doi:10.3850/38WC092019-8882

21ST CENTURY TECHNOLOGY TO SUPPORT FLOODING SOLUTIONS: USE OF WATER DRONES, AND HIGH PERFORMANCE 2D NUMERICAL FLOOD AND HYDRAULIC SIMULATIONS USING CLOUD COMPUTING

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ABSTRACT

Water drone technology are making available huge amount of high-resolution bathymetric data for hydraulic simulation models. However, the application of two-dimensional (2D) models that make use of this data confronts several obstacles, including the model limitation to handle the enormous quantity of elevation points, and very long runtimes, which often make the use of 2D models impractical if not impossible. There have been attempts to use square cell models to large scale applications, but this type of model need to use very small cell size all over the modeling area, leading to excessive number of cell elements. The development of parallelized versions of 2D numerical finite-volume algorithm for Graphic Processing Units (GPUs) on flexible meshes, is radically changing the hydrologic and hydraulic modeling practice. However, until recently, the cost of top-of the line hardware had prevented widespread use of this technology. In this work we discuss a high-resolution application of the RiverFlow2D model running in the Google Cloud to simulate flow around hydraulic structures in the Everglades National Park in the USA. One to 4 million cells were generated using a plugin developed for the QGIS open source Geographic Information System. The model was calibrated with ADCP velocity data. In order to perform simulations remotely and using the most advanced hardware, the model was implemented in Google Cloud VMs (Virtual Machines) with NVIDIA Tesla V100 cards. The GPU Cloud model allowed reducing runtimes from 50 to 600 times costing less than 2 US$ per hour. Results demonstrate that high-resolution applications, that were not feasible until recently can be realistically done using highly detailed bathymetric surveys gathered with water drones and GPU flexible mesh 2D models in the Cloud.

Keywords: Water drones, 2D models, GPU, Cloud Computing

1 INTRODUCTION

Water flood assessments using numerical models were until recently forced to use relatively coarse resolution due to limitations in bathymetric, and exceedingly low performance of sequential computer codes. However, often there is a need to use high resolution models in areas where many small canals, and terrain features drive the water hydrodynamics generating a significant impact on the spatial and temporal distribution of inundation. The increased availability of high-resolution bathymetric surveys provided by the use of water drones, and novel water velocity and sounding instrumentation, has brought the opportunity to use flexible-mesh models with cells small enough to ensure capturing the complex environment. Still, many numerical modeling tools sometimes require days if not weeks to run typical simulations. Hydrologic and hydraulic models using Graphic Processing Units (GPUs) have proven able to accelerate simulations more than 700 times with respect to conventional models, opening new opportunities for sub-meter evaluations. This article will discuss hyper-resolution hydrodynamic and sediment transport simulations in Everglades National Park canals located in the state of Florida, USA, with high performance computing models using GPU parallelization with the RiverFlow2D model (Hydronia, 2019). The models use unstructured meshes that can handle millions of computational cells ranging from a few centimeters to several meters. These meshes can resolve flow and determine solute and sediment distribution at canals, culverts, bridges, and over highly irregular bathymetry. We present preliminary results of applications to the canals surrounding a gated hydraulic structure.
The high-resolution model that has been implement can simulate extremely detailed water velocity fields, and suspended sediment concentration patterns, and highlight the importance of mesh resolution to accurately assess detailed hydrodynamics and flood mitigation solutions.

2 WATER DRONES

In this project a high-resolution bathymetric sounding was conducted using an autonomous surface vehicle (ASV), multi beam sonar, and three broadband split beam echo sounders. The vessel followed a preprogramed path over the survey site while recording data from all the instruments simultaneously.

The ASV is designed and manufactured by Sea Robotics as the ASV model 3.6. The vessel uses Torqeedo Cruise 2.0 motors for propulsion and Torqeedo Power 26 batteries for power. The vessel uses a customized sonar pole and plate assembly to hold the instruments below the surface. The instrument assembly was submerged approximately 0.6m below water surface. All transducers were aligned in the forward direction of travel and level with respect to the horizontal plane. The speed of the vessel was determined using GPS output and maintained at approximately 3 nautical miles per hour.

