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AUTOMATIC DISCRETIZATION AND PARAMETERIZATION OF WATERSHEDS USING A DIGITAL ELEVATION MODEL

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Abstract: Characterization of both overland and channelized flow is crucial for understanding the sources and fate of catchment runoff. It is essential that care is taken when delineating catchments to ensure that these two types of flow are distinguished from one another. Unfortunately, due to the level of complexity associated with large watersheds, obtaining detailed watershed data necessary to adequately characterize the hydrological process is not always possible. To represent stream response within in a watershed the sheet flow, channelized flow, flow path slope and contributing area must first be considered. This paper examines the Stormwater Management Model (SWMM) hydrology setup and parameterization for the Toronto and Region Conservation Authority's Don River flood forecasting model using an automatic watershed delineation, parameterization and discretization tool developed in PCSWMM. In addition, two scenarios, with varying parameterization and hydrologic and hydraulic resolutions, will be compared using observed rainfall and flow data.

1 INTRODUCTION

Modeling large watersheds requires the characterization of both overland and channelized flow. This can be achieved by creating a higher resolution model that better accounts for the watershed processes, particularly in headwater areas, by better representing additional processes occurring on watershed surfaces.

Due to common project time and budget constraints, model discretization is limited, both in the required data collection and model development time. Thus, watersheds are generally divided into a small number of coarse subcatchments with resolutions of 100 - 400 ha and parameters such as slope, imperviousness and infiltration averaged across each subcatchment.

Calibrating coarse watershed models to match observed flows at downstream locations can result in calibrating parameters beyond their reasonable bounds thus producing unrealistic head water hydrographs. For example, Figure 1 shows a section from a watershed model showing a subcatchment being routed two kilometers downstream of the outlet. It is likely that, in this instance, the transition from overland to channelized flow and the accompanying hydraulic lag did not do an adequate job representing the multitude of complex flow transitions within the subcatchment. In this case, the length of overland flow was artificially increased to match observed flows. And although this action improved the computed response time, it came at the expense of artificially inflating infiltration time.

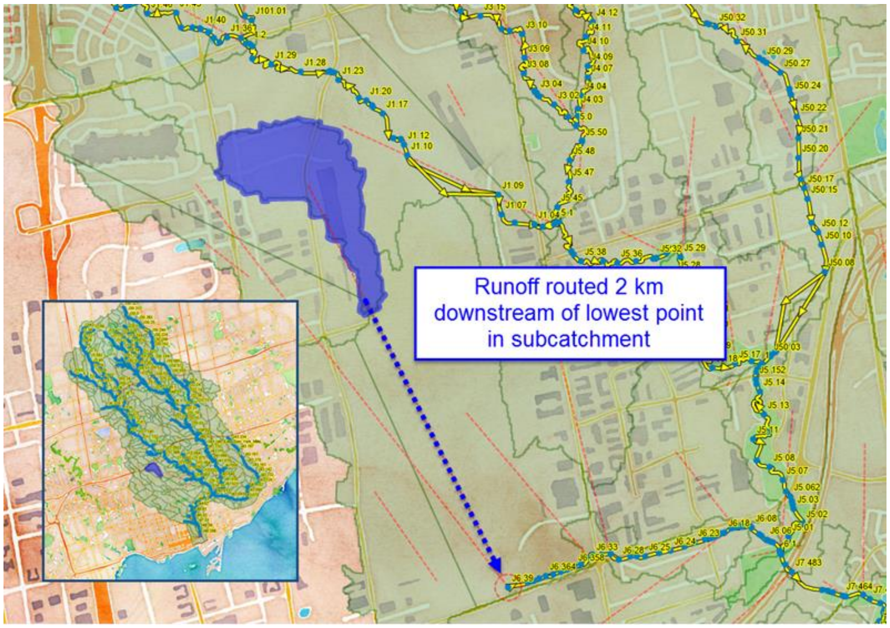

Figure 1: Example of subcatchment located significantly upstream of hydraulic network

While it is never possible to completely characterize watershed hydrological processes, separating sheet flow from concentrated flow and groundwater can better account for the overland processes without having to artificially change parameters to meet observed flows.

