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THE ROLE OF RASTER RESOLUTION INTO OVERLAND FLOW AND TOTAL SUSPENDED SOLIDS MODELING IN SMALL URBAN CATCHMENTS

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ABSTRACT

Parallel computing and high-resolution available geographical information data allow the use of complex hydrological models to perform spatial analysis of flow and pollutant spatial distribution. In this paper, we applied a fully distributed model based on the methods of Green-Ampt for infiltration loss, non-linear reservoir for flow routing and build-up and wash-off approach for total suspended solids (TSS) accumulation to investigate the role of raster resolution in water quantity and quality. The model was applied in a parking lot catchment (7.85 ha) at the University of Texas at San Antonio. We compared the results for TSS and overland flow for resolutions of 1-m, 2-m and 5-m. Results indicate that for calibration purposes, a 5-m resolution is suitable to match the observed hydrograph and pollutograph at the outlet, however, might not present accurate spatial distribution of TSS and water surface elevation.

1 – INTRODUCTION

Surface runoff flow dynamics is a complex process-based phenomena. Recent advances in computational power, data availability, and visualization tool has allowed for accurate temporal and spatial simulation of physics-based modeling that relies on the principles of mass and momentum equations for flow and water quality (AHMAD; SIMONOVIC, 2004; GOMES JR. et al., 2021; LIU et al., 2003). For water quality purposes, several hydrological models as the Stormwater Water Management Model (SWMM) (ROSSMAN; HUBER, 2016), the Soil and Water Assessment Tool (SWAT) (NEITSCH et al., 2011) are freely available. These models require a calibration of water quantity and water quality hydrological model. Depending on the pollutant of interest and on the catchment area, not only overland flow parameters have to be calibrated, but also groundwater, river, and evapotranspiration parameters, as well as decay rates for the pollutants (FERRANT et al., 2011; JOHNSON; GERALD, 2006; WHITEHEAD et al., 2011).

For highly urbanized areas, the Total Suspended Solids (TSS) is considered a representative pollutant to depict the degree of pollution of a catchment system (AL ALI et al., 2018; DI MODUGNO et al., 2015; HAN et al., 2006; JOHNSON; GERALD, 2006) and can be modeled by the Build-up and Wash-off modeling approach (ROSSMAN; HUBER, 2016). Although the SWMM model allows to simulate sub catchments including routing by the non-linear reservoir method and pollutant transport and fate by the Build-up and Wash-off approach, it does not account for a spatialized interconnected grid of cells. This type of modeling allows the spatial visualization of overland flow and pollutant distribution rather than only hydrographs and pollutographs at the outlet of the sub catchments. Using high-resolution digital elevation and land-use and land-cover (LULC), the spatial distribution of overland flows and TSS can be visualized throughout the catchment, indicating critical areas in terms of floods and water quality (GOMES JR. et al., 2021).

The use of higher resolution GIS information as input data for hydrological models may not always provide an adequate representation of the processes due to issues as numerical instability (FRY; MAXWELL, 2018). There is a trade-off between cell resolution and the hydrological model properties (e.g flow discharge, infiltration, pollutant concentration) (SHIVAKOTI et al., 2008). The objective of this article is two-fold: (1) assess the role of grid cell resolution into Total Suspended Solids (TSS) concentration and into (2) overland flow. Using available high resolution GIS data (i.e., Light Detection and Ranging (LiDAR), land use and land cover information (LULC) obtained from San Antonio River Authority at the City of San Antonio) and using a fully gridded distributed model, the influence of cell resolution in an urban catchment at the University of Texas at San Antonio is assessed.

2 - MATERIAL AND METHODS

The model is divided into (a) infiltration model by the Green-Ampt model (GREEN; AMPT, 1911), (b) overland flow by the non-linear reservoir method (ROSSMAN; HUBER, 2016), and (c) pollutant accumulation and transportation by the Build-up and Wash-off model (ROSSMAN; HUBER, 2016). The modeling approach uses gridded information of: (a) DEM, (b) LULC, (c) Manning’s roughness coefficient, (d) Initial Abstraction, (c) Green-Ampt Parameters, (d) Build-up and Washoff Parameters, and (e) Precipitation. A detailed description of the model can be found in (GOMES JR. et al., 2021).