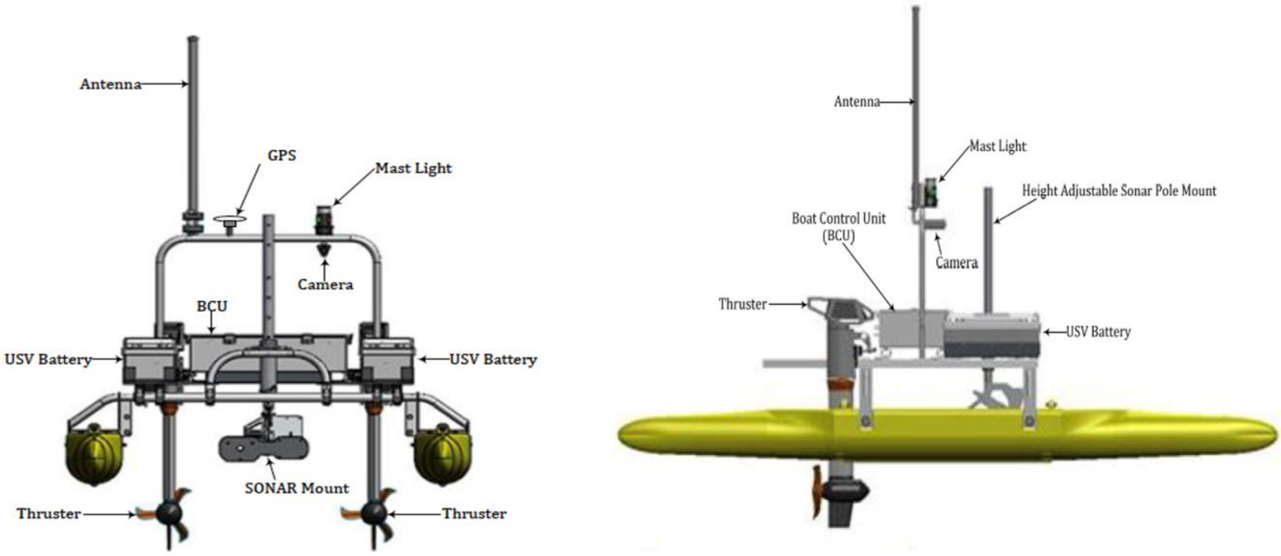

Figure 1. Frontal and lateral schematic views of the water drone.

The vessel uses an SBG Ekinox-D INS/GNSS for autonomous navigation. The system utilizes a dual antenna GPS configuration using manufacturer recommended antennas. The SBG transmits relevant GPS and motion data to the vessel for real-time navigation as well as to the data acquisition computer (DAC) for recording with the acoustics data. The data acquired from the SBG includes but is not limited to GPS position, GPS heading, GPS speed, roll, pitch, and heave.

The multi beam sonar used for bathymetric survey was a Kongsberg M3 system. The sonar was connected to and operated by the DAC computer. The Kongsberg M3 proprietary software was used to record data. The software allows information about the orientation of the sensor and information from the navigation system to be integrated with acoustic data in real time during the survey. The M3 was configured to record using the "Bathymetric Profiling" setting to collect an appropriate acoustic profile of the bottom. A handheld YSI was used to collect water quality information at different increments in the water column for the purpose of generating a sound velocity profile.

The echo sounders used for bathymetric classification were Simrad EK80 scientific echo sounders along with echo sounder transducers. The data was collected using three different frequency transducers: 38khz, 120khz, and 200khz. The Simrad EK80 proprietary software was used to record data. The software allows information about the orientation of the sensor and information from the navigation system to be integrated with acoustic data in real time during the survey. The EK80 software was configured to record an acoustic profile of the water column and bedrock features from each transducer on single frequency mode. A calibration of the system was performed at the site prior to the survey.

Bathymetric profiles were created using QPS Qimera software. M3 data was rerecorded in the acceptable format to be read by Qimera software. The data was then analyzed based on NOAA SOP for Bathymetric Surveys. Bathymetric profiles were cleaned of noise and erroneous soundings. Information on the mapping projection was incorporated into data as well as sound velocity profile generated from water quality data. Finished profiles were exported in a standard GIS format for further use.

Acoustic data from echo sounders was analyzed with Echoview software. An investigation of sediment stratification was conducted based on multi-frequency analysis techniques. The data was also analyzed using recommended procedures to derive hardness and roughness information. Relevant data was exported in CSV format for further analysis.

