Spatial Decision Support System for Urban Streams

by

Kimisha Ghunowa

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The change of land use from rural to urban tends to radically alter the implicated streams with many symptoms of the "urban stream syndrome". The key driver of the syndrome is hydrologic change; the product of increased imperviousness and efficient conveyance and characterized by frequent larger flows, increases in peak flows, and seasonal shifts in flood occurrence. Streams are unable to maintain stability due to an imbalance between sediment transport processes and the flow energy, which leads to morphological alteration, ecological degradation and a reduced capacity to support ecosystem services. Many strategies have been tried to prevent damage in or rehabilitate these urban streams. However, significant uncertainty remains about their outcomes because current practices do not consider the marginal impact of additional land use changes within a watershed or the cumulative impact of urbanization beyond the local scale. The objective of the current paper is to describe a spatial decision support system (SDSS) to predict changes in stream power under different scenarios of land use and cover change at the network scale. Change in stream power is modelled as a predictor of changes in channel stability. The SDSS is written as Python scripts and packaged as an ArcGIS toolbox for ease of use. The current framework integrates empirical relationships between discharge, drainage area and imperviousness to assess pre- and post- development impacts of urbanization along the stream networks. A sediment particle size predictive model is also developed for integration in the SDSS. A case study of an urbanizing watershed is presented to demonstrate the application of the SDSS. Continued development of the tool will allow increased use of field and site -specific model results to refine the accuracy of predictions. Cartographic displays of the spatial and temporal sensitivity of streams to urbanization can assist in decision making processes.

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University of Waterloo

My Family

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Chapter 1: Introduction

Urbanization is occurring at an unprecedented rate and is having a marked effect on natural ecosystems' functions across different spatio-temporal scales (Paul and Meyer, 2001; Poff et al., 2006; Walsh et al., 2005a). The transformation of land cover from rural to urban is more pervasive in streams than any other human modifications (Chin et al., 2013). The addition of impervious surfaces and efficient drainage conveyance structures induces changes to the hydrologic cycle by increasing surface runoff to streams and correspondingly, decreasing infiltration and evapotranspiration (Walsh et al., 2005d). Urban streams manifest larger flows, seasonal shifts in flood occurrences and increases in peak flows, all of which are symptoms of the 'urban stream syndrome' (Bernhardt and Palmer, 2007a; Walsh et al., 2005d). Implicated streams are unable to balance sediment transport processes, channel form and flow (TRCA, 2008). Consequently, they develop an unstable course which induces impairment to geomorphic processes of relevance to ecological functions (Florsheim et al., 2008; Lucas and Ferguson, 1995; Vietz et al., 2014). With forecasted increase in frequency of rainfall events due to climate change (Kerr and Packer, 1998) and continuous urban growth (United Nations, 2015), these problems will worsen.

Different stream management strategies have been used to treat the 'urban stream syndrome'. Centralized stormwater management (SWM) practices such as retention ponds and wetlands aim to control hydrological conditions by reducing and treating increased surface runoff to streams. However, unsuccessful outcomes can result from their implementation (Burns et al., 2012) and streams typically experienced erosion and degradation (Booth et al., 2002; Hancock et al., 2010). Low Impact Development (LID) practices of SWM such as bioretention areas and pervious concrete manage surface runoff near or at its source (Berndtsson, 2010; Palanisamy and Chui, 2015) but they are implemented at the site scale (Dietz, 2007) and can only mitigate surface runoff for small rainfall events (Brander et al., 2004; Hood et al., 2007; Palanisamy and Chui, 2015; Schneider and McCuen, 2006; Trinh and Chui, 2013; Williams and Wise, 2006). Despite the implementation of the best practices, sediment erosion may still exacerbate within streams (Bledsoe, 2002a) indicating a lack of understanding of fundamental processes such as sediment transport along stream networks. Stream restoration techniques such as removal of dams, culvert replacement and re-contouring also focus on reach-scale enhancements and their implementation have resulted in failures (Booth, 2005; Schiff et al., 2011; Shields et al., 2003; Simon et al., 2013; Walsh et al., 2005b) and high erosion (Leopold et al., 2005). Current stream management does not consider the cumulative impact of urbanization on streams at the network scale (Booth et al., 2002; Li et al., 2017; Roy et al., 2008a) and the coupled interaction between hydrologic and sediment transport processes for a comprehensive understanding of their spatial responses to urbanization (Bledsoe and Watson, 2000;

Hogan et al., 2014; Kaufman, 2000). As a result, catastrophic effects continue to persist in urban streams (Wohl et al., 2005a).

Poor decisions have been made and are still being made due to a lack of understanding of the cumulative impact of urbanization on streams beyond the local scale and a lack of technologies to spatially model stream instability to facilitate decision making (Bernhardt et al., 2005; Wohl et al., 2005b). In the Greater Toronto Area (GTA) of Southern Ontario, decision makers of conservation organizations and consulting partners (City of Toronto, Toronto Region Conservation and Authority (TRCA) and Matrix Solutions Inc.) working in collaboration to this research have expressed concerns for streams affected by the ‘urban stream syndrome’ and the unsuccessful outcomes of current practices. They are not equipped to perceive the degree of longitudinal, lateral and vertical connectivity of stream networks and their spatially continuous responses to urban developments for rational management. They require a better understanding of the coupled interaction of hydrologic and sediment regimes along stream networks to prevent failures of SWM and stream restoration projects. They need a process based solution which allows them to visualize, question, analyze and interpret data for understanding relationships, trends and patterns of interacting processes along stream networks in urbanizing watersheds to assess a stream’s relative susceptibility to hydromodifications.

The goal of this research is to develop a spatial decision support system (SDSS) to aid in assessing and restoring the resilience of urban stream networks affected by the ‘urban stream syndrome’. It will have visualization and analytical capabilities for exploration of both temporal and spatial sensitivity of streams to ensure that all affected areas are targeted by stream management practices, land use planning is improved and inhabitants and infrastructures are secured.

Literature on the cumulative impacts of urbanization and spatial decision support systems (SDSS) are reviewed in Chapter 2 and specific objectives are presented in section 2.4. The SDSS of this research is described in Chapter 3. Application of the SDSS to a case study of the Ganetsekaigon Creek in GTA is described in Chapter 4. Discussion of the developed system and future directions are presented in Chapters 5.

Chapter 2: Literature Review

2.1 Cumulative Impacts of Urbanization

Urbanization affects the timing, volume and peak flow rates of runoff (Chin, 2006; Poff et al., 2006) and the timing, volume and caliber of sediments (Chin, 2006; Church, 2016). Increased imperviousness and efficient conveyance of runoff by drainage infrastructure increase surface runoff, reduce lag times to peak flows and increase peak flows to produce a flashy hydrologic regime in streams (Bledsoe and Watson, 2000; Chapuis et al., 2014; Chin, 2006; Poff et al., 2006). Streams adjust their sediment erosion, transport and deposition within the network in response to these consistent hydrologic perturbations (Apitz, 2012; Booth, 1990; Dunne and Leopold, 1978; Walsh et al., 2012). The implicated streams exhibit morphological alterations, ecological degradation and reduced capacity to support ecosystem services. Damage to channel form occurs when sediment erosion, transport and deposition are exacerbated during increases in peak flows (Coleman et al., 2005; Vietz et al., 2012). Riparian vegetation, ecotones, and habitat quality are lost with channel widening and migration (Vietz et al., 2014). Habitat structures are damaged when sediments are deposited with changes in flow (Vietz et al., 2013). Sediment erosion along channels (Coleman et al., 2005) reduces biotic richness (Duncan et al., 2011) and hydrologic connectivity with the floodplain which in turn, reduce water quality and bank stability (Vietz et al., 2014; Wallace et al., 2013; Walsh et al., 2005d). Additionally, urbanization decreases coarse sediment supply and this decrease is detrimental to biotic life (Florsheim et al., 2008). It reduces foraging and refuge for macroinvertebrates (Morley and Karr, 2002) and fish (Wheaton et al., 2015). It also reduces hyporheic exchange of flow for nutrient transport, oxygen exchange, pollutant capture and temperature regulation (Florsheim et al., 2008; O'Driscoll et al., 2010). These observed patterns in urban streams were coined as the 'urban stream syndrome' (Walsh et al., 2005c).

There are three stages of urbanization which affect sediment dynamics in relation to hydrologic flow: 1) pre-development stage, 2) aggradation/construction stage and 3) degradation/post-development stage (Booth and Fischenich, 2015; Chin, 2006; Doyle and Harbor, 2000). In pre-development, the stream network is typically assumed to be in equilibrium. During the initial development of urban land, erosion of exposed land surfaces increases sediment supply by 10^2-10^4 times pre-development stage (Harbor, 1999; Wolman and Schick, 1967). The soil erosion rates from construction sites can be 60 (Chen, 1974) to 120 (Douglas, 1974) times larger than those from non-construction sites. As sediments are exported in streams, deposition decreases stream depths and the decreased channel capacity can result in greater flooding and increased bank heights (Wolman and Schick, 1967). After the aggradation stage, hydrologic flow is increased and coarse-grained sediment supply is decreased due to the increased impervious cover (Apitz, 2012; Wolman and Schick, 1967). Streams readjust by initiating erosion and their structure undergoes incision, often leading to bank failure (Booth, 1990; Chin, 2006; Vietz et al., 2014).

2.1.1 Urban Stream Management

Urban stream management has two main strategies to rehabilitate urban streams with the 'urban stream syndrome': stormwater management (SWM) and stream restoration.

SWM practices help to treat the quantity and quality of surface runoff at the end of pipes, in conveyance and at the source (Ministry of the Environment, 2003). Traditional end of pipe controls such as retention ponds, wetlands and infiltration basins aim to capture and detain runoff to reduce flows for flood and erosion control and to improve water quality (Bledsoe and Watson, 2000; Booth et al., 2002; Ministry of the Environment, 2003). However, their success cannot be generalized (National Research Council (NRC), 2009) and their ability to retain peak flows and reduce volume through infiltration and evapotranspiration has been limited (Burns et al., 2012), thus having little effect on providing stream stability (Bledsoe et al., 2012). Failures have occurred due to improper sizes and designs, ambiguities in regulatory standards and underpredictions of modeled post development runoff, thus resulting in increased peak flows to streams (Booth et al., 2002; Fennessey et al., 2001; Hancock et al., 2010). Watershed scale processes of reduced infiltration and evapo-transpiration are also not considered in their design (Booth et al., 2002), thus leading to accelerated erosion, degraded aquatic habitat, channel instability (Booth et al., 2002) and flooding (Hancock et al., 2010). In addition to inadequate hydrologic control, designs of end of pipe controls also lack sufficient consideration of sediment transport processes (Bledsoe and Watson, 2000; Hogan et al., 2014; Kaufman, 2000). They may exacerbate erosion in streams (Baker et al., 2008; Bledsoe, 2002b; Russell et al., 2017), especially for 2 year rainfall events (MacRae, 1996; McCuen, 1979; Moglen and Mccuen, 1988) because they increase the frequency and duration of flows exceeding channel erosion thresholds (Navratil et al., 2013; Tillinghast et al., 2011). Therefore, there is a need to consider erosion potential of streams in their designs (Pomeroy et al., 2008; Rohrer and Roesner, 2006). They also only attenuate flows for which they've been designed instead of flows from smaller, more frequent rainfall events (Roesner et al., 2001). Wetland ponds designed for pollutant load reduction have shown success at reducing loads but they can reduce baseflows (Burns et al., 2012), increase toxicity of pollutants (Helfield and Diamond, 1997) and deplete streams of coarse grained sediments (Houshmand et al., 2014) by trapping sediments which can further exacerbate bed scour and channel instability (Vietz et al., 2016). Aside from these significant shortcomings of traditional

SWM practices, reports on their success at reproducing pre-development hydrologic conditions at the watershed scale and stabilizing sediment regimes along stream networks are very scarce, therefore there is still a need for such quantification.

Recently, increasing efforts have focused on more decentralized practices of SWM such as Low Impact Development (LID) which are used to mitigate the impacts of increased runoff and aim at reducing the risk of flooding by managing runoff near or at its source (Berndtsson, 2010; Dietz, 2007; Palanisamy and Chui, 2015). They consist of distributed, small scale structural site designs such as stormwater detention tanks, grass swales, bioretention areas, and pervious concrete and non-structural measures such as alternative configuration of roads and buildings to allow runoff to be infiltrated, evapotranspirated, harvested, filtrated and detained (United States Environmental Protection Agency (U.S. EPA)., 2007). However, they are not effective for large rainfall events (Brander et al., 2004; Damodaram et al., 2010; Holman-Dodds et al., 2003; Hood et al., 2007; Palanisamy and Chui, 2015; Schneider and McCuen, 2006; Trinh and Chui, 2013; Williams and Wise, 2006) and they are localized (Dietz, 2007). Therefore, only parts of stream networks benefit. Limited consideration of their spatial location in conjunction with the spatial configuration of urban development and land use can also lead to their ineffectiveness (Loperfido et al., 2014; Martin-Mikle et al., 2015; Passeport et al., 2013; Williams and Wise, 2006). Sediment erosion may still be exacerbated within stream networks due to a lack of consideration of sediment transport processes (Bledsoe, 2002b) and a lack of a watershed scale approach to their implementation (Li et al., 2017; Roy et al., 2008a). It is difficult to assess their effectiveness at the watershed scale to understand downstream improvements due to insufficient knowledge of their performance and cost compared to traditional practices, lack of institutional capacity necessary to support and enforce their implementation, lack of design guidelines and strict standards (Roy et al., 2008a). Therefore, there are still uncertainties with current SWM practices and there is a need to implement them with full consideration of changing hydrologic and sediment regimes by urbanization at the watershed scale.

Stream restoration practices aim to restore ecosystem functions to meet ecological and socio-economic standards by reconfiguring channels, regrading banks, creating pools and riffles and adding wood and boulders for channel stabilization, habitat creation, water quality improvement and fish passage (Bernhardt and Palmer, 2007b; Kristensen et al., 2011; Palmer et al., 2010). However, their success has been limited because they focus on site scale enhancements which do not match the scale of degradation along stream networks at the watershed scale (Booth, 2005; Schiff et al., 2011; Shields et al., 2003; Simon et al., 2013; Walsh et al., 2005b). Their sites are selected opportunistically (Bernhardt et al., 2007;

Clarke et al., 2003) and the projects are often done on a trial and error basis (Downs and Kondolf, 2002) without strategic planning guided by clearly defined objectives (Woolsey et al., 2007). Their placements along streams disrupt the longitudinal connectivity of streams by introducing different ecosystems (Lake et al., 2007) acting as a disturbance (Tullos et al., 2009), thus contradicting and impeding the natural evolution of stream morphology (Gillilan et al., 2005). They address only symptoms of degradation instead of the underlying geomorphological processes and they are not implemented in the context of watersheds (Larson et al., 2001; Wohl et al., 2005c). Their implementation has resulted in progressive sediment erosion and enlargement (Leopold et al., 2005) and there are also practical limitations to their abilities (Roy et al., 2008b). They may improve one aspect of stream restoration such as habitat creation (Palmer et al., 2010; Sudduth and Meyer, 2006) but they do not necessarily improve the sediment transport and flow regimes needed to maintain stream stability nor do they focus on the importance of variable ecological processes within the entire stream network (Clarke et al., 2003) to support biodiversity (Palmer et al., 2010). They also only qualitatively describe enhancements (Biggs et al., 1998; Larson et al., 2001). Failures occur due to improper designs, poor installation (Bernhardt and Palmer, 2007b) , designs built to mitigate only current conditions, a lack of consideration of channel enlargement and planform changes in urbanizing watersheds (Brown, 2000) and unintended erosion produced by increased flows and decreased sediment supply (Thompson, 2002; Wolman, 1967). Monitoring studies which assess restoration projects are scarce and were found to be of poor quality and contradictory for 44 French pilot projects (Morandi et al., 2014). To increase their effectiveness, practices must incorporate understanding of hydrologic and sediment regimes (Bravard et al., 1999; Shields et al., 2003). A report on 37099 projects in the United States attributed failures of projects to a lack of recognition of the temporal and spatial response of streams to urbanization and a lack of understanding of stream processes and a lack of monitoring as only 10% of projects were monitored (Bernhardt et al., 2007). Therefore, there is a need for current restoration practices to incorporate the understanding of hydrologic and sediment transport processes at the watershed scale to achieve better results.

2.2 Linking Sediment, Hydrology and Land Use

The erosion, transport and deposition of sediments by water flow are critical to the dynamicity of stream networks and to the viability and sustainability of ecosystems (Thomson et al., 2003; Vietz et al., 2014). These geomorphological processes determine the physical structure of streams by enabling the formation of complex morphology (e.g. pools, riffles, bars, undercut banks and floodplains), therefore they also determine stream stability. In addition to structural formation, sediments are important for providing habitat heterogeneity to support biodiversity in aquatic ecosystems (Bernhardt and Palmer, 2007a; Vietz et al., 2014). The quantity and quality (e.g. grain size, organic content, nutrients, contaminants and pathogens) of sediments influence the health of habitats for benthic communities. Sediments can be a stressor when they inhibit ecological functions by increasing turbidity, decreasing light penetration and binding to contaminants (Apitz, 2012). A balance in the geomorphological processes of erosion and deposition is needed to improve the quality of habitats for biomass production, nutrient cycling, food capture, refuge and primary production (Apitz, 2012). Since the mobility of sediments by water flow dictates the stability and the integrity of ecosystems, their coupled interaction must be considered to better understand the impacts of urbanization. Hydrologic flow changes induced by impervious cover of land use developments during urbanization must also be considered. Quantifying the link between these interacting stressors is crucial for assessing morphologic changes of streams. More importantly, the spatial variability of the changes within streams must be understood for improved decision making in watershed management practices such as stream rehabilitation and land use planning.

Changes in stream stability are often measured using field assessments of morphology of reaches (Rinaldi et al., 2009; Surian and Rinaldi, 2003; TRCA, 2009) and sophisticated hydrodynamic models (Langendoen and Alonso, 2008; Olsen, 2003). Three-dimensional geometry of streams can be measured using topographic equipment. Surveys of plan form, longitudinal profile and cross-section are recorded and compared with subsequent surveys. Changes in bed properties can be monitored using erosional pins and by analyzing bed grain size distribution. However, comparative assessments do not allow for any predictive capability of future morphological changes nor is it a viable method for analysing the branching network of streams. Hydrodynamic models also require elaborate information on bed and flow properties. Although quantifying incoming sediment and outgoing sediment (i.e. sediment flux) of a reach is an accurate assessment of stream stability, it is data and time intensive.

Stream power is a measure of sediment transport capacity by water flow that describes the potential for streams to mobilize their sediments (Doyle and Harbor, 2000). It is defined as the rate of work that occurs in streams as water flows along an energy or slope gradient (Bagnold, 1966; Knighton, 1999a; Rhoads, 1995). It has shown to be a useful indicator of morphological changes along stream networks, for instance by predicting channel form types (Chang, 1992; Rhoads, 1990) such as dunes (Simons and Richardson, 1966), channel migration (Nanson and Hickin, 1986) and spatial patterns of processes and extents of sediment erosion, transport and deposition (Bawa et al., 2014; Chang, 1979; Graf, 1983; Knighton, 1999b; Labbe et al., 2011; Lecce, 2013). There are many variations of the definitions of stream power. Total stream power, Ω (W/m) is defined as the power per unit length (Bagnold, 1966):

$$\Omega = \rho g Q S \tag{1}$$

where ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81m/s^2), Q is the discharge (m^3/s) and S is a dimensionless slope gradient (m/m). Specific stream power, ω(W/m^2) is defined as the power per unit area (Bagnold, 1966):

$$\omega = \frac{\Omega}{w} \tag{2}$$

where **Ω** is total stream power (W/m) and w is the channel width (m). Critical specific stream power, ω_c (W/m^2) is defined as the threshold of motion for a given particle size (Bagnold, 1980):

$$\omega_c = c_1 D^{1.5} \log(c_2 d/D) \tag{3}$$

where d is the depth of flow at the threshold of motion, D is the modal bed sediment particle diameter and c_1 and c_2 are numerical constants. Excess specific stream power, ω_e (W/m^2) is defined as the difference between specific stream power and critical stream power:

$$\omega_e = \omega - \omega_c \tag{4}$$

where ω_c is critical stream power and ω is total stream power. Relevant information about the potential of water flow to perform geomorphic work, in particular sediment transport can be extracted using the different variations of stream power. Bagnold, (1966) recognized the importance of total stream power when he used it to estimate sediment transport rates. Phillips (1989) found that total stream power provided a physically based index to determine thresholds of sediment delivery by stream networks when studied as a larger system rather than discrete, independent units. Specific stream power has been robust at estimating thresholds of sediment movement during rainfall events (Bizzi and Lerner, 2015; Costa, 1983; Mao et al., 2008; Petit et al., 2005; Williams, 1983) and thresholds of floods causing stream instability (Baker and Costa, 1987; Magilligan, 1992). It has also been used to classify stream networks' sensitivity to erosion and deposition based on the joint configuration of point locations (Bizzi and Lerner, 2015). Houbrechts et al., (2015) studied tagged sediment particles for eight gravel bed rivers in the Ardenne Region of Belgium and found a strong correlation (R=0.84) between specific stream power and the virtual velocity (i.e. the travel distance per year) of the median sediment particle size in riffles. Excess specific stream power has been found to be a useful predictor of the mean distance of travel of sediment particles during peak discharges (Houbrechts et al., 2015; Schneider et al., 2014) and maximum specific stream power has been found to predict the thickness of the actively transported layer of sediment particles (Schneider et al., 2014). Recently, the theoretical framework of specific stream power has led to new derivations of critical stream power equations (Ferguson, 2012, 2005; Petit et al., 2005). Bagnold (1980)'s critical stream power was found to have deficiencies and was modified to include sediment particle size to study sediment transport (Ferguson, 2012, 2005; Petit et al., 2005). Ferguson, (2005) proposed two critical stream power equations. They integrate transported sediment particle size, sediment particle size of the bed and critical flow depth. The two equations are based on a logarithmic flow resistance law (Equation 5) and Manning-Strickler law (Equation 6), respectively:

$$\omega_{ci} = \frac{2.30}{k}\rho(\theta_{cb}RgD_b)^{1.5} log\left(\frac{30\theta_{cb}R}{emS}\left(\frac{D_i}{D_b}\right)^{1-b}\right) x \left(\frac{D_i}{D_b}\right)^{1.5(1-b)} \quad (5)$$

$$\omega_{ci} = ap\ (\ \theta_{cb}RgD_b)^{\frac{3}{2}}(\frac{\theta_{cb}R}{S})^{1/6}\left(\frac{D_i}{D_b}\right)^{5(1-b)/3} \quad (6)$$

where ρ is density of water (1000 kg/m^3), k is von Karman's constant (0.41), Θ_{cb} is dimensionless Shields stress for entrainment of size D_b, R is submerged specific gravity (1.6), g is the gravitational acceleration (9.81m/s^2), D_i is sediment particle size entrained by flow (mm), D_b is sediment particle size representing the bed (mm), S is slope (m/m), e is the natural logarithm base (=2.718), m is a parameter of channel bed roughness and b is the hiding and protrusion factor (~0.7). For gravel bed sediment particles, Θ_{cb} is typically assumed to be constant (0.045) (Ferguson, 2005). Unlike the approach of Petit et al., (2005) which hypothesized that critical stream power is affected by shear stress from flow resistance, Ferguson, (2005) hypothesized that equations 5 and 6 are dependent on sediment particle size and do not require any information on instream flow properties, therefore sediment transport can be studied based on gross channel properties at the network scale. Modelling variations of stream power can allow the generation of new information about sediment transport processes to characterize stream networks and it helps to identify areas of potential sediment transport discontinuity (Reinfelds et al., 2004). Therefore, it can be used as an assessment tool to understand the cumulative impact of hydrologic regimes on stream networks (Bledsoe et al., 2012; Vocal Ferencevic and Ashmore, 2012).

Traditional methods used to model stream power include collecting measurements of morphological variables such as slope, width and discharge along lateral cross sections and extrapolating their values between cross sections (Winterbottom and Gilvear, 1997), however they are spatially limited, time consuming and restrictively expensive (Jordan and Fonstad, 2005). High resolution digital elevation models (DEMs) enable mapping of spatially continuous and inexpensive calculations of stream power (Jordan and Fonstad, 2005). DEMs are continuous surfaces represented as a matrix of cells with each cell containing a square unit of area and a numeric elevation value. New surfaces such as slope, direction of the flow of water out of each cell in the steepest downslope direction and the number of cells flowing into each cell and drainage area can be produced from DEMs, thus allowing for hydrologic analysis and watershed characterization. Analysis with DEMs also preserves the locational context of results to enable more detailed assessments of relationships between channel characteristics and stream power with a high degree of relative accuracy (Reinfelds et al., 2004). Many studies made use of high resolution spatial data, empiricism and field measurements to investigate the spatial distribution of stream power from DEMs (Table 1). The most common method which is also recognized as an assessment tool (Vocal Ferencevic and Ashmore, 2012) is a combination of spatial analysis of DEMs to calculate slope and of hydraulic geometry equations to calculate discharge and width. To calculate slope, elevation values from DEMs are extracted to create long profiles of stream networks. Reaches are then defined as longitudinal segments along the stream networks based on a constant difference in elevation, also called "vertical slice" (Phillips and Desloges, 2014; Reinfelds et al., 2004) or based on a constant difference in channel length, also called "horizontal slice" (Bizzi and Lerner, 2015; Jordan and Fonstad, 2005; Parker et al., 2015; Vocal Ferencevic and Ashmore, 2012). Slope is calculated for each reach as

$$S = \frac{Elevation_2 - Elevation_1}{length\ of\ reach} \tag{7}$$

Cells from which water will not flow out (i.e. in depressions) can be corrected using smoothing to obtain long profiles (Jain et al., 2006). Smoothed long profiles are the least transformed data and provide the most variability in stream power distribution at the reach scale in comparison to theoretical (e.g. equation by Knighton, (1999b) in Table 1) and curve fitting techniques (Jain et al., 2006). Continuous discharge can be approximated as a first dependent parameter of drainage area for a given watershed because it is closely connected with the drainage area from which surface runoff is conveyed to streams. An empirical power law relationship which has been widely employed for rural watersheds to model this relationship for total stream power calculations is

$$Q = aA^b \tag{8}$$

where A is the drainage area (km^2) and coefficients, a and b are derived from statistical regression of data (Galster et al., 2006; Jain et al., 2006; Knighton, 1999a; Lea and Legleiter, 2016; Magilligan, 1992; Phillips and Desloges, 2014; Vocal Ferencevic and Ashmore, 2012). Drainage area is advantageous as a substitution because it is easily created from DEMs by locating all the cells which flow towards a reach whereas discharge measurements made in the field are time intensive. Channel width has also been modelled using drainage area whereby the latter served as a proxy for discharge in specific power calculations (Knighton, 1999a; Phillips and Desloges, 2014; Reinfelds et al., 2004; Vocal Ferencevic and Ashmore, 2012). The empirical relationship is given as:

$$\mathrm{w} = a\mathrm{A}^{b} \tag{9}$$

where A is the drainage area (km^2) and coefficients, *a* and *b* are derived from statistical regression of data.

Table 1: Summary of equations used to calculate stream power using digital elevation models (DEMs) for rural watersheds.