2 HYDROLOGICAL AND HYDRAULIC MODELING

The Stormwater Management Model (SWMM), originally developed by the United States Environmental Protection Agency (US EPA) in 1971, is a spatially distributed, rainfall-runoff simulation model used for single event or continuous simulation of runoff quantity and quality. SWMM has been updated many times since its first release, the most recent version being SWMM5.1. SWMM5 hydrology operates on a collection of catchments that receive precipitation and generate runoff and pollutant hydrographs, accounting for evapotranspiration, infiltration and groundwater percolation (Rossman 2008). SWMM5 models have been used for a wide variety of watershed applications (Bhaduri et. al. 2001; Davis et. al. 2007; Tränckner et. al. 2008).

SWMM5's non-linear reservoir formulation uses a kinematic wave approach to estimate overland flow. This approach requires that irregular subcatchments are converted into equivalent rectangles with a sloping plane, each with an associated width representing the width of the overland flow.

If the subcatchment width, W, is assumed to represent a true prototype width of overland flow, then the reservoir will behave as a rectangular catchment. In reality, subcatchments are delineated using topography/contour maps and land use layers and are unlikely to be perfect rectangles and the width (and the slope and roughness) may be considered calibration parameters.

Although SWMM5 uses a physically based approach to modeling surface hydrology, there is still only one flow equation representing runoff for each subcatchment, ostensibly representing sheet flow. Equation 1 shows the overland flow equation used in SWMM5.

[1] $Q = W * \frac{1.49}{n}\left(d - d_p\right)^{5/3} S^{1/2}$

Where:

W = Subcatchment width, ft.

n = Manning's roughness

d = water depth, ft.

d_p = depth of depression storage, ft.

S = Subcatchment slope, ft./ft.

Once runoff or overland flow reaches the subcatchment outlet, the flow becomes channelized and is transported through a system of pipes, channels, storage/treatment devices, pumps, and regulators.

Watershed delineation analysis tools, including the WDT, are available in PCSWMM and allow for seamless automated watershed and hydraulic network creation, parameterized for use in SWMM.

First released in 1984, PCSWMM is a spatial decision-support system for the US EPA SWMM program that was built upon a GIS engine, making it a powerful interface for developing models using GIS-based input data. The software provides all the hydrologic-hydraulic-water quality computational capabilities of US EPA SWMM5 while providing many additional tools for easier project management, model parameterization, calibration, data analysis, results inference and reporting.

3 Watershed Delineation Tool (WDT)

The Watershed Delineation Tool (WDT) provides a versatile way to delineate subcatchments based on a digital elevation model (DEM). It can be used to create models from scratch, or to increase the level of discretization for existing models.

In comparison to existing watershed delineation software, the WDT goes beyond watershed delineation, generating a dendritic SWMM network of subcatchments, junctions and conduits, partially parameterized from DEM features. If there are existing hydraulic entities (links and nodes) in the SWMM5 project, these entities are preserved and additional hydraulic components are generated as is necessary to connect the WDT-discretized subcatchments to the existing network.

In addition, while the watershed delineation tool may produce somewhat similar results as other watershed delineation tools, actual subcatchment delineations will differ as this approach uses the concept of a target subcatchment size, rather than a minimum area for channelization. The WDT also provides an option to burn-in streams (using a stream line layer) to create a hydrologically-corrected DEM, and can be set to discretize subcatchments to a set of predefined delineation (or "pour") points. At this time, elevation contours in a vector layer cannot be used to provide elevation data for the WDT.

The watershed delineation tool uses sequential computations of flow direction, flow accumulation, and stream definition based on a threshold and watershed delineation (Jenson and Domingue, 1988; Maidment, 2002). The results of each process are saved to a grid layer for review by the user. All created grid layers are saved to the same folder as the selected DEM layer in Arcinfo binary grid format (FLT).

If there are outfalls defined in the model, watersheds are delineated considering outfalls as drainage points. If there are no outfalls defined, watersheds will be delineated for the whole extent of the DEM. If there are existing drainage entities (links/nodes), the WDT created entities will be connected to the existing system where appropriate.

The remaining overland flow parameter, subcatchment slope, is also assigned by the WDT. The average subcatchment slope is estimated based on the flow direction for each cell. To ensure the WDT does not bias the slope because of micro-undulations in the DEM, a second coarser resolution DEM can be generated to reduce this effect and provide a more accurate hydraulically effective slope calculation.