The M3 reportedly can generate up to 256 soundings/ ping and has a max ping rate of 40hz. The points per unit area generated depends on the beam coverage of the area, the vessel speed, and the processor capability. Assuming the survey is average speed of 1 m/s and the beam has full coverage of sampling area, these specs lead to about 10240 soundings points per m^2.

The program used to plan the missions is called Mission Planner. The way points generated from Mission Planner can be loaded into the sea robotics proprietary software for translation and transmission to the boat onboard computer (see Figure 2). The resulting point cloud representing bed elevations is depicted in Figure 3.

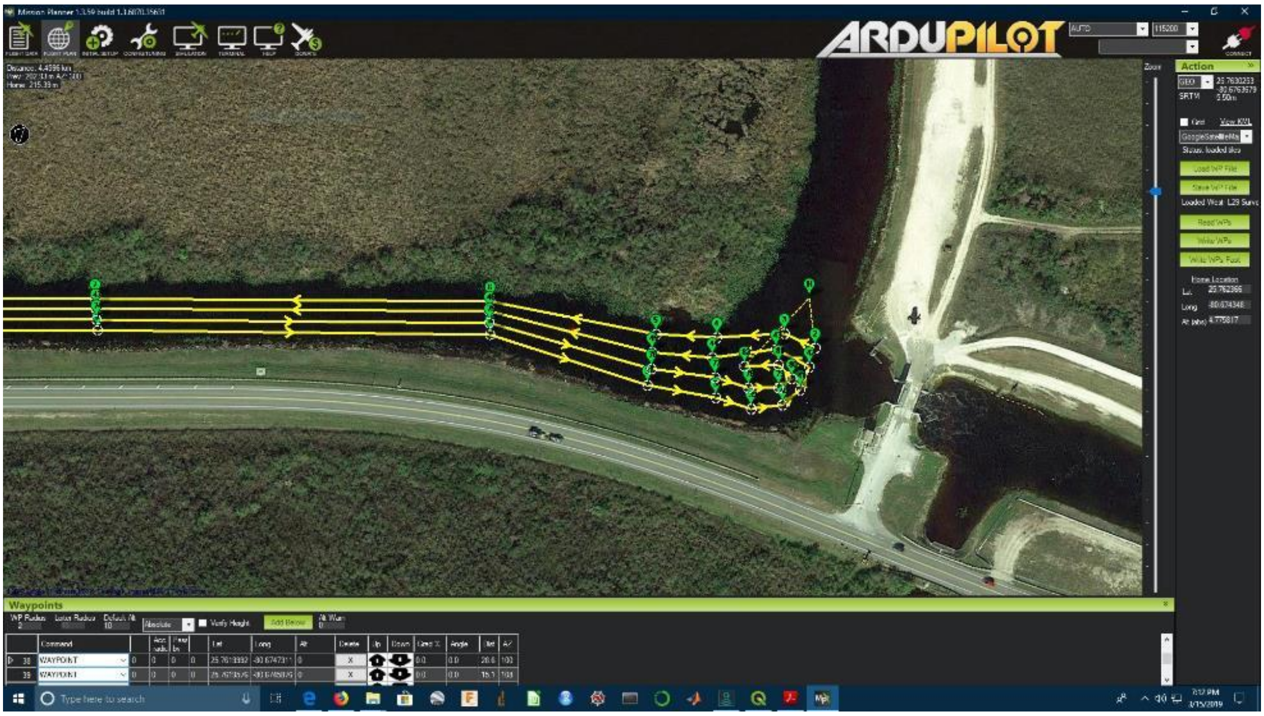

Figure 2. Navigation plan on the western part of the canal.