Source	Stream Power	Morphological Variables
Graf, (1983)	$\Omega = \rho gRS\mathrm{VW}$	
Bledsoe et al., (2012)	Potential Stream Power Index: $\omega_v = S_v Q_{10}^{0.5}$	$Q_{10} = 18.2A^{0.87}P^{0.77}$ S_v: field measurements
Jordan and Fonstad, (2005)	$\Omega = \frac{\rho g w D^{\frac{5}{3}} S^{\frac{3}{2}}}{n}$ $\omega = \frac{\rho g D^{\frac{5}{3}} S^{\frac{3}{2}}}{n}$	*D*: regression of brightness values and depth measurements from the field *S* and *W*: field measurements
Jain et al., (2006b)	$\Omega = \gamma \mathrm{QS}$	$Q = cL^{d}$
Knighton, (1999b)		$S = \alpha e^{-\beta L}$
Bizzi and Lerner, (2015)		$Q_2 = 8.5m^{0.58}$; $r^2 = 0.93$ $Q_2 = 2.90m^{0.67}$; $r^2 = 0.95$ *S* = horizontal slice (1km) $w = 3.42Q_2^{0.46}$
Bawa et al., (2014)	$\Omega = \gamma \mathrm{QS}$ $\omega = \frac{\Omega}{\mathrm{w}}$	$Q_{10} = 2.4x10^{-12}A^3 + 1.47x10^{-6}A^2 - 0.13A + 6409$ *S* = horizontal slice (2 km) *w*: field measurements
Lea and Legleiter, (2016)		unspecified
Lecce, (2013)		*Q, S, w: field measurements* $Q = 2.416A^{0.724}$: for missing Q data
Parker et al., (2015)		$Q_2 = 1.8632A^{0.8422}$; r^2=0.94 *S* = horizontal slice (500m) *w*: field measurements

Source	**Stream Power**	**Morphological Variables**
Phillips and Desloges, (2014)		$Q_2 = 0.248A^{0.910}$; $r^2 = 0.86$, n = 210, $p < 0.001$ S = vertical slice $w = 1.160A^{0.508}$; $r^2 = 0.87$, n = 542, $p < 0.001$
Vocal Ferencevic and Ashmore, (2012)		$Q_{bankfull} = 0.52A^{0.74}$; $r^2 = 0.64$, n =47 (Annable, 1996a) S = horizontal slice (100m) $w = 2.69A^{0.36}$; n = 47 (Annable, 1996a)
Jain et al., (2006b)		$Q_2 = 1.21A^{0.72}$ S = horizontal slice (1km)
Reinfelds et al., (2004)		$lnQ_2 = \gamma(0.7966ln + 0.8902)S$; r^2=0.976, p<0.0002 $w = Q_2^{0.7}$

Graf (1984, 1983, 1981) recognized the importance of spatial variability of stream instability when non-spatial deductive approaches were ineffective at predicting the location and nature of morphological changes. The above empirical approaches have been successfully applied to calculate stream power for spatial stream assessments with the facilitation of spatial software (Bawa et al., 2014; Jordan and Fonstad, 2005; Phillips and Desloges, 2014; Reinfelds et al., 2004; Vocal Ferencevic and Ashmore, 2012). However, they do not incorporate the changes in discharge by urban developments and they do not explain variability in morphology for disturbed watersheds (Bawa et al., 2014), therefore, the impact of future land use changes cannot be assessed. Decisions pertaining to watershed management cannot be facilitated without any predictive capabilities.

In urbanizing drainage areas, increased magnitudes of peak discharges have been linked with increased imperviousness by urban land developments (Anderson (USGS), 1970; Bledsoe and Watson, 2001; Huang et al., 2008; Klein, 1979; Leopold, 1968). Impervious surfaces increase the volume and rate of surface runoff conveyed to streams by decreasing frictional resistance of overland flow (Barnes et al., 2001). Therefore, measurements of imperviousness are useful to predict the potential of flooding and urban sprawl (Arnold and Gibbons, 1996; Hatt et al., 2004; Schueler, 1994; Shuster et al., 2005). Regional empirical relationships have been developed to model both drainage area and impervious area to predict the magnitude and frequency of floods for un-gaged sites (Bledsoe and Watson, 2001; Harman et al., 1999). The most common relationship is given as

$$\mathrm{Q} = a\mathrm{A}^{b}\ \mathrm{IA}^{c} \tag{10}$$

where A is the drainage area (km^2), IA is percentage imperviousness (%) and coefficients *a, b* and *c* are derived from statistical regression of data. Percentage imperviousness can be easily quantified with advancements in remote sensing (Goetz et al., 2003; Walsh et al., 2002). This approach allows for convenient approximations of peak flood discharges which can facilitate the identification of streams with high sensitivity to changes in discharge and stream power. Consequently, watershed management efforts can be redirected.

Table 2: Summary of equations for urban watersheds.

Source	Location	Discharge Equation
Bledsoe and Watson, (2001)	Missouri	$Q = 2.98A^{0.79}\,IA^{0.18}$
	Alabama	$Q = 2.98A^{0.7}\,IA^{0.36}$
	Tennessee	$Q = 1.07A^{0.74}\,IA^{0.48}$
	Georgia	$Q = 2.15A^{0.67}\,IA^{0.28}$
Ward and Trimble, (2004)	Georgia	$Q = 2.11A^{0.70}\,IA^{0.30}$
	Northwest Carolina	$Q = 0.38A^{0.68}\,IA^{0.28}$
Doll et al., (2002)	North Carolina	$Q = 4.77A^{0.63}$
Navratil et al., (2013)	Rhone River, France	$Q = 1.50A^{0.69}$
Wissmar et al., (2004)	Washington	$Q = 0.08A^{0.91}$

Critical stream power can be modelled for thresholds of sediment mobility of stream networks but it cannot be done without prior knowledge of sediment particle size. It has been possible to model sediment particle size at the watershed scale using gross channel properties such as slope whereby spatially distributed information is not available. Sediment particle size has been predicted at the watershed scale by empirical modelling (Snelder et al., 2011) or semi-empirical modelling (Buffington et al., 2004; Gorman et al., 2011; Mugodo et al., 2006; Snyder et al., 2013). Mugodo et al., (2006) developed logistic regression models of fish species distribution using watershed scale habitat variables in 53 sites in Queensland, Australia. Sediment particle size characteristics such as sand (%), cobble (%) and rocks (%) were predicted and used as indicators of fish species distribution. Buffington et al., (2004) predicted the median grain size (D_{50}) to evaluate the potential effect of hydraulic roughness of specific channel types on salmon spawning habitat suitability in mountainous watersheds. The proposed theoretical model related D_{50} to drainage area and slope derived from DEMs:

$$D_{50} = \frac{(\rho \alpha A^{\beta} S)^{1-n}}{(\rho_s - \rho) k g^{n}} \tag{11}$$

where A is drainage area, S is slope, g is gravitational acceleration, ρ is density of fluid, ρ_s is density of sediment and α, β, k and n are empirical constants for specific channel types of a certain physiographic region. Spawning habitat suitability maps showed that almost 90% of the stream length are predicted to be unsuitable due to the high steep slopes and boulder bed. More than 65% of spawning habitat availability were predicted and they could be controlled by hydraulic roughness (wood and bars). Gorman et al., (2011) developed a power-law relationship for D_{50} as a function of total stream power:

$$\mathrm{D}_{50} = 1.88\Omega^{0.39} \quad \textbf{(12)}$$

where **Ω** is total stream power. Total stream power was calculated using DEMs (slope and drainage area extraction) and a hydrologic model (discharge calculation). Sediment particle size data was collected in the field for 20 stream reaches of northeastern Ohio streams draining Lake Erie. Slope and drainage area derived from DEMs were not statistically different from field measurement. A significant predictive model (Equation 11; r^2=0.45, p =0.0013) was developed by regressing total stream power and measured sediment particle size. Snyder et al., (2013) proposed a similar model to equation 11:

$$D_{pred} = \frac{\rho g n^{3/5} Q_2^{3/5} w^{-3/5} S^{7/10}}{(p_s - \rho) g \tau_c^*} \quad (13)$$

where n is the Manning roughness coefficient, S is slope, g is gravitational acceleration, ρ is density of fluid, Q_2 is 2-year peak discharge, *w* is channel width, ρ_s is density of sediment and τ_c^* is the dimensionless Shields' stress for entrainment (0.04). DEMs were used to calculate slope, drainage area and width. The sediment particle size predicted were compared to those of equations 11 and 12 and with field measurements from 276 stations in Maine. All three models had about 70% of success in predicting sediment particle size and about 80% of success for coarse gravel rivers (D_{50}>16mm). Therefore, there is potential in using DEMs to model bed sediment particle size at the watershed scale. Such models assume a threshold relation, making them unsuitable for situations such as urban areas where channels may be unstable. However, they may be suitable for assessing sediment particle size distributions in pre-urbanized watersheds, making them applicable to understanding the degree of instability that may result due to urbanization.

2.3 Spatial Decision Support Systems (SDSS)

Spatial Decision Support Systems (SDSS) evolved in parallel with Decision Support Systems (DSS) and Geographic Information Systems (GIS). In 1970s and 1980s, DSS were primarily used to solve semi-structured problems for making decisions in areas of strategic planning, operational management, database management, investment management and graphical and analytical modelling (Densham, 1991; Díez and Mcintosh, 2008). Semi- structured problems are defined as multi-dimensionally complex problems with poorly-defined or undefined goals and objectives and many alternatives as solutions (Carlson, 1979). They require an interleaved and iterative problem solving environment (Carlson, 1979) which was difficult to achieve with a lack of analytical models, interactive capability for decision makers (Densham, 1991) and cognitive deficiencies of decision makers (Sugumaran and Degroote, 2010). Consequently, DSS were built as interactive, flexible and adaptable computer-based information systems with data management, model management and user friendly interface management to facilitate the ability of decision makers to solve semi-structured problems (Matthies et al., 2007; Power, 2008). Their framework originates from the concept of organizational decision making in early 1970s (Gorry and Morton, 1971) which consists of three phases: 1) intelligence, 2) design and 3) choice (Simon, 1960). It means that systems were built to 1) facilitate the entry of necessary data and knowledge based on decision makers' specific needs, 2) enable the generation of different alternatives by changing the importance of different factors and display memory aids for better understanding and 3) allow decision makers to evaluate the alternatives to make a choice. With the assistance of DSS, decision making was improved by transforming data and knowledge into useful information to decrease the time in which a decision was made (Mcintosh et al., 2011; Volk et al., 2010). In late 1980s, DSS were augmented with knowledge management by integrating artificial intelligence into the systems to support decision makers in scenario analyses with risk assessments (Courtney et al., 1987; Dutta, 1996; Holsapple and Whinston, 1996). Rational reasoning as provided by knowledge of decision makers and reproducibility of the process ensured quality assurance and transparency (Mcintosh et al., 2011). In 1990s, the Web facilitated the market for DSS by allowing users and providers to distribute decision support services (e.g. data, models, systems etc.) electronically, thus allowing the development of Web-based DSS (Barlishen and Baetz, 1996; Bhargava, 1997; Power and Kaparthi, 2002; Sikder and Gangopadhyay, 2004; Wild and Griggs, 2008).

GIS are systems which are explicitly designed to enter, store, edit, retrieve, analyze and display information with a geographic location (DeMers, 2009). In a critical review by Malczewski, (2004), the growth of DSS was motivated by the necessity for decision formulation and solution and the growth of GIS was motivated with the advancement in computer technology and quantitative spatial science. In 1950s and 1960s, spatial data became easier to store, manipulate and display due to new theoretical concepts of spatial data representation (points, lines and polygons) and analysis (adjacency, containment and connectivity). The systems were primarily built on mainframe computers for automated mapping projects to increase productivity in spatial analysis (Keenan, 2006) but in early 1980s, the increase in computing power led to object-oriented GIS for microcomputers (e.g. desktops, PCs and laptops) such as Environmental Systems Research Institute (ESRI) and Intergraph Corporation. Object-oriented GIS comprised of spatial data management to store spatially indexed data and enable model management to explicitly define the geometric relationships within the data (Sugumaran et al., 2010). In 1990s, user-oriented GIS proliferated as distributed GIS, open GIS, multimedia GIS and Web-based GIS because user friendly and customizable graphical user interfaces (GUIs) were being developed, data became more accessible using networks, data interoperability was possible between different software applications and the Web facilitated the use of multimedia for spatial applications. Continuous increase in spatial data and increasingly robust functionality led to a rise in commercial knowledge based GIS products for general uses (Malczewski, 2004) .

The development of SDSS gained traction with the growth of both DSS and GIS. In 1970s, automated mapping allowed spatial data to be included in DSS for command-line interactive problem solving environments with low processing power and limited graphics such as Geo-data Analysis and Display System (GADS) (Mantey and Carlson, 1980) and Generalized Planning System (GPLAN) (Holsapple and Whinston, 1976). In mid 1980s, the progression to microcomputers and spatial scenario analysis (what-if analysis) in GIS led to the idea of SDSS applications using ESRI's ArcInfo and Arc Macro Language (AML) (Armstrong et al., 1986; Chang et al., 1997; Jain et al., 1995). In 1990s, SDSS applications became intelligent systems with the addition of knowledge management from DSS (Bellamy and Lowes, 1999; Matthews et al., 1999) and were augmented to address the gap of collaborative decision support using multicriteria analysis and face to face communication (Jankowski et al., 1997). In late 1990s, development of SDSS applications moved from integrating different technologies to implementing specific problem solving technologies as GIS and DSS became more utilized by academics, businesses and agencies (Sugumaran et al., 2010). Advancement in user-oriented GIS and increasing availability of open data enabled SDSS applications to take advantage of better geoprocessing power, user friendly interfaces, analytical and statistical modelling techniques, visualization functionalities and the Web. In 2000s, customized and coupled standalone SDSS with improved analytical model management to solve specific spatial problems emerged because Web-based mapping increased the use of both Web-enabled and mobile SDSS (Sugumaran et al., 2004). Therefore, the progress of SDSS depended on both DSS and GIS capabilities and the necessity to support spatial decision making.

SDSS are explicitly designed to help decision makers solve specific spatial problems by facilitating a decision-making process that is "iterative, integrative and participative" (Brail and Klosterman, 2001).

The architecture of SDSS consists of both DSS and GIS components (Table 3) (Armstrong and Densham, 1990; Densham and Goodchild, 1989; Lolonis, 1990; Malczewski, 1999; Sugumaran et al., 2010):

- Interface Management: provide capability for interaction or flow of data and information between the decision makers and the system using customizable and user-friendly graphics.
- Database Management: allow storage and integration of complex structures common in spatial and non-spatial data. Databases have been developed as repository systems containing systematically organized spatial and non-spatial data for rapid search, update, analysis and retrieval.
- Model Management -include analytical model frameworks that are unique techniques to spatial analysis (e.g. Spatial Modeler, location allocation model, analytical hierarchy process (AHP), artificial neural networks, statistical, process based, mathematical, and multi-criteria evaluation).
- Knowledge Management: allow stakeholders (e.g. decision makers, analysts, developers and experts) to add facts, rules and logic to the system's architecture prior and post development
- Multi-Linear Spatial Problem- Solving Environment: allow decision makers to generate alternative solutions to their spatial problem through integration of different knowledge for every solution.

SDSS can be built by developing a new system as a stand-alone operational technology, by building a system within another platform (e.g. GIS) (Herzig, 2008) or by coupling existing stand-alone operational technologies together (Djokic, 1996). Platforms are underlying computing architectures with a programming development environment which allows for the development, integration and deployment of new technologies. SDSS can be achieved by coupling new technologies with themselves or with other existing technologies and integrated toolboxes within the platform. Integrated toolboxes are integrated within platforms or deployed as stand-alone tools which allow for specialized spatial analysis.

Table 3: A comparison summary of the capabilities and components of Decision Support Systems (DSS), Geographic Information Systems (GIS) and Spatial Decision Support Systems (SDSS).

Capabilities and Components			DSS	GIS	SDSS
1. Interface Management			✓	✓	✓
	Cartographic Visualization			✓	✓
	Graphic and Tabular Reporting		✓	✓	✓
2. Model Management		*Non-Spatial*	✓	✓	✓
		Spatial (generic)		✓	✓
		Spatial (specialized)			✓
3. Data Management		*Non-Spatial*	✓	✓	✓
		Spatial		✓	✓
4. Knowledge Management			✓	✓	✓
	Stakeholder Involvement		✓	✓	✓
5. Multi-linear Spatial Problem-Solving Environment					✓

2.3.1 Existing Stream Network Spatial Decision Support Technologies

There has been significant development of spatial technologies and decision support model frameworks for studying stream networks. Only a partial list of technologies that are relevant to hydrology, geomorphology and stream management are presented here to help guide the development of the SDSS of this research. In this review, the technologies were classified based on 1) computer- or web-based platforms defined as commercially available software with user-friendly interfaces or high- level programming language within which new technologies can be developed 2) stand-alone and integrated toolboxes defined as a set of automated processes for data management and specialized analyses without the capability to solve semi-structured problems 3) databases defined as systems for sharing information, 4) model frameworks defined as unautomated analytical designs to solve a semi-structured problem and 5) fully-integrated systems defined as systems used for spatial decision making. They are catalogued and compared to demonstrate their capabilities and constraints in Tables 4 and 5.

Platforms (Table 4):

- ArcGIS for Desktop (Environmental Systems Research Institute (ESRI), 2016) is a commercial GIS platform used for building maps in 2D and 3D environments, for performing spatial analysis using a suite of tools and for creating, managing and sharing geographic data. It consists of all five components of SDSS. It has a graphical user interface with menus, toolbars and dockable windows with a configuration to adapt to a user's preference which allows for mapping and visualization of geographic data. Its data management is provided by its internal relational database management system (RDMS) to allow easy access to spatial and non-spatial data. Data can be created, managed, maintained and archived as different data structures (e.g. feature classes, datasets, layers, rasters etc.) with rich attributes in a folder system called a geo-database which interacts with the internal RDMS. Its model management component provides existing tools for basic spatial analysis but they are not flexible to support variations in the context and the process of spatial decision making. For more specialized spatial analyses, a model building or Python-programming environment is provided to create new contextualized toolboxes by combining existing tools or by integrating data models within the system. This functionality has facilitated the development of many open-source contextualized toolboxes.
- MATLAB (MathWorks, 2017) is a proprietary high- performance interactive system and programming language for matrix computation, data visualization, interface creation, algorithm implementation and application development. It offers similar application specific toolboxes like ArcGIS to extend its problem-solving environment to specialized problems. It has mapping and image processing algorithms as toolboxes, however, ArcGIS has a more comprehensive collection of algorithms and spatial data management capabilities that are optimized for storage and queries.
- Excel Visual Basic for Applications (VBA) (Chinowsky, 2014) is a proprietary programming language used for tasks automation, data visualization and software prototyping within Excel's interface. It has been used to develop a screening tool which performs cost-effective analysis of management practices for spatial decision making (U.S. Environmental Protection Agency (EPA), 2013) but it does not support spatial data visualization, handling and analysis.

- R (The R Foundation, 2017) is an open source programming environment that offers effective data manipulation, data/statistical analysis, high quality graphics and visualization. It is highly suitable for development of statistical data analysis applications.

Integrated Toolboxes (Table 4):

- Hydrological toolboxes such as ArcHydro (Maidment, 2002), Hec-GeoDozer (Environmental Systems Research Institute (ESRI), 2009) and TauDEM ArcGIS (Tarboton, 2004) have been developed for a comprehensive watershed characterization using digital elevation models (DEMs). They consist of analytical models for terrain preprocessing, terrain morphology, watershed processing, attribute-based property assignments and network generation. Data interoperability models are also available for advanced data management in ArcHydro. Data can be exchanged or used with other tools or models (FEMA DCS Hydraulic/ Hydrologic, ICPR Model, HEC-HMS, HEC-RAS, HEC-EFM, ICPR, WSE, DSS, Green and Ampt etc.) within the same geoprocessing environment. To obtain surface characteristics and basin morphometric measures, DEM Surface Tool (Jenness, 2013) and Extraction Tool (Magesh and Ch, 2012) offer such capabilities.
- Geomorphic toolboxes such as RESonate (Williams et al., 2013), V-BET (Gilbert et al., 2016), FLDPLN (Williams et al., 2013) can be used to extract watershed hydrogeomorphic features such as river valleys and channels. In order to use RESonate, users have to be experienced at ArcHydro (Maidment, 2002) and FLDPLN (Karsten, 2008). ArcHydro is used to generate the stream network, the watershed and the subwatersheds and FLDPLN is a 2D flood model which uses intermediate outputs of ArcHydro, flood depth and flood iteration to generate the valley floor. RESonate uses right and left points of highest amplitude meanders to generate the left and right channel belt lines. V-BET is integrated within ArcGIS, therefore it is more user-friendly and it delineates valleys with better accuracy. More detailed characteristics of channels can be extracted by Stream Profiler (Snyder et al., 2007; Whipple et al., 2007) and Fluvial Corridor (Roux et al., 2015). Stream Profiler extracts stream profiles and generates statistics such as steepness index and concavity of channels. Fluvial Corridor is a multi-scale planimetric and longitudinal network tool developed to characterize channel reaches. Its models based on the work of Alber and Piégay (2011), Bertrand (2013) and Leviandier et al. (2012) provide core functionalities for extraction of spatial geomorphic entities (stream network, valley bottom, active channel,

channel centreline) and disaggregation process (i.e. reach creation) to calculate homogeneous reach metrics and statistics (e.g. sinuosity, length, amplitude and widths). Many limitations are present because this tool is still under development. Using DEMs with a low resolution can cause the valley bottom to be inaccurate at extremities whereby head reaches are unidentifiable. Correct parameters must be set to obtain a continuous valley bottom because holes in the spatial coverage are problematic for delineating the centreline. Moreover, the river used for testing this tool is the Drôme River, located in the mountainous terrain of the Southern French Alps. It is 106km long and it has a drainage area of 1640km^2 with an elevation ranging from 800m to 2000m (Pont et al., 2009). It has only been tested in a rural area whose tributaries are sparsely distributed. Further information within channels can be obtained using River Channel Morphology Model (RCMM) (Merwade, 2006). It is an analytical model to extrapolate 3D mesh (FishNet) of river channel using cross sections and profile lines by relating the thalweg location and the cross-sectional shape with the channel planform. It is useful when bathymetry data is not available. The thalweg is identified from a raster surface created by inverse distance weighting using bathymetry data (x, y, z points). The thalweg polyline (x, y, z points) is converted into piecewise Bezier curves to obtain the orthogonal curvilinear (s, n, z) coordinates. The data is converted to a continuous raster surface by spatial interpolation (kriging). The mesh is created using the FishNet tool and is transformed back into the Cartesian coordinate system to obtain the 3D river bathymetry.

Model Frameworks: Analytical designs for stream network assessments exist as either deterministic or probabilistic models. They can be automated in the model management component of SDSS to be used as tools.

- *Deterministic model:* A one dimensional numerical sediment routing model by Lewicki et al. (2007) was developed to predict the effects of urbanization on channel bed from 1952 to 1996 in the gravel bedded stream network of the Good Hope Tributary, Maryland, USA. The model updates parameters of flow and channel bed at every time step of 5s for the discretized channel grid. Relationships based on bed sediment continuity (Exner, 1925) were developed and calibrated using field and flume experiments to predict bed elevation, bed material distribution and fractional bed material transport rates. A hydrological model was used to estimate yearly discharge and the database from Department of Planning provided land use, elevation and hydrologic soils data. Channel width and depth were calculated based on a channel enlargement model (Allmendinger et al., 2007). Initial sediment supply was obtained from field data and historical data was used in the model to obtain initial channel bed and grain sizes. A predictive simulation to the year 2042 was run to predict the evolution of the channel bed. This model is dependent on a large set of field data and neglects the process of floodplain storage (Allmendinger et al., 2007). The predictive scenario showed bed coarsening and a declined sediment yield.

- *Probabilistic model:* A Bayesian network model by Borsuk et al. (2012) was developed to represent the probabilistic relationships among morphology, hydraulics, ecology and socioeconomics as a set of interconnected variables within a hierarchical network. The probability of a variable in the network is determined by knowing the probability of the immediate variables from which it stems and the structure of the network is determined by the causal interpretation. Valley slope, mean annual flood discharge and median gravel diameter were the factors used to predict the probability of a river being single-threaded or multi-threaded. The effect of width constraints on the natural morphology was then considered to predict the sinuosity of the channel. This was done by a regression analysis of the bankfull width with mean annual flood discharge and median gravel diameter. If the constrained width is narrower than the natural width, the river will be straight. For the opposite condition, the single threaded river will be sinuous with alternating bars. To check if predicted multi-threaded rivers may still be single-threaded when the width constraints are too severe, the pattern diagram of da Silva (1991) is used for a known gravel size, mean depth at bank-full discharge and channel geometry. Mean depth is estimated using equations from Strickler (1923) for single-threaded rivers and from Zarn (1997) for multi-threaded rivers. Lastly, gravel supply is considered to determine the development of the predicted morphology and annual erosion. This model was tested to predict a rehabilitation scenario for the Thur River in Switzerland. Static input parameters (porosity, hydraulic conductivity for unsilted bed material, hydraulic gradient and pressure head) were taken from groundwater maps and past studies of the river and dynamic input parameters (time series discharge, suspended particle concentration and water temperature) were taken from daily measurements from 1990 to 1994. The model predicted a straight incising river bed as confirmed by observation and the probability of the river to be single threaded was 68% without any width constraints. With a constraint width of 30m, the river was predicted to be homogenous and straight as its current condition. This model can be only applied to gravel bed rivers with mean discharge between 1 and 60 m^3s^{-1} and without artificial conveyance structures. Its linkages of multiple models offer a comprehensive rehabilitation assessment but the lack of spatial information discounts locational assessments along streams.

- *Probabilistic model:* Bledsoe et al. (2012) developed a hydromodification susceptibility assessment tool under the guidelines of regional stakeholders to perform risk analysis of channel instability of stream segments for Southern California. The probabilistic framework is underlain by a logical decision support structure formulated based on an assessment of 83 sub reaches with differences in hydrogeomorphic characteristics. Field data on bed material, channel geometry, valley setting, watershed data and topographic surveys was collected and geospatial data was used to delineate watershed features. A pool of watershed, geomorphic, hydraulic and sedimentary metrics was assessed using multivariate analysis and logistic regression to determine each of their predictive potential for inclusion in the tool and their effectiveness at discriminating between stable and unstable channel forms. Two statistical models for lateral (i.e. widening) and vertical (i.e. incision) susceptibilities provided significant results ($0.001<p>0.0001$) with the inclusion of these metrics: 1) power index, bed material composition and associated armoring potential, degree of incision and proximity to a downstream hard point and 2) a bank stability threshold based on bank height and angle of banks respectively. For each model, a decision support structure with four ratings (low, medium, high and very high) was developed with a logical flow built upon weighted evidence in support of the predicted hydromodification outcome. The tool was validated using historical data for the sub reaches and by resurveying the sites after four years. This risk-based tool indicated that channel susceptibility was the driver of changes in channel form and its rating scheme was informative of the effects of hydromodification, however the predicted channel form cannot be visualized due to the lack of spatial functionality to the model. This assessment tool is also heavily dependent on large sets of field data and the logistic regression analysis can be limited without the availability of a complete set of data for all streams. Moreover, this approach assesses the predictive ability of different drivers for different channel forms instead of assessing the impact of the drivers to predict areas of susceptibility within stream networks, therefore it is not very practical for effective stream management.

Probabilistic model frameworks are useful for predicting possible consequences of interacting processes of streams. They provide informative assessments but the spatial configuration of stream morphologies remains unknown because the models are not automated. Spatial assessments cannot be realized due to the lack of visualization of the results generated from them.

Databases: Many databases are integrated within larger systems (e.g. ArcSDE, Microsoft SQL and Oracle Spatial) or are available as stand alone distributed systems for sharing information.

- Flowing Water Information Systems (FWIS) is a distributed web-based database system developed specifically for Ontario to capture all new and existing data related to water from all agencies (The Centre for Community Mapping (COMAP), 2017). Physical, chemical, hydrological, biological and spatial data containing summaries on site locations, project design, timestamps, proprietary rights and changes are easily queried and downloaded in multiple formats. Every change is tracked for quality control purposes.

Systems: There are SDSS for assessing specific processes of watersheds at multi-scales.