To estimate flow length, the WDT uses the Guo and Urbonas (2009) method that applies a kinematic wave approach to convert irregular shaped subcatchments to equivalent rectangular planes. Using this method, subcatchment length values are estimated using a kinematic shape factor assigned based on the stream location in relation to the subcatchment and longitudinal elevation drop of the receiving concentrated flow channel. Thus, application of the WDT helps to avoid excessively long overland flow paths that violate the sheet flow approximation, and helps to overcome rectangular subcatchment shape limitations.

4 WDT processes

The following section goes through the WDT processes automated by the tool. In many cases, a resultant raster layer is created and used for the next process, ultimately delineating the hydrology and hydraulics networks.

4.1 Delineation points (optional)

The watershed delineation tool allows users to define an optional delineation points layer to generate individual subcatchments draining to each point in the layer. A delineation points layer (also called a pour points layer) is used to specify the outfall/outlet points, which will affect flow direction calculation. This option can be used for subcatchment or sewershed delineation in urban areas where surface runoff drains to manholes or catchbasins (Junctions), or to significant hydraulic structures such as ponds, bridges or culverts. Using a delineation points layer is not recommended for a model with no existing hydraulic network (i.e., minor drainage system).

4.2 Stream burn-in (optional)

The Stream burn-in option carves a trench in the original DEM along a specified line layer. The approach uses the AGREE DEM approach (Hellweger, 1997) for this purpose. It involves a sharp drop of 100 meters along the stream line and a smooth drop of 10 meters within a specified stream width. This allows for the removal of any dams created by captured DEM elevations of road crossings and actual dams.

4.3 Filling pits

Any local low spots in the burned DEM introduce difficulty for continuous flow over the DEM cells. Filling pits ensures a “hydrologically conditioned” DEM. The Planchon and Darboux (2001) approach is used to remove all the pits/depressions. During the pits removal operation, if outfalls exist, these outfalls will be used as a mask to preserve their elevations (this is to prevent the burnt-in stream from being filled up again). A new DEM layer, “WDT Fill Pits” will be saved.

4.4 Flow direction

Flow direction is defined for all cells by considering the direction of water flow out of the cells. This is based on the steepest slope to any of the eight adjacent cells. Thus, the methodology is called D8 (Jenson and Domingue, 1988; Tarboton, 1997).

Assigning flow direction is challenging within flat areas. Analyzing flow direction in flat areas is based on Barnes et al. (2014), and provides similar results to Garbrecht and Martz (1997), but is more efficient. The flow direction grid assigns each cell a number that indicates the direction of the flow, that is, the direction that water will flow from that particular cell. These grids are created and will find the lowest neighboring cell for every 3x3 cell neighbourhood. A new raster grid layer, “WDT Flow Direction” will be saved.

4.5 Slope

The Slope layer is used to generate average slope for delineated subcatchments. Subcatchment width is calculated using Guo and Urbonas (2009) method. Slope is calculated based on flow direction. For each cell, if the flow direction is given (there is elevation difference), slope can be calculated as elevDiff / distance. A new raster grid layer, “WDT Slope” will be saved.

4.6 Contributing area

Based on the flow direction grid, a “Contributing Area (or flow accumulation)” DEM layer (the number of grid cells draining through each grid cell) is developed. The contribution area calculates the flow into each cell by accumulating the cells that flow into each downslope cell. The contributing area for each grid cell is taken as its own contribution plus the contribution from upslope neighbours that drain to it according to the D8 flow model. A new raster grid layer, “WDT Contributing Area” will be saved.

4.7 Stream threshold

Each pixel is assigned with a value of 0 (shown in green) and 1 (shown in red). If a pixel is assigned with a value of 1 it means that the area draining into that pixel is significant enough to consider it part of the river network. A new raster grid layer, “WDT Stream Threshold” will be saved.

4.8 Flow Paths

The flow paths for runoff over the subcatchments based on the stream threshold layer used to determine subcatchment flow lengths. A new line layer, “WDT Flow Paths” will be saved.

