the running control sub-section are relative high because the spatial resolution adopted allow to use bigger timer discretization with fewer risk of numerical instability.

Flags of rainfall, real time satellite rainfall, river height compensation were activated. Notice that in Fig. 36 the Flag of forecast unit appears as activated, this only apply for the second unit, we explain this with more details in the next section.

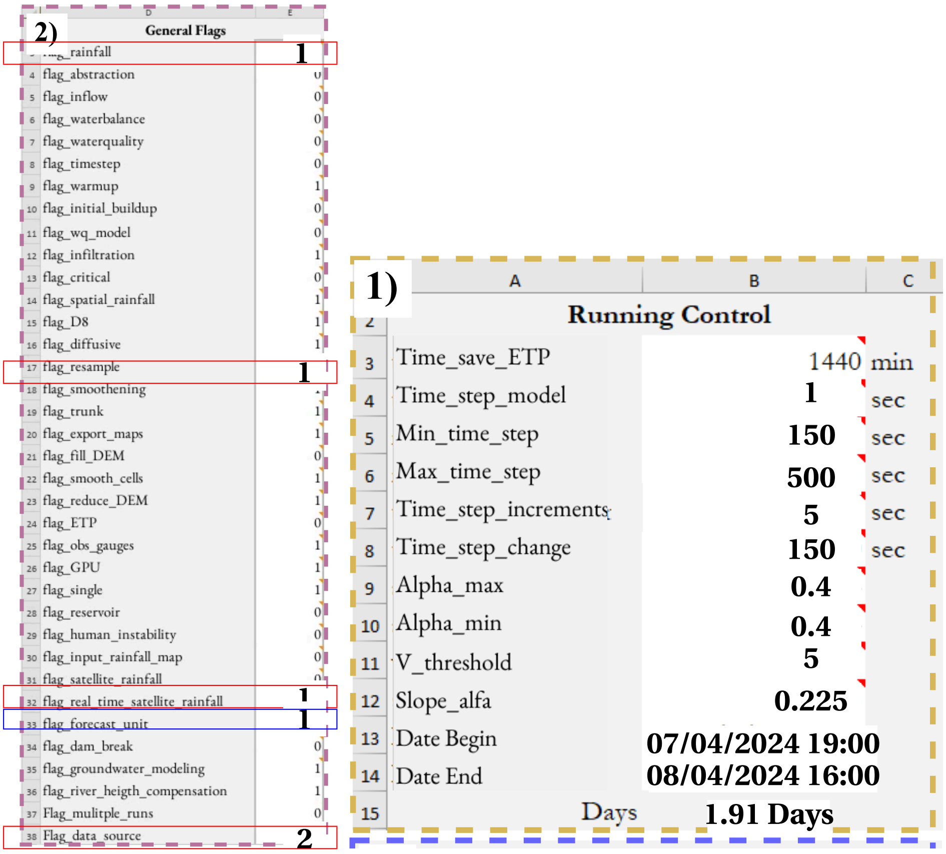


Figure 36: South America Model Set Up.

Related to the LULC and Soil parameters, In Fig. 37 are show the initial values. Here, we highlight that these parameters are not calibrated and for this simulation scale, it could require high discretization because LULC between different biomes has different behaviour in the hydrological context. For this study case, we simplify this parametrization into the 9 classes available within the Dynamic World.

Related to the soil type, according to the soil texture, it can be used to estimate key hydraulic parameters including saturated conductivity (K_{sat}), soil suction head (ψ), and moisture deficit ($\Delta\theta = \theta_{sat}$-$\theta_i$). We employed values from Rawls et al. (1983, 1982) as reference.

HydroPol2D - LULC Parameters

LC	Index	n ($m.s^{-1/3}$)	h0 (mm)	d0 (mm)	C_1	C_2	C_3	C_4	index_impervious
Water	0	0,028	0	1	5,72	0,17	1200	1,2	6
Trees	1	0,04	7	0	5,72	0,17	1200	1,2	
Grass	2	0,025	4	0	5,72	0,17	1200	1,2	
Flooded Vegetation	3	0,033	0	1	5,72	0,17	1200	1,2	
Crops	4	0,04	6	0	5,72	0,17	1200	1,2	
Shrub and Scrub	5	0,03	5	0	5,72	0,17	1200	1,2	
Built Areas	6	0,03	0	0	27	0,3	1200	1,2	
Bare Ground	7	0,044	1	0	27	0,17	1200	1,2	
Snow and Ice	8	0,0325	0	0	27	0,17	1200	1,2	

HydroPol2D - Soil Parameters

Soil_type	Index	k_{sat} (mm/h)	ψ (mm)	I_0 (mm)	θsat (cm3.cm-3)	θi (cm3.cm-3)
12746	12746	0,12	581,8	0	0,45	0,1
27694	27694	0,12	581,8	0	1,45	0,1
27677	27677	0,12	581,8	0	2,45	0,1
18768	18768	0,12	581,8	0	3,45	0,1
27670	27670	0,12	581,8	0	4,45	0,1
27673	27673	0,12	581,8	0	5,45	0,1

Figure 37: South America LULC and Soil Parameters.

For the observation points, we selected multiple gauge stations that currently are online telemetric stations, this is useful in order to compare the water level of the simulation with those observed on the field by the sensors in the land stations. For this, the flag_data source = 2 is activated to gather information for the National Agency of Water in Brazil. Notice that the label must follow the instructions explained in Sec. 2.12.

Observation Points

Gauge	Easting (m)	Northing (m)	Label	Withd
1	-6494147,00	-341593,00	16030000 - Amazonas	5300
2	-6248667,00	-266732,00	18390000 - Amazonas	5400
3	-5488886,00	-561567,00	29200000 - Tocantins	1300
4	-5529494	-411041	29680090 - Tocantins	1800
5	-4123531	-1116575	49340200 - São Francisco	900
6	-4093476	-1146543	49706250 - São Francisco	1100
7	-5708673	-2311300	62020080 - Parana	4500
8	-5938891	-2606180	64575001 - Paranapanema	3785

Figure 38: South America Observation points.

4.7.3 Running the Model

To running the model as a digital twin and forecast system, as explained in Sec. 2.12 and Sec. 2.13, it is required two units with similar hardware characteristics, this means, if one unit has a GPU with 6 Gb of VRAM, the second unit must have also 6 Gb of VRAM on their GPU. This is to avoid error due to memory requirement by the model. Moreover, for this execution mode, two general data and two HydroPol2D.m files will be required.

For both units will be necessary to modify the HydroPol2D.m script to read different generals' data. For example, for the digital twin (red box in Fig. 39), in line No.12, the user must specify the digital twin general data such as "General_Data_HydroPOl2D_DT.xlsx". On the other hand, for the forecast (blue box in Fig. 39), the user must specify the digital twin general data such as "General_Data_HydroPOl2D_forecast.xlsx". It is important to mention that in the case of the digital twin, the forecast flag (flag_forecast = 0) must be deactivated, whereas, for the forecast system, this flag must be activated as shown in Fig. 36 with the blue box.

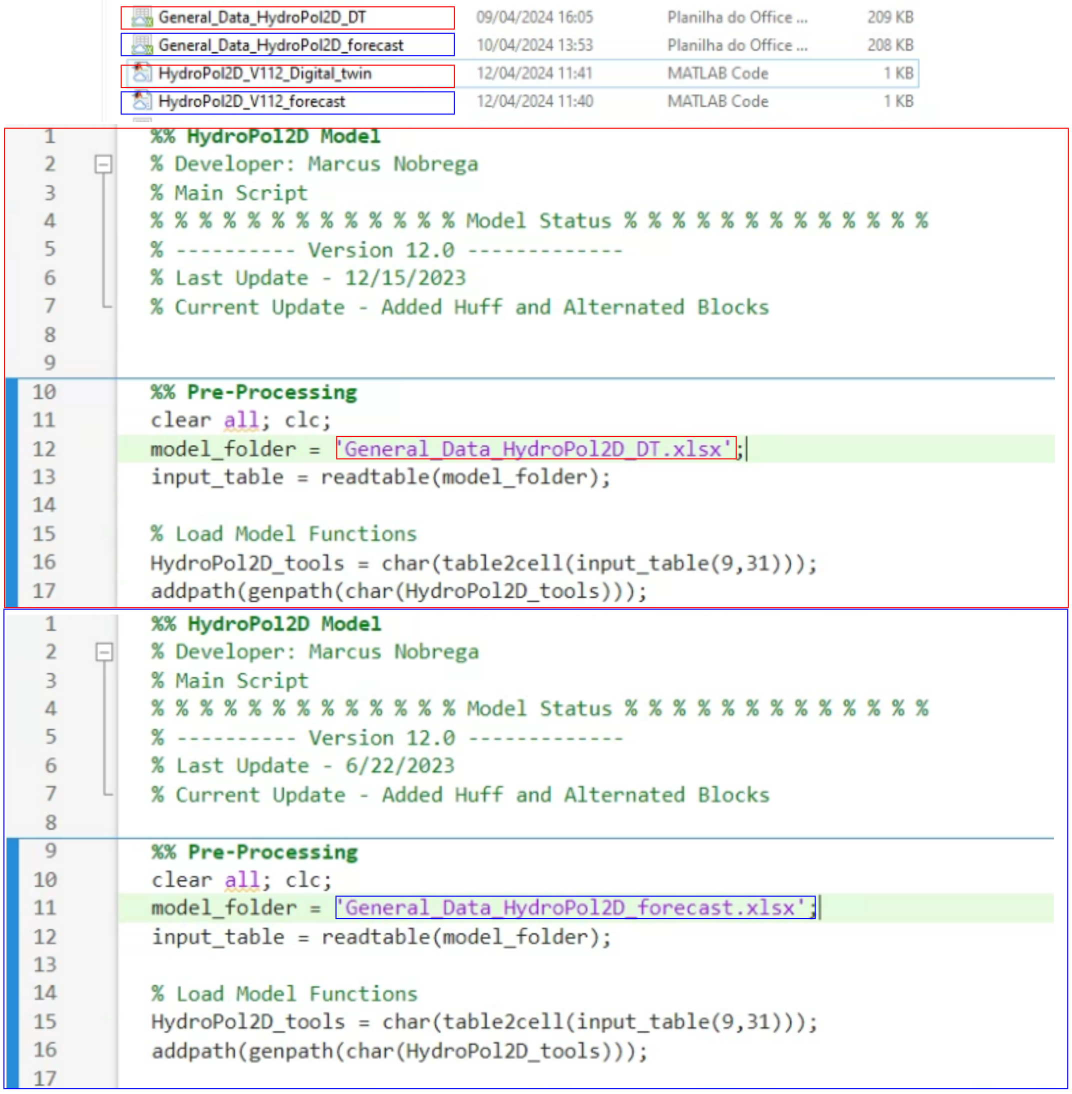


Figure 39: South America HydroPol2D model Set Up For Two Units.

4.7.4 Analysing the Systems

For each unit, graphical interfaces will be displayed, showing relevant information. For the digital twin (Fig. 40), the information of satellite rainfall, water depths, flow velocities and soil moisture content is displayed for the last 6 hours. Moreover, for the desired observation gauges, the user can monitor the simulated water levels of each station and compare with the real water level in real-time.

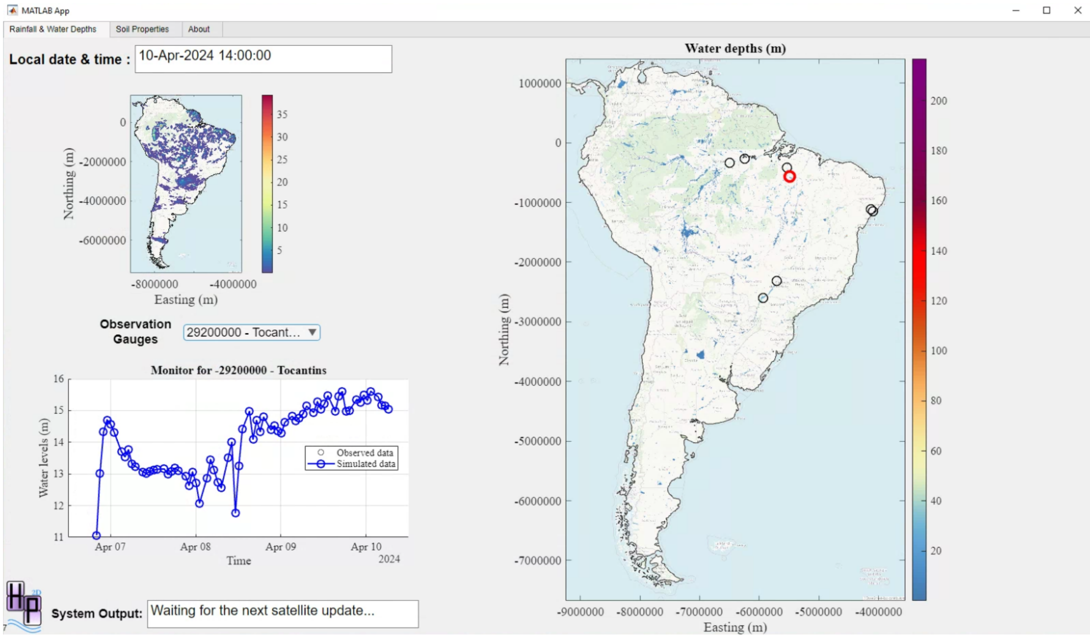


Figure 40: South America Digital Twin.

Related to the forecast system (Fig.41), the system is similarly as the digital twin with the information display; however, the system shows the information from forecast for the next 120 hours (5 days). The forecast of water level are also plotted for each observation points. It is worth mentioning that this system in terms of computational requirements is under more stress since the system is simulating four scenarios for five days ahead. The relation between number of elements and GPU capabilities will be a relevant technical topic for high resolution simulation with this execution mode.

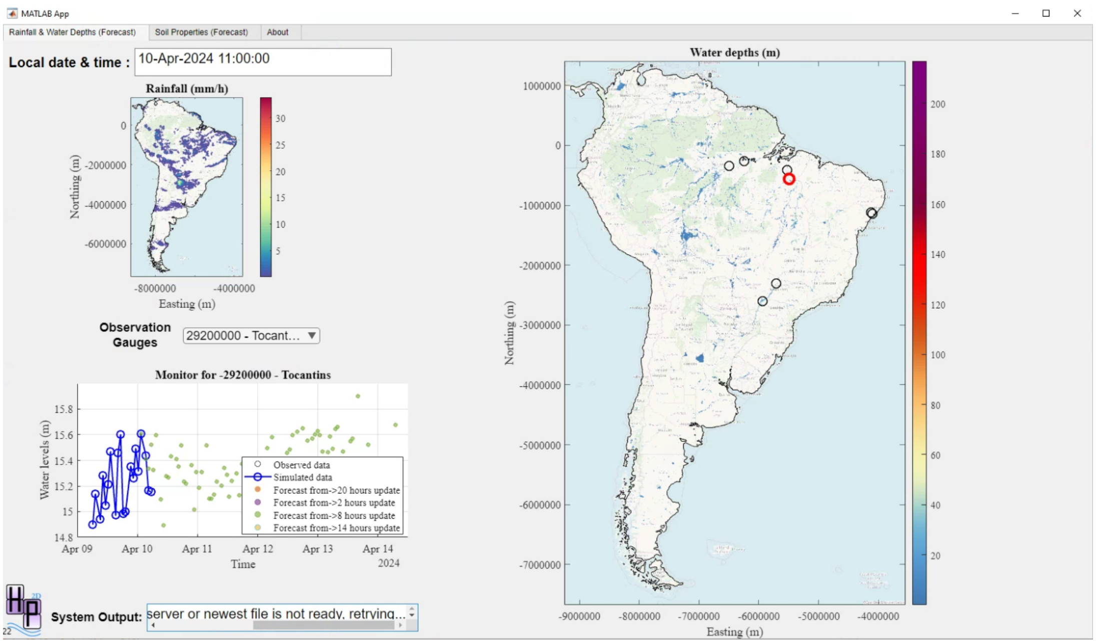


Figure 41: South America Forecast System.

4.8

SUB-SECTION

Case Study 8 - Testando Inflow Hydrograph

4.8.1 QGIS - Data

4.8.2 Input Data

4.8.3 Running the Model

4.8.4 Extracting Results

4.8.5 Analyzing Results

4.9

SUB-SECTION

Case Study 9 - Testando Chuva de Projeto

4.9.1 QGIS - Data

4.9.2 Input Data

4.9.3 Running the Model

4.9.4 Extracting Results

4.9.5 Analyzing Results

4.10

SUB-SECTION

Case Study 10 - Testando Chuva Interpolada por Gauge

4.10.1 QGIS - Data

4.10.2 Input Data

4.10.3 Running the Model

4.10.4 Extracting Results

4.10.5 Analyzing Results

4.11

SUB-SECTION

Case Study 11 - Dam-Break

4.11.1 QGIS - Data

4.11.2 Input Data

4.11.3 Running the Model

4.11.4 Extracting Results

4.11.5 Analyzing Results

4.12

SUB-SECTION

Case Study 12 - Modeling Water Quality

4.12.1 QGIS - Data

4.12.2 Input Data

4.12.3 Running the Model

4.12.4 Extracting Results

4.12.5 Analyzing Results

5

SECTION

Future Directions of HydroPol2D

The HydroPol2D model has proven to be a valuable tool for simulating a wide range of hydrodynamic processes. However, there are several areas where future development and improvement of the model could enhance its capabilities and performance.

Some key areas for future development of HydroPol2D include:

- Improving the modeling of base flow contribution from groundwater. The current representation of groundwater inputs could be enhanced through the inclusion of more sophisticated groundwater modeling approaches.
- Incorporating the inertial term into the flow propagation within the cellular automata framework. This would allow for a more accurate representation of dynamic flow phenomena, such as in dam breaks.
- Transitioning to an irregular mesh structure to improve the computational performance and overall accuracy of the modeling. The current regular grid approach has limitations in representing complex topographies and is memory expensive.
- Expanding the integration of remote sensing data sources. Incorporating a wider range of high-resolution databases from satellite and aerial imagery could enhance the model's capability to capture spatially-distributed hydrologic processes such as evapotranspiration and soil moisture.
- Optimizing the performance of the model's various modules and subcomponents. Targeted improvements to the computational efficiency and parallelization of the code could lead to significant reductions in simulation times.

Addressing these future development priorities would help position the HydroPol2D model as an even more robust and versatile tool for hydrodynamic analysis and prediction across a variety of water resources applications.

6

SECTION

Troubleshooting

SECTION 7

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