HYDROLOGY OF URBAN FLOODING IN BALTIMORE

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Abstract. Flash flooding is a serious issue in urbanized areas. Increasing urbanization will worsen the problem by limiting stormwater infiltration and increasing flash flooding. To mediate flash flooding, a better understanding of flood control responses is needed. Evaluating a hydrologic model traditionally can inform us about relationships that affect urban flooding. Using a different hydraulic model can confirm previously drawn conclusions or even lead to clearer conclusion. This paper evaluates the use of kinematic runoff and erosion model (KINEROS2) in the Baltimore area. This work discusses the calibration process of the KINEROS2 in two Baltimore watersheds. The validation of KINEROS2 in Baltimore has important consequences, notably that KINEROS2 can be used in humid climates and subsequently that work focusing on different areas can use the same model, easing collaboration within research groups and across the Network. Further use of KINEROS2 will allow for investigations on the relationships that govern flash flood responses. In the long term, this will facilitate both better urban planning and flash flooding interventions.

INTRODUCTION

Flash flooding is a significant issue globally. Standing water often impedes travel. Large volumes of water entering quickly into rivers and streams can alter their paths. Runoff from flash flooding can bring hazardous contaminants into streams, lake, and other bodies of water, causing notable ecological harm. Flooding can also cause immediate danger to humans. According to the National Weather Service, flooding is the second-deadliest weather event in the United States.

Stormwater management infrastructure can alleviate some of the negative effects of flash flooding by reducing peak discharge. The same infrastructure can also exacerbate other flooding problems, such as increasing runoff within a watershed. The change in land use due to urbanization reduces surface permeability, which increases the volume of stormwater that does not infiltrate into the ground. As urbanization continues to expand, more information is needed on the relationships that affect urban flooding. Additionally, as climate change increases the likelihood of extreme weather events, a larger knowledge base becomes increasingly important for the development of effective flood interventions. New tools can evaluate urban flooding in different ways allowing for a new perspective. Using techniques that are common in other areas permits for better collaboration and comparison.

This study seeks to better understand flood control responses in small watersheds in urban areas and to expand upon past findings. The research focuses on urban areas because the flashiest watersheds are located in urban areas, especially east of the Rockies (Smith, B.K, and Smith, J.A., 2015). This study examined two subwatersheds within the Baltimore area, portions of Moore's Run and White Marsh Run. The Baltimore region is of particular importance for hydrological research due to its susceptibility to flash flooding. Smith, B.K, and Smith, J.A., 2015 found that the flashiest region of the Mid-Atlantic was along the I-95 corridor in Maryland, Virginia, and North Carolina. [Note: flashiness was defined as number of peak discharges of the threshold of $1 m^3/s\ km^2$ separated by at least 6 hours per year]. Baltimore is located on this corridor and, in fact, that study classifies Baltimore as one of the flashiest cities in the United States.

Smith, B.K., et al., 2013 found a range of hydrologic responses amongst various Baltimore watersheds. The authors noted that the high runoff ratios could be the result of high hydraulic conductivity in the watershed provided by transportation corridors and stormwater management infrastructure. Other Baltimore-area watersheds experienced anomalously large flood peak magnitudes. Smith, B.K., et al., 2013 attribute the broad spectrum of hydrologic responses to differences in stormwater management infrastructure. B.K. Smith et al., 2013 found that stormwater management infrastructure is effective at reducing peak discharges and delaying timing of peaks.

This research utilized hydrological modelling to evaluate flood events. The kinematic runoff and erosion model (KINEROS2) was used in this project. KINEROS2 is a process-based hydrologic model, meaning that with user-designated inputs, KINEROS2 simulates physical processes in order to return data to the user, in this case, peak discharge, runoff volume, etc. The data inputs will come from publicly-available data sets from various governmental agencies as discussed in the materials and methods section. KINEROS2 is not frequently used on the East Coast. Previous studies, such as *Exploring storage and runoff generation processes for urban flooding through a physically based watershed* (Smith, B.K., et al., 2015), hydrologically modelled the Dead Run Watershed in Baltimore County using Gridded Surface Subsurface Hydrologic Analysis (GSSHA). GSSHA is normally used more frequently in the East. KINEROS was originally designed for the American Southwest because of the difficulty of hydrologically modelling arid regions. GSSHA models watersheds by cells, while KINEROS2 divides the watershed into subwatersheds. GSSHA typically has a longer runtime than KINEROS2. KINEROS2 also can operate with less data and data preparation relative to GSSHA (Kalin, L. and Hantush, M. M., 2003). GSSHA is the preferred model of the Army Corp of Engineers. U.S. Department of Agriculture uses KINEROS2.