4.9 Watershed creation

Watersheds are delineated using the stream grid and contributing area. Separate watersheds are delineated at any stream line confluence points. If there are outfalls, all outfalls will be relocated to nearest stream before watershed delineation. Subcatchment delineation is optimized to reduce small subcatchments by joining them and further discretizing larger subcatchments using a smaller stream threshold for the larger watershed areas (based on internal parameters). Subcatchments boundaries are smoothed to remove the jagged lines. A new raster grid layer, “WDT Watersheds” will be saved.

4.10 Creating a new model

Created watersheds will be used as subcatchments for the hydrologic model. Before watershed delineation, if there are existing subcatchments, they will be moved to a background layer called “Old Subcatchments”. It will be rendered as red lines with clear fill. The newly delineated subcatchments will be rendered as blue lines with clear fill.

After watershed delineation, the newly generated hydraulic network (junctions and conduits) will be merged into existing network if one exists. Existing conduits will be rendered as solid yellow lines, and newly generated DEM conduits will be rendered with dotted red lines. Some existing conduits could be split to allow connection to a new branch. The DEM layer is used to get invert elevation for new junctions.

4.11 Attributes for WDT entities

The following attributes are calculated by the WDT for all newly created entities. All other attributes values are populated based on the settings in the Defaults dialog. Existing SWMM5 entities are not edited unless a conduit is split to allow lateral inflow from the WDT network. If existing hydraulics are in place, the attribute values entered by the user remain the same.

5 Guo and Urbonas (2009) method

Guo and Urbonas conducted a study in 2009 to determine a method to better parameterize subcatchments for analysis using kinematic wave (KW) routing. In this study, the continuity and energy principles were interpreted as the preservation of watershed area and vertical fall over the receiving waterway’s length. In the analysis, the watershed shape factor was used to correlate the waterway length in the natural watershed to the KW plane width. A parabolic one-to-one single valued function was derived to translate the watershed shape into its equivalent KW plane width, length, and slope. After numerous tests, it was confirmed that the watershed and KW shape factors provide a consistent and stable basis for watershed geometric conversion. (Guo and Urbonas, 2009)

The KW approach is to apply the one-to-one single valued rating curve relationship to the overland flow generation (Guo 2006). Similarly, the one-to-one relationship needs to be established between watershed and KW shape factors. The study had several conclusions which are summarized below:

The shape factor, X, of a natural watershed is defined by:

[2] $X = \frac{A}{L^2} \cong \frac{B}{L} (\leq K)$

Where:

A = tributary area [L^2]

B = watershed width [L]

L = length of collector channel [L]

K = limit for KW shape factor

The KW shape factor, Y, for the equivalent KW plane is defined by:

[3] $Y = \frac{L_w}{L}$

Where:

Lw = width of the KW plane [L]

The relationship between these two shape factors, X and Y, is described by Eq. 4 and 5 that was derived based on the channel alignment and the application limit on X. The area skewness coefficient, Z, varies from 0.5 for central channel to 1.0 for side channel. As recommended, the application limit, K, varies from 4 to 6.

[4] $Y = (1.5 - Z)\left(\frac{2}{1-2K}X^2 - \frac{4K}{1-2K}X\right)$

and

[5] $X = \left(\frac{A_m}{A}\right)$

Where:

Z = the area skewness coefficient

A_m = dominating area [L2]

The energy potential along the water course is preserved by the Eq. 7 and 8 (shown below) between the natural watershed and KW cascading model.

[6] $\left(\frac{S_0}{S_w}\right) = \frac{X}{Y} + Y(X \leq K)$

and

[7] $Y = aX^2 + bX + c$

Where:

a = constant used in shape factor relationship

b = constant used in shape factor relationship

c = constant used in shape factor relationship

S_0 = longitudinal slope along waterway through watershed

S_w = slope on KW plane [L/L]

Using this method, subcatchment length values are estimated using a kinematic shape factor assigned based on the stream location in relation to the subcatchment and longitudinal elevation drop of the receiving concentrated flow channel. Thus, application of the WDT helps to avoid excessively long overland flow paths that violate the sheet flow approximation, and helps to overcome rectangular subcatchment shape limitations.

6 Case Study

The following case study compares two similar models of the Don River watershed. Situated in Southern Ontario, the Don River watershed has an area of ~ 36000 ha and is home to 1.2 million residents. The first model, referred to heron in as the original model, has a relatively coarse resolution with 67 subcatchments, 2842 conduits and 2472 junctions. The second model was built using the WDT and had a significantly higher resolution, specifically in the hydrology portion of the model, with 475 subcatchments, 2938 conduits and 2581 junctions.