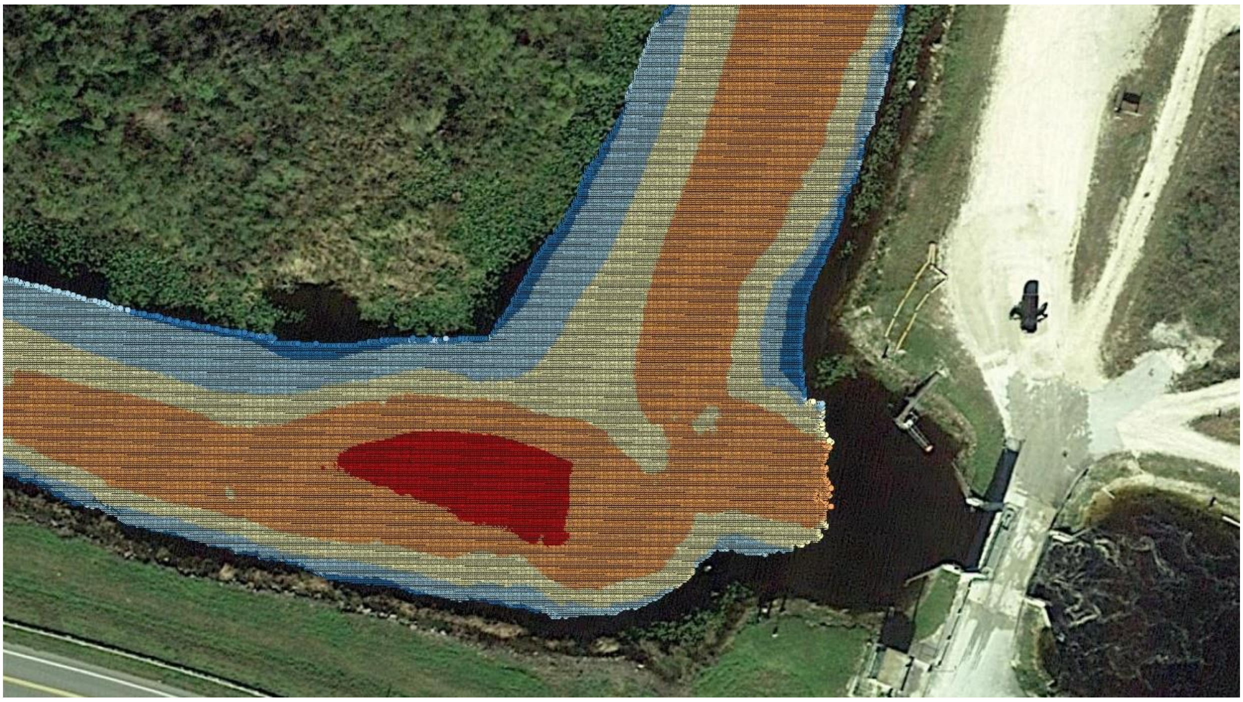

Figure 3. Point cloud obtained from the water drone sounding.

3 RiverFlow2D MODEL EQUATIONS

The system of equations used in RiverFlow2D are obtained by coupling the full mass and momentum shallow-water equations in 2D. That system of non-linear partial differential equations is formulated in a conservative form as follows:

(1)
$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}(\mathbf{U})}{\partial x}+\frac{\partial \mathbf{G}(\mathbf{U})}{\partial y}=\mathbf{S}(\mathbf{U},x,y)$$

Where $\mathbf{U}=(h, q_x, q_y)^T$ is the vector of conserved variables with h representing the material depth, $q_x=uh$ and $q_y=vh$ the unit discharges, with (u, v) the depth averaged components of the velocity vector along the (x, y) coordinates respectively. The flux vectors are given by:

(2)
$$\mathbf{F}=\left(q_x, \frac{q_y^2}{h}+\frac{1}{2}gh^2, \frac{q_x q_y}{h}\right)^T, \qquad \mathbf{G}=\left(q_y, \frac{q_x q_y}{h}, \frac{q_y^2}{h}+\frac{1}{2}gh^2\right)^T$$

Where *g* is the gravitational acceleration. The terms ½ gh2 in the fluxes have been obtained after assuming a hydrostatic pressure distribution in the vertical, as usually accepted in shallow water models. The source term vector (**S**) incorporates the effect of pressure force over the bottom and the tangential forces generated by fluid viscosity,

(3)
$$\mathbf{S}=\left(0, -gh(h\frac{\partial z_b}{\partial x}+\frac{\tau_{bx}}{\rho}), -g(h\frac{\partial z_b}{\partial y}+\frac{\tau_{by}}{\rho})\right)^T$$

Where z_b is the terrain elevation, ρ is the fluid density and τ_{bx} and τ_{by} are the bed stresses in x and y direction respectively that depend on turbulent friction.