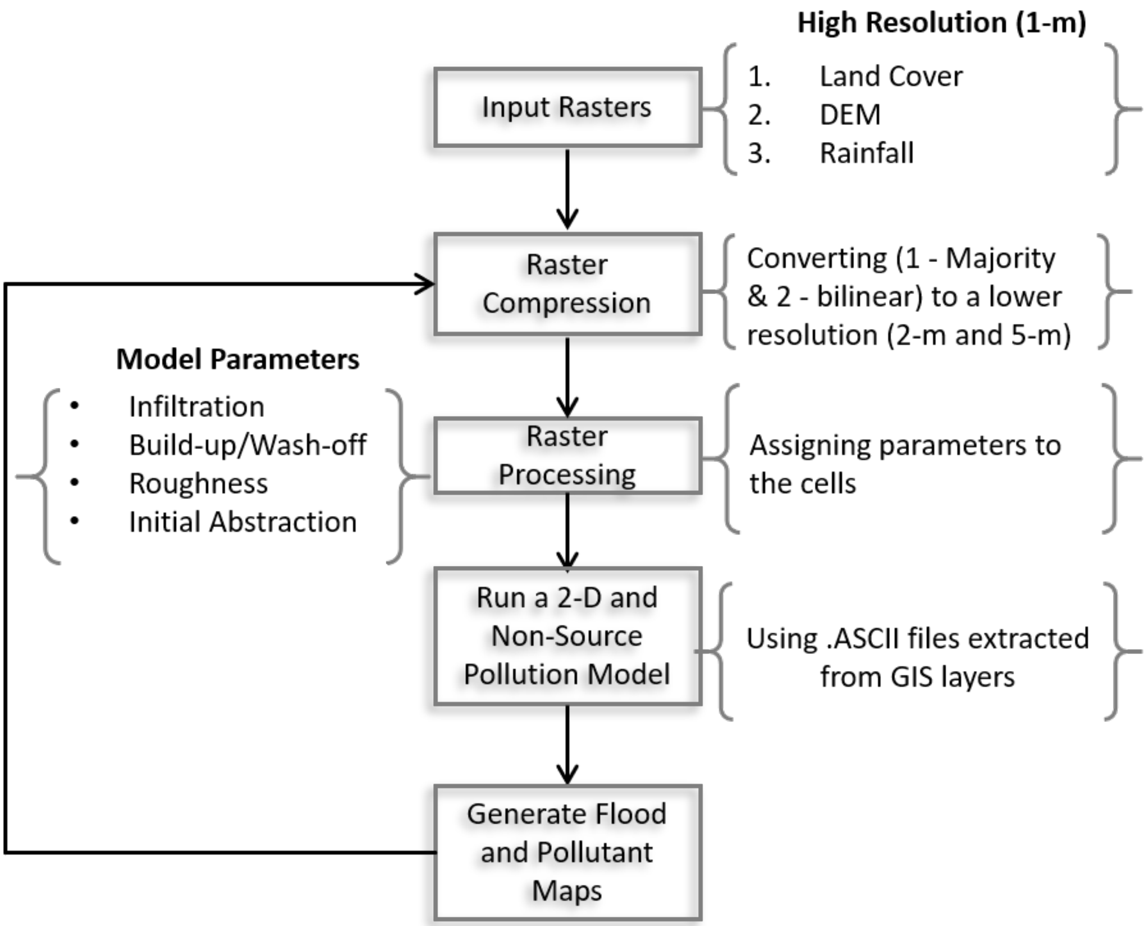
2.1 Computational Time Performance

One of the most important criteria to decide or not using a specific model is its computation speed, which may depend on several variables, such as: (a) computational power, (b) domain discretization, (c) model inputs (i.e., rainfall pattern, soil properties variation) and (d) time-step resolution. The time to solve the system of equations for one step is a function of the number of cells in the domain, but it varies according to the complexity of the process modeled (e.g., in the beginning of the time domain, the system of equations is less complex because all water typically infiltrates). In this analysis, several runs in the model were done assessing computational times for a uniform storm of 10.8 $mm.h^{-1}$ for 30, 60, 90, 120 and 150 minutes of routing time. The model was applied in the V-Tilted catchment (KOLLET; MAXWELL, 2006). The grid resolution domain was defined for cells of 10, 20, 40, 50, 100 and 200 m, especially because these values are multiples of the hillslope length (1000 m) and width (800 m) and can represent different range of cells (KOLLET; MAXWELL, 2006). The time-step was defined for an average velocity of 2 $m.s^{-1}$. After the computation of each simulation (Routing Time x Resolution), the variables were normalized by the routing time and drainage area.