In the area of integrated water resources management, SDSS such as R-SWAT-DS (Udías et al., 2016), WMOST (U.S. Environmental Protection Agency (EPA), 2013) and L-THIA (Hunter et al., 2010) have been developed to find optimal management practices for reducing nutrient and sediment loading, for meeting water supply demand and for pollution reduction under land use change scenarios respectively. Eco-Health Report Cards (University of Maryland (Centre for Environmental Science), 2017), (America's Watershed Initiative, 2010), (Save the Sound, 2016), (Government of India (Ministry of Environment, 2012), (Queensland Government, 2014) are used globally to provide an overall assessment of the health of watersheds worldwide. They incorporate different types of data such as surveys, samples and imageries, data management, desktop or web-based user interfaces, stakeholders and analytical models for analyzing hydrological, chemical, biological and physical processes within watersheds.

Table 4: A comparative summary of existing toolboxes and unautomated model frameworks for spatial decision support.

Name	Reference	Approach[1]	Automated	Platform[2]	SDSS component[3] 1	2	3	4	5	Description
ArcHydro	ESRI, 2013	D	Y	ARCGIS	✓	✓				Watershed characterization
TauDEM	Tarboton, 2004	D	Y	ARCGIS	✓	✓				Terrain characterization
HEC-GeoDozer	ESRI, 2009	D	Y	ARCGIS	✓	✓				Mozaicks and reprojections of DEM
DEM Surface Tool	Jenness, 2013	D	Y	ARCGIS	✓	✓				Surface characterization (slope, aspect, hillshade and curvature)
Extraction tool	Magesh and Ch, 2012	D	Y	ARCGIS	✓	✓				Basin morphometry (slope, drainage density, hill shade)
RESonate	Williams et al., 2013	D	Y	ARCGIS & FLDPLN	✓	✓				Valley and channel characterization
V-BET	Gilbert et al., 2016	D	Y	ARCGIS	✓	✓				Valley bottom delineation
FLDPLN	Williams et al., 2013	D	Y	MATLAB	✓	✓				2D Valley morphology extraction
HEC-GeoRAS	HEC, 2003	D	Y	HEC-RAS	✓	✓				Floodplain mapping and computations
Fluvial Corridor	Roux et al., 2015	D	Y	ARCGIS	✓	✓				River corridors
Stream Profiler	Snyder et al., 2007	D	Y	ARCGIS & MATLAB	✓	✓				River profile, steepness index
River Channel Morphology (RCMM)	Merwade, 2006	D	Y	ARCGIS	✓	✓				3D mesh river profile using cross sections and profile lines
Sediment Routing	Lewicki et al., (2007)	D	Y		✓	✓	✓	✓	✓	Bed characteristics prediction
Hydromodification Assessment	Bledsoe et al., (2012)	P	N			✓	✓			Risk analysis of channel instability
River Rehabilitation	Borsuk et al., (2012)	P	N			✓				Channel morphology prediction using Bayesian networks

[1] P=Probabilistic, D=Deterministic, Q= Qualitative and C= Conceptual
[2] Integrated or Stand-alone
[3] 1 = User Interface Management, 2= Model Management, 3=Data Management, 4= Knowledge Management and 5 = Multi-linear Spatial Problem-Solving Environment

Table 5: A comparative summary of existing technologies for spatial decision support systems.

Name	Reference	Approach[1]	Automated	Platform[2]	SDSS Component[3] 1	2	3	4	5	Description
R-Soil Water Assessment Tool Decision Support (R-SWAT-DS)	Udías et al., (2016)	D	Y	R	✓	✓	✓	✓	✓	Cost effective Best Management Practices (BMPs) placement simulations for nutrient reduction
Watershed Optimization Support Tool (WMOST)	U.S. Environmental Protection Agency (EPA), (2013)	D	Y	Microsoft Excel 2010 (VBA and Lp_solve 5.5)	✓	✓	✓	✓	✓	Water flow (storm water, waste water and water supply) modelling for evaluating management options
Long Term Hydrologic Impact Assessment (L-THIA) tool	Hunter et al., (2010)	D	Y	WEB	✓	✓	✓	✓	✓	Evaluation of LID practices on water quantity and water quality
Eco-Health Report Cards	University of Maryland (Centre for Environmental Science), (2017); America's Watershed Initiative, (2010); Save the Sound, (2016); Government of India (Ministry of Environment), (2012); Queensland Government, 2014	D	Y	WEB	✓	✓	✓	✓	✓	Data collection by scientists and volunteers to assess the health of ecosystems using a grading system
NetMap	NetMap, (2016)	D	Y	ARCGIS	✓	✓	✓	✓	✓	Landscape analysis system using different specialized apps

[1] P=Probabilistic, D=Deterministic, Q= Qualitative and C= Conceptual
[2] Integrated or Stand-alone
[3] 1= User Interface Management, 2= Model Management, 3=Data Management, 4= Knowledge Management and 5 = Multi-linear Spatial Problem-Solving Environment

Name	Reference	Approach[1]	Automated	Platform[2]	SDSS Component[3] 1	2	3	4	5	Description
Atlas of Hawaiian Watersheds and their Aquatic Resources	Hawaii Division of Aquatic Resources (DAR), (2017)	D	Y		✓	✓	✓	✓	✓	Survey data (land use, biotic species, physical and chemical) for watershed ratings located on the Hawaiian Islands
Brook Trout Conservation Decision Support Tools	Eastern Brook Trout Joint Venture, (2017)	D	Y		✓	✓	✓	✓	✓	Riparian Prioritization and Restoration, Fish Habitat Ranking and Catchment Analysis

Based on the comparative review of current spatial technologies, there is not a currently available SDSS capable of analyzing the cumulative impact of urbanization on streams at the network scale. There is also lack of automated analytical models to model the imbalances in sediment continuity as induced by changes in hydrologic regimes from increasing impervious land use cover. Visualization capabilities of spatial adjustments which occur along streams prior to urban land use developments also do not exist. Therefore, there is a need to develop a SDSS which allows decision makers in urban stream management to establish the spatial context within which decisions and quantitative analysis are made.

2.4 Objective

The objectives of this research are

1. to develop a SDSS with a flexible architecture to allow for a multi-linear flow of information for multiple scenario analysis which will include:
    a. an analytical model framework for testing stream power models on available datasets
    b. an illustrative application of a case study using existing empirical models
2. to develop a predictive model for sediment particle size to be included in the SDSS

This research positions itself between the scientific understanding of stream networks and the direct practice of watershed management by addressing the lack of a SDSS to support decision makers in assessing the cumulative impact of urbanization on stream networks, therefore this SDSS can be applied to any watersheds or stream networks to investigate the risks associated with urban developments.

Chapter 3: Architecture of Stream Network SDSS

The SDSS was developed as a fully integrated system within a platform using existing spatial technologies and specialized model frameworks to achieve the essential five components: interface management, data management, model management, knowledge management and a multi-linear spatial problem-solving environment (Figure 1). ArcGIS for Desktop Version 10.3.1 (Environmental Systems Research Institute (ESRI), 2016) was selected as the platform for development because the essential five main components are already integrated within its system and existing generic processes only need to be specialized to solve specific spatial problems. The architecture of the SDSS has a flexible design to allow for extensibility of the system and to support the addition of new model frameworks and new information from different sources for its continuous enhancement at any time.

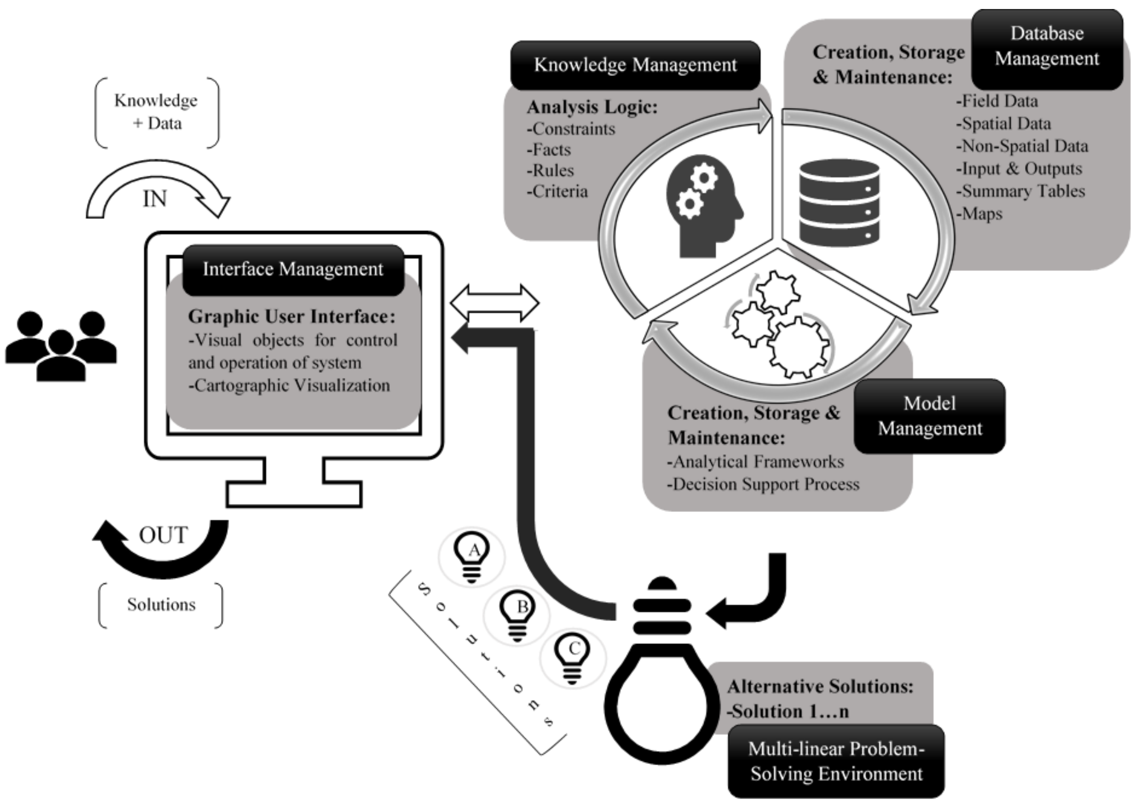


Figure 1: Summary diagram of the five components of SDSS.

3.1 Interface Management

The interface management system consists of a graphical user interface (GUI) which extends the functionalities of the system to the user through visual objects and cartographic visualization for control and operation of the system (Figure 2). The user will use the GUI to enter data and knowledge for specialized analyses automated by the tools in the ArcToolbox to solve a spatial problem and it will present the results of the specialized analysis to the user as cartographic, tabular and documented information in a structured way to facilitate their interpretation. Results will be listed in the Table of Contents where they can be organized in the order in which they are to be drawn and customized using different symbologies and display properties, in the Dataframe where they can be visualized and explored using menus from the Toolbar and in the Catalog where they can be accessed at any time by other tools or the user.

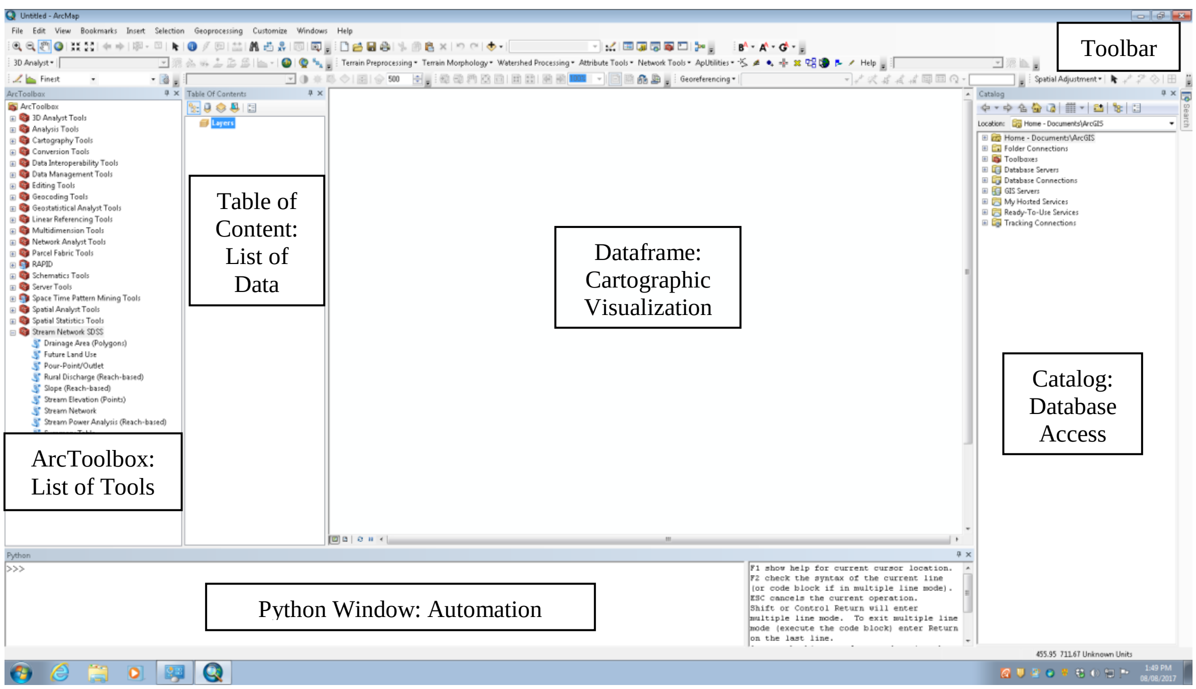


Figure 2: Graphical User Interface (GUI) of ArcGIS Desktop (ArcMap) Version 10.3.1.

The current model framework of the SDSS is presented as an integrated toolbox. The toolbox has contextualized tools which are presented in the GUI (Figure 3). The toolbox package is portable to other desktop computers with ArcGIS Desktop installed. It is a plug-in which is added to the ArcToolbox window to facilitate its use and to enable a user interface for accessing the tools within the package. Each tool represents an automated specialized process and has its own dialog interface with instructions to prompt the user for data, parameter controls and folder paths (Figure 4). The specialized processes are written as a script (.pyt) within the Python programming environment and organized to allow for coding explanations, parameter definitions and validations, optional control for parameter validations and execution of processes in the dialog interface (Figure 5). For example, default parameters can be pre-defined and the execution of processes within a tool can be controlled using checkboxes by the user (Figure 6). Incorrect data entered by the user is validated as a specific error code (e.g. ERROR 000732 in Figure 7). By clicking on the error code, an ArcGIS Help window opens to provide possible solutions (Figure 8). The scripts consist of both new algorithms and existing generic tools essential for spatial analysis and geoprocessing. The tools are created independent of each other to quickly modify the process as needed and to facilitate continuous development of new contextualized tools using existing contextualized tools. Errors can be easily troubleshooted during processing because messages are written to the dialog box to indicate progress (Figure 9) and the location and type of error (Figure 10). The execution of the tools occur in a sequence whereby results from one tool are fed into another tool as needed.

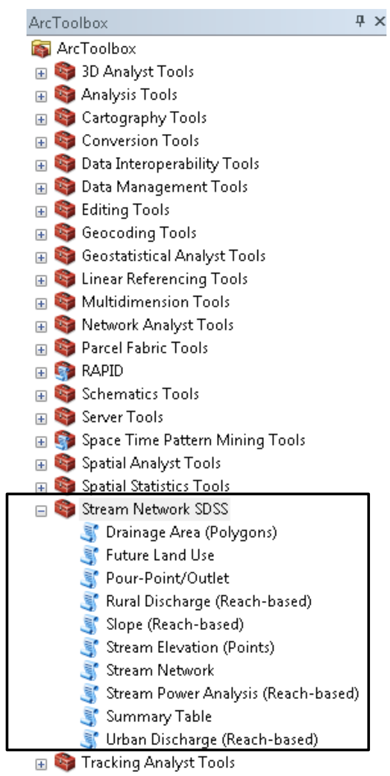


Figure 3: Stream Network SDSS as an integrated toolbox and its contextualized tools.

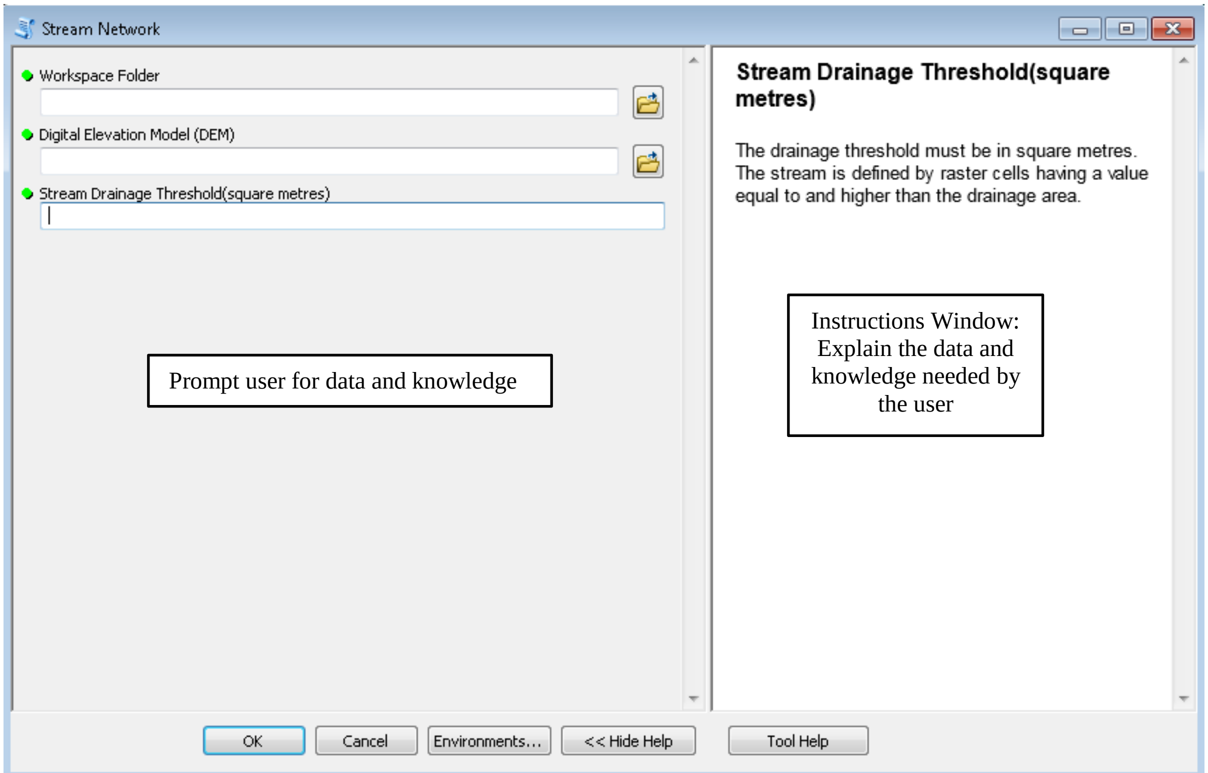


Figure 4: Example of a dialog box window.

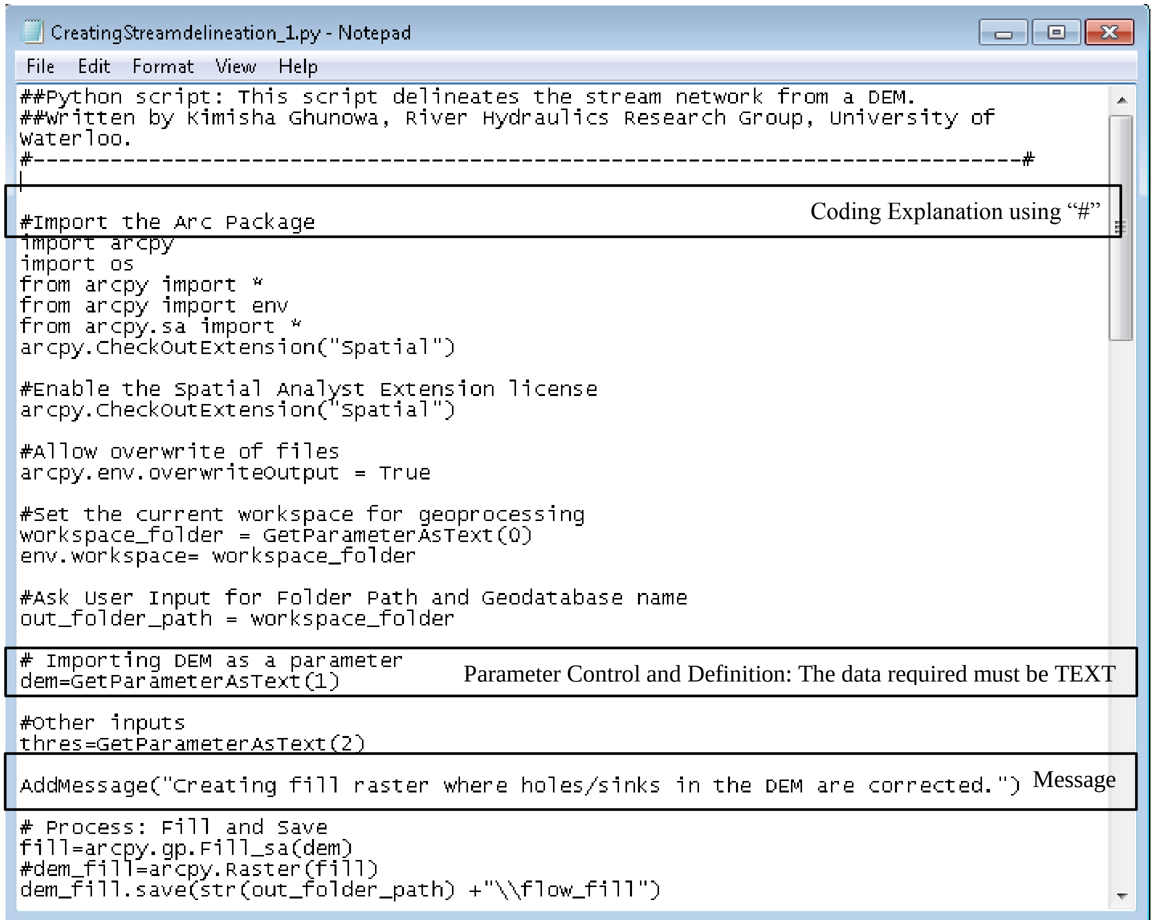


Figure 5: Example of a python script (.py) window.

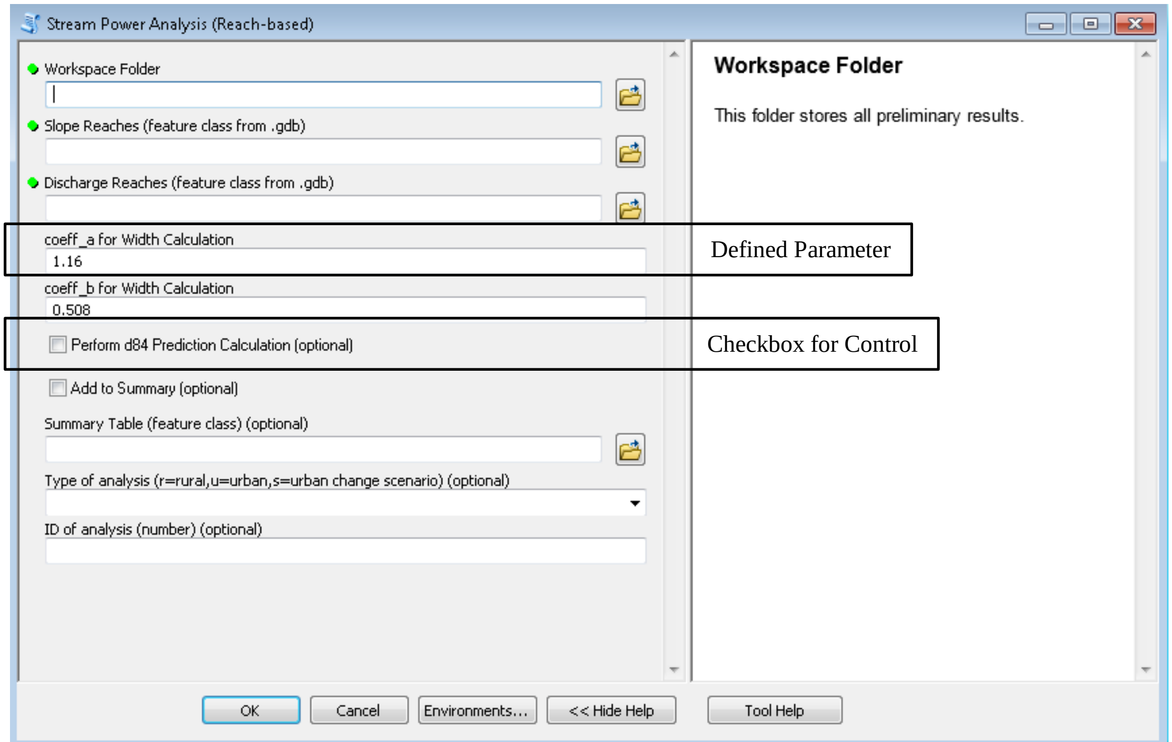


Figure 6: Example of a dialog box window with parameter definitions and process controls.

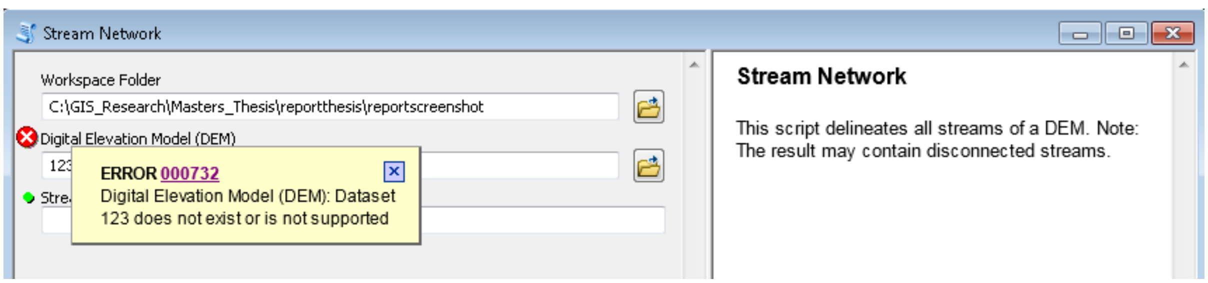


Figure 7: Error Message presented to user after entering the wrong data.

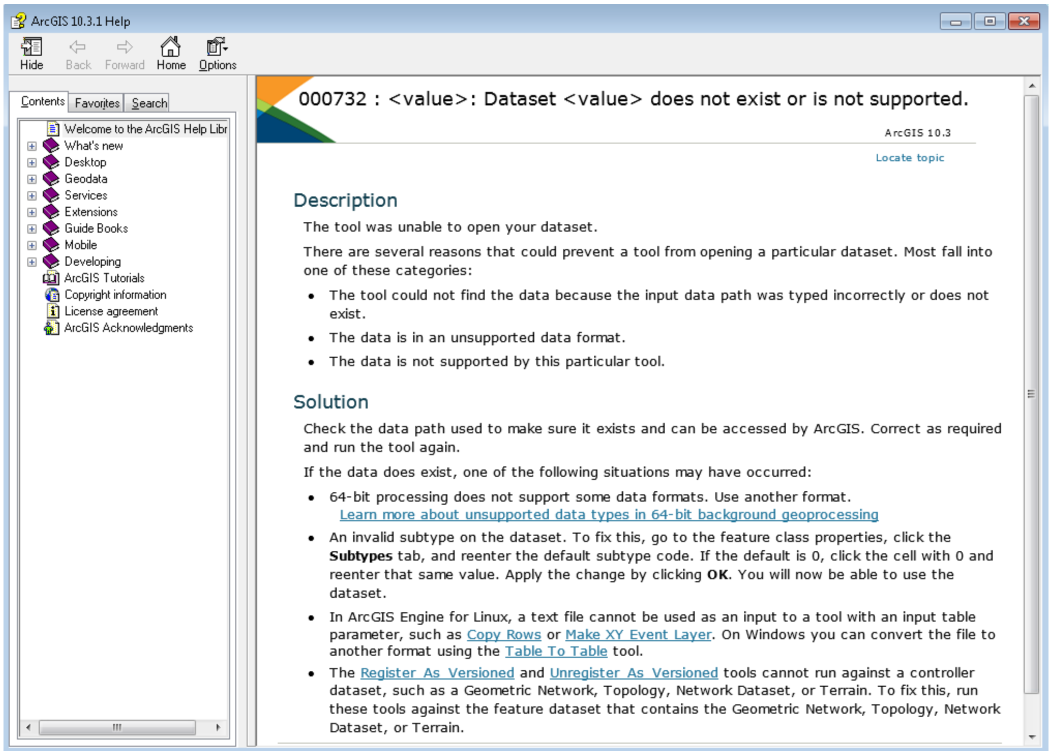


Figure 8: Example of ArcGIS Help window.