The RiverFlow2D model performs its calculations on a flexible mesh formed by triangular cells of different size that can be adapted to virtually any geometry (see Figure 4). Cell data include the bottom elevation and the surface roughness based on the terrain characteristics. The numerical engine then determines the velocity vector and depth at each cell throughout the simulation using a finite-volume scheme, described in detail in (Brafau et al. 2004, Murillo et al. 2007; Murillo and García-Navarro 2010). The Gauss theorem is applied to each volume cell allowing the computation of the flux through the edges of each cell. Each variable is updated using an explicit first order scheme in time. The allowable time step sizes are assigned dynamically and are automatically controlled by the Courant–Friedrich–Lewy condition, The model is well balanced and allows a stable computed solution under all ranges of flow problems ensuring exact mass conservation. The model has been validated for accuracy using a number of tests (Murillo & García-Navarro 2010). The numerical methods ensure virtually zero error in volume conservation and stability through a dynamic time-stepping scheme that does not require user-defined adjustments.

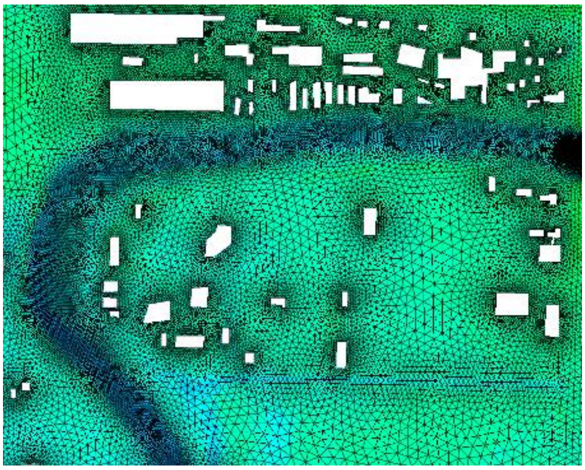

Figure 4. Flexible-mesh over an urban area with variable resolution allowing adaptation to irregular boundaries and complex terrain.

4 GPU ACCELERATION

The acceleration of the calculation has been developed by using Shared Memory programming Model and Many-Core Model by means of OpenMP for Intel Processors and CUDA for the NVIDIA GPU programming. Some works such as Lacasta et al. (2012) demonstrated how OpenMP can be applied to achieve a 4x or 8x speed-up factor depending on the processor used in the test while other works such Lacasta et al. (2014) deal with the implementation of the shallow water equations using the same method in distributed memory machines. The last option is very useful when very big domains are required and then, a large number of cells (>100M Cells) is used in the simulation. In these cases, the main drawback is the amount of memory required to perform the simulation and then, the distribution of the complete domain in different memory systems appears to be a solution.

The GPU contains a large number of processors working all together applying the same operation over different elements. In order to program using this paradigm, NVIDIA has developed CUDA (Compute Unified Device Architecture) that abstracts some aspects of the hardware, allowing programmers to develop general purpose programs efficiently. There are two main points to understand the performance of GPUs by means of CUDA. The first is based on the way CUDA applications are developed. The basic element to be processed is called Thread. Threads are identified by labels ranging between 0 and BlockDim. The group of Threads is called Block, and it contains a (recommended) 32 multiple number of Threads. Finally any group of Blocks is called Grid. The second aspect of interest is the hardware architecture. The minimum unit is the Streaming Processor (SP), where a single Thread is executed. A group of SP's form the Streaming Multiprocessor (SM), typically with 32 SP's. Finally, a GPU is generally composed by between 2 and 16 SM's. The GPU distributes the Blocks among the SMs. The SMs in turn assigns the Threads to the SP's. All SP's inside the multiprocessor perform the same operations at the same time, but each of them applies it to a different element inside a vector. The designing of the GPU is the reason of the recommendation of configure blockDim multiple of 32. The set of 32 threads processed in a SM is called warp. GPU programming requires being careful with the next four aspects:

- Number of elements to be processed: It is required that the number of blocks and threads per block is greater than or equal to the number of elements to be processed.
- Bottlenecks: In order to process all the operations following the GPU paradigm, special attention must be paid to the shared information between the processing elements.
- Floating Point data precision: The GPU arithmetic performance is halved when using double precision data. Many applications require double precision because of numerical aspects but there exist many others for which simple precision is enough to develop the calculations. When single precision is acceptable, performance can be almost doubled on GPU
- Data transfer reduction: The communication between CPU and GPU is very slow. In general, all the operations must take place inside the GPU, otherwise the overhead caused by data transfers may generate such a cost that the global performance of the implementation can be lower than on CPU.