2.2 GIS Data Extraction

Using a 1-m resolution GIS data, we assessed whether the role of compression in the data will play an important role in the quality of the output data of the hydrological model. Cell resolutions of 2, and 5 meters derived from the 1-m resolution data were tested. A flowchart depicting this methodology data acquisition part is presented in Figure 1.

Figure 1 - Methodology scheme using high resolution LULC and Terrain data from LiDAR to estimate the impact of cell resolution into TSS distribution in an urbanized catchment at UTSA recreation center parking lot.



2.3 Study Case – UTSA Recreation Center Parking Lot

The UTSA recreation center catchment has a drainage area of approximately 7.85 ha (19.4 acres), with 36.5% of pervious areas (natural soil cover areas with average slope of 9%) and 63.5% of impervious areas (parking lots and roads with average slope of 2.5%) as shown in Figure 2. The average slope of the watershed is 5% (GOMES JR. et al., 2021). The drainage network was determined for flow accumulations larger than 1000-cells. To correct eventual failures and provide continuity in the hydrologic models, sinks larger than 0.2 m were filled, as well as boundary watershed elevations were filtered running the model to identify where flows were being accumulated due to inaccurate elevations. The model was previously calibrated and was developed in MATLAB. The rainfall duration and rainfall volume are approximately 2 hours and 31 mm, respectively, and the initial pollutant mass was calibrated for pervious and impervious area, resulting in 11.2 and 14.3 g/m^2 of TSS. Rainfall, surface runoff and TSS concentrations were monitored through 1 year.

Figure 2 - Study Case at the UTSA recreation center parking lot, where the red dashed line represents the watershed boundary, the red dot represents the outlet of the catchment and the blue dot the rain gauge.

2.4 Watershed Delineation

Using a 1-m resolution LiDAR data and land-use data, we resampled a new digital elevation data for resolutions of 2-m and 5-m. Using a 10-m resolution did not properly generated a watershed due to coarse resampled data, thus we excluded it from the analysis. The first step was to fill any natural sink or generated by data noise to avoid hydraulic continuity problems in the modeling. For the DEM, we used a bilinear resampling, whereas for the imperviousness we used the majority resampling criteria. These resampling methods were selected due to the behavior of the GIS properties (i.e., elevation is a continuous measure and imperviousness is a categorical data). After resampling the GIS data, we generated 8-D flow direction and flow accumulation rasters. Using the raster calculator, we also created a raster showing the cells with flow accumulation larger than 50 cells. This raster helped to define the outlet feature, which was defined as a point that intersects a cell of the flow accumulation raster.

Catchments for resolutions of 1, 2 and 5-m were created. Afterwards, we converted these rasters into polygons and extracted them by mask. We repeated this process for all resolutions. Finally, we exported ASCII files containing the gridded DEM and impervious rate data. These files are input data for the 2-D overland flow and pollutant distribution model in Matlab. The ASCII file contains information about the number of rows, columns, and no-data values, which were assigned to -9999. When extracting the watershed from the GIS, it is important to include in the mask a negative number for the blank data, so that the model avoid unnecessary calculations and converges faster to the final solution.

2.5 Spatial Analysis of Overland Flow and Total Suspended Solids

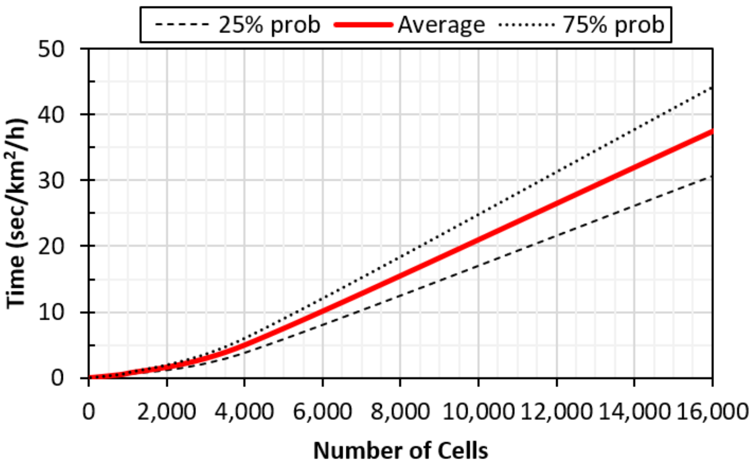
The temporal dynamics of TSS and stormwater runoff is assessed with time-varying maps of these variables with respect to their spatial distribution. This analysis is performed using results from the 1-m resolution DEM. With the modeling results, we generated flood maps (maximum water surface elevation) and pollutant accumulation maps (final pollutant mass after the storm event) to assess the differences between a more computationally expensive model in comparison with a faster but coarser resolution.