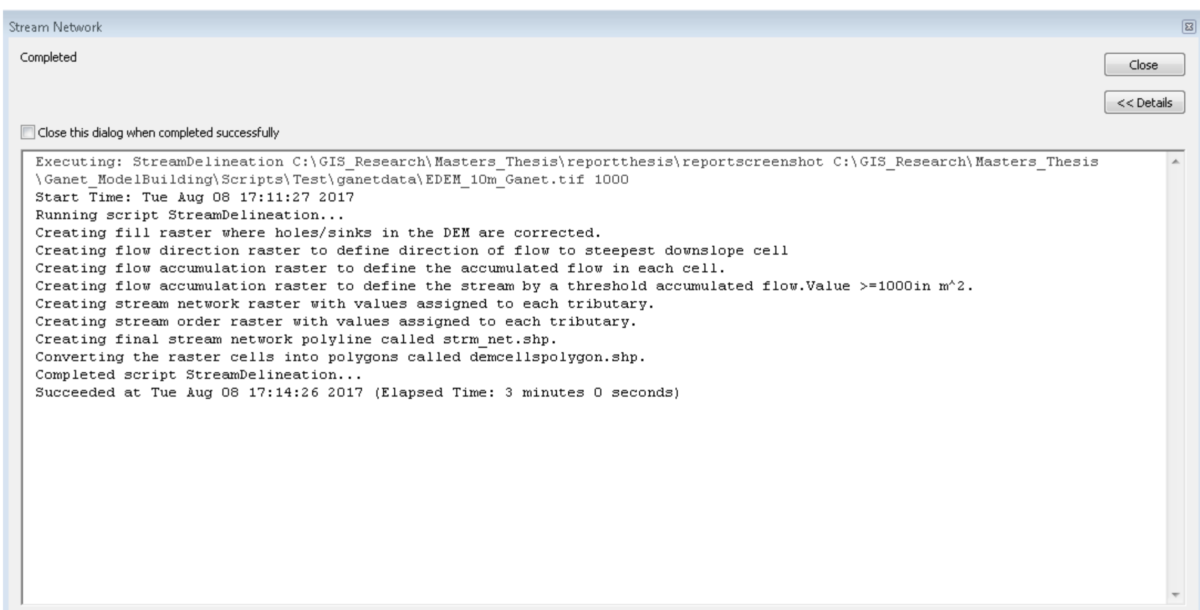


Figure 9: Example of a dialog box window showing progress messages during processing.

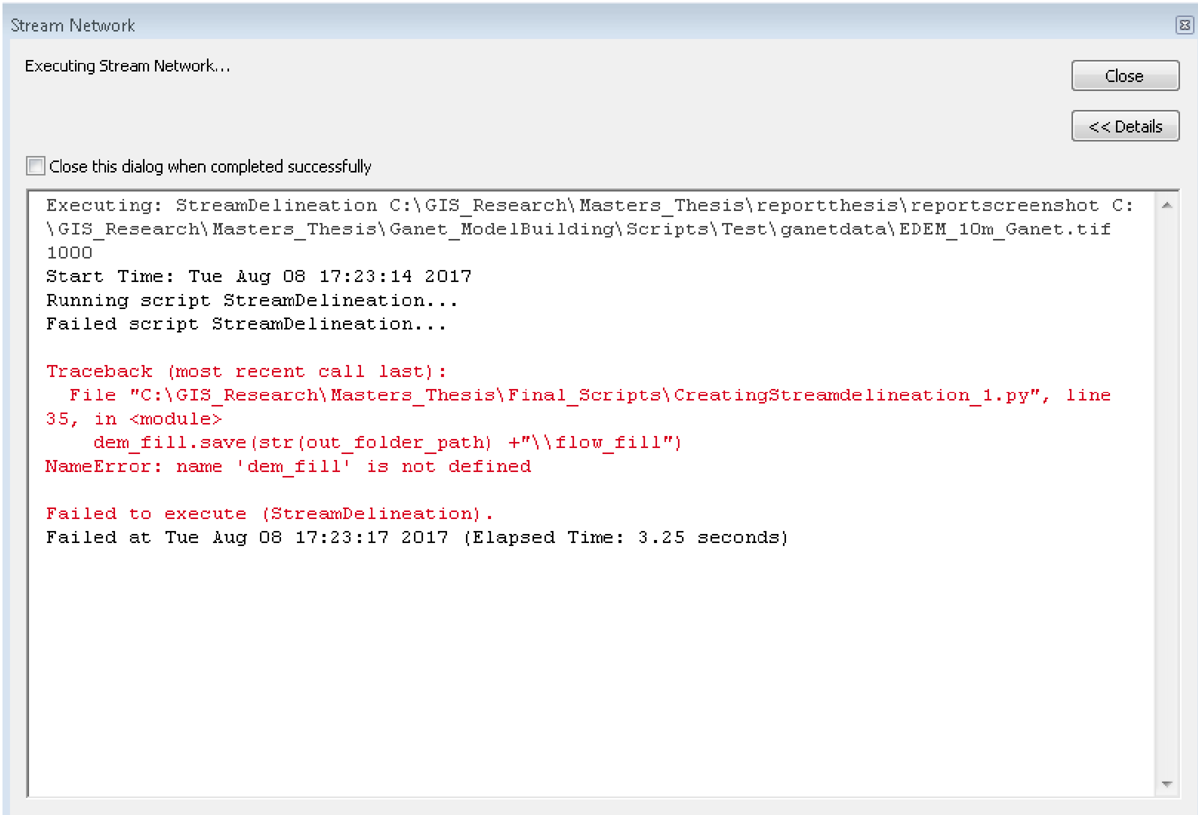


Figure 10: Example of an error message indicating type and location of error during processing.

3.2 Data Management

Required data and knowledge entered by the user and information stored within the database are automatically retrieved from their location during processing. Intermediate and final results are stored, managed and maintained in a specified folder by the user within the database (Figure 11). Final results are stored in a geo-database which is a folder with a collection of geographic data designed to maintain spatial integrity and flexibility during processing due to its unique information model and large storage capacity. Intermediate results are stored in the folder to facilitate troubleshooting of errors. Data provided by the user and presented to the user through the GUI is also stored, managed and maintained by the database. Data can be read, queried, edited and displayed from the database using the attribute table (Figure 12).

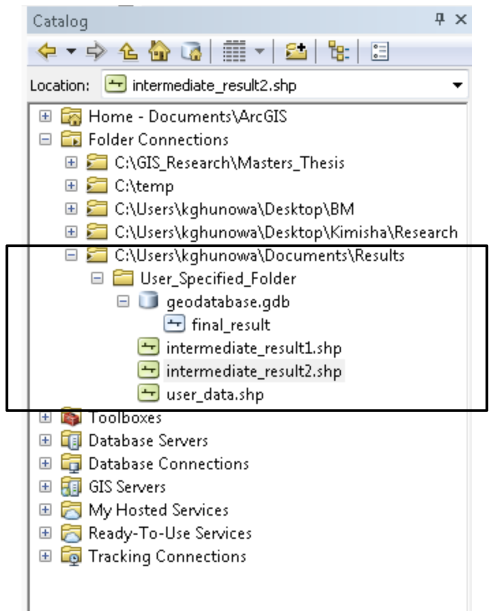


Figure 11: An example of user specified folder and geodatabase containing results.

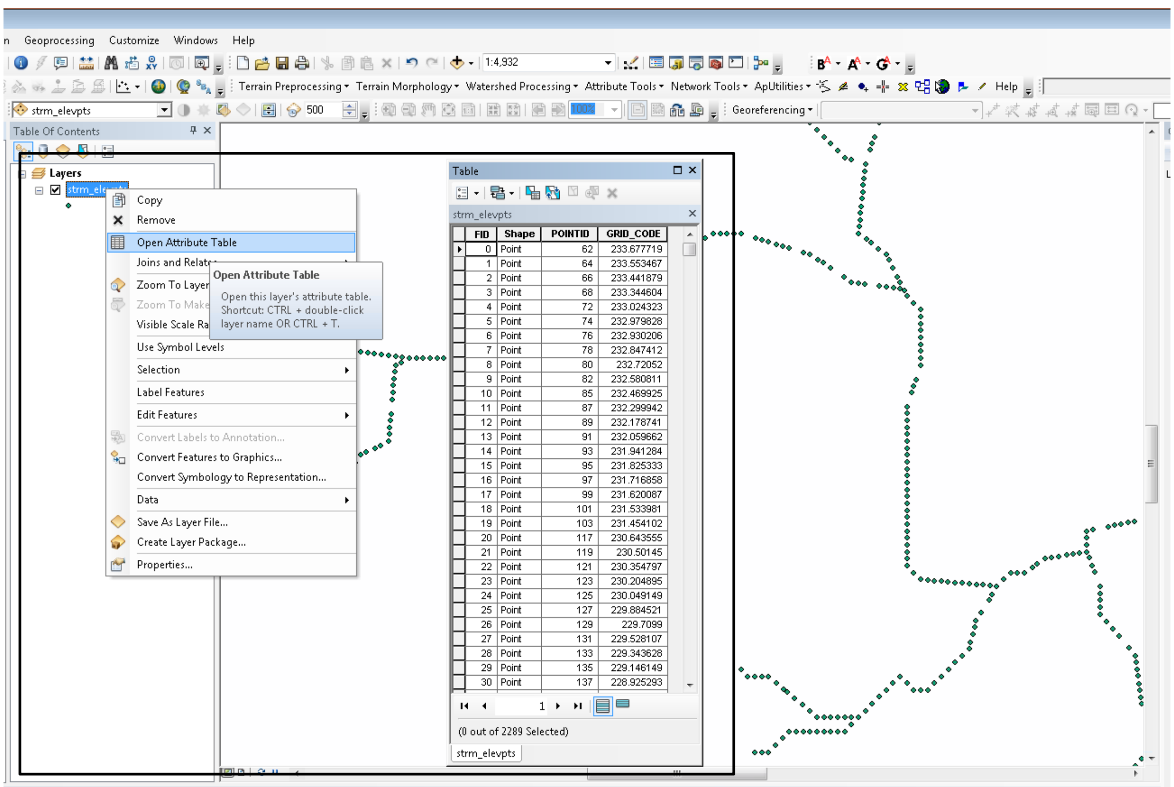


Figure 12: An example of attribute table showing information associated to data being drawn in the dataframe.

3.3 Model Management

The model framework of the SDSS is created, stored and maintained within the internal model management system of ArcGIS. It is designed to support a decision-making process of a complex spatial problem. The user accesses the model framework through the contextualized tools of the toolbox. The tools automate specialized analyses which solve smaller spatial problems as part of the complex spatial problem. The smaller spatial problems are solved in a sequence to generate a final solution to the complex spatial problem. Alternative solutions to the complex spatial problem are generated through iteration of the sequential process using the same data but different knowledge. The iterative and participative process is meant to help the user understand, organize, study, solve and compare solutions to arrive at a decision.

3.3.1 Current Model Framework

The current model framework automates spatial modelling of stream power due to its suitability as an assessment tool for stream stability (Vocal Ferencevic and Ashmore, 2012). It integrates empirical relationships between discharge, drainage area and imperviousness to assess pre- and post development impacts of urbanization on stream power along stream networks. A DEM approach is used to model stream power similar to the approach of Bawa et al., (2014); Jain et al., (2006); Lea and Legleiter, (2016); Lecce, (2013); Parker et al., (2015); Phillips and Desloges, (2014); Reinfelds et al., (2004) and Vocal Ferencevic and Ashmore, (2012). The level of land development is represented by the percentage of imperviousness of land use and cover type of the watershed. Two types of stream power scenarios are provided: rural and urban. It is assumed that rural scenarios are for stream networks which have pervious land use and cover type and urban scenarios are for stream networks which have impervious land use and cover type. Stream power can be calculated for each type of scenario and for different levels of land development to generate alternative scenarios of stream power. A scenario-based approach is used because it allows for a comparative analysis of the impact of different land developments spatially and quantitatively. Predictive analysis can also be performed for possible future land developments as a form of projection of the impacts of urbanization. Scenarios of future land developments are performed by creating new land parcels to generate stream power calculations. A predictive model for sediment particle size for the rural scenario was developed and integrated within the model framework to allow for analysis of mobility thresholds of sediments.

Scenario analysis of stream power modelling requires two spatial data as input: 1) a hydrologically enforced raster Digital Elevation Model (eDEM) and 2) a vector shapefile containing land parcels representing land use type and their associated imperviousness (%). Specialized analyses consist of stream network delineation, their segmentation as interconnected reaches, calculations of slope, discharge, stream power and sediment particle size for defined reaches along the stream network under different scenarios. All python scripts to the specialized analyses are provided in the Appendix B. The specialized analyses are classified as general analyses (subsection 3.3.1.1) and scenario analyses (rural scenario in subsection 3.3.1.2 and urban scenario in subsection 3.3.1.3). General analyses must be executed before scenario analyses in the sequence in which they are presented in this report.

3.3.1.1 General Analysis

3.3.1.1.1 Stream Network tool (Script in Appendix B- page 93)

The dialog box of the stream network tool prompts the user to enter a folder path, an eDEM and a drainage threshold in square metres (Figure 13). If an eDEM is not available, a DEM can be hydrologically conditioned with an enhanced stream network using plug-in tools such as ArcHydro (Maidment, 2002) and TauDEM (Tarboton, 2004). The drainage threshold is the drainage area for which a stream is defined. The process for delineating stream networks from an eDEM is a widely used method by O ’Callaghan and Mark (1984). The eDEM is pre-processed to remove small imperfections, i.e. sinks and peaks. Sinks are cells which do not have lower cells surrounding them into which to drain and peaks are cells which have an elevation greater than their expected surrounding surface. Sinks are filled to the minimum elevation of their surrounding cells and peaks are removed to the maximum elevation of their surrounding cells to create a raster of flow fill (Figure 14). A raster of flow direction is created to represent the direction of each cell to its steepest neighbour cell in the downstream direction (Figure 15). This raster is used to create a raster of flow accumulation to represent the accumulated flow in each cell (Figure 16). The accumulated flow represents the cumulative number of cells flowing into a cell. The accumulated flow is multiplied by the cell resolution of the eDEM to obtain the total drainage area of each cell. Cells which have drainage areas equal to or higher than the drainage threshold are extracted to create a raster of flow accumulation threshold. The extracted cells represent the cells of the stream network (Figure 17). The stream cells are linked to each other and their orders are identified using the Shreve method (Tarboton et al., 1991). The Shreve method assigns all stream segments without any links a magnitude order of 1. When two stream segments intersect each other, their magnitude order is added and assigned to the downslope stream segment (Figures 18 and 19). This method accounts for all stream segments and their magnitudes, therefore, it is easy to differentiate the location of the stream segments within the watershed with respect to the stream segment upstream of the pourpoint. The stream network is vectorized as a line feature with its directionality of flow (Figure 19). The directionality is given by the upstream endpoint called FROM_NODE (i.e. the point where the stream segment begins) to the downstream endpoint called TO_NODE (i.e. the point where the stream segment ends) in the attribute table (Figures 20 and 21and Table 6). The raster cells of the eDEM is vectorized into a grid as polygon features to be used by other tools (Figure 22).

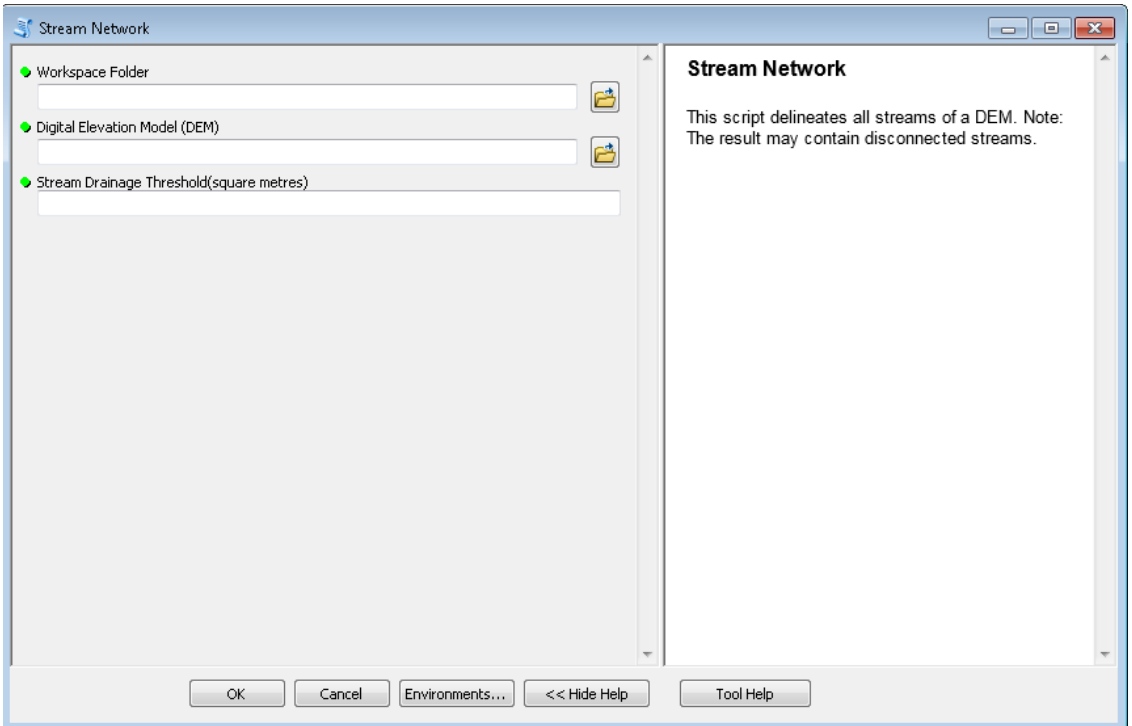


Figure 13: Dialog box of Stream Network tool.

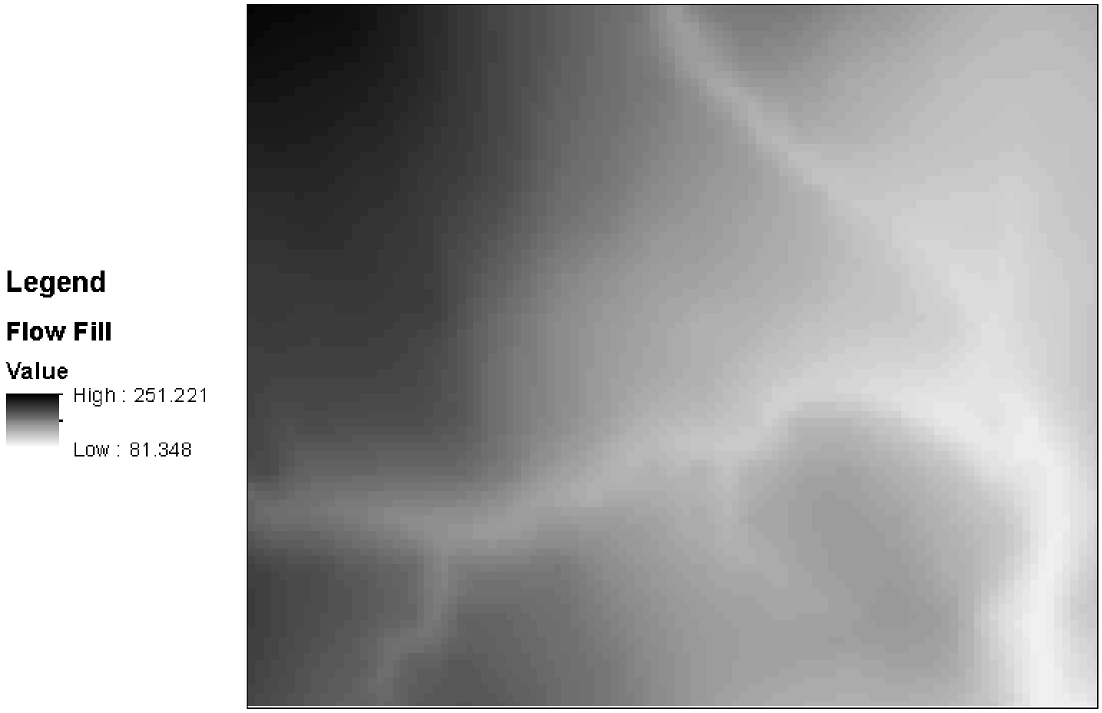


Figure 14: Raster of flow fill.

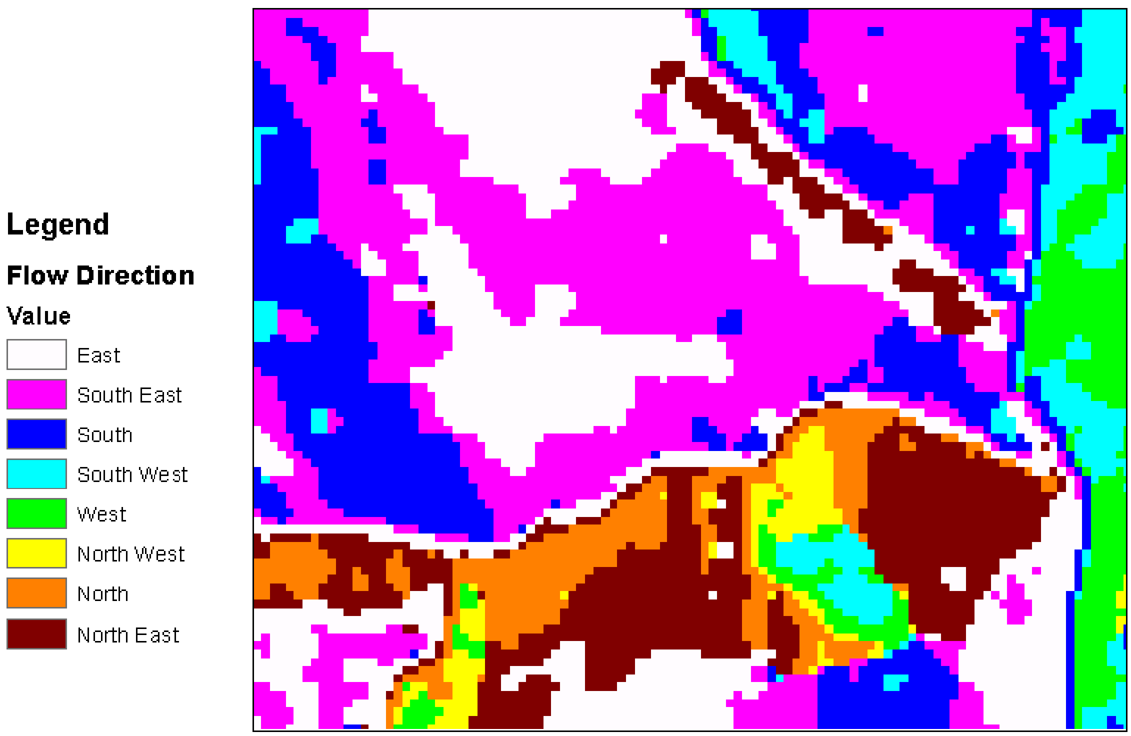


Figure 15: Raster of flow direction.

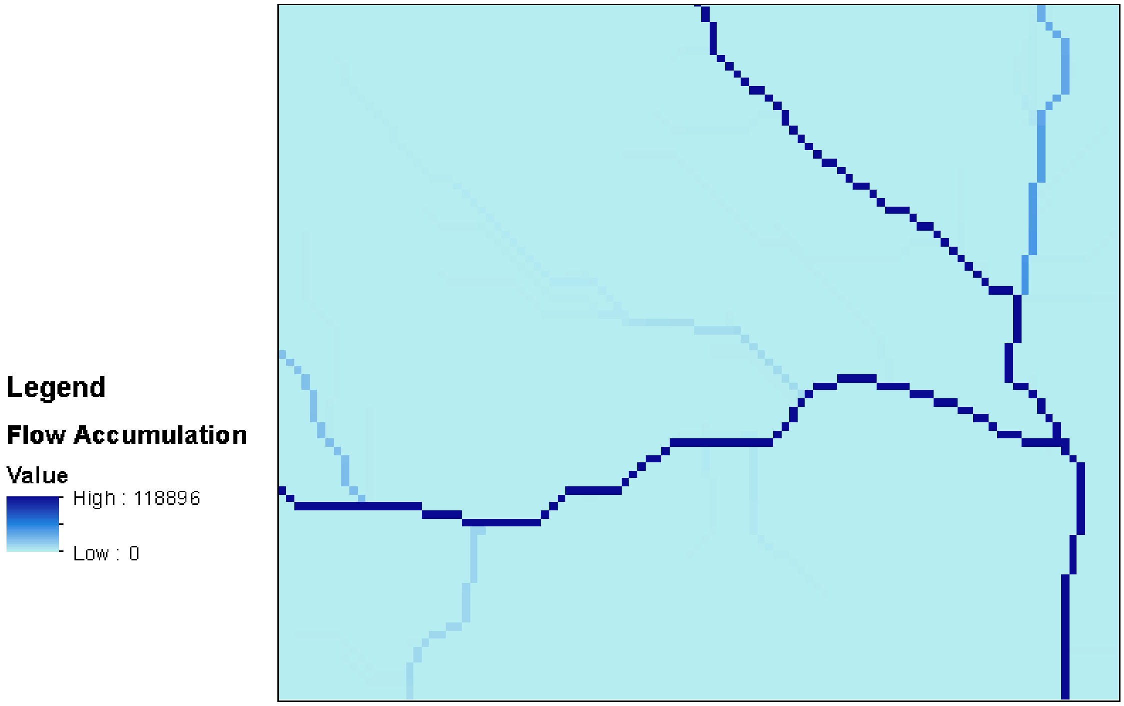


Figure 16: Raster of flow accumulation.

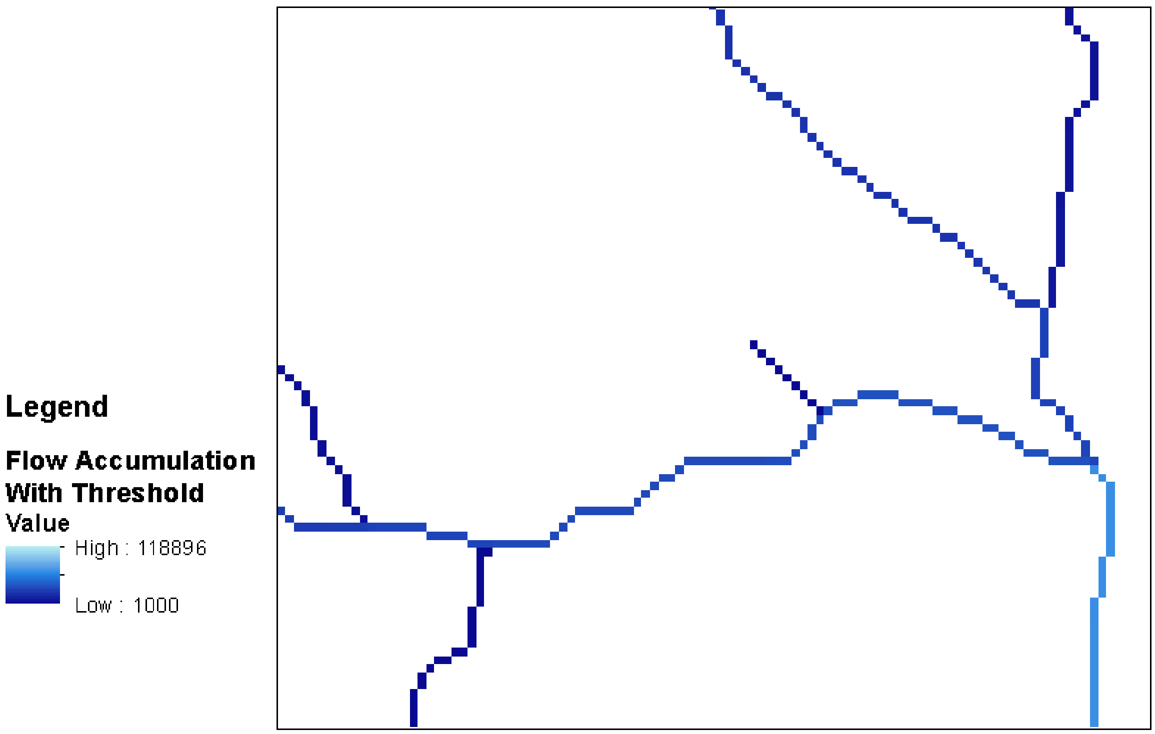


Figure 17: Raster of flow accumulation with applied drainage area threshold of 1000m^2.