5 APPLICATION

We present an application of the water drone techniques and 2D modeling that aim at understanding the flow dynamics around a gated hydraulic structure at the Everglades National Park (ENP) northern boundary in Florida, USA (see Figure 5). The gated structure controls the flow into the ENP from man-made canals that drain from Okeechobee Lake in the north. The purpose is to obtain highly detailed velocity fields that would help in locating gauges to measure water stages and pollutant concentrations

Figure 5. Location of project site.

6 RESULTS

In order to setup the model data we used the RiverFlow2D plugin for QGIS. QGIS is an open source Geographical Information System software that allows extensions via Python programming. The RiverFlow2D plugin takes advantage of this capabilities and provides tools to process the Finite Volume mesh, enter the boundary conditions, bed roughness, DEM interpolation to the mesh, and running the model. After the model finalizes a run, the plugin can be used to import results and generate velocity field, depths, animations, and other maps of interest. Figure 6 shows the DEM loaded in the QGIS software and the boundary conditions which were discharge upstream and free outflow downstream. Figure 7 shows the generated flexible mesh refined around the hydraulic structure. The meshes range from 4 million cells with triangles varying from 0.09 m^2 to 3.3 m^2. Figure 8 shows the velocity field around the gated structure where depicting recirculation patterns downstream of the structure.

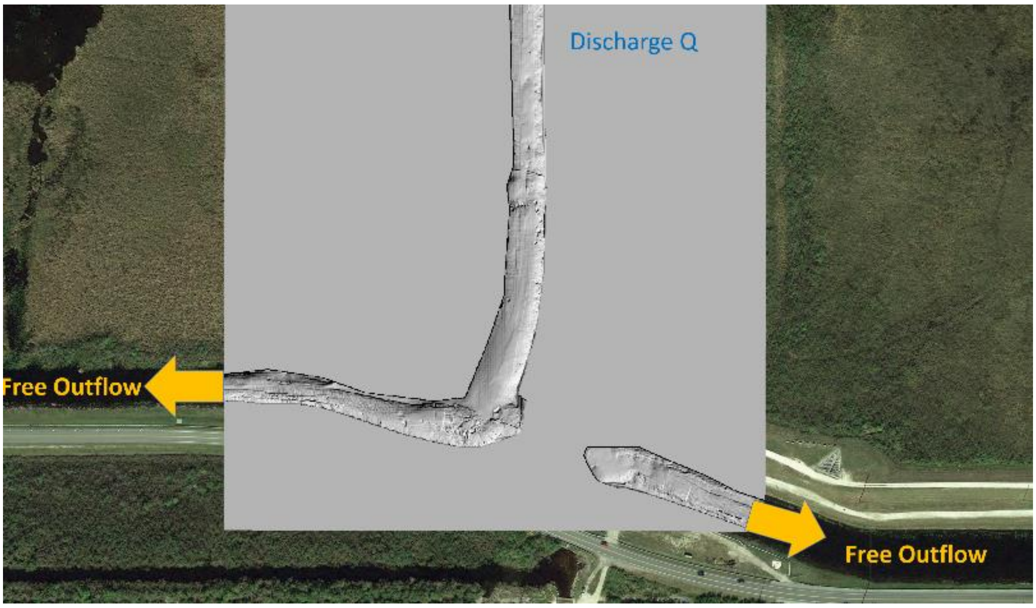

Figure 5. Processed Digital Elevation Model.