3 – RESULTS AND DISCUSSION

3.1 Computational Time Performance

The computational time variation is depicted in Figure 3, indicating the 25th percentile and the 75th percentile of the calculations. For instance, a watershed with 1 km^2 for a 1-h routing time using 6.000 cells would take a computational time between 8 to 12 seconds for a complete simulation.

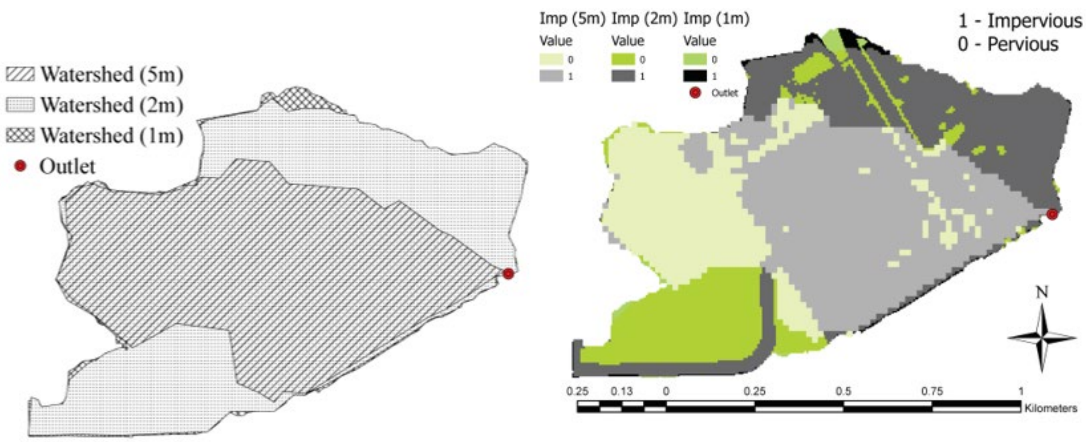
Figure 3 - Required Computational Time per square km of catchment, per hour of routing time chart for a laptop Aspire A515-51 Intel® Core™ i7-7500 CPU @ 2.70 GHz 2.90 GHz, 8.00 GB Memory RAM



3.2 Watershed Delineation

The watershed delineation and the impervious map for the different resolutions is presented in Figure 4. The different resolutions used for the DEM resulted in different watershed areas. Generally, the higher resolution DEM resulted in larger drainage areas. For the 5-m resolution, however, the drainage area is mostly composed by the parking lots, whereas for the 2-m and 1-m DEM there are more pervious areas included in the catchment.

Figure 4 - Recreation Center Watershed Delineation and Impervious map for 5m, 2m and 1m resolution



According to the impervious rate, the hydrological model assigns infiltration, hydraulics, and pollutant parameters to solve the pollutant transport and water balance equations in each cell of the raster.

3.3 Hydrographs and Pollutographs

The model was calibrated for the 5-m resolution DEM. Calibration process was performed by a genetic algorithm for 40-population 100-generations using parallel computing (GOMES JR. et al., 2021). Thus, the model with 5-m meter resolution is more suitable for calibration. Since the model is mostly physically based, we hypothesize that the calibrated parameters are valid for 1-m and 2-m resolutions. The results indicate that the 5-m, even though might not provide as much spatially detailed information as 1-m and 2-m, is an appropriate resolution to represent the hydrology of the parking lot, or at least to represent the outlet hydrograph and pollutograph (NSE = 0.91, R^2 = 0.96 for TSS and NSE = 0.89, R^2 = 0.95 for Overland Flow) (GOMES JR. et al., 2021). The model ran for approximately 1-sec to perform the calculations for a simulation with 5-m resolution.