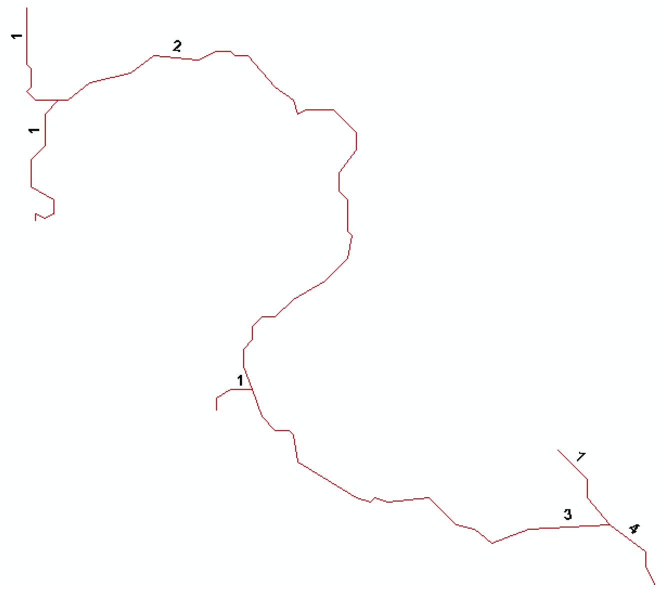


Figure 18: Shreve's method of ordering streams.

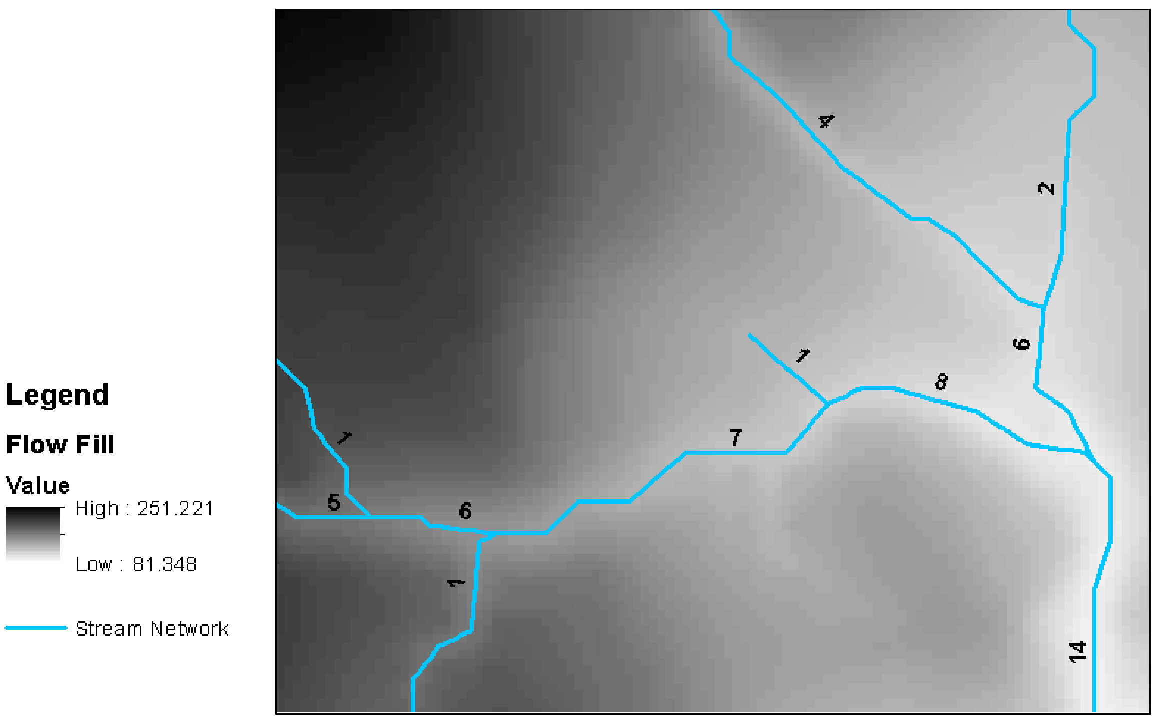


Figure 19: Magnitude order of stream segments using Shreve's Method and stream network vectorized as a linear feature.

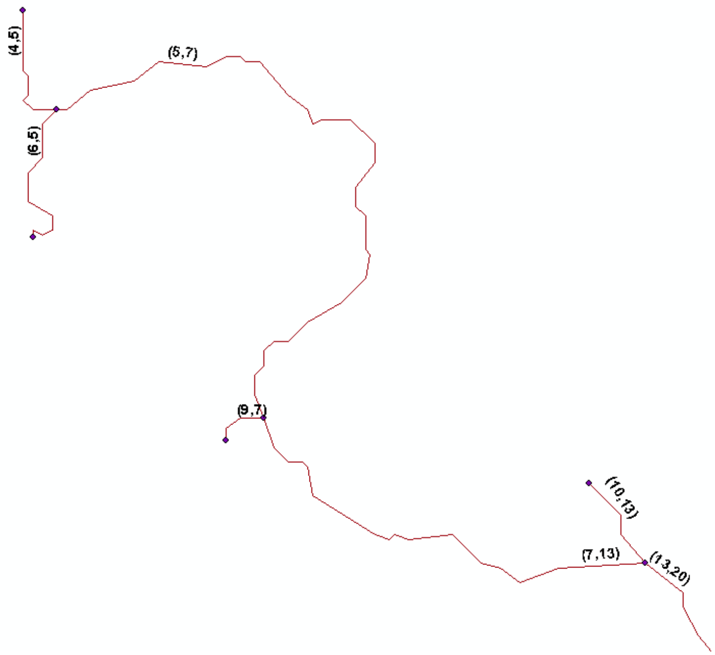


Figure 20: Stream directionality represented by their endpoints as (FROM_NODE, TO_NODE).

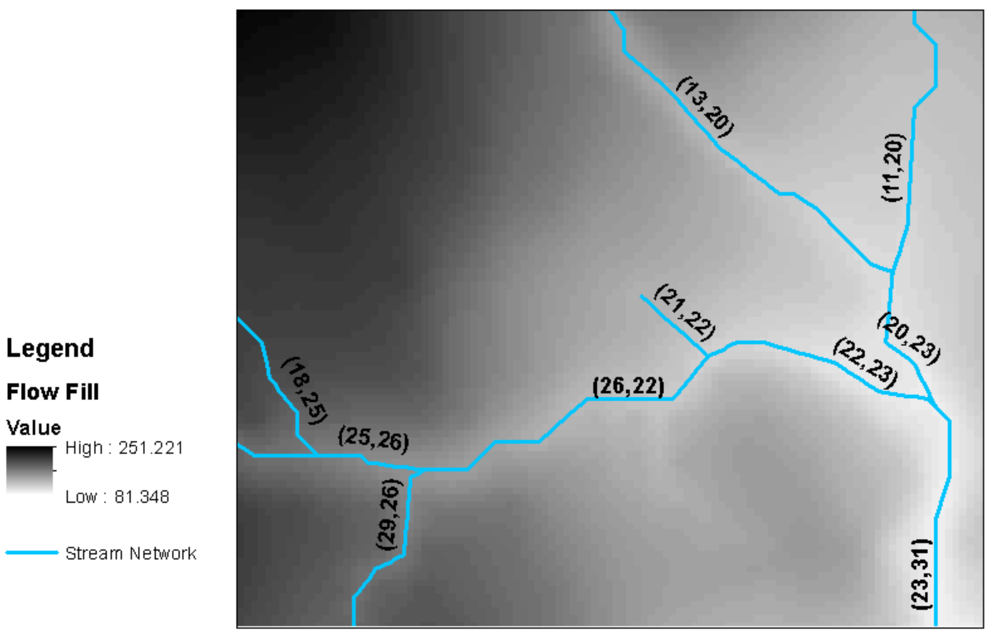


Figure 21: Stream directionality of stream network linear feature represented by their endpoints as (FROM_NODE, TO_NODE).

Table 6: Attribute table of stream network linear feature showing their directionality.

FID	SHAPE	ARCID	GRID_CODE	FROM_NODE	TO_NODE
0	Polyline	1	2	1	3
1	Polyline	2	3	4	5
2	Polyline	3	5	6	5
3	Polyline	4	4	5	7
4	Polyline	5	6	9	11
5	Polyline	6	7	8	11

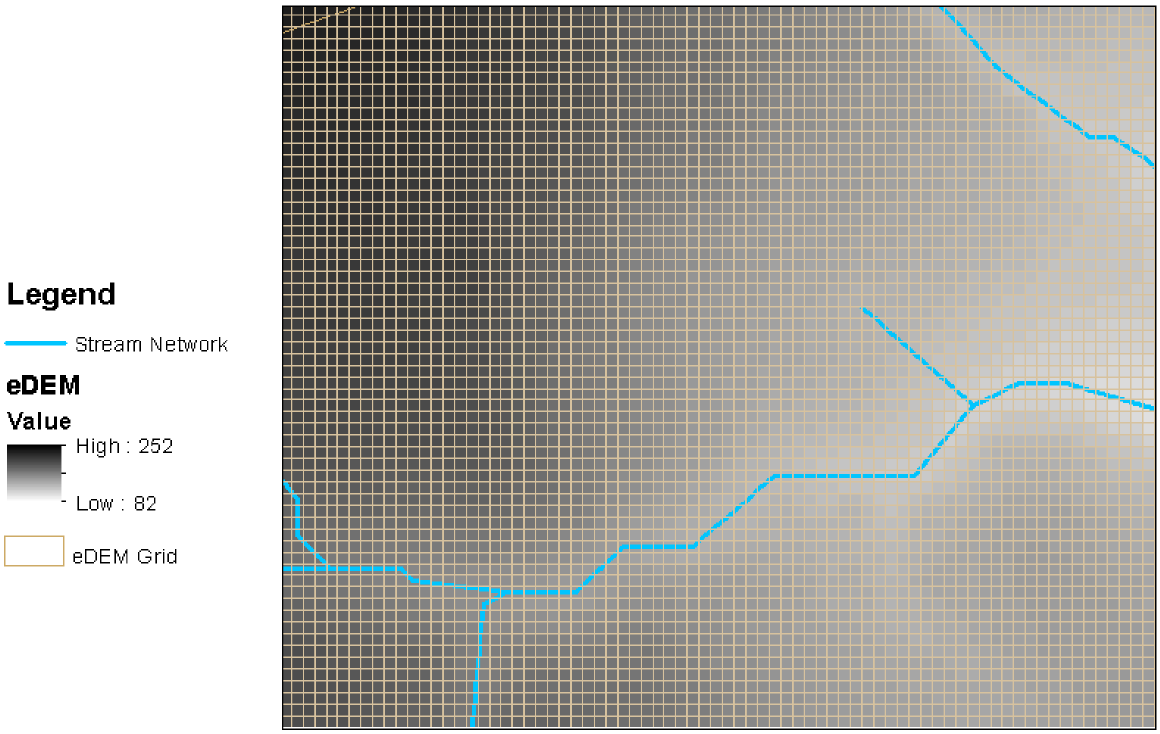


Figure 22: Grid of cells vectorized from the eDEM as polygon features.

3.3.1.1.2 Pourpoint/Outlet tool (Script in Appendix B – page 96)

The dialog box of the Pourpoint/ Outlet tool prompts the user to enter a folder path, the raster of flow accumulation, the cell size of the raster of flow accumulation (i.e. the size of the cells of the eDEM) and the stream network linear feature (Figure 23). The raster of flow accumulation is vectorized to create point features and the point feature with the maximum accumulated flow is extracted. The cell size of the raster of flow accumulation is the distance within which the endpoint of the stream network is located. Once the endpoint is located, the point is placed at the endpoint of the stream network (Figure 24).

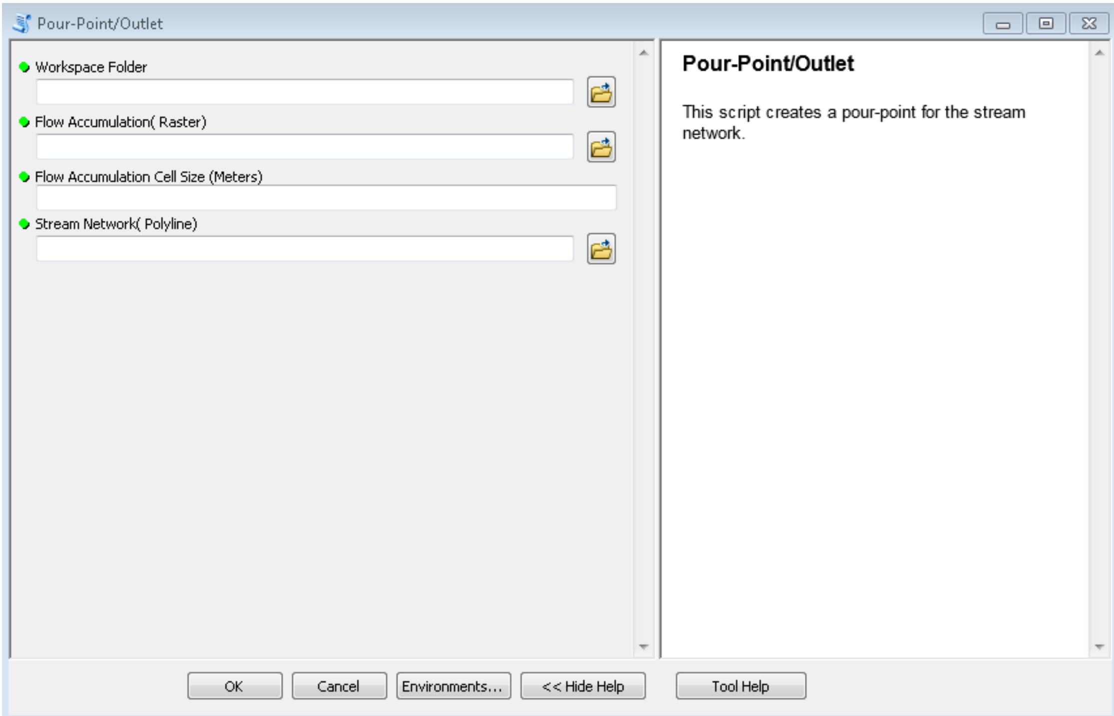


Figure 23: Dialog box of Pourpoint/ Outlet tool.

Figure 24: Pourpoint/ Outlet point feature created for the stream network.

3.3.1.1.3 Stream Elevation tool (Script in Appendix B- Page 98)

The dialog box of the Stream Elevation tool prompts the user for a folder path, the raster of flow fill, the raster of flow accumulation threshold, the grid of cells as polygon features, the stream network linear feature and the cell size of the eDEM (Figure 25). The elevation values from the raster of flow fill is assigned to the raster of flow accumulation threshold by intersecting both rasters (Figure 26). The resulting raster of flow accumulation threshold contains the elevation values belonging to the stream network linear feature. It is vectorized to create point features and the point features are joined to the cells in the grid of cells within which they are contained (Figure 27). The cells in the grid of cells which completely contain the stream network linear feature are selected and are vectorized to create elevation point features. The elevation point features are placed on the stream network line feature (Figure 28).

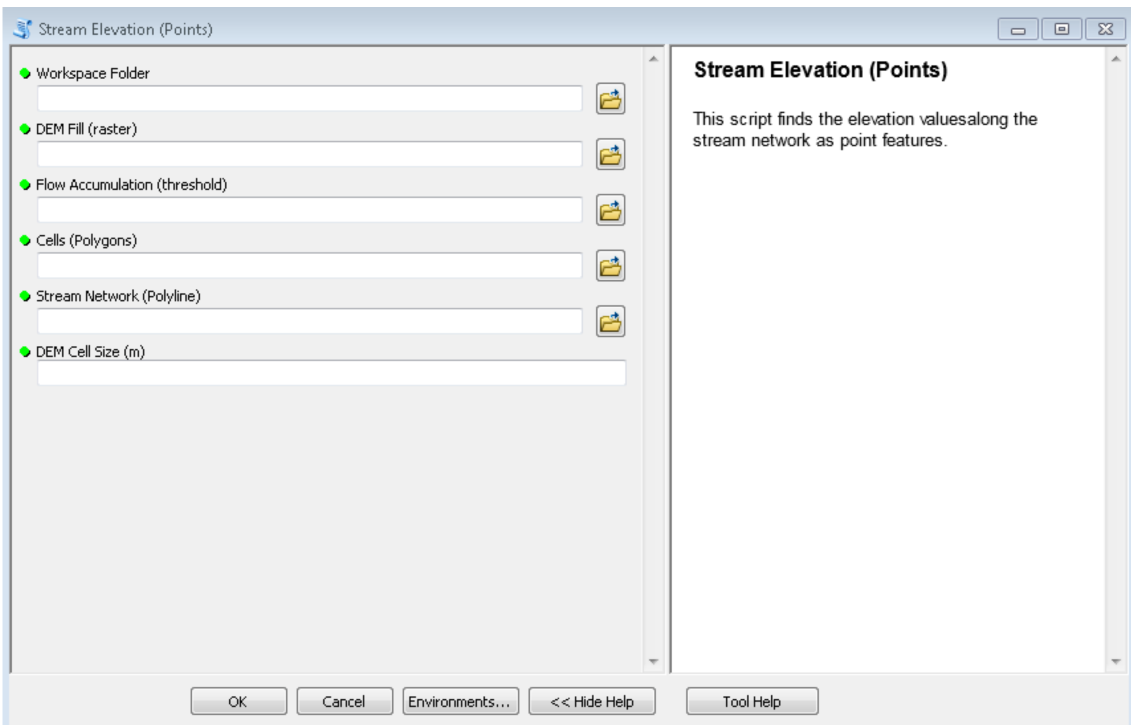


Figure 25: Dialog box of Stream Elevation tool.

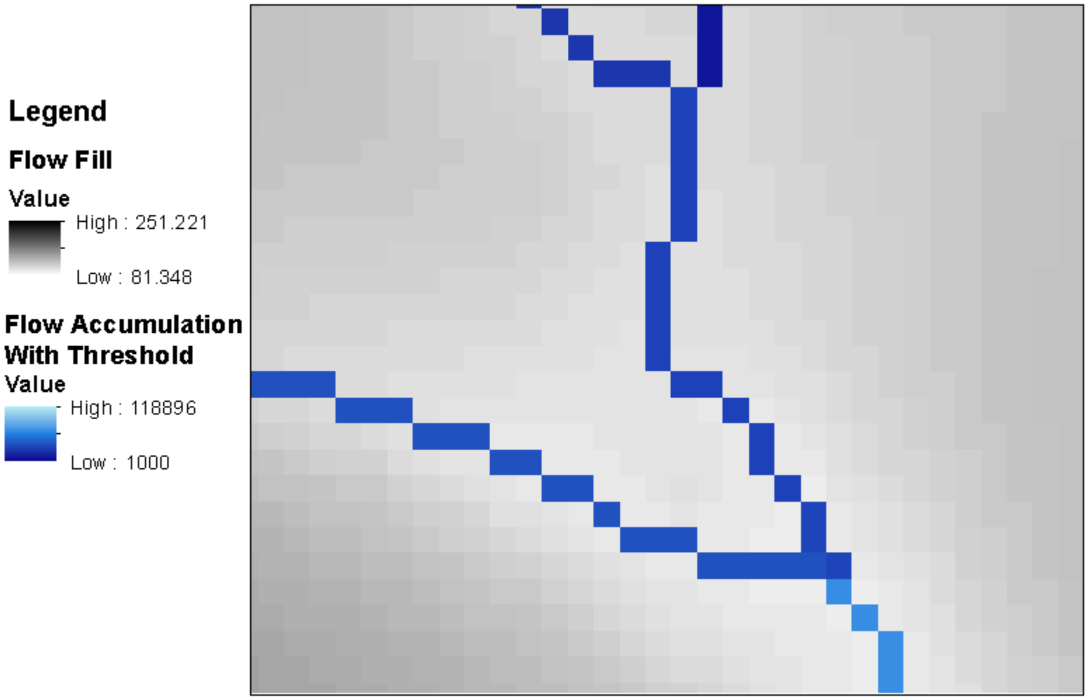


Figure 26: Intersection of raster of flow accumulation threshold and raster of flow fill.

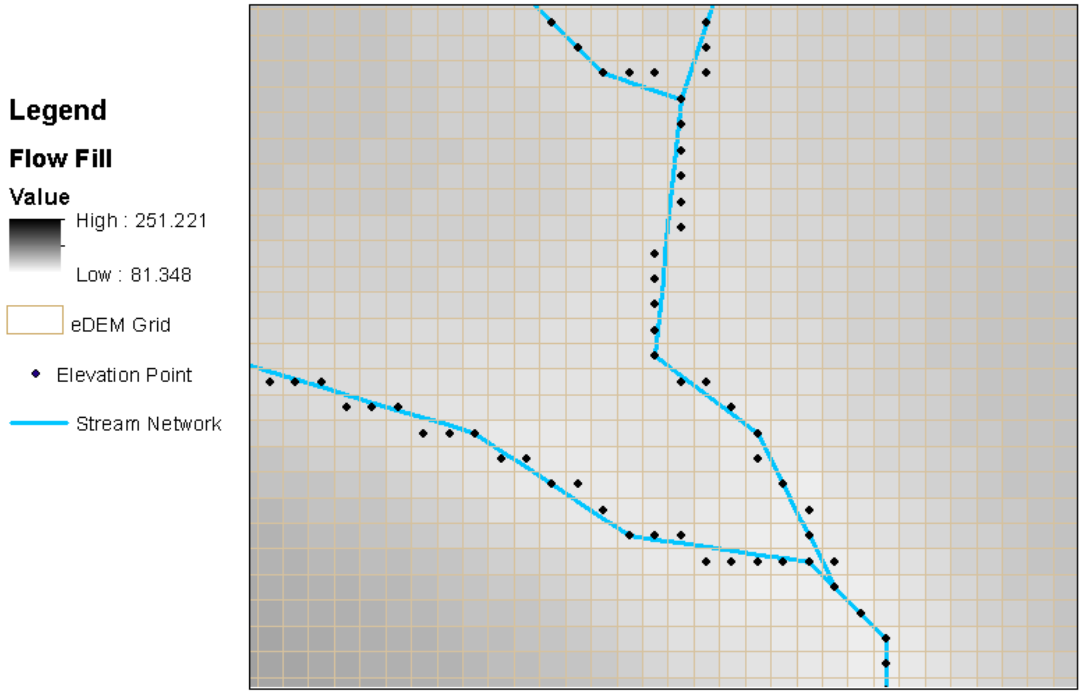


Figure 27: Vectorized point features containing elevation values from the raster of flow accumulation threshold joined to the grid of cells.

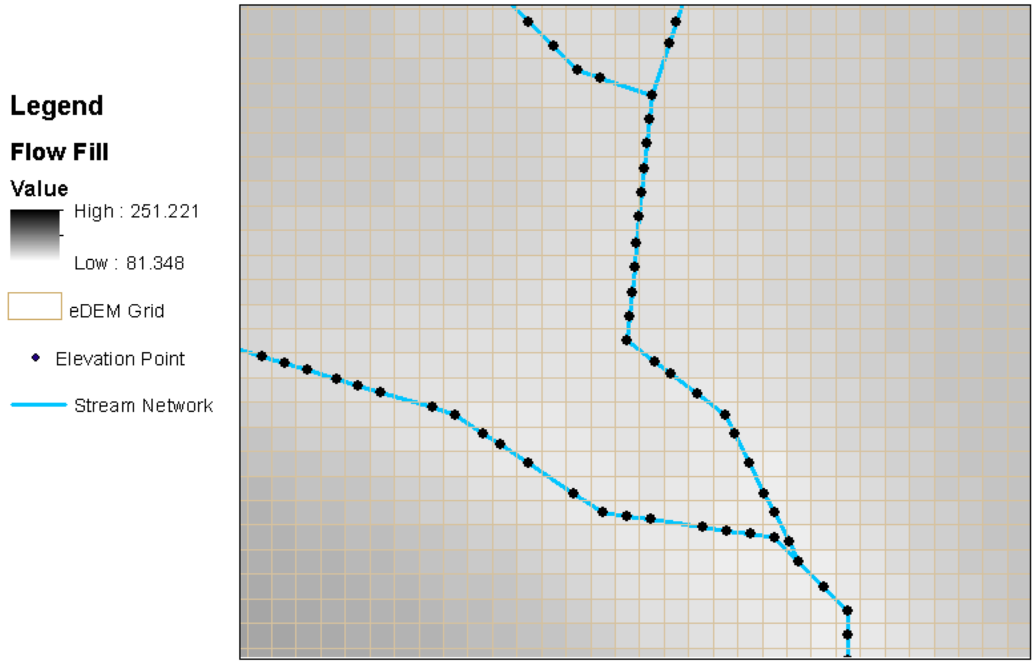


Figure 28: Elevation points placed along the stream network linear feature.

3.3.1.1.4 Stream Slope tool (Script in Appendix B: page 100)

The dialog box of the slope tool prompts the user to enter a folder path, the stream network linear feature and the elevation point features (Figure 29). The elevation point features are integrated into the stream network linear feature as vertices. The stream network linear feature is segmented using "horizontal slice" (Bizzi and Lerner, 2015; Jordan and Fonstad, 2005; Parker et al., 2015; Vocal Ferencevic and Ashmore, 2012) method, i.e. it is split at the integrated elevation point features' vertices to create reaches as linear features. The "horizontal slice" was used because total stream power is described as the rate of work per unit length, therefore channel length must be constant. This method also allows reaches to be defined at a higher spatial resolution because the shortest channel length is chosen. The "vertical slicing" method defines reaches by various channel lengths which decreases the spatial resolution of the reaches. Each reach has an elevation point feature' vertex at each end: upstream end and downstream end. Coordinates of the ends of are populated in the attribute table of the reaches and coordinates of the elevation point features are populated in the attribute table of the elevation points. Elevation values of the elevation point features are joined to both ends of the reaches based on their coordinates. The difference between the two elevation values of the ends is divided by their corresponding reaches' length to calculate the slope values (Figure 30).