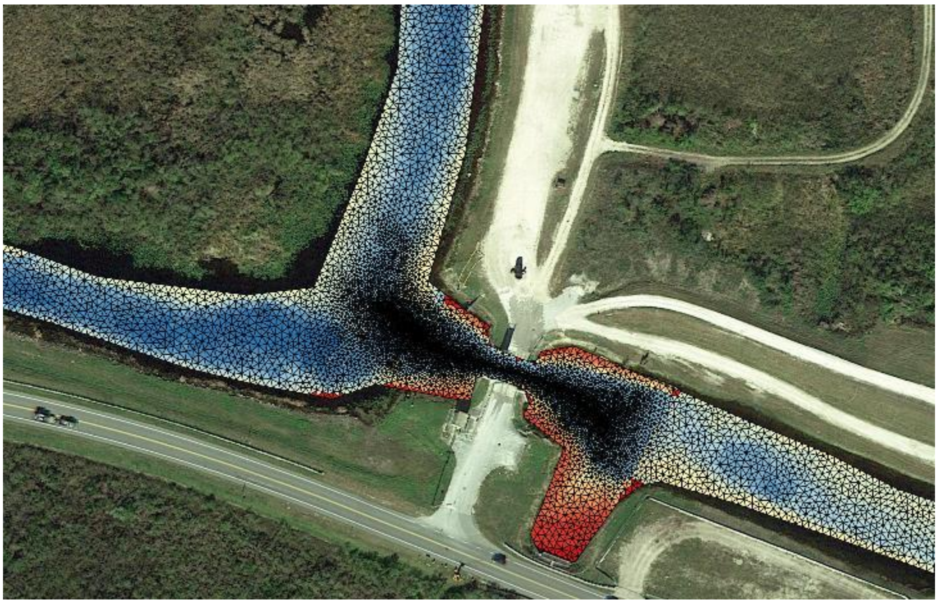

Figure 6. Flexible-mesh on the approach canals and hydraulic structure area.

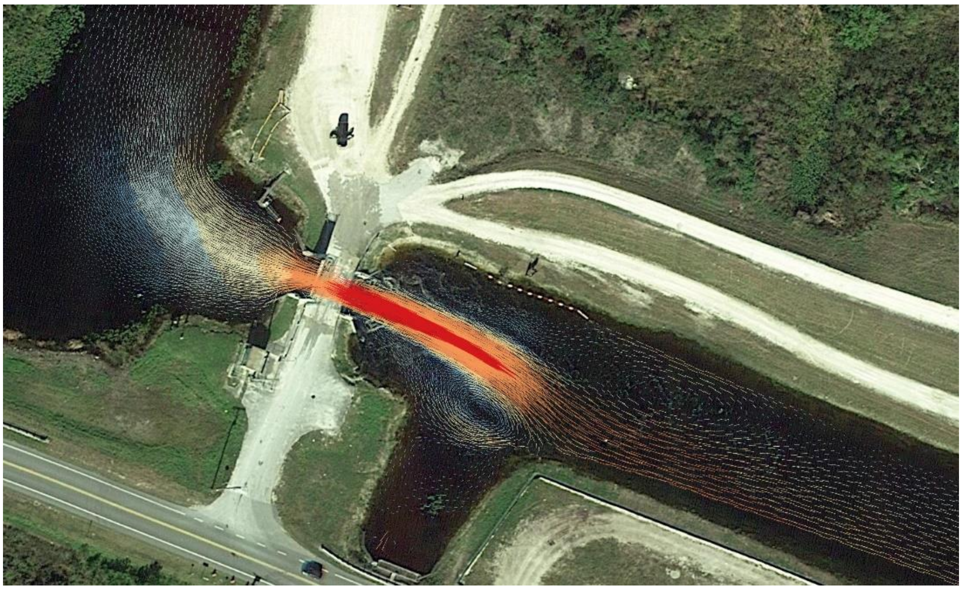

Figure 7. Velocity field around the structure.

7 MODEL PERFORMANCE

Table 1 shows computer times using the RiverFlow2D CPU and GPU versions corresponding to runs of a 2-hour hydrograph using the 539,177-cell mesh and also a more refined mesh of 1,640,606-cells. The CPU runs were made with the non-parallelized model in an overclocked Intel I7 3.83 GHz processor using only one core. The GPU runs were performed with RiverFlow2D GPU using a Virtual Machine configured in the Google Cloud equipped with an NVIDIA Tesla V100 GPU card with 5,120 cores.

Table 1. Computer times of the RiverFlow2D model to simulate a 2-hour hydrograph with the non-parallelized model (CPU) and with the GPU model.

Number of Cells	CPU 1 CORE	GPU NVIDIA TESLA V100	SPEEDUP
164,282	3.35 hrs	45 sec	268X
1,856,159	214.62 hrs	17 min	757X

8 CONCLUSIONS

In this paper we illustrate the use of water drone technology to provide high-resolution bathymetric data for hydraulic simulation models. We applied the RiverFlow2D model running in the Google Cloud to simulate flow around hydraulic structures in the Everglades National Park in the USA. Ongoing activities include the model calibration with ADCP velocity data. Results demonstrate that high-resolution applications, that were not feasible until recently can be realistically done using highly detailed bathymetric surveys gathered with water drones and GPU flexible mesh 2D models in the Cloud.

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