The other cell resolutions required longer modeling times (i.e., 210 min for 1-m resolution, 25 min for 2-m resolution), especially because the time-step of the model must decrease to avoid numerical instability (i.e., typically a 1-m resolution require a 0.2-sec time step) and due to the exponential increasing number of cells. These results were overly different than the ones found in the Computational Time Performance section, indicating that the model performance must be assessed with different catchments to properly provide a guide for the modeling time. Moreover, with higher resolutions, the definition of the outlet might be more difficult and might be defined through a line, instead of a point. Therefore, to compute the outflow from the catchment is required to perform the flow summation of all outflow cells. Assuming wrong outlet boundary conditions can lead to an increasing in the water surface flood depth in the outlet and change the dynamics of the watershed (i.e., with larger flood depths, the flow direction change).

3.4 Spatial Analysis of Overland Flow and Total Suspended Solids

Using the 1-m resolution modeling results, the overland flow and TSS dynamics from 5-min to 24-min of the storm is showed in Figure 5. This figure shows that the TSS is moving towards the roads and lateral channel, quickly reaching the outlet of the system.

The water surface flood depths and the TSS accumulated at the end of the storm for each cell and resolution is presented in Figure 6. The maximum flood depths for 1-m, 2-m and 5-m were 89, 98 and 94 mm, respectively. Even though the rainfall event was not strong enough to produce higher flood depths, the model is still able to capture the relatively ow flood depths. In the 1-m and 2-m resolution results is possible to note that the curbs and a small culvert got flooded during this storm event. In the 5-m resolution, however, the flood depths were more concentrated towards the outlet of the catchment, which is also a pattern seen for 1-m and 2-m resolutions.

For the washed pollutant mass and hence accumulated mass of TSS at the end of the storm, the maximum accumulation nearly followed the same pattern for 1-m, 2-m and 5-m resolutions. However, the magnitude dramatically changed from 5-m (20 g/m^2) and 6-m (28 g/m^2) to 1-m (60 g/m^2). Although the final accumulated masses varied spatially, the spatial averages were similar. It is possible to note that the 1-m resolution generated a more concentrated area of TSS accumulation, whereas for 2-m and 5-m, this final accumulation area was wider. Most part of this pollution came from the pervious upstream area and was not completely washed for this 120-min event period.

Figure 5 - TSS concentration and overland flow distribution in the recreation center for, where inf (mm/h) is the infiltration rate and Depth (mm) is the water surface elevation in each cell. Note the TSS movement towards the outlet of the catchment.