KINEROS2 procedures require calibration of the model to better reflect watershed conditions. After calibration, validations of the model's predictions with actual event outcomes assures proper use of the model.

METHODS

This project hydrologically modelled White Marsh Run and Moore's Run using the kinematic erosion and runoff model (KINEROS2).

KINEROS2

KINEROS2 is a distributed, physically-based, event-oriented hydrologic model. The model represents the processes of interception, infiltration, surface runoff, and erosion. KINEROS2 can accommodate spatial variations of several parameters, including rainfall, runoff, infiltration, and erosion. The model converts elevation maps and stream flows into a series of overland flow planes and open trapezoidal channels. KINEROS2 uses partial differential equations and solves them by finite difference techniques. The Automated Geospatial Watershed Assessment (AGWA) tool expedites the process of performing the KINEROS2 model. AGWA, as an add-in to GIS, utilizes GIS data input to parameterize, execute, and illustrate the results of KINEROS2.

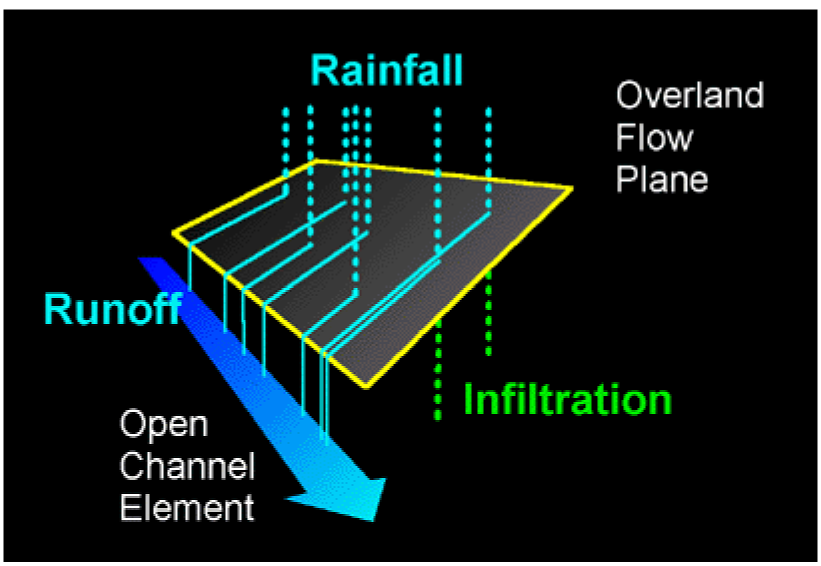

FIGURE 1: FLOW SIMULATION, as performed by KINEROS2. (Image from KINEROS2 webpage).

Data Sources

The United States Department of Agriculture (USDA) Natural Resources Conservation Service's (NRCS) Geospatial Data Gateway (GDG) is an online resource that allows access map libraries of environmental and natural resources data, available at high resolutions with both vector and raster layers available.

The United States Geological Survey (USGS) Water Data for the Nation (WDN) provides data on occurrence, quantity, quality, distribution, and movement of surface and underground waters.

Data Required	Type	Source
Elevation	National Elevation Dataset 30m	USDA NRCS GDG
Hydrologic Units	12 Digit Watershed Boundary Dataset	USDA NRCS GDG
Soils	Soil Survey Spatial and Tabular Data (SSURGO 2.2)	USDA NRCS GDG
Outlet Location	Latitude and Longitude	USGS WDN
Watershed Area	Drainage Area	USGS WDN
Outflow	Discharge data (volume per unit time)	USGS WDN
Precipitation	Radar rainfall shields	Princeton Hydrometeorology Group

TABLE 1: DATA INFORMATION

Input files for KINEROS2, such as stream vectors, flow accumulation, flow direction, etc., were created using ArcHydro and elevation data. The other data served as an input for AGWA to execute the KINEROS2 model.

Various runs were completed for each event using different input parameters, such as hydraulic conductivity multipliers. The model-predicted and observed peak discharges were compared to validate the model. An analysis of calibration techniques is provided in the discussion section.