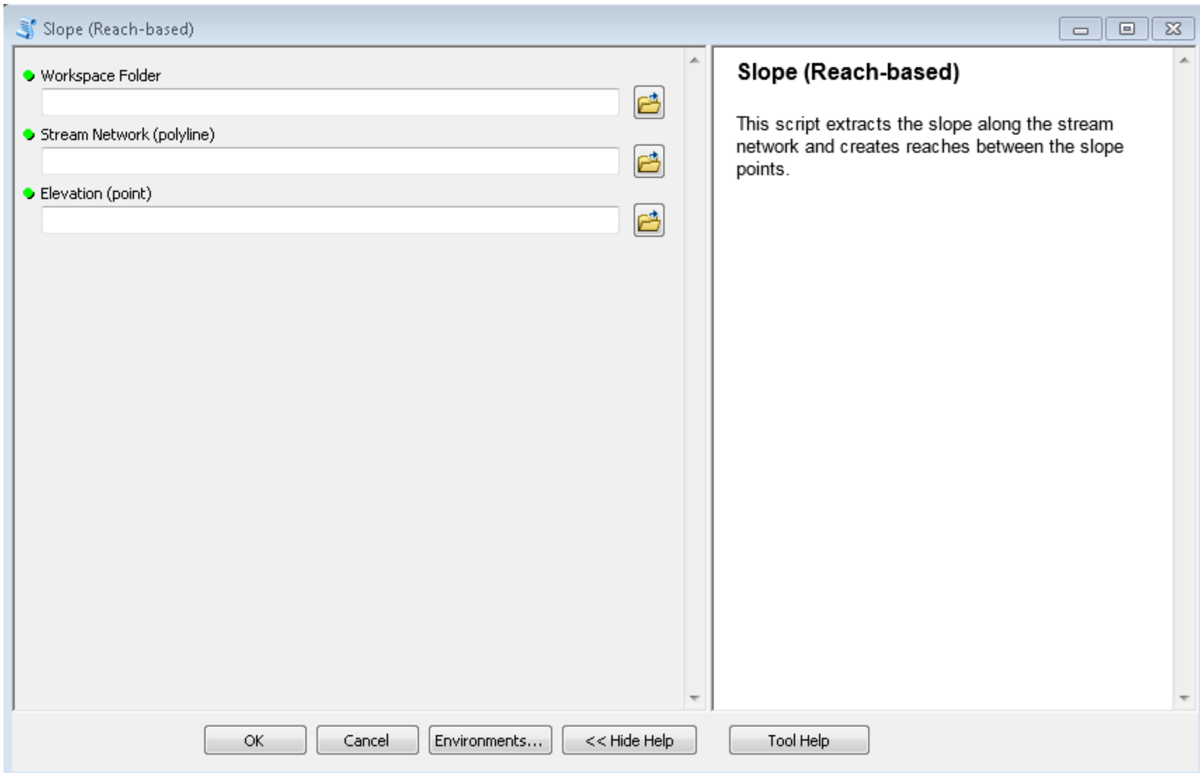


Figure 29: Dialog box of Slope tool.

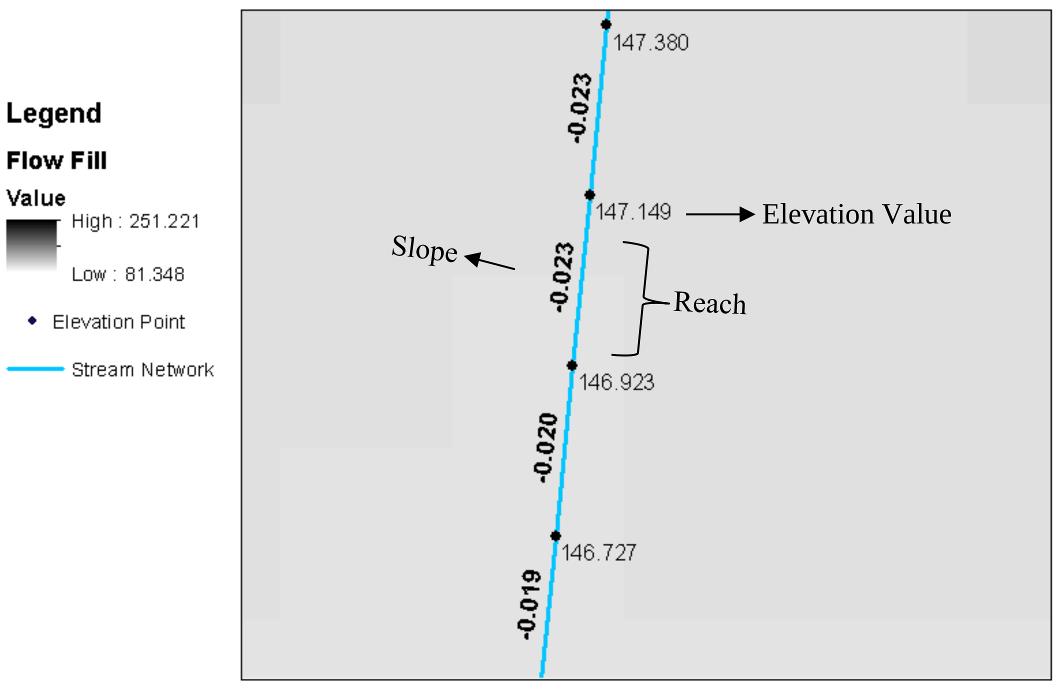


Figure 30: Definition of reach between elevation points and calculated slope for each reach.

3.3.1.1.5 Summary Table tool (Script in Appendix B: page 103)

The dialog box of the summary table prompts the user to enter a folder path, the raster of flow direction, the raster of stream order and the raster of flow accumulation threshold (Figure 31). The raster of stream order is vectorized to create a stream network linear feature. The magnitude order is assigned to each stream segment in the summary table (Figure 32). The summary table is used by the stream power tool to record results of the scenario analyses for comparative analysis.

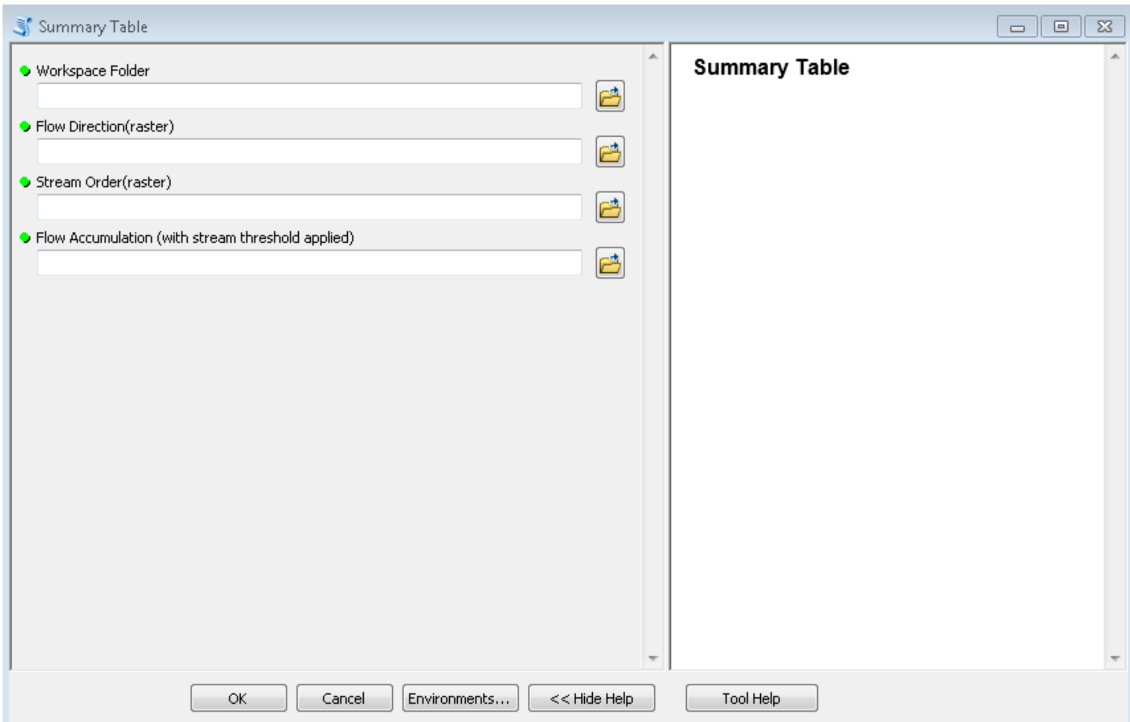
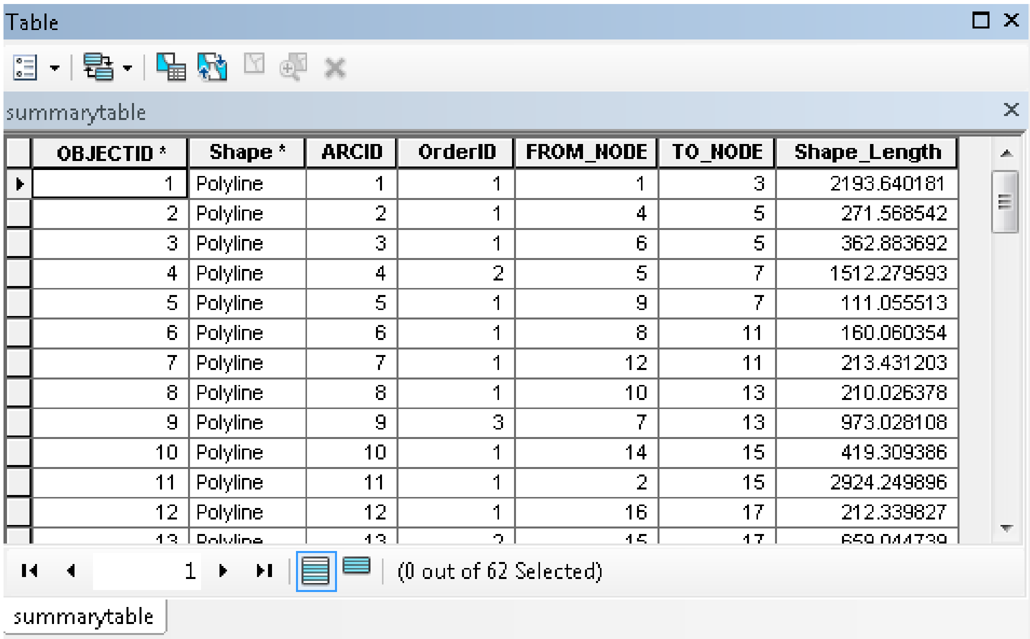


Figure 31: Dialog box of Summary Table tool.



Table

summarytable

OBJECTID *	Shape *	ARCID	OrderID	FROM_NODE	TO_NODE	Shape_Length
1	Polyline	1	1	1	3	2193.640181
2	Polyline	2	1	4	5	271.568542
3	Polyline	3	1	6	5	362.883692
4	Polyline	4	2	5	7	1512.279593
5	Polyline	5	1	9	7	111.055513
6	Polyline	6	1	8	11	160.060354
7	Polyline	7	1	12	11	213.431203
8	Polyline	8	1	10	13	210.026378
9	Polyline	9	3	7	13	973.028108
10	Polyline	10	1	14	15	419.309386
11	Polyline	11	1	2	15	2924.249896
12	Polyline	12	1	16	17	212.339827
13	Polyline	13	2	15	17	659.044739

1 (0 out of 62 Selected)

summarytable

Figure 32: Summary table's attribute table showing stream segments and their corresponding stream order: OrderID.

3.3.1.2 Rural Scenario Analysis

3.3.1.2.1 Rural Discharge tool (Script in Appendix B- Page 106)

The dialog box of the Rural Discharge tool prompts the user to enter a folder path, the stream network linear feature, the raster of flow accumulation threshold, the grid of cells, the cell size of the raster of flow accumulation and the coefficients for discharge calculation (Figure 33). The raster of flow accumulation threshold is vectorized to create point features with their corresponding accumulated flow value and the point features are used to select the cells (i.e. the cells belonging to the stream network) of the grid of cells by intersection (Figure 34). The accumulated flow values from the point features is assigned to the selected cells. The selected cells are vectorized to create discharge point features. The discharge point features are placed on the stream network linear feature (Figure 35). In the attribute table of the discharge point features, the accumulated flow value is converted into kilometres and divided by the square of the cell size of the raster of flow accumulation to obtain the drainage area in square kilometres. Rural discharge is calculated by applying the discharge-drainage area relationship (Equation 8: $Q = \alpha A^{\beta}$) with defined coefficients α and β. The stream network linear feature is segmented to create reaches as linear features between the discharge point features using the same method described in subsection 3.3.1.4. Each reach has a discharge point feature at the upstream end. Coordinates of the upstream end are populated in the attribute table of the reaches and coordinates of the discharge point features are populated in the attribute table of the discharge points. Discharge values of the discharge point features are joined to the upstream end of the reaches based on their coordinates (Figures 36 and 37).

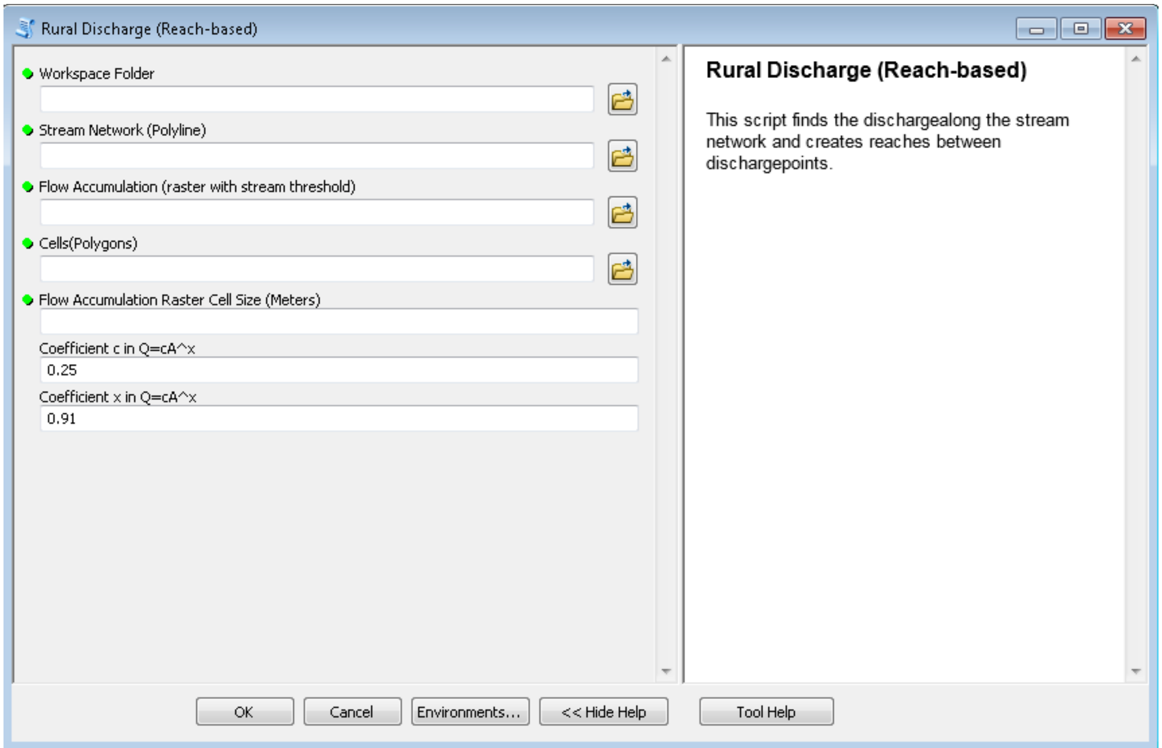


Figure 33: Dialog box of Rural Discharge tool.

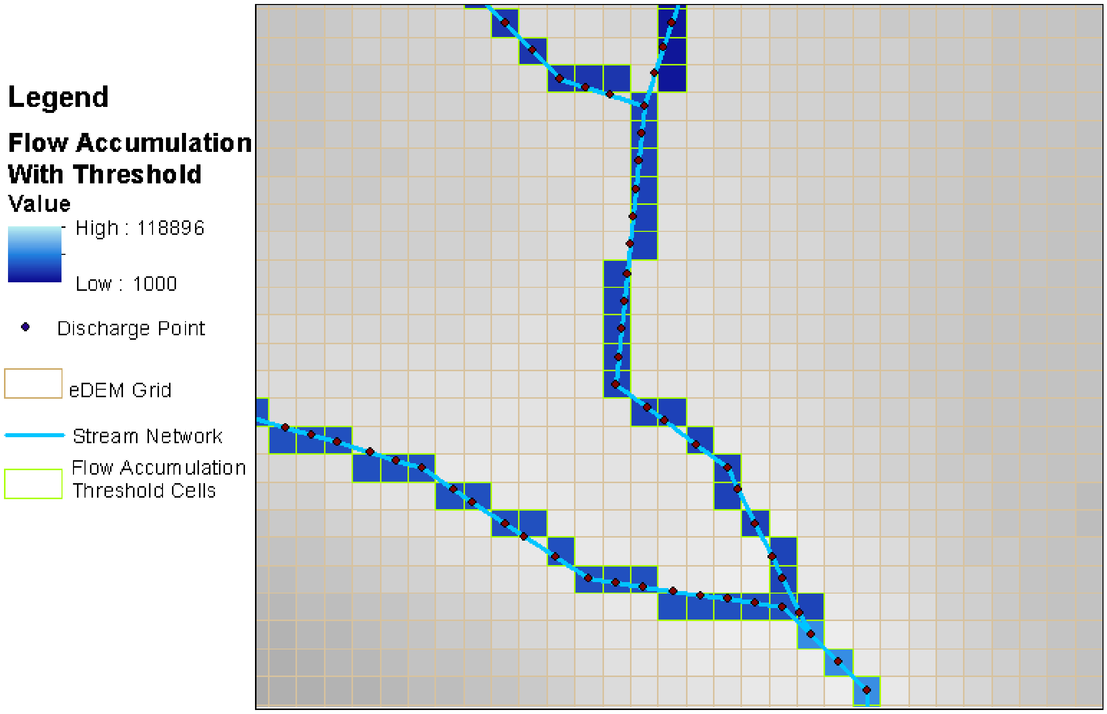


Figure 34: Cells which belong to the raster of flow accumulation threshold, i.e. the cells which define the stream network and point features with their corresponding accumulated flow value.

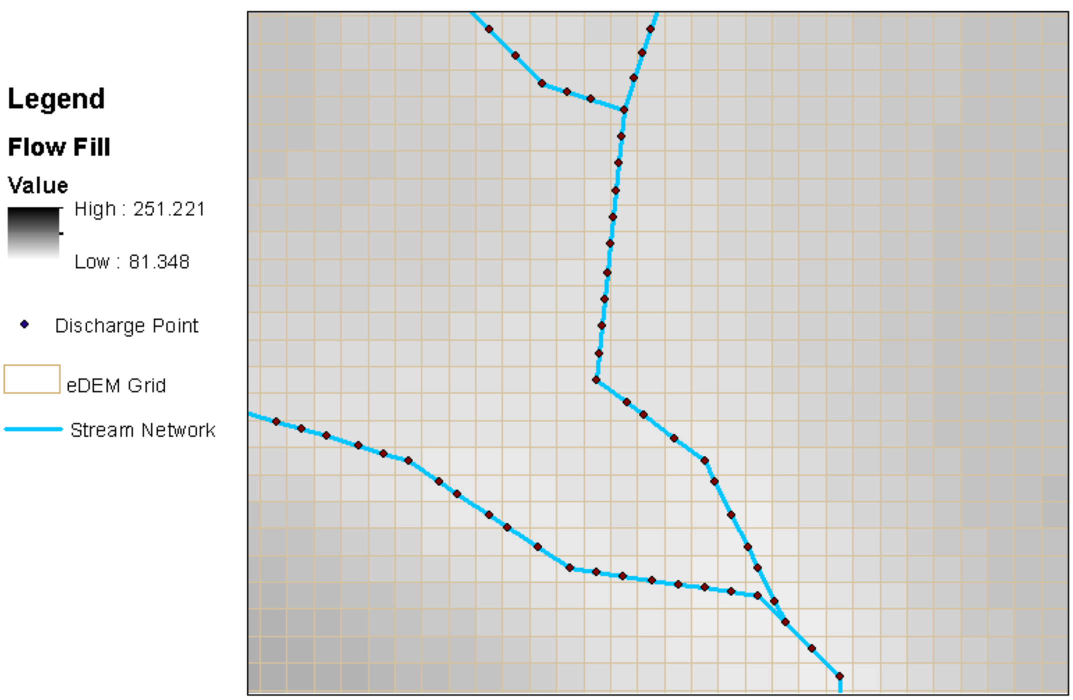


Figure 35: The discharge point features along the stream network linear feature.

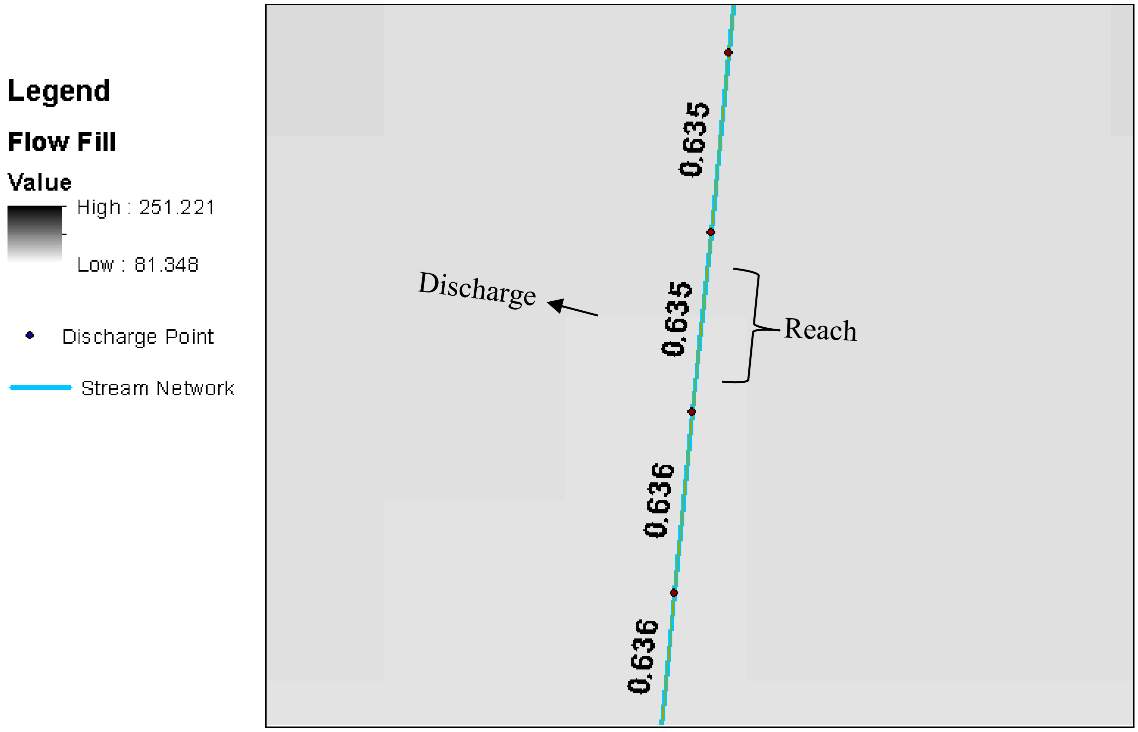


Figure 36: Reach as linear features with calculated discharge values

3.3.1.2.2 Stream Power Tool (Script in Appendix B – page 109)

The dialog box of Stream Power tool prompts the user to enter a folder path, the reaches with slope values, the reaches with (rural) discharge values, coefficients for the width equation, a checkmark for the sediment particle size (d84) prediction analysis, a checkmark for the summary table update, the path of the summary table and labels for the type and ID of the analysis (Figure 37). The reaches with slope values and the reaches with discharge values are intersected to create reaches for stream power calculations. The reaches for stream power calculations contain both slope and discharge values. To calculate total stream power (Equation 1), a field with the specific weight of water (9800N) is added and multiplied with the slope and discharge values. Another field is added to calculate width. Width is calculated using the width-drainage area relationship (Equation 9) with defined coefficients a and b. Another field is added to calculate specific stream power. Specific stream power (Equation 2) is calculated using calculated total stream power and width. The calculated values found in the attribute table can be added to the summary table.

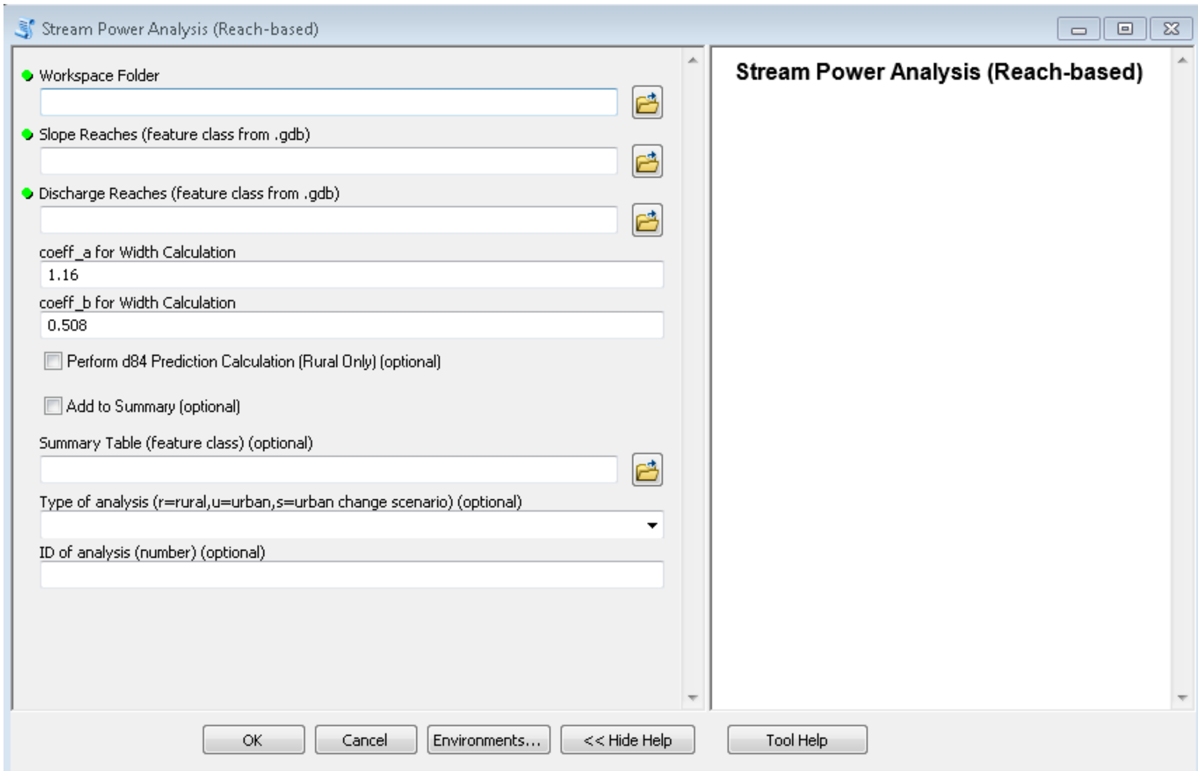


Figure 37: Dialog box of Stream Power tool.

Sediment Particle Size Model: The optional analysis of sediment particle size prediction was based on a predictive model developed from the critical stream power equations (Equations 5 and 6) proposed by Ferguson, (2005).

Data: Two sets of data were tested. The first set of data was obtained from the database prepared by Annable (1996b) on streams in Southern Ontario. A series of cross-sectional surveys were conducted on 47 streams where gauges were available for estimating discharge. Drainage area, slope, bankfull width, bankfull discharge, 2-year flood discharge, Manning's coefficient, n, and sediment particle sizes (d50 and d84) were extracted from the database for the 47 streams. Only rivers with sediment particle sizes between 2mm and 1000m were used from the data. The second set of data was obtained from the database called Flowing Water Information Systems (FWIS) (The Centre for Community Mapping (COMAP), 2017). The database contained sediment particle sizes (d50 and d84) collected by the TRCA, Ontario Ministry of Natural Resources and academic institutions in Southern Ontario. Drainage area and slope were obtained from spatial analysis of an enhanced DEM of 10m spatial resolution from the Ontario Hydrologic dataset. Empirical relationships developed by Annable (1996a) were used to calculate bankfull discharge ($Q_{bf} = 0.52A^{0.75}$) and bankfull width $W_{bf} = 3.7Q_{bf}^{0.50}$.