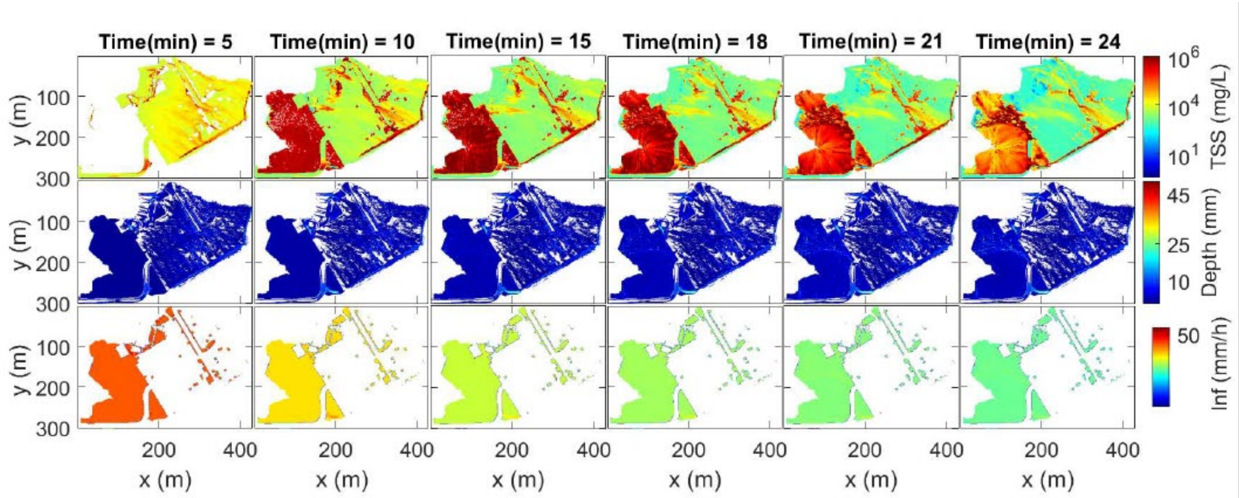
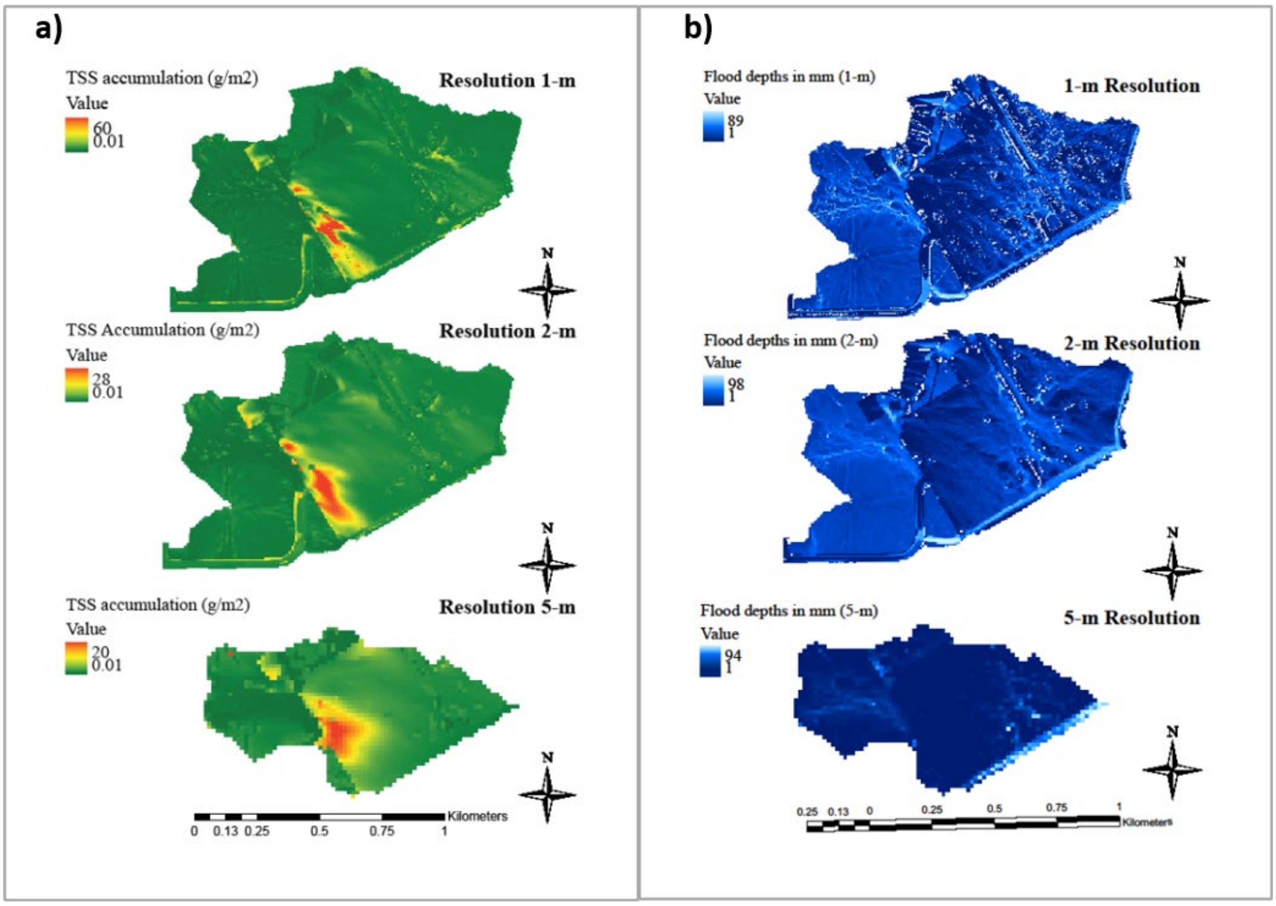


Figure 6 – TSS accumulation at the end of the storm event and maximum water surface depths



4 – CONCLUSIONS

Delineating the watershed using LiDAR information typically requires a pretreatment (e.g., filling sinks) to be used for hydrological models in high-temporal and spatial resolution. The fully distributed hydrological model performance is influenced by the DEM and imperviousness GIS information and depending on the methods of resampling, more errors can be propagated. Fully distributed models can provide important spatial information to be used in drainage plans, helping enhancing decision making and ultimately providing evidence for the creation of policies for water resources planning and management. Future investigations should evaluate the spatial distribution of other pollutants such as zinc, copper, and lead. In addition, the inclusion of low impact development facilities as bioretentions and permeable pavements in the hydrological model would enhance the analysis of the potential benefits that these green infrastructures would provide for urban catchments.

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