RESULTS

Watershed Extraction

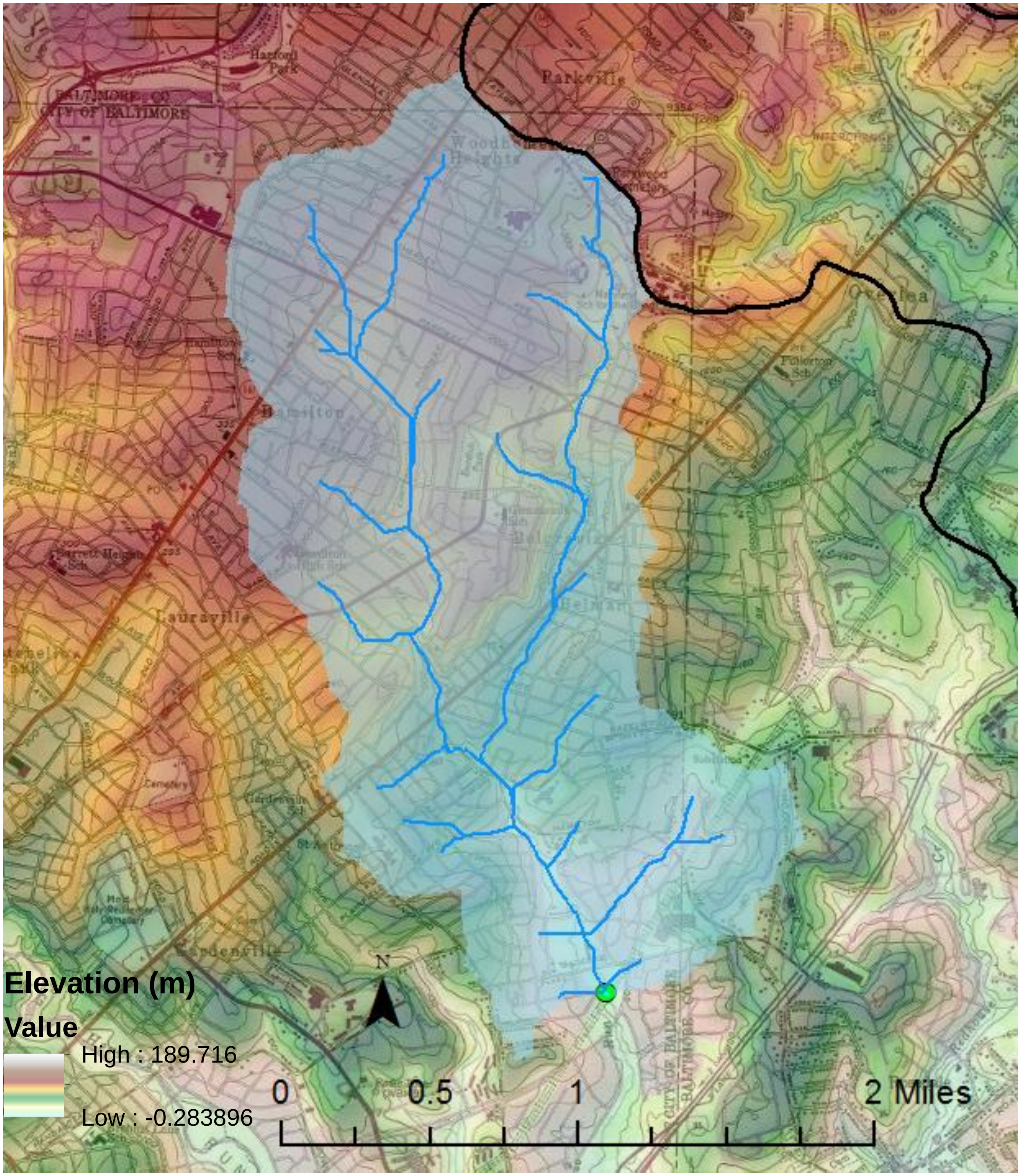

FIGURE 2: MOORE'S RUN: The central region of this watershed is located primarily within the boundaries of the City of Baltimore. The area shaded light blue represents the area that drains to the above green point. The blue lines are the existing stream network. The black outlines aggregate watershed basins. The watershed was extracted using a 10m digital elevation model.