Methods: The logarithmic flow resistance law (Equation 5) and Manning-Strickler law (Equation 15) of critical stream power were used to predict sediment particle size for the two sets of data by assuming a stability criterion (i.e. $D_i = D_b$) and bankfull critical stream power, ω_{ci}:

$$\mathrm{D_b} = \frac{(\omega_{ci}k)^{1.5}}{\theta_{cb}Rg\left(2.30p\ log\left(\frac{30\theta_{cb}R}{emS}\right)\right)^{1.5}} \tag{14}$$

$$\mathrm{D_b} = \frac{{\omega_{ci}}^{2/3}\ S^{1/9}}{ap^{\frac{2}{3}}\ g(\theta_{cb}R)^{10/9}} \tag{15}$$

For gravel bed sediment particles, Θ_{cb} is typically assumed to be constant (0.045) (Ferguson, 2005) and m is assumed to be 2.80 for d84 (Lopez and Barragan, 2008).

Results and Discussion: The Manning-Strickler law (equation 6) was not effective at producing a good predictive model for both sets of data, therefore only the logarithmic flow resistance law is discussed here. The d50 sediment particle size was poorly predicted and only a small range of d84 sediment particle size was predicted from the second set of data (i.e. FWIS). Only the d84 sediment particle sizes predicted were in line with the measured d84 sediment particle sizes for the first set of data (i.e. Annable 1987). The higher utility of the Annable dataset is likely because the width and discharge are measured values instead of being derived from empirical relations, which reduces the uncertainty of the specific stream power estimation. Prediction error was calculated using the Phi scale. The phi scale is a scale for sediment particle size distributions which emphasizes finer sediment particle sizes using a negative logarithmic (Equation 16) transformation of sediment particle diameter (mm) (Krumbein and Sloss, 1951). Phi size values range from -5 phi (for sediment particle diameter of 32mm) to +10 phi (for sediment particle diameter of 1/1024mm) (Donoghue, 2016).

$$\Phi = -\log_2 \frac{D}{D_0} \tag{16}$$

The error in predicted d84 sediment particle sizes is quite low where slope is higher than 0.5% (less than one phi class) (Figure 38). Poor predictions occurred where slope is lower than 0.5% (Figure 38). The error was also correlated with channel width (R^2 = 0.44) whereby wider channels showed a greater error (Figure 39). These relationships are reasonable because high errors could be a result of measurement errors. Slope is difficult to measure in channels with low slopes and the overall water surface slope (or friction slope) is seldom measured. Measurements often rely on topography of beds. It is also difficult to measure d50 and d84 of wide channels due to their high variability. Lateral sediment sorting could be significant with the development of lateral bars that are sedimentologically distinct from the main channel. In addition, the d84 sediment particle size predictions were smaller than the actual measured values. Since Southern Ontario is characterized by glacial till, coarse non-alluvial materials are constantly added to the channel, thus biasing the particle sizes in the streams where they may be coarser than predicted.

Given the reasonable results by equation 5, it can be used to predict d84 sediment particle sizes for specific ranges of slope and width for reaches along stream networks. It is available to the user in the SDSS as an optional analysis. A checkmark in the dialog box is used to activate the particle size analysis.

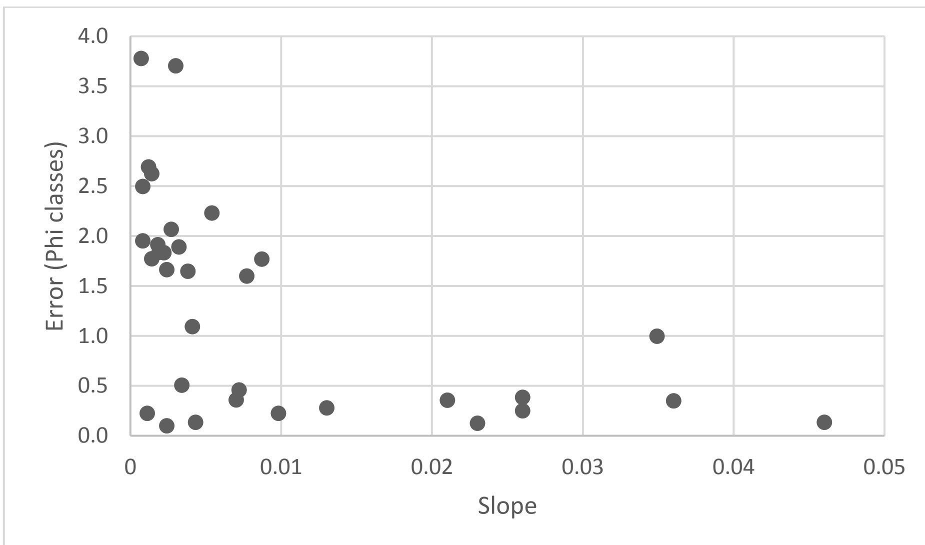


Figure 38: Effect of channel slope on accuracy of d84 sediment size prediction.

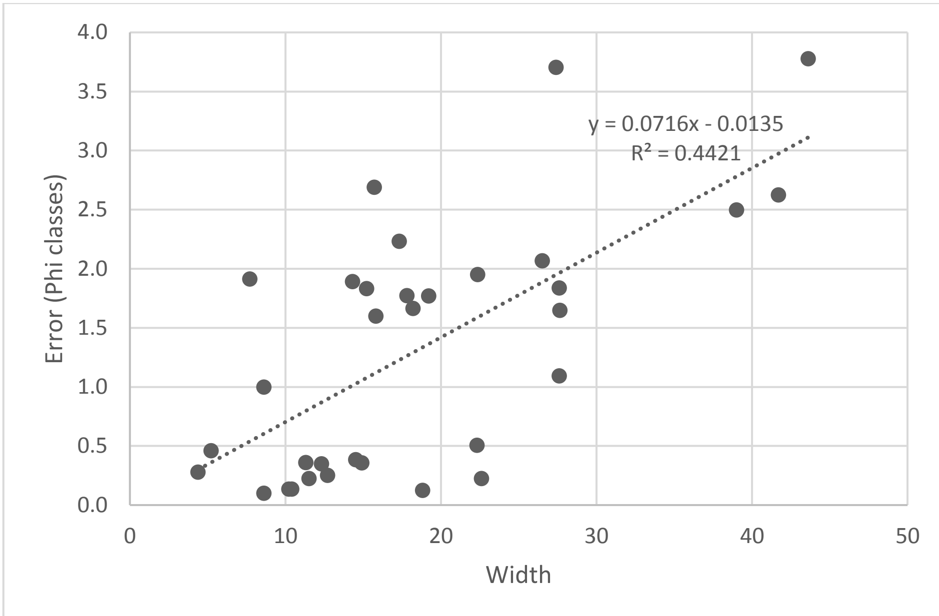


Figure 39: Effect of channel width on accuracy of d84 sediment size prediction.

3.3.1.3 Urban Scenario

3.3.1.3.1 Drainage Area tool (Script in Appendix B – page 115)

The dialog box of the Drainage Area tool prompts the user for a folder path, the discharge point features, the raster of flow accumulation threshold and the raster of flow direction. The raster of flow direction is used to find all the cells which flow to each cell of the raster of flow accumulation threshold (Figure 40). The cells flowing into each cell of the raster of flow accumulation threshold are vectorized into a single polygon feature representing the drainage area (Figure 41). The discharge point features are joined to their corresponding drainage area polygon features.

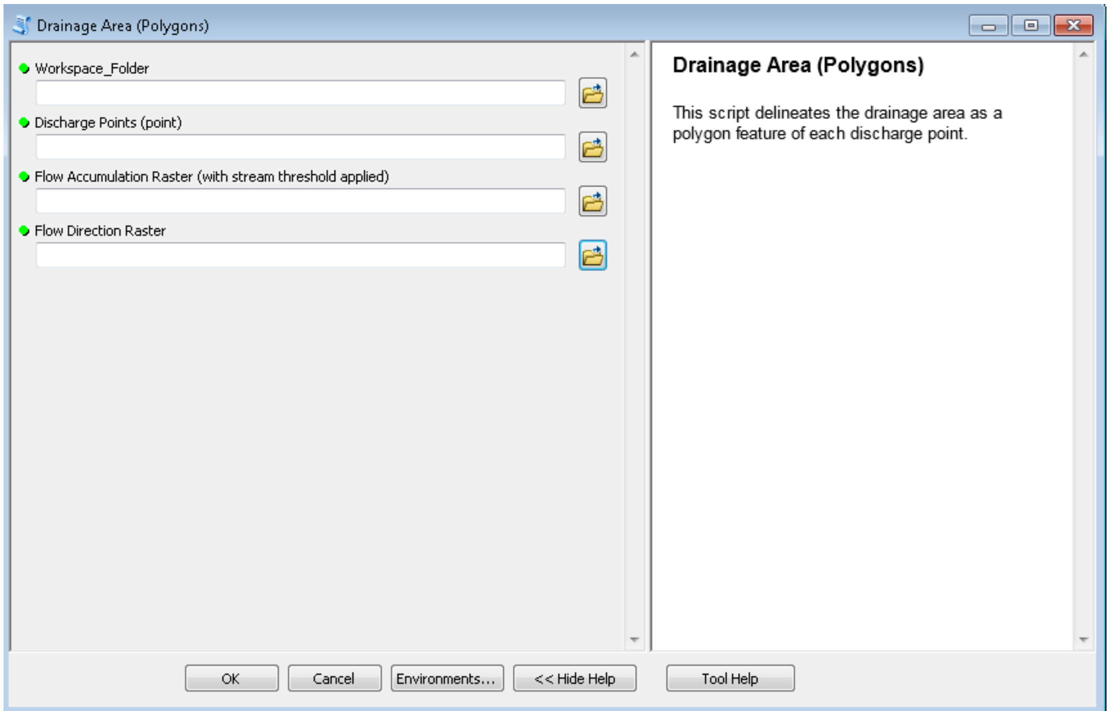


Figure 40: Dialog Box of Drainage Area tool.

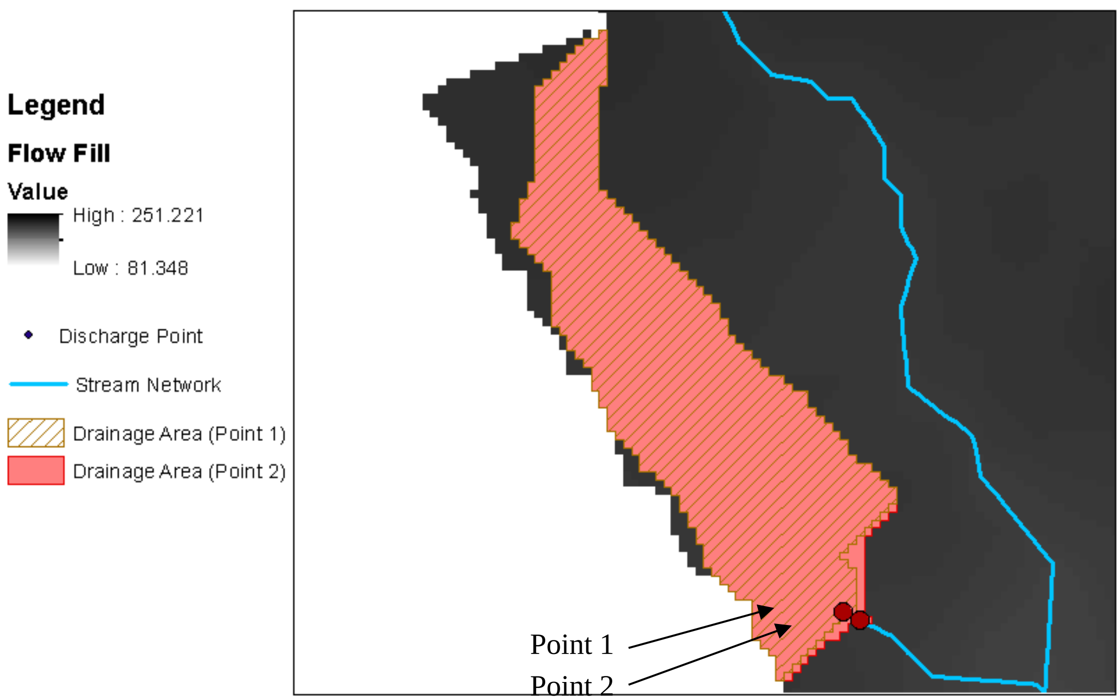


Figure 41: Drainage area polygon features delineated for two discharge points along the stream network linear feature.

3.3.1.3.2 Future Land Use tool (Script in Appendix B – page 117)

The dialog box of the Future Land Use tool prompts the user for a folder path, a pre-development land use and cover and a new land use and cover with post-development or future land developments (Figure 42). The user can create new land parcels as polygon features in a shapefile (.shp) in Editing Mode and adds an attribute field called "imper_pcnt" to store their associated imperviousness (%) or they can provide existing land use and cover. Actual (or pre-development) land parcels (Figure 43) are replaced using the new (or post- development) land parcels to produce a new vector polygon feature for land use and cover (Figure 44) which can be used to calculate urban discharge.

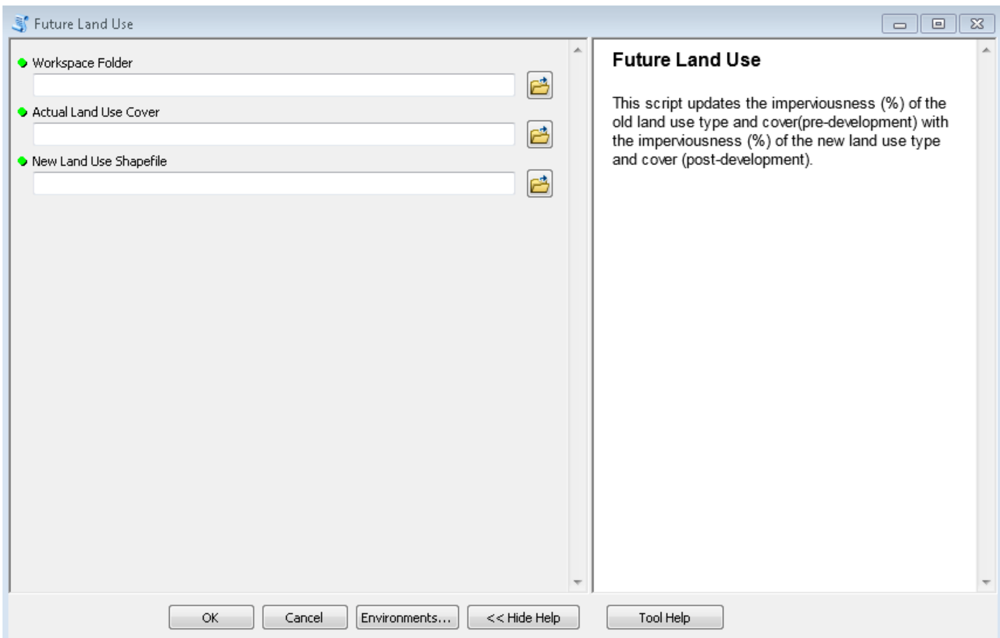


Figure 42: Dialog box of the Future Land Use tool.

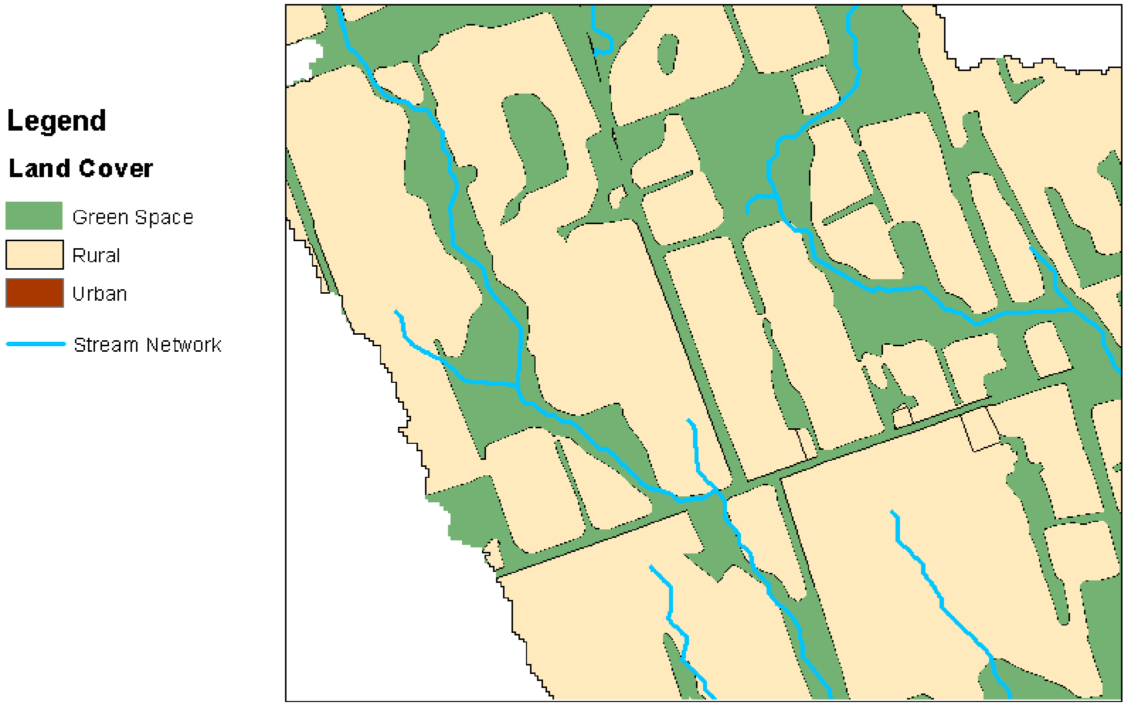


Figure 43: Example of a pre-development area within an urbanizing watershed.

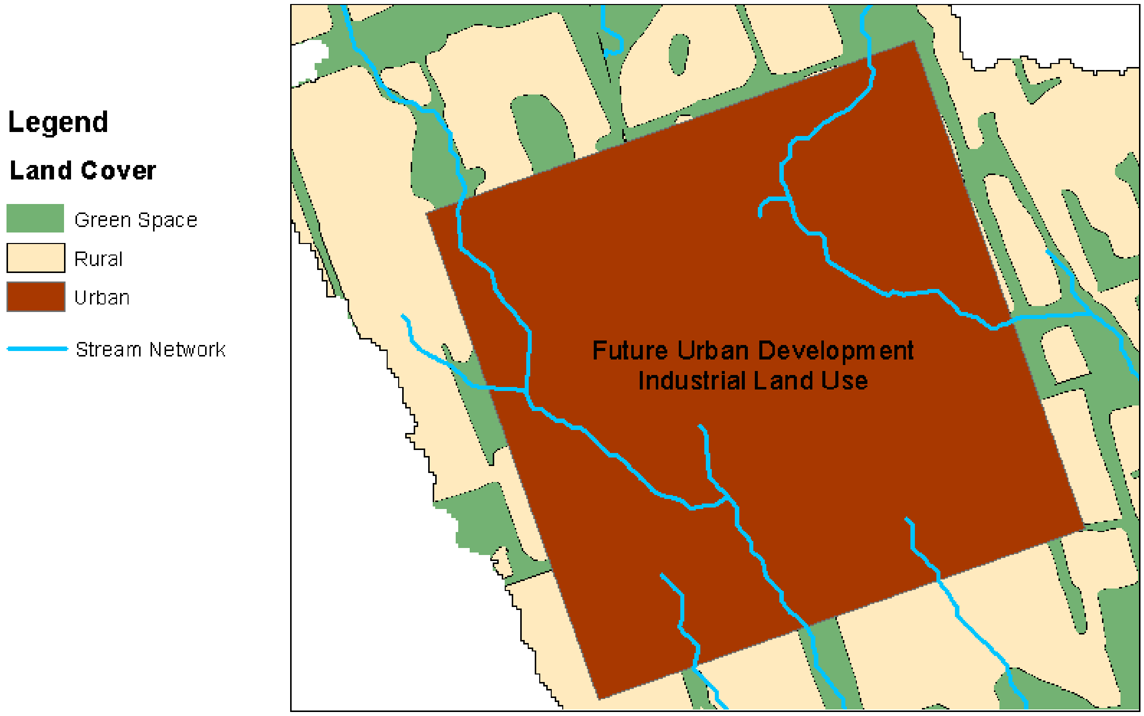


Figure 44: Example of future land development within an urbanizing watershed.

3.3.1.3.3 Urban Discharge tool (Script in Appendix B – page 119)

The dialog box of the Urban Discharge tool prompts the user for a folder path, the discharge point features from the rural scenario, the drainage area polygon features, the land use and cover polygon features, the coefficients for the urban discharge equation and the reaches with discharge values calculated from the rural scenario (Figure 45). In the attribute table of the drainage area polygon features, the cell size of the eDEM is squared and multiplied by the area of the polygons to calculate the drainage area in square kilometres. The drainage area polygon features are intersected with the land use polygon features to determine the area occupied by each land use within the drainage area polygon features. The area of each land use type is multiplied by their associated imperviousness to obtain their area of imperviousness. This area of imperviousness is summed for each drainage area polygon feature to obtain total area of imperviousness. The ratio of total area of imperviousness and total area of the drainage area polygon feature is calculated as a percentage and assigned to each discharge point feature of the reaches. Urban discharge is calculated by applying the discharge -drainage area - total imperviousness relationship (Equation 10) with defined coefficients a, b and c. The discharge values of the highlighted stream segment (Figure 46) is higher after post- development of the urban industrial land use and cover (Table 7).

To analyze different scenarios of land use and cover changes, users can enter different land use and cover polygon features in the dialog box to calculate urban discharge.

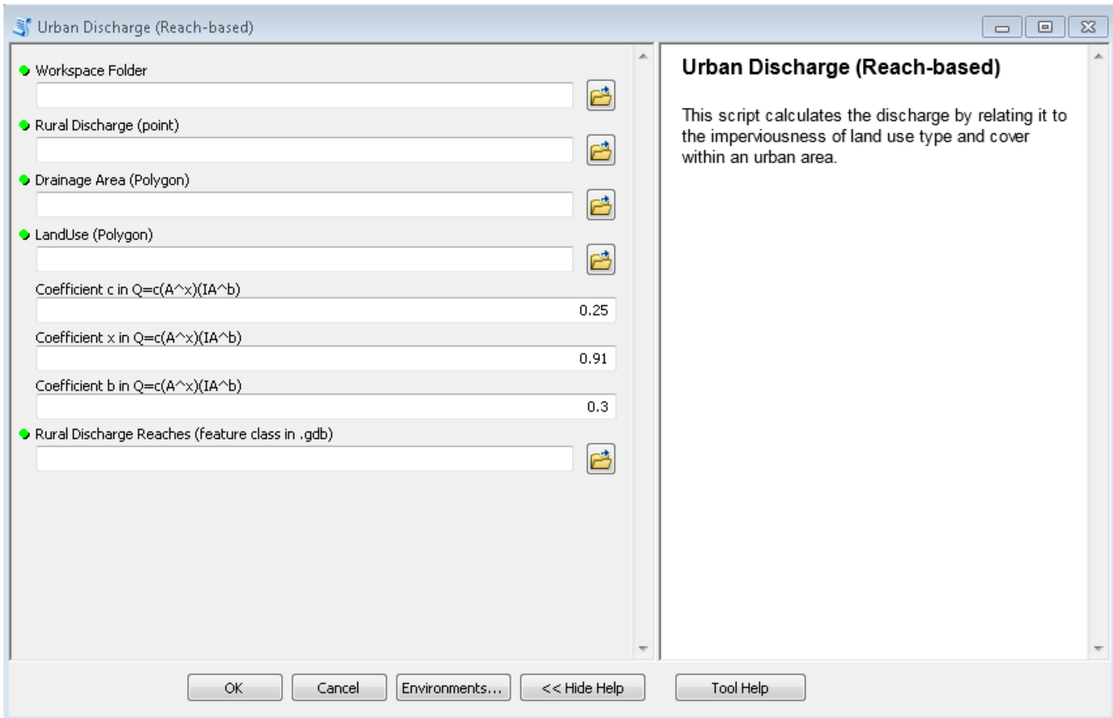


Figure 45: Dialog box of Urban Discharge tool.

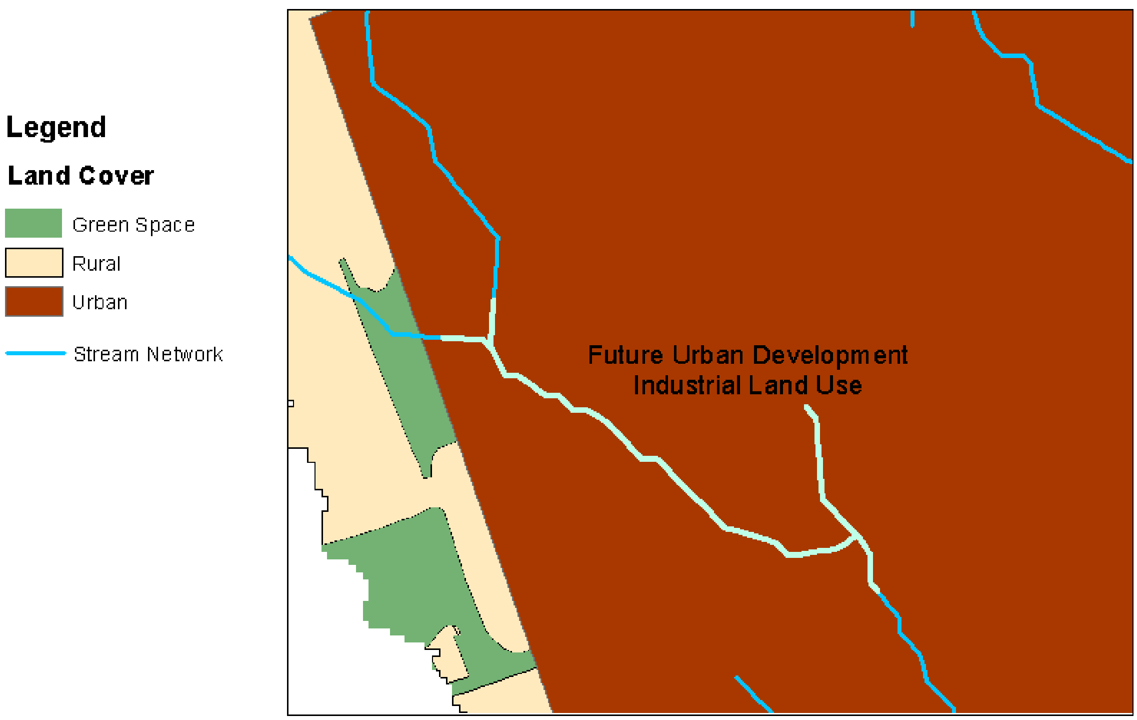


Figure 46: Highlighted (light blue) stream segment.

Table 7: Pre-development discharge values vs post-development discharge values of each reach of the highlighted stream segment in figure 46.