The following section reviews the model background, setup and comparison of the two models.

6.1 Model background and comparison

The hydraulic network in the original Don River SWMM5 model was assembled using 35 existing HEC-RAS basin models, with some modifications based on stormwater infrastructure updates. Stormwater management (SWM) ponds were included in the model and were based on a "lumped" SWM pond modelling procedure. The hydrology portion of the model was based on a subcatchment layer and the attribute values were estimated using area-weighting operations from a soils and land-use map. The remaining subcatchment attributes were estimated using a provided digital elevation model (DEM). The model was calibrated using observed rainfall and flow monitoring data to a level suitable for predicting the peak flows for large events.

The second model was built using the WDT and allowed every subcatchment to have an outlet node directly downstream. In this model, the original hydraulics were kept and additional branches were added to the upstream areas of the watershed. Lumped stormwater ponds from the original model were edited to match the resolution of the new WDT subcatchments. Hydrology parameters were assigned using the same soils and land-use layers used in the original model.

Both sets of model parameters were calibrated separately and optimized to best match observed flows, using the same level of effort.

A total of 10 events were selected for the comparison and ranged from 10.2 mm – 51.8 mm. Figures 2 and 3 show the resultant hydrographs for the two largest events compared. In both plots the peak flows in the detailed model better match the observed flows when compared to the coarse model. In addition, both the receding limbs and climbing limbs were improved in the detailed model.

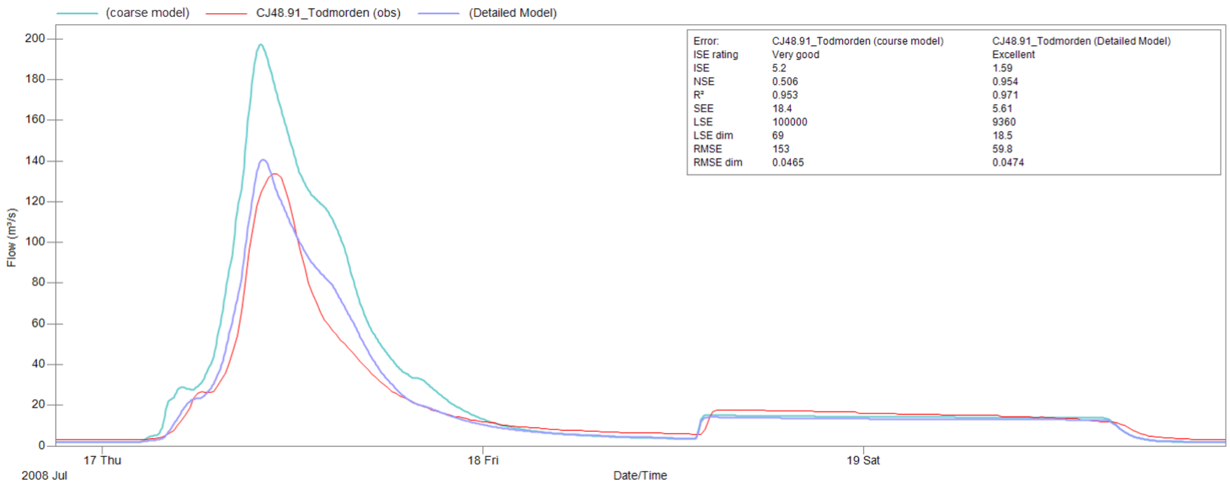

Figure 2 : Event 1 comparison showing hydrographs for both the coarse and detailed models