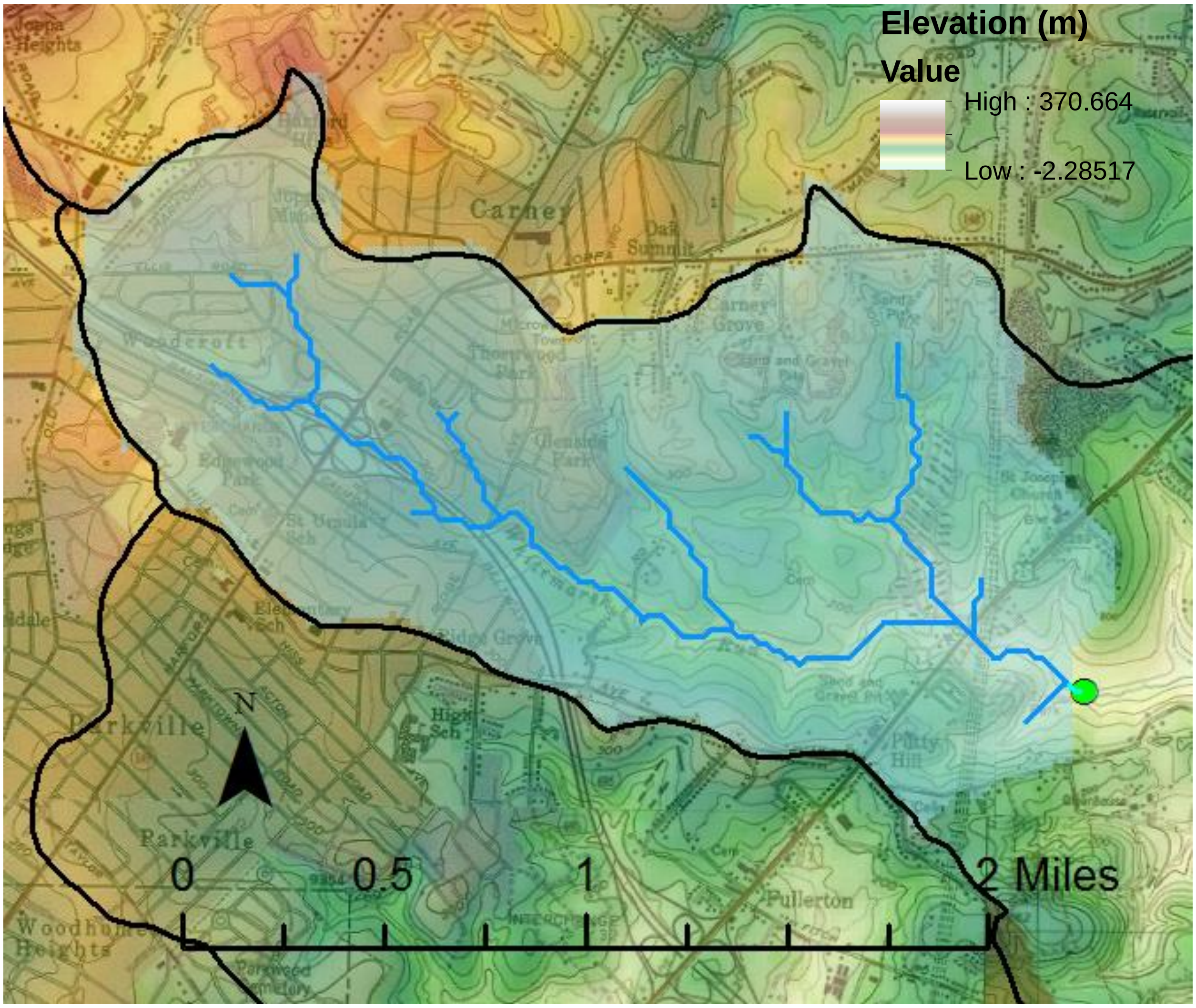

FIGURE 3: WHITE MARSH RUN: This eastern part of the White Marsh Run Watershed is northeast of the City of Baltimore. The area shaded light blue represents the area that drains to the above green point. The blue lines are the existing stream network. The black outlines aggregate watershed basins. The watershed was extracted using a 30m digital elevation model.

Calibration and Adjusting the Model

Calibration makes the model more accurate and can account for factors that are not accounted for in the input data. Less calibration was needed for each event when radar rainfall data were used in comparison to single rain gauge rainfall data. This is likely because the radar rainfall fields account for spatial variability. For both watersheds, default element parameterizations options were not used. Using the default channel type resulted in little to no discharge for all events. The default hydraulic conductivity was too high, causing all the simulated rainfall to infiltrate into the channel. The hydraulic conductivity was set to 0, rendering the channels essentially impervious. The roughness (Manning's coefficient) was set as low as possible, at 0.0100. Increasing channel roughness by values of 10 to 30 % has little effect. The default saturation in KINEROS is 0.2. The saturation seen in the Baltimore area varies and can be considerably higher than this. Increasing soil saturation causes the peak discharge to increase (**FIGURE 4**).