OBJECTID	SHAPE	Total Imperviousness (%)	Drainage Area (km^2)	*Pre-Development* Discharge (m^3/s)	*Post-Development* Discharge (m^3/s)
366	Polyline	1.583	0.148	0.049	0.050
367	Polyline	1.715	0.150	0.049	0.052
368	Polyline	1.901	0.151	0.049	0.054
369	Polyline	1.963	0.151	0.049	0.054
370	Polyline	2.024	0.151	0.049	0.055
371	Polyline	2.086	0.151	0.049	0.055
372	Polyline	2.147	0.151	0.050	0.056
373	Polyline	2.209	0.151	0.050	0.056
374	Polyline	16.594	1.201	0.390	0.680
615	Polyline	11.400	1.116	0.373	0.569
616	Polyline	11.438	1.116	0.373	0.569
617	Polyline	11.453	1.117	0.373	0.570
618	Polyline	13.218	1.141	0.378	0.606
619	Polyline	13.347	1.142	0.379	0.609
620	Polyline	13.561	1.145	0.379	0.613
621	Polyline	14.279	1.156	0.381	0.628
622	Polyline	14.523	1.159	0.382	0.633
623	Polyline	14.523	1.159	0.382	0.633
624	Polyline	15.419	1.172	0.385	0.651
625	Polyline	15.742	1.178	0.386	0.658
626	Polyline	16.184	1.184	0.387	0.667
627	Polyline	16.528	1.200	0.390	0.679
628	Polyline	16.580	1.200	0.390	0.680

3.3.1.3.4 Stream Power tool.

The dialog box of Stream Power tool prompts the user to enter a folder path, the reaches with slope values, the reaches with (urban) discharge values, coefficients for the width equation, a checkmark for the summary table update, the path of the summary table and labels for the type and ID of the analysis (Figure 37). The same process of 3.3.1.2.2 is followed. Total stream power (Equation 1) is calculated using calculated slope and discharge. Width is calculated using the width-drainage area relationship (Equation 9) with user-defined coefficients a and b. Specific stream power (Equation 2) is calculated using calculated total stream power and width. All calculated values are found in the attribute table (Figure 47).

Table

strmpower_reach

OBJECTID *	Shape *	totalimp_percnt	drainarea_km2	Q_m3pers	lengthr_m	S_mperm	Wg_Nperm3	Power_Wperm	a	b	Width_m	SPower_Wperm
1	Polyline	<Null>	<Null>	<Null>	5	<Null>	9810	<Null>	1.1	0.50	<Null>	<Null>
2	Polyline	18.175814	0.1042	0.075607	10	-0.011336	9810	-8.407732	1.1	0.50	0.367735	-22.863573
3	Polyline	18.256524	0.1047	0.076038	10	-0.010255	9810	-7.649827	1.1	0.50	0.36863	-20.752035
4	Polyline	18.332892	0.1069	0.077587	10	-0.011334	9810	-8.626838	1.1	0.50	0.372545	-23.156503
5	Polyline	18.425717	0.1075	0.078102	10	-0.012526	9810	-9.5971	1.1	0.50	0.373606	-25.687778
6	Polyline	18.404599	0.1082	0.078537	10	-0.013377	9810	-10.306625	1.1	0.50	0.37484	-27.496096
7	Polyline	18.293954	0.109	0.078923	10	-0.013086	9810	-10.131551	1.1	0.50	0.376245	-26.928074
8	Polyline	18.14414	0.1099	0.07932	10	-0.009782	9810	-7.61194	1.1	0.50	0.37782	-20.147008
9	Polyline	17.660082	0.1139	0.08128	10	-0.009222	9810	-7.353593	1.1	0.50	0.384744	-19.112943
10	Polyline	17.42902	0.1164	0.082575	10	-0.009496	9810	-7.692007	1.1	0.50	0.389011	-19.773226
11	Polyline	17.038539	0.1201	0.084385	10	-0.009932	9810	-8.221837	1.1	0.50	0.395245	-20.801902
12	Polyline	16.353098	0.1294	0.089206	10	-0.010278	9810	-8.994624	1.1	0.50	0.410507	-21.911011
13	Polyline	16.04495	0.1329	0.090878	10	-0.010349	9810	-9.22588	1.1	0.50	0.416111	-22.171706

1 (0 out of 2443 Selected)

strmpower_reach

Figure 47: Attribute table of reaches with stream power values.

The following is a figure showing the analytical design of the model framework of the SDSS:

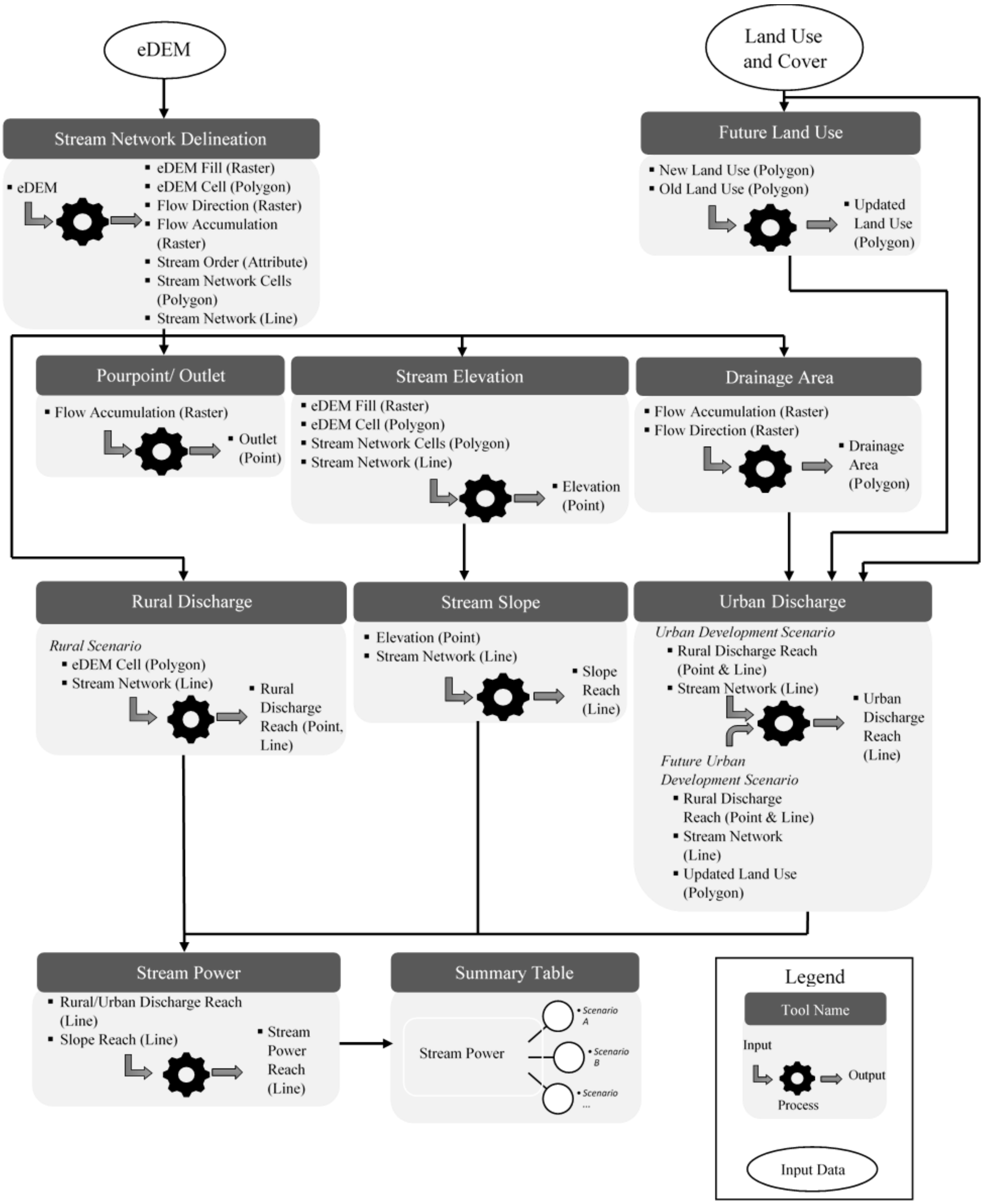


Figure 48: Model framework's workflow of Stream Network SDSS for modelling stream power for two types of scenarios: rural and urban.

3.4 Knowledge Management

The user is required to provide intelligent support when following instructions presented in dialog boxes of the tools, controlling different processes using checkboxes, entering rational parameters, interpreting progress and error messages during processing, resolving errors, modifying and creating scripts and making cartographic displays. Knowledge entered by the user is handled by the internal knowledge management system to apply facts, rules, logic, criteria and constraints during operation of the SDSS. Utility-based knowledge is provided through the GUI of the toolbox and dialog boxes to guide the user with entry of knowledge and data and usage of tangential tools. Process-based knowledge is provided as instructions and an illustrative case study in this report to guide the user in using the SDSS. Model-based knowledge is provided within scripts as coding explanations to guide the user in understanding the logical structure of the specialized analyses behind the decision support process. A knowledge- driven decision logic allows for plausible and consistent scenario development when exploring possible results of stream power which may arise under different land use and cover changes. Users can explicitly question, control and assess assumptions of future land use and cover changes as provided by the flexibility of predictive scenario analysis.

3.5 Multi-Linear Spatial Problem-Solving Environment

Alternative solutions of the spatial problems are generated through iteration with the application of different knowledge for a multi-linear problem-solving environment. Different eDEMs can be used to analyse different watersheds' slope, discharge, total stream power, specific stream power and sediment particle size. Different land use and cover data can be used to calculate total stream power and specific stream power values for urban scenarios for comparative analyze.

Chapter 4: Illustrative Application (Case Study)

The TRCA works with the City of Toronto, Municipality of Durham, Municipality of Peel, Municipality of York, Township of Adjala-Tosorontio and Town of Mono to manage nine watersheds and a portion of the Lake Ontario shoreline of the GTA, Southern Ontario (ON), Canada (Figure 49) (TRCA, 2013). The total area of jurisdiction of TRCA is 3495 km^2 and is characterized as rural (38%), urban (52%) and urbanizing(10%) (TRCA), 2013). All watersheds have been impacted by urbanization (Table 8) and are experiencing annual increases from 0.3% to 2.9% in flow volumes (TRCA, 2016a). There are more than half of the urban areas which can be at risk at flooding and water quality degradation because they are not equipped with stormwater control (TRCA, 2016b). Water quality and aquatic life are at threat due to increasing amount of chlorides. The GTA is projected to be the fastest growing metropolitan area with a population of 52.7% of total population of Ontario by 2041 (Ministry of Finance, 2016).

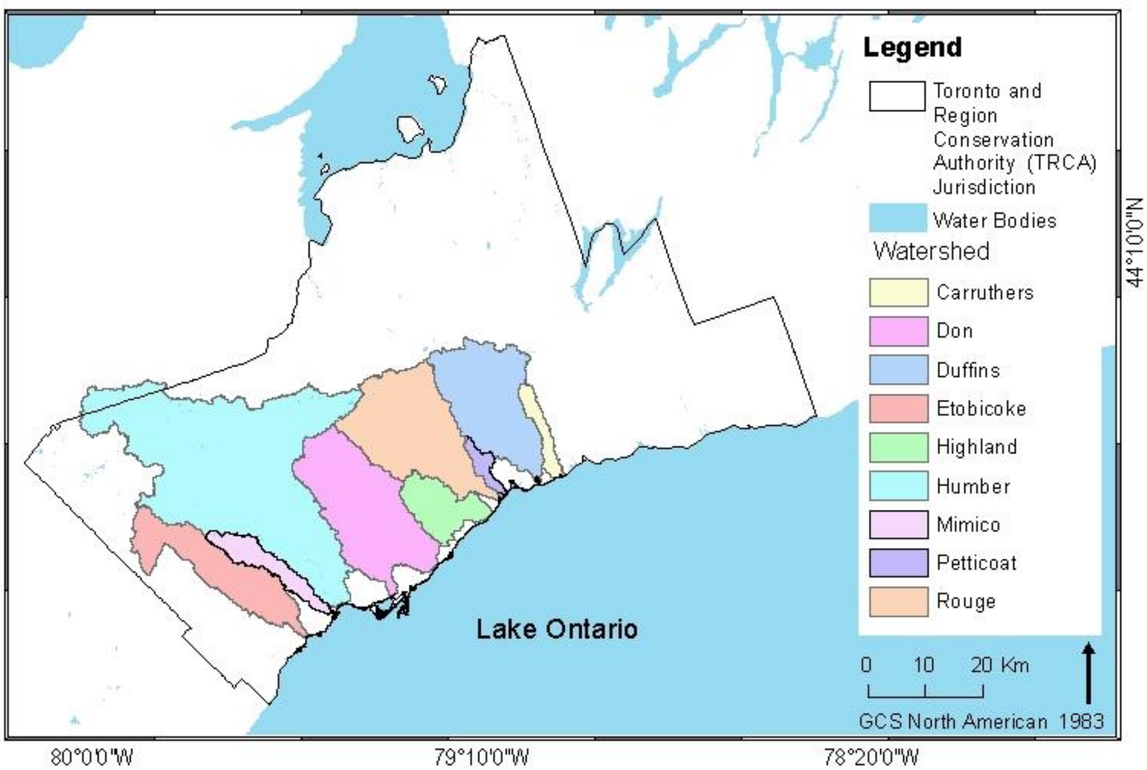


Figure 49: Map of area of jurisdiction and watersheds managed by Toronto Region Conservation Area (TRCA), Greater Toronto Area (GTA), Ontario (ON), Canada.

Table 8: Nine watersheds managed by Toronto Region Conservation and Authority and their characteristics (TRCA, 2016).

Watershed	Population	Drainage Area (km^2)	Land Use			Impact of Urbanization
			Rural	*Urban*	*Urbanizing*	
1.Etobicoke	286361	211	27	68	5	
2.Mimico		77	0	100		
3.Humber	856200	911	54	33		Stream erosion, flooding, fragmentation of forested areas, loss of heritage and fish migration barriers
4.Don River	1.2 million	360				Stream erosion and flooding
5.Highland	360000			85		Erosion, flooding and degradation of natural habitats
6.Rouge River		336	40	35		Stream erosion, sedimentation and instability, loss of biodiversity and water pollution
7.Petticoat		27	70	21		Increased risk of erosion and flooding, stream sedimentation and water pollution
8.Duffins			71	10	19	Increasing pressure on water, fauna and flora in the face of growth
9.Carruthers						

4.1 Study Site

Illustration of the SDSS focused on Ganetsekaigon Creek in Duffins watershed (Figure 50). Ganetsekaigon Creek has a drainage area threshold of $1000m^2$ which defines the stream network. The land use is predominantly agricultural (58%) and there is 2% of urban land and 40% of natural cover consisting of forest, meadow and wetland (TRCA, 2002). The subwatershed is approximately 13.1 km^2 and it is underlain by the till deposits in the north and Lake Iroquois glaciolacustrine deposits in the south (TRCA, 2004).

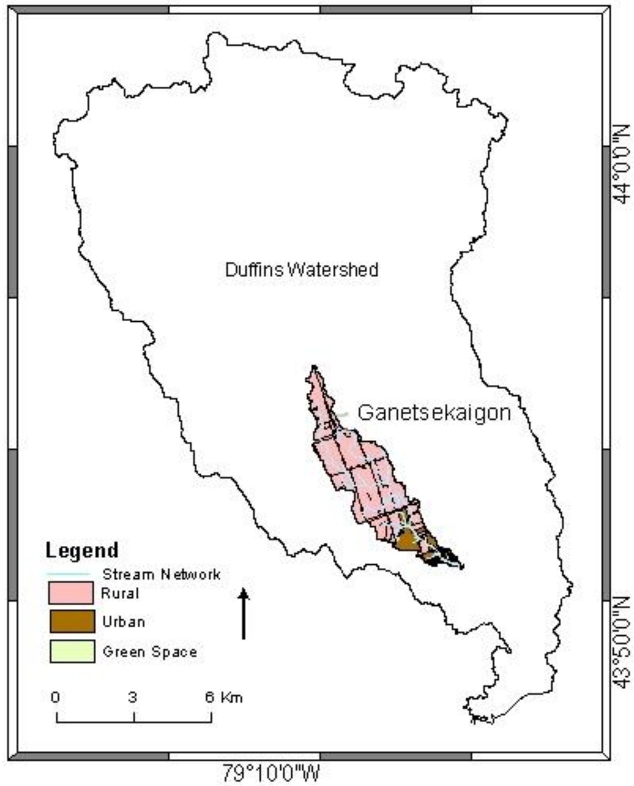


Figure 50: Selected study site Ganetsekaigon Creek, Duffins watershed to illustrate the SDSS.

4.2 Data

All spatial data was acquired from the web-based spatial database system, Flowing Waters Assessment Information System (FWIS) (The Centre for Community Mapping (COMAP), 2017). Its visualization capability enabled easy data access and its versatility enabled data extraction in the formats used by ArcGIS. An enhanced DEM (eDEM) from the Ontario Integrated Hydrology Data collection and land use vector data from the TRCA were used. The eDEM was created on 17 November 2012 by the Ontario Ministry of Natural Resources and Forestry – Mapping Unit, Peterborough, Ontario, Canada and distributed by Land Information Ontario. It has a spatial resolution of 10 metres and its geographic extent is N: 57.32100, W: -95.83800, S: 41.35800 and E: -73.90100 for World Geodetic System 1984. Its last update was in March 2017. The land use vector data consists of existing land parcels and their associated land use type and imperviousness (%). Information on imperviousness (%) was obtained from Wet Weather Flow Management Guidelines (WWFM) of the City of Toronto - HSP-F Water Quantity Model Calibration and Validation (City of Toronto, 2006) (Appendix A-Tables 1 and 2).

4.3 Methods

Total and specific stream powers for both types of scenarios (rural and urban) were modelled by integrating existing empirical models in the SDSS. Regional coefficients for empirical models (Table 9) were entered in the dialog box of the Rural Discharge, Urban Discharge and Stream Power tools before processing. Regional coefficients of discharge for the rural scenario and for width of specific stream power were obtained from Phillips and Desloges, (2014) whose study was based on streams in Southern Ontario. Total stream power was calculated using the empirical equation developed by Annable (1996b) and used by Vocal Ferencevic and Ashmore, (2012) for comparison of results. Regional coefficients for the empirical model of discharge for the urban scenario were approximated from equations in Bledsoe and Watson, (2001) and Ward and Trimble, (2004). A future urban development scenario was also modelled by creating an industrial land parcel polygon shapefile using Editing Mode and its imperviousness (95%) was entered as an attribute under the field "imper_pcnt". It was placed on an existing farm land parcel of the urban land use vector data. The Future Land Use tool was used to replace the area of the existing farm land parcel with the area of the new industrial land parcel. Main results of the SDSS are presented at the reach scale to illustrate the specialized analyses. Final results of total and specific stream power from the case study are presented at the watershed scale.

Table 9: Summary of empirical models used for the case study.

Scenario	Equations	Source
Rural Discharge	$Q_2 = 0.248A^{0.910}$; $r^2 = 0.86$, n = 210, $p < 0.001$	Phillips and Desloges, (2014)
	$Q_2 = 0.52A^{0.74}$ $r^2 = 0.64$, n = 47	Vocal Ferencevic and Ashmore, (2012)
Urban Discharge	$Q_2 = 0.248A^{0.910}IA^{0.3}$	Approximations from Bledsoe and Watson, (2001) and Ward and Trimble, (2004)
Specific Stream Power	$w = 1.160A^{0.508}$; $r^2 = 0.87$, n = 542, $p<0.001$	Phillips and Desloges, (2014)

4.4 Results

Rural Scenario: The maximum total stream power is ~1530 W/m and the maximum specific stream power is ~455 W/m^2 for the rural scenario (Figures 51 and 52). Both total stream power and specific stream power are spatially heterogenous along the stream network (Figures 51 and 52). Areas with medium to high values of total stream power and specific stream power are found from the middle section to the lower section of the stream network (Figure 51). Areas of medium to high specific stream power increased among the reaches in comparison to total stream power due to changes in width (Figures 51 and 52). Specific stream power coincided with generalized surficial geology as observed by Phillips and Desloges, (2014) for streams in Southern Ontario. High values of specific stream power are found in Lake Iroquois sand deposits whereby the land surface is characterized by a shoreline of steep slopes and low values of specific stream power are associated with till deposits whereby the land surface is characterized by gentle slopes (Figure 53) (Gerber, 2003). Phillips and Desloges, (2014) also found specific stream power to be above 100^{+} W/m^2 whereby streams are transitioning between glacial landforms. Similar specific stream power values are obtained in this study where the stream network transitions from till deposits to recent sand and gravel alluvium and from till deposits to Lake Iroquois glaciolacustrine sand deposits (Figure 53: white circles). The maximum total stream power (2253.031 W/m) calculated using Annable's (1996b) equation is similar to the basin scale total maximum stream power (2001-4000 W/m for reach length 50m) obtained by Vocal Ferencevic and Ashmore, (2012) for Highland Creek which is also located in the GTA (Figure 54).

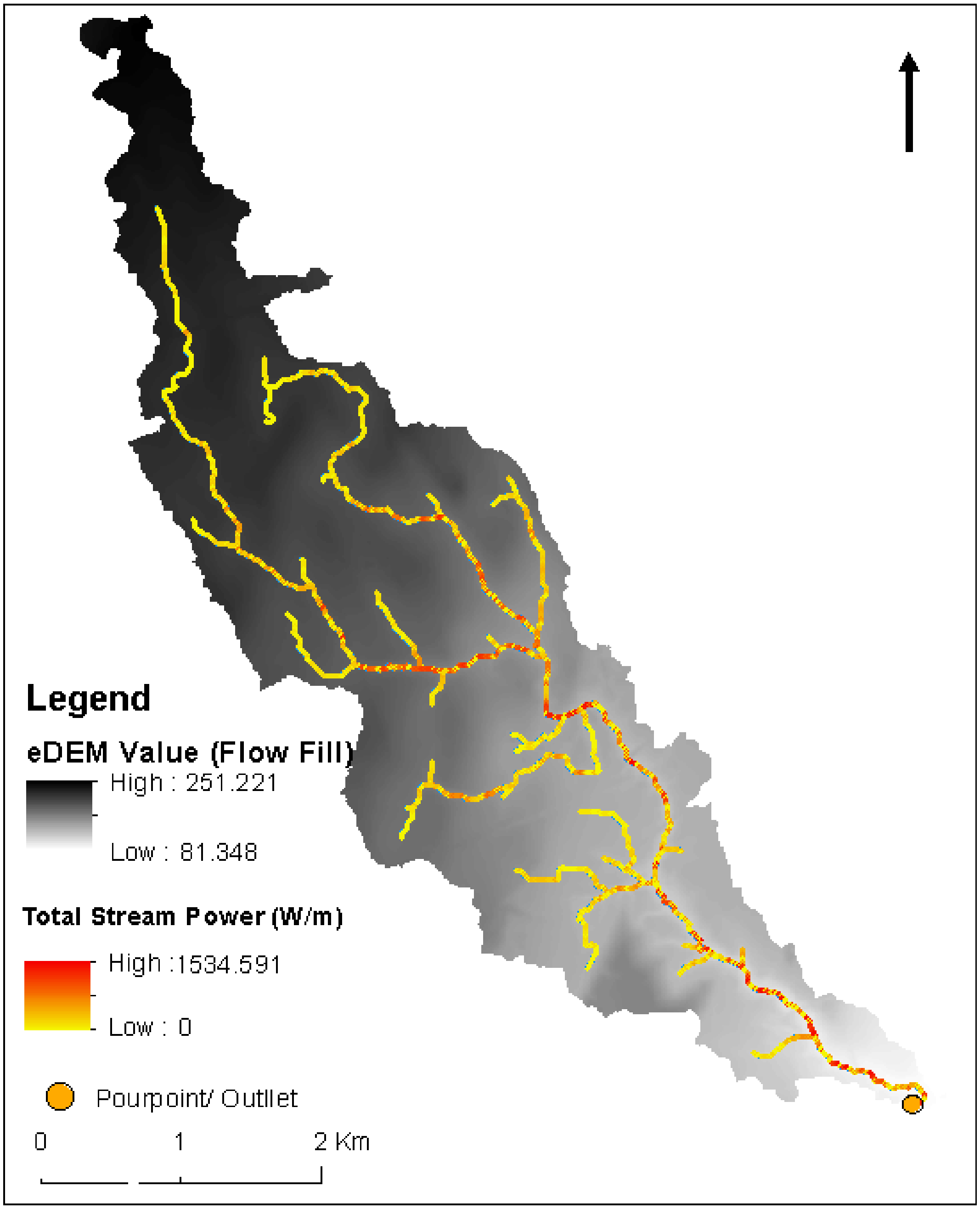


Figure 51: Total stream power of Ganetsekaigon Creek at the watershed scale for rural scenario.

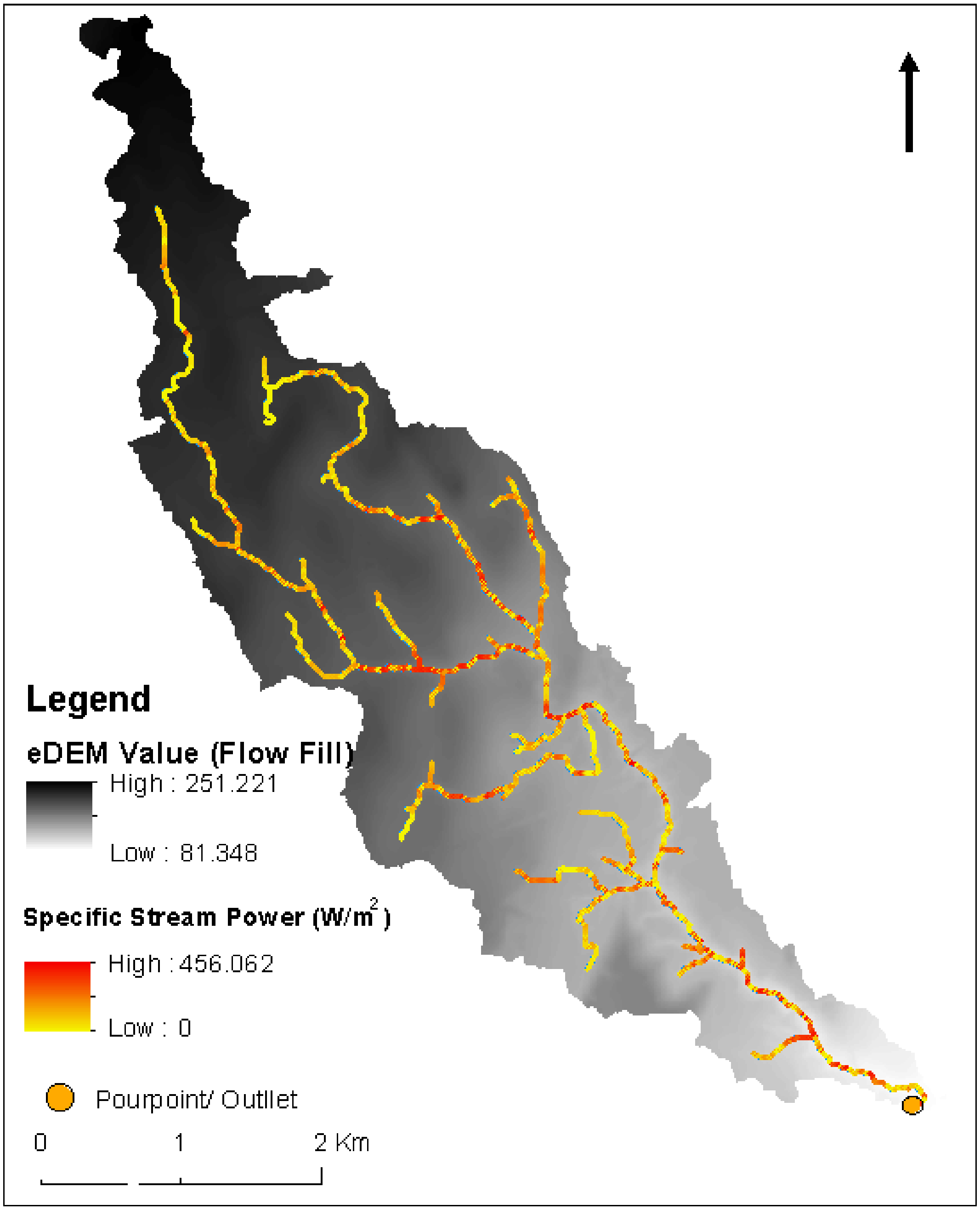


Figure 52: Specific stream power of Ganetsekaigon Creek at the watershed scale for rural scenario.