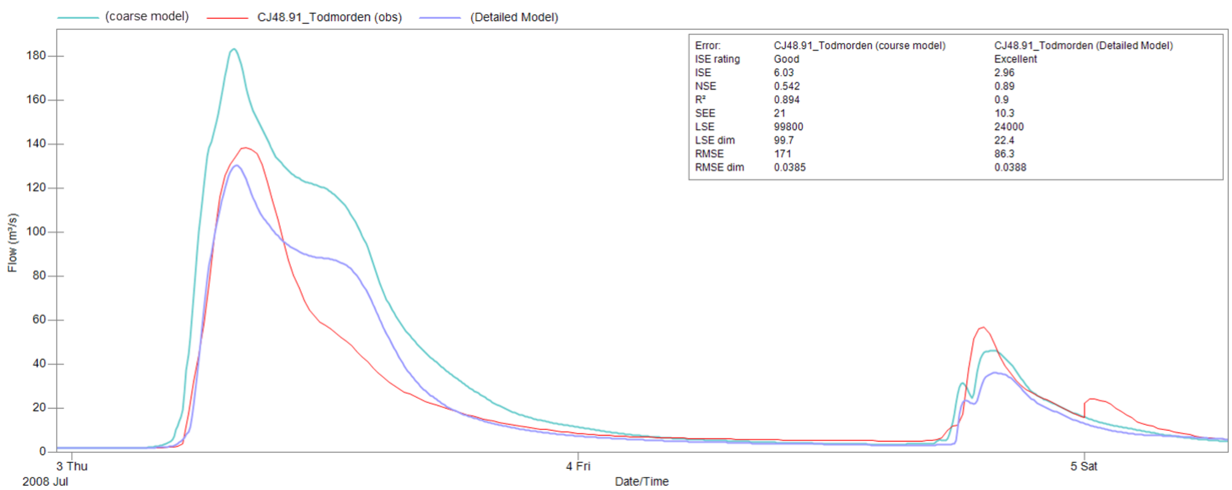

Figure 3 : Event 2 comparison showing hydrographs for both the coarse and detailed models

Figures 4 and 5 show the event comparison plots for the event peak and totals. In both comparisons, the detailed model better matched the observed flows when compared to the original model.

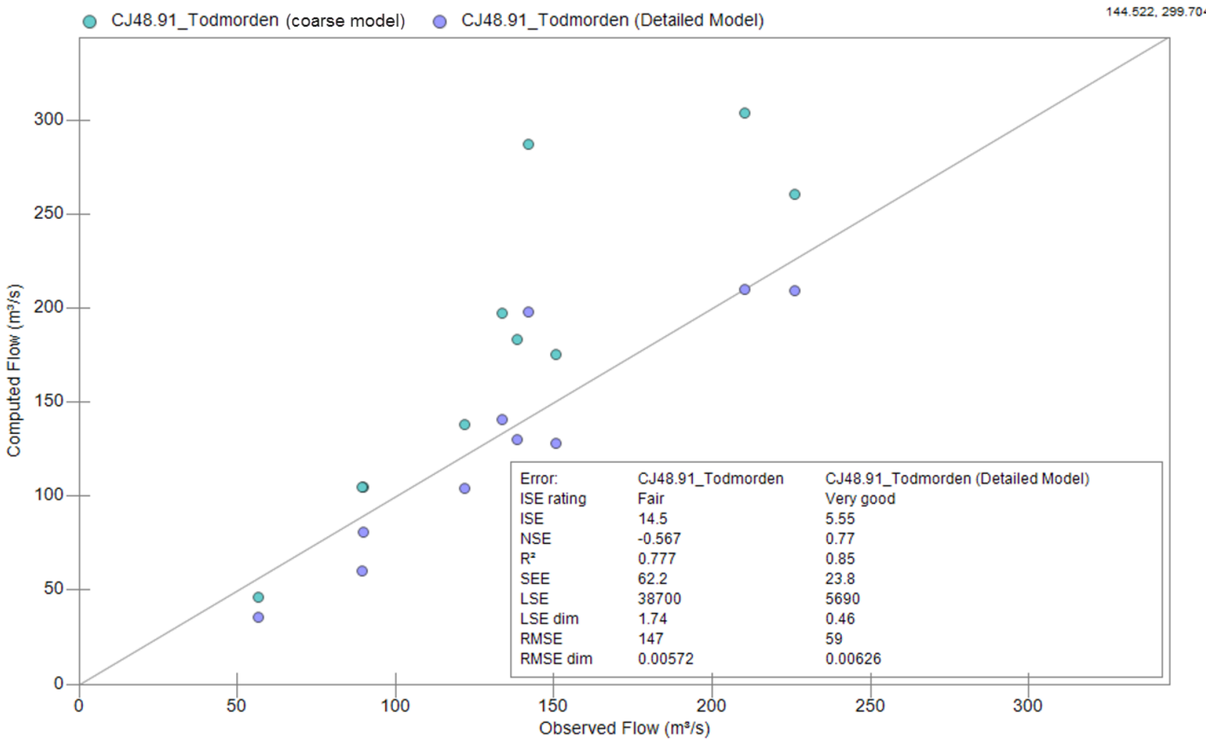

Figure 4 : Peak flow event comparison for coarse and detailed models

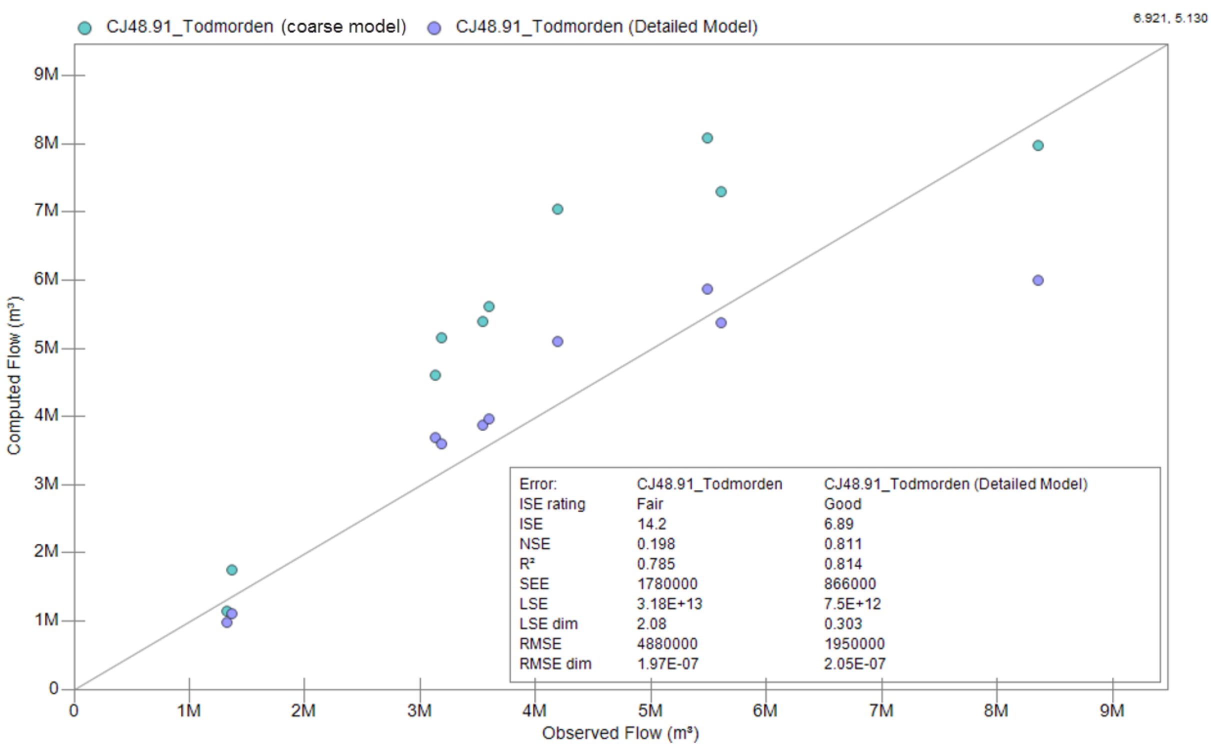

Figure 5 : Total flow event comparison for coarse and detailed models

7 Conclusion

The WDT automatically generates subcatchments and parameterizes elevation based attributes such as slope and overland flow length using a DEM layer and a user-defined target discretization value. By further discretizing the watershed, the processes involved with channelized flow and sheet flow can be better represented.

Although limited modeling budgets and short time lines likely are here to stay the technology and the data resources to improve model calibration and validation is available.

Creating a higher resolution model that better accounts for the watershed processes, particularly in headwater areas, result in a reliable tool that can be used for numerous future applications and automating this process can help reduce model error while staying within existing budget and time constraints.

Significant infrastructure expenditures are based on the application of stormwater models and it is therefore important to have a model capable of predicting flows for a variety of events. For the modeler, the benefits of a high-resolution calibrated / validated model include: better understanding of the modeled system; improved confidence and reliability in model results, model credibility and wider acceptance of engineering recommendations.

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