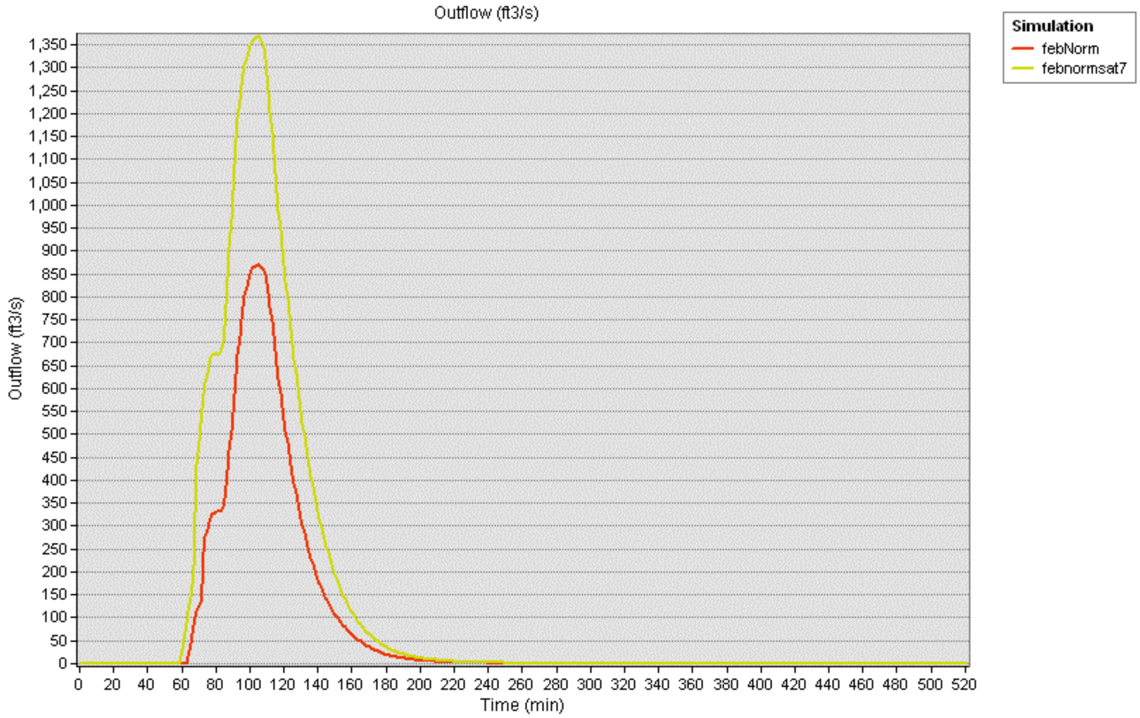

FIGURE 4: Saturation. Peak discharges of two simulations of the storm at White Marsh Run on February 24, 2016. Note peak discharge increased by approximately 50% when the soil saturation was altered from 0.2 (febNorm) to 0.7 (febNormsat7).

To reduce the amount of infiltration in the planes, a hydraulic conductivity multiplier term was used. Values of the multiplier higher than one decrease infiltration, therefore increasing runoff and peak discharge (**FIGURE 5**). Values of the hydraulic conductivity multiplier less than one increase infiltration, thus decreasing runoff and peak discharge. Ideally, the hydraulic conductivity multiplier used for each watershed should be the same for all events. However, changing the multiplier value for events in different seasons may be necessary due to factors such as frozen ground, differences in water temperature, etc. Possibly, changes in land use or change in soil compaction could explain the need for different hydraulic conductivity multipliers of events in the same season but different years. However, there may be an alternative explanation as well.

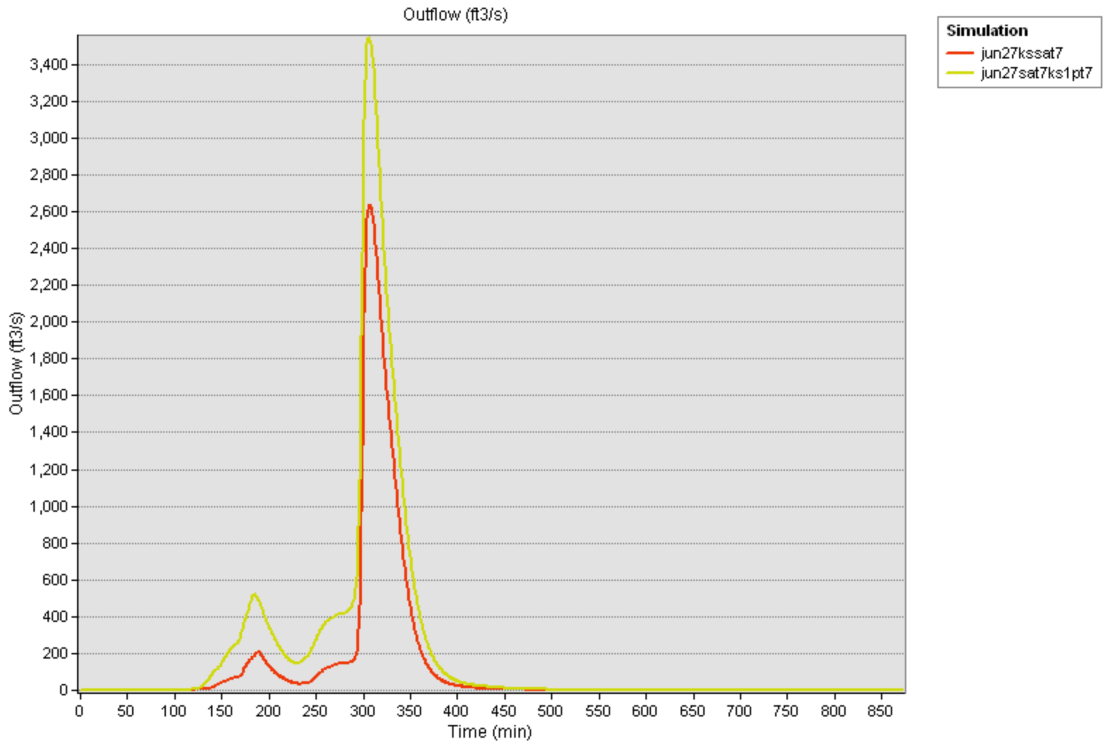

FIGURE 5: Hydraulic Conductivity Multipliers: Run with no multiplier (jun27kssat7) and with hydraulic conductivity multiplier of 1.7 (jun27sat7ks1pt7).

Comparing Moore's Run and White Marsh Run

The extractions of each watershed had a percent difference of approximately 4% when compared to the USGS measured area (**TABLE 2**).

Watershed	Predicted Area (km^2)	Measured Area (km^2)	Percent Difference (%)
Moore's Run	9.52	9.12	4.4
White Marsh Run	6.81	7.07	3.7

TABLE 2: Watershed Area. Notice that the predicted area for Moore's Run is larger than the measured area, but that White Marsh Run's predicted area is smaller than the measured area. Note that the utility for measuring areas in ArcGIS is not very accurate, so the numbers are not exact.

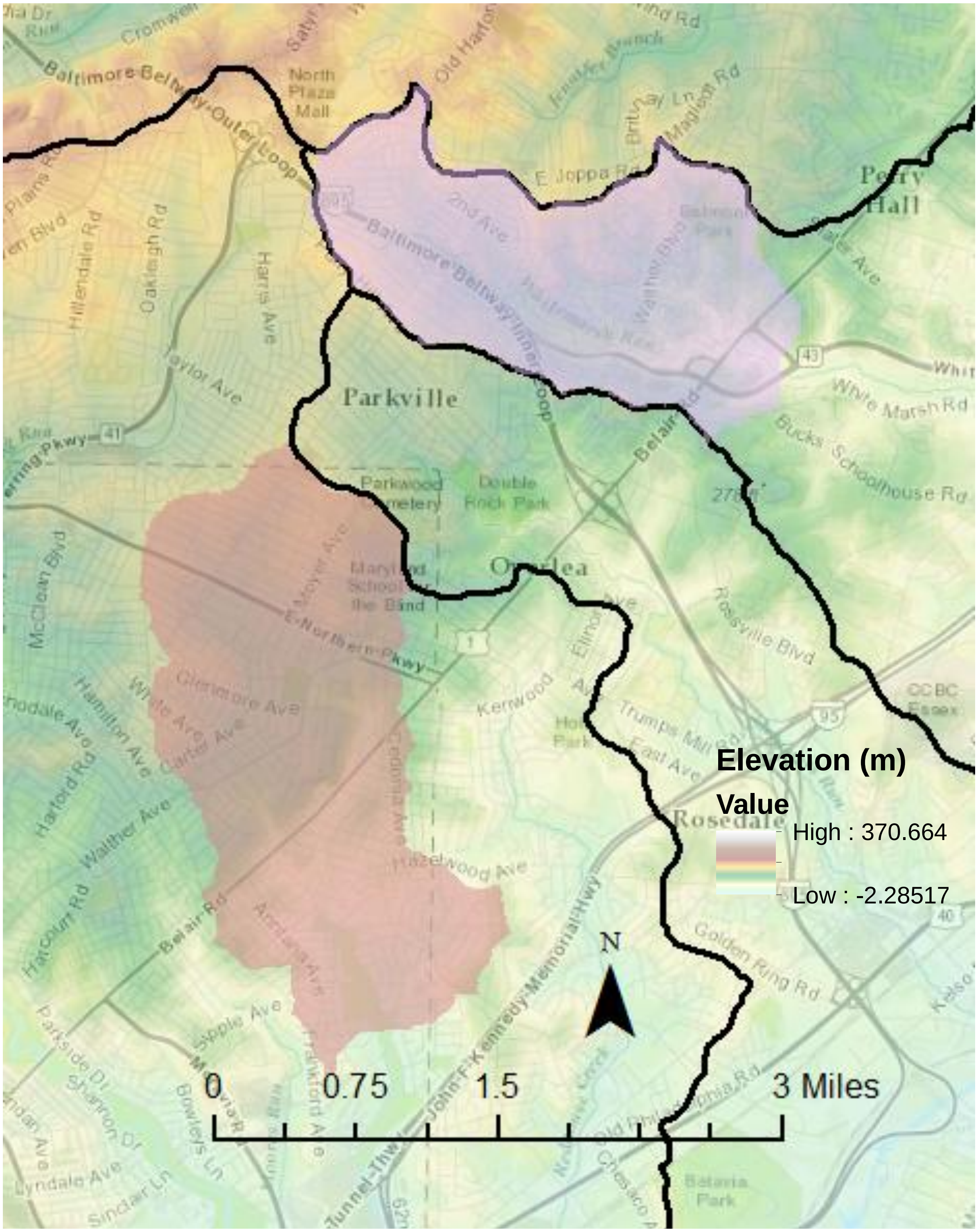

FIGURE 6: LOCATION OF WATERSHEDS White Marsh (lilac) and Moore’s Run (red). Note that the legend refers to elevation in meters.

Moore’s Run is a highly urbanized watershed. The urbanization occurred largely before the Clean Water Act and as result, does not have much storm water management infrastructure. Moore’s Run is the third flashiest watershed in the country (Smith and Smith, 2015). White Marsh Run is somewhat less urbanized than Moore’s Run. The urbanization happened later, and as a result, White Marsh Run has stormwater management infrastructure. The Beltway runs through the White Marsh Run watershed.

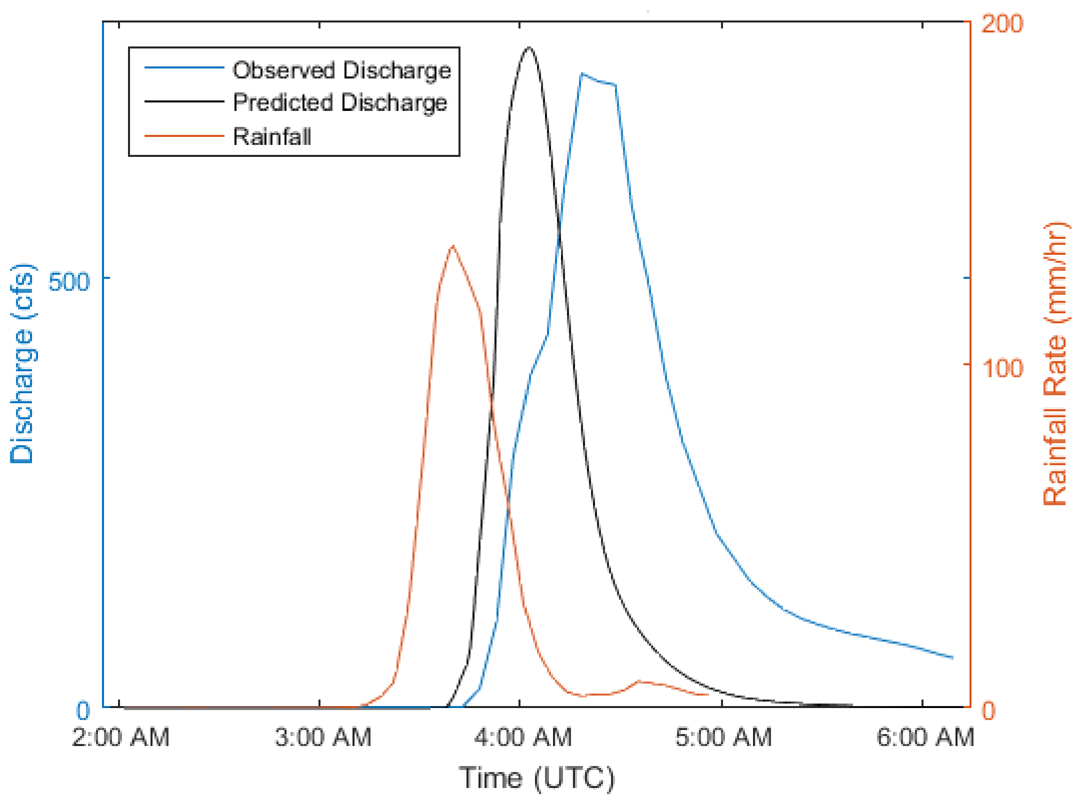

FIGURE 7A: Hydrograph of White Marsh (USGS station 02060003) with rainfall for event on June 30, 2012 comparing observed and KINEROS2-predicted discharge.

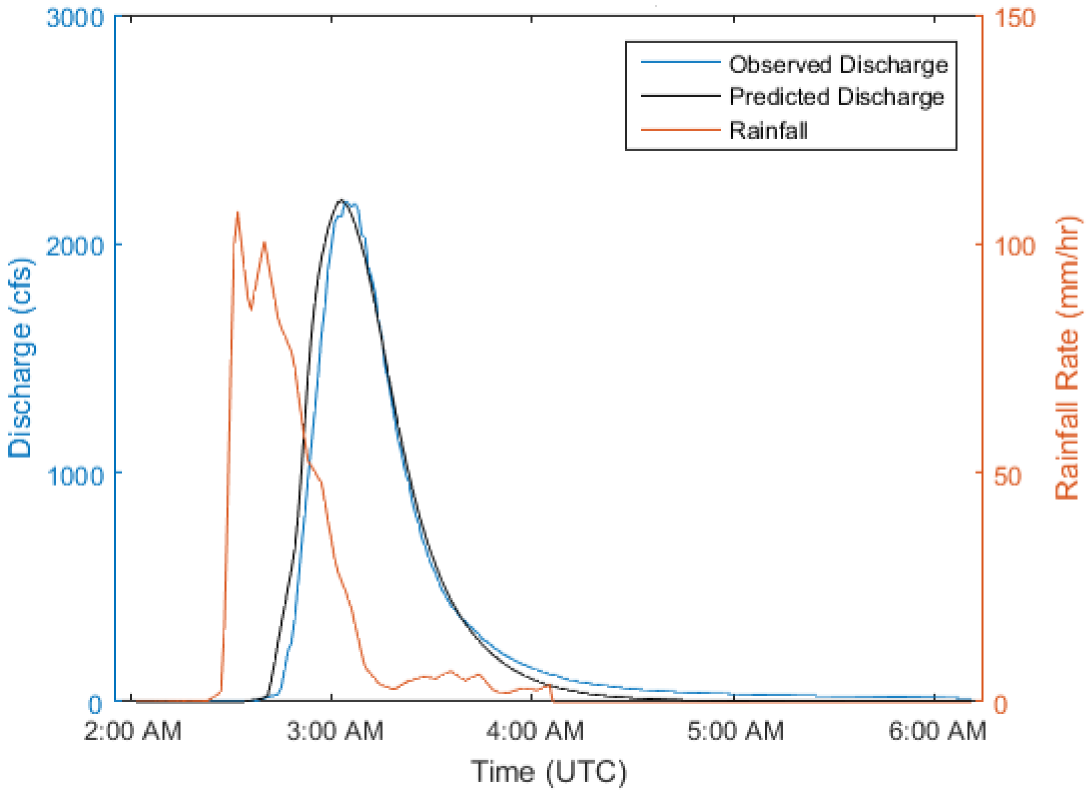

FIGURE 7B: Hydrograph of Moore's Run (USGS station 01585230) with rainfall for event on June 30, 2012 comparing observed and KINEROS2-predicted discharge.

Validity of KINEROS2

In **FIGURE 7**, the predicted rainfall is very close to the observed discharge. The predicted and observed peaks are similar, with some difference in width of peak and timing of peak. This can likely be attributed to discrepancies from the data input into KINEROS2 (such as land use land cover, soils data, etc.) and actual conditions in the watershed. This study concludes that KINEROS2 can be validly used in Baltimore and likely other humid watersheds.

DISCUSSION

This is the first research of Baltimore watersheds using KINEROS2. KINEROS2 was successfully implemented in the Baltimore region. Calibration of the model is critical because KINEROS was designed with a dramatically different landscape in mind. With proper calibration, especially of hydraulic conductivity values, KINEROS2 produces good results. This study concludes that KINEROS2 can be used in Baltimore and likely other humid watersheds.

In addition, this project expanded the knowledge of the KINEROS2 model. Using KINEROS2 in place of GSSHA could reduce the amount of time and work to run a hydrological model in certain circumstances. Using the same model eases collaboration within and across research groups. The study also increases the diversity of hydrological models in Baltimore.

Limitations

There was not enough time to evaluate additional locations. AGWA and ArcGIS frequently return errors that are very difficult to troubleshoot and that often not the fault of the user. Due to these issues, certain models could not be completed. The model was not identical to the observed values. Some of this difference is likely attributable to the accuracy of input parameters. The land use land cover map is limited by its resolution. Soils data are limited because the data often do not take into account soil compaction. The USGS stream monitoring stations are susceptible to time drift and volume measurement error.

Future Research

Future studies using KINEROS2 in Baltimore should evaluate a larger number of watersheds, such as Jones Falls and Dead Run. This could further validate KINEROS2 for non-arid use, expand KINEROS2 calibration knowledge, and produce valuable information about Baltimore watersheds. These studies could rectify issues associated with using AGWA and KINEROS2. Research using KINEROS in other humid regions of the country, such as Florida, could further validate KINEROS2 use in non-arid areas.

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