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River mapping using the shallow-water equations on GPU clusters: Costa Rica as a case study

Mapeo de ríos utilizando ecuaciones de aguas poco profundas en clústeres de GPU: Costa Rica como un caso de estudio

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Abstract. Costa Rica's River systems play a pivotal role in providing valuable resources for society. Given that the country is exposed to a water-dense, tropical climate, it is crucial to assess flooding risk and plan for extreme events. In this paper, the first step towards a river simulation pipeline is established using the Reventazón River as a case study. To achieve this, a High-Performance Computing – HPC portable shallow water equation solver was implemented. Boundary and initial conditions were set using QGIS and Python, and a simple Manning model was considered for friction. No rainfall, infiltration, or subsurface modeling was implemented in this work. The simulation yielded good qualitative results for water flow for the whole Reventazón River. More complex simulations are enabled with these results, given that an initial condition for water flow in the river was established.

Keywords: River mapping, shallow water equations, GPU computing.

Resumen. Los sistemas fluviales de Costa Rica desempeñan un papel clave al proporcionar recursos valiosos para la sociedad. Dado que el país se encuentra expuesto a un clima tropical con abundantes precipitaciones, es crucial evaluar el riesgo de inundaciones y planificarse para eventos extremos. En este artículo, se establece el primer paso hacia un proceso de simulación fluvial utilizando el río Reventazón como caso de estudio. Para lograrlo, se implementó un solucionador portátil de ecuaciones de aguas poco profundas para *High-Performance Computing – HPC*. Las condiciones de contorno e iniciales se establecieron utilizando *QGIS* y *Python*, y se consideró un modelo simple de *Manning* para la fricción. En este trabajo no se implementó ningún modelo de precipitación, infiltración ni subsuelo. La simulación arrojó buenos resultados cualitativos para el flujo de agua en todo el río Reventazón. Estos resultados permiten realizar simulaciones más complejas, dado que se estableció una condición inicial para el flujo de agua en el río.

Palabras clave: Mapeo de ríos, ecuaciones de aguas someras, computación con *GPU*.

1 Introduction

Costa Rica is located in the tropical region of America. The country is renowned for its tropical climate, its natural landscapes, and complex river systems. The latter are fundamental not only to its overall biodiversity, but to society itself. These river systems provide the water resource for irrigation, human consumption, and hydroelectric power generation. However, climate change driven by anthropogenic factors will lead to changes in temperature and precipitation cycles affecting these watersheds, posing a potential increase in flood risks (Intergovernmental Panel on Climate Change, 2023).

Furthermore, inadequate or outdated urban and rural planning has raised the potential risk of floods in many areas of the country (Fernández Arce et al., 2019). Poorly planned development can lead to floods in

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towns, like the floods caused by the dykes built to protect agricultural activity in Sixaola, Matina, or Filadelfia in Costa Rica (Presidencia de la República de Costa Rica, 2021; ProDUS - UCR, 2014). This is often related to storm sewage systems or conveyance structures –e.g., culverts and bridges– (ProDUS - UCR, 2014) often under-designed for current urbanization and climate conditions.

The Costa Rican National Emergency Commission – CNE has assessed flooding risk on several Costa Rican watersheds including Aguas Claras, La Estrella, Pirrís, Candelaria, Zapote, and Parrita (Rojas González & Coto Fonseca, 2020; Rojas González, 2020; Guzmán Arias et al., 2017; Saborío, 2012) by using remote sensors, along with hydrological and hydraulic analysis. The hydrological and hydraulic analyses consisted of the simulation of the watersheds, starting with a Digital Elevation Model – DEM, followed by a quantification of the coefficients of the domain simulations of the river, and finally an evaluation of the risk using return periods of extreme flood conditions.

1.1 Related work

The simulation software used in previous studies was IBER (Bladé et al., 2014), an open channel flow modeling tool based on the finite volume method. It combines hydrodynamic, turbulence, and sediment transport modules for the solution of hydrological and hydraulic problems. The hydrodynamic model is based on a formulation of the Shallow Water Equations – SWE to solve for the velocity and height of the fluid. This software is used for watershed runoff simulation, stream and channel flow hydrodynamics, erosion, and sedimentation transport processes.

Similar studies using 2D hydrological simulations have been done in other countries to assess flood risk in rivers. The TELEMAC-2D code was used to design a pipeline to analyze the Shenzhen River Basin in China. The code solves the non-conservative two-dimensional SWE using the finite element/volume method and non-uniform triangular meshes to discretize the domain. Validation was carried out using rainstorm scenarios, and the whole pipeline was tested for 12 different rainfall scenarios over 3 different rainfall returns periods. The hazard-vulnerability method was used for urban flood risk assessment in that work (Li et al., 2022).

A dam-break flood risk assessment was carried out for the Chengbi River Dam in Baise, China. Using the HEC-RAS 2D code and the hazard-vulnerability method, flood risk was quantified for 3 cases: a full dam breach, a half dam breach, and a third dam breach. In that work, a flood risk map was developed, aiming at measures and structure development for flood control (Mo et al., 2023).

The aforementioned software, i.e., IBER, TELEMAC-2D, and HEC-RAS, offers different technological features. For example, IBER is GPU-ready, TELEMAC-2D is MPI-ready and open-source, and HEC-RAS is a well-established industry standard. However, none of them offer highly scalable multi-GPU capabilities and a fully open-source environment. This makes this software not well suited for HPC applications and implies strong limitations on the use of these models.

1.2 Contributions

This work aims to establish the river mapping phase of a river simulation pipeline using a new implementation of the SWE, the Simulation EnviRonment for Geomorphology, Hydrodynamics, and Ecohydrology in Integrated form – SERGHEI (Caviedes-Voullième et al., 2023). River mapping is a procedure where the SWE are solved to gain information about water flow given a DEM of the terrain being simulated. This step is crucial in the simulation pipeline design to ensure the DEM correctly captures the river's bathymetry. This is critical to correctly quantify water flow in the simulation. This step is also crucial to specify initial conditions of height and flow for other simulations.

In the context of distributary channels, as well as tidally-affected streams, the solution of the SWE might be the only method for understanding the direction of water flow in a river. Consequently, this becomes the only reliable approach to acquire valuable information concerning the river's initial conditions. To carry this out optimally, SERGHEI's implementation of the SWE was chosen as it is an open-source, portable High-Performance Computing – HPC solver. The river mapping process is intended to be executed on NVIDIA GPUs to accelerate the data generation process.

Simulations of this nature prove beneficial for analyzing rivers of interest, such as those on the Costa Rican Caribbean. The Caribbean presents a humid and rainy climate; by analyzing river dynamics, such as

those present in the Reventazón River, useful insights on possible floods and disasters may be obtained. This would give an understanding of how the watershed may behave if any extreme flow conditions are imposed upstream.

2 Background

2.1 SERGHEI implementation of the SWE

The Simulation EnviRonment for Geomorphology, Hydrodynamics, and Ecohydrology in Integrated form – SERGHEI is a performance-portable multiphysics model framework for environmental and landscape simulation based on Kokkos (Caviedes-Voullième et al., 2023; 2023). This code solves for the SWE describing a shallow layer of fluid with constant density. The most important assumption in this model is that the horizontal scale of the flow is greater than the vertical fluid depth (Vallis, 2019). These equations are a reduced set of the full Navier-Stokes formulation for fluid dynamics, which allows for a clearer analysis of complex problems such as river flow modeling. The SWE implemented by the SERGHEI code are the following:

$$\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = \mathbf{S_r} + \mathbf{S_b} + \mathbf{S_f}, \tag{1}$$

$$\mathbf{U} = \begin{bmatrix} h \\ q_x \\ q_y \end{bmatrix} \mathbf{F} = \begin{bmatrix} q_x \\ \frac{q_x^2}{h} + \frac{1}{2} g h^2 \\ \frac{q_x q_y}{h} \end{bmatrix} \mathbf{G} = \begin{bmatrix} q_y \\ \frac{q_x q_y}{h} \\ \frac{q_y^2}{h} + \frac{1}{2} g h^2 \end{bmatrix}, \tag{2}$$

$$\mathbf{S_r} = \begin{bmatrix} r_o - r_f \\ 0 \\ 0 \end{bmatrix} \mathbf{S_b} = \begin{bmatrix} 0 \\ -gh\frac{\partial z}{\partial x} \\ -gh\frac{\partial z}{\partial y} \end{bmatrix} \mathbf{S_f} = \begin{bmatrix} 0 \\ -\sigma_x \\ -\sigma_y \end{bmatrix} \tag{3}$$

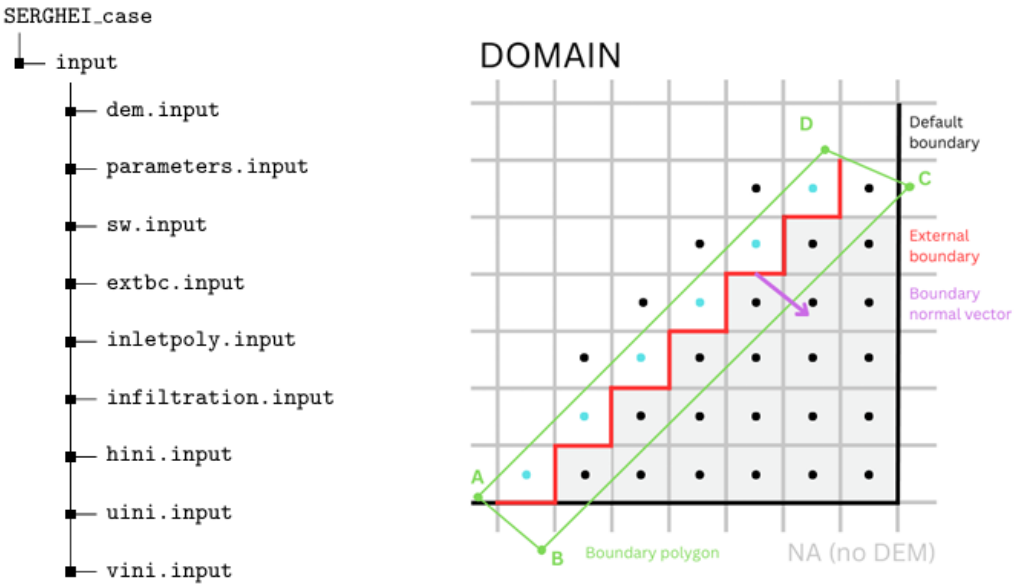
where h is the water depth, q_x and q_y are the unit discharges in the x and y directions, and g is gravity. The terms in $\mathbf{S_r}$, r_o and r_f are the sources for rainfall and infiltration and exfiltration, respectively. In $\mathbf{S_b}$, z is the elevation of the domain, and in $\mathbf{S_f}$, σ is the friction of the slope of the river (Caviedes-Voullième et al., 2023).

SERGHEI solves these equations using a first-order accurate finite volume method over a uniform Cartesian grid defined by a DEM. The equations are integrated in time using a forward Euler time scheme. Well-balancing and water depth positivity are ensured using augmented Riemann solvers to solve for fluxes. The decomposition is made along the x and y coordinates, generating $p_x \cdot p_y$ subdomains which are divided into $(n_x + 2) \cdot (n_y + 2)$ cells to account for subdomain boundary data exchange.

2.2 Simulation case structure

The SERGHEI code works with a specific folder case structure as shown in Figure 1a). This case structure consists of an input folder which contains a DEM in ASCII format, a parameter file which controls simulation execution and output, a shallow water parameter file that sets friction models and initial conditions, and a file which controls the water infiltration model used in the simulation. An external boundary file also needs to be specified to account for the different behavior on the boundaries of the domain, such as variable inlets and outlets. With all these parameters, polygons on the DEM have to be specified to define the boundaries in other input files. Figure 1b) shows SERGHEI's definition of the boundary polygon.

DEM preprocessing and visualization to specify the boundaries were done using the QGIS software and the Rasterio Python module. The river DEM was clipped to about 10m around the boundaries due to the specification in the DEM of NODATA value as 0, which presented conflicts with valid data values in the whole area and the inlet boundary condition.



a) SERGHEI case structure b) SERGHEI's boundary condition polygon definition

Figure 1. SERGHEI Shallow-water simulation software

3 Methodology

3.1 Simulation case and setup

The river to be simulated is the Reventazón River located in the Caribbean basin of Costa Rica. It is the second longest river in Costa Rica, with approximately 140 km in length. The main focus of this work is to apply the river mapping procedure to the downstream reach of this river. The DEM was obtained from *Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento* –SENARA– and covers approximately 40km of the last section of the watershed with a resolution of 1 m. The coordinate system used in this DEM was the projected coordinate system for Costa Rica, CR05/CRTM05. Figure 2 shows the Reventazón River and its mouth to the Caribbean Sea.

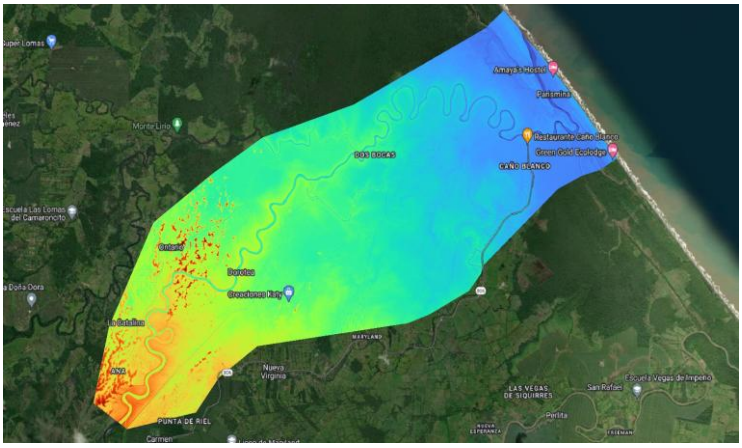
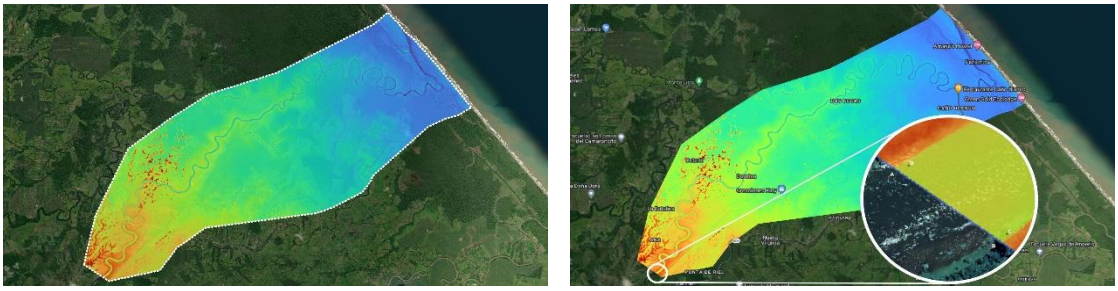


Figure 2. Reventazón River DEM overlaid on the ESRI satellite map

As this work only focuses on river mapping, precipitation, infiltration, and subsurface modeling were not taken into account. Friction was considered in the simulation by using the Manning model, with a coefficient of $n = 0.035\ sm^{-1/3}$. This coefficient was used for all terrain in the DEM as a simplification since the river channel is the domain of interest.

The boundary conditions applied were a constant discharge inlet and transmissive flow at the extents of the DEM shown in Figure 3. The constant discharge condition was specified as the vector $[h \quad q_x \quad q_y] = [3.5\,m \quad 12.0\,m^2/s \quad 10.0\,m^2/s]$. The simulation was carried out until the water covers the entire reach of the river. Checkpoint states were read and post-processed in Python using the Xarray library so as not to lose progress of each simulation.



a) Boundary with transmissive flow. b) Inlet boundary defined by the polygon ABCD.

Figure 3. Boundary conditions imposed on the Reventazón DEM

3.2 Computational infrastructure

Kabré supercomputer is hosted at the Costa Rica *Centro Nacional de Alta Tecnología – CeNAT*. Kabré is a heterogeneous supercomputing infrastructure, addressing the needs of workflows in scientific computing, bioinformatics, data science, and artificial intelligence. Equipped with 52 computational nodes, Kabré has several GPU-enabled nukwa nodes. Each nukwa node has an Intel Xeon processor with 24 cores, running at 2.2 GHz, along with an NVIDIA Tesla V100 GPU and 32 GB of main memory. For data post-processing, the Andalan nodes were used; these have 128 GB of main memory and an Intel Xeon processor with 24 cores running at 2.4 GHz.

JUWELS supercomputer is a multi-petaflop modular supercomputer located in the Jülich Supercomputing Centre. It functions as a Tier-0 European and national supercomputing resource for the Gauss Centre for Supercomputing – GSC. JUWELS consists of two modules, the Cluster and the Booster module. The Cluster module is comprised of Intel Xeon Skylake-SP processors with Mellanox EDR InfiniBand. The Booster module consists of AMD EPYC processors running at 2.8 GHz along with four NVIDIA A 100 GPUs with 40 GB of main memory and NVIDIA/Mellanox HDR InfiniBand

(Forschungszentrum Jülich, 2024). For data post-processing, the batch partition was used. These nodes are comprised of two Intel Xeon Platinum 8,168 processors with 24 cores each, running at 2.7 GHz.

In this work, a single nukwa node in Kabré was used to test the inlet boundary condition before deploying the whole river simulation. Two JUWELS Booster nodes were used for the river mapping simulation.

3.3 Post-processing and visualization

The SERGHEI code outputs the results in the NetCDF4 format as a multidimensional array with the variables h, u, v, z as raster arrays at the previously specified save frequency. Depending on the DEM size, the output files generated can be rather large. Due to this, the simulation processes were launched on both supercomputing clusters instead of desktop computers. The outputs were analyzed and processed with Python scripts using the Xarray library, which is highly compatible with the NetCDF4 format. The Matplotlib library and QGIS were used for visualization of flow output.

4. Results

4.1 Inlet boundary test

Before simulating the whole river, the inlet boundary condition was tested on a small reach of the river clipped from the full DEM, as shown in Figure 4. The variables obtained in each simulation are water height over the terrain h, water speed u and v and the original terrain height z. Figure 5 shows the water height and flow velocity magnitude for this DEM. The results show that the inlet boundary condition was set up correctly for the river mapping procedure. On the Kabré supercomputing cluster, this simulation was executed in 21.8 min.

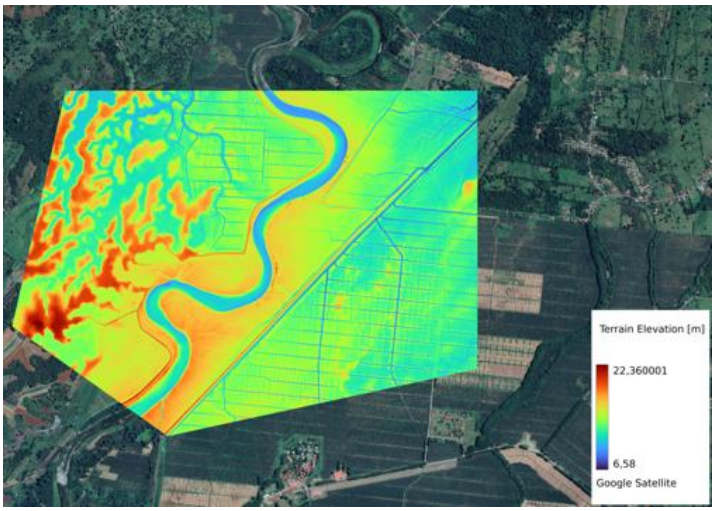
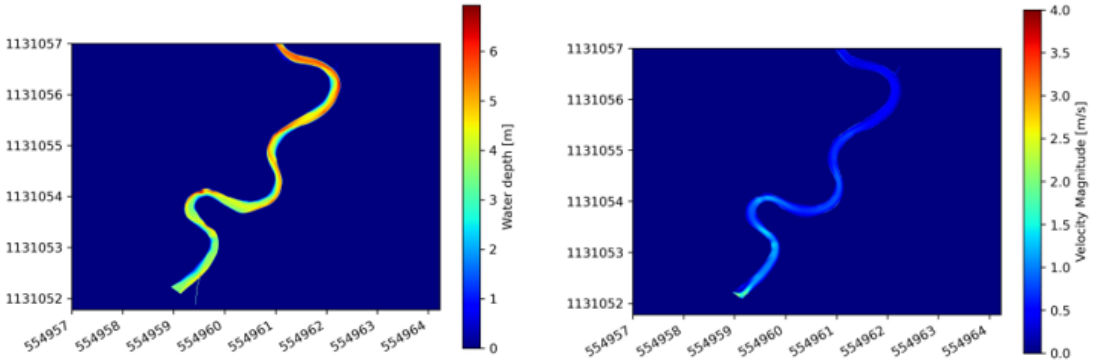


Figure 4. Terrain elevation of the small reach of the river. The DEM was clipped from the larger model shown in Figure 2



a) River depth obtained from the simulation. **b)** River simulation velocity magnitude.



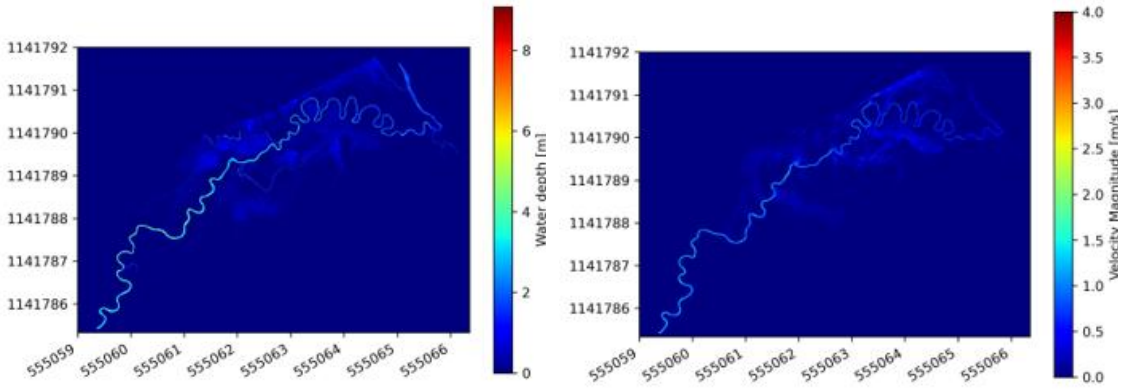
c) Water depth results overlayed onto satellite map for flow qualitative validation.

Figure 5. Inlet boundary simulation results

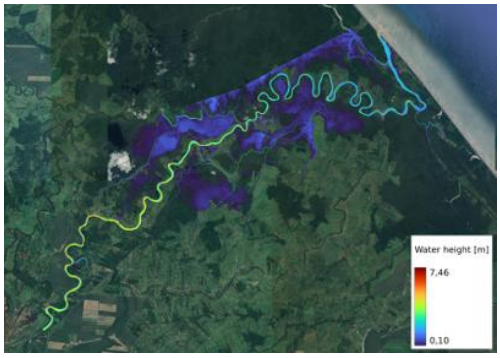
4.2 Reventazón River mapping

The Reventazón River was simulated using a similar procedure. Simulations were executed to map the entire reach of the river. Figure 6 shows the results for the water height h, and the water speed u, v alongside with the overlay onto the satellite raster image. This overlay can be useful to qualitatively validate the simulation output.

The Reventazón River mapping results show high qualitative fidelity of flow with the satellite maps. However, there are areas of the DEM that are flooded mainly due to the model being used for the simulation, as the terrain had no infiltration capacity and just acted as non-porous material. Furthermore, canals for field irrigation are present in the DEM. Though this was the case, the simulation was still able to map the Reventazón River to the river mouth.



a) River simulation water height. b) River simulation velocity magnitude.



c) Water depth results overlaid onto satellite map for flow qualitative validation.

Figure 6. Reventazón River simulation results. Flooding is present in the results due to artificial canals and the simulation model.

Each simulation was carried out for $tsim = 25000\ s$ at a time on the GPU nodes using checkpoints. The executions lasted an average of 16.66 h each on the JUWELS infrastructure. In total, two simulations were executed for the river mapping.

5. Conclusion

A river mapping simulation was implemented using the SERGHEI code executed on a GPU to establish the first step of a river simulation pipeline. This mapping was done for the Reventazón River in Costa Rica. The data generated allow the definition of initial water height and flow velocity conditions for future simulations of the Reventazón. The river mapping methodology can now be implemented on any DEM, provided it has good bathymetry and resolution.

The next steps in the development of a river simulation pipeline for risk assessment are the implementation of hydrograph inputs and outputs to shore in the simulation, a roughness coefficient raster to account for different terrain in the domain, and rainfall and infiltration data. It is important to state that the SERGHEI code has functionality for all of these physical phenomena. Furthermore, the implementation of the Exner equation for riverbed sediment transport is needed for the quantification of changes in the river bathymetry, or erosion on the sides of the watershed. In addition to computing modules, an in-situ visualization using ParaView Catalyst is in the scope of this pipeline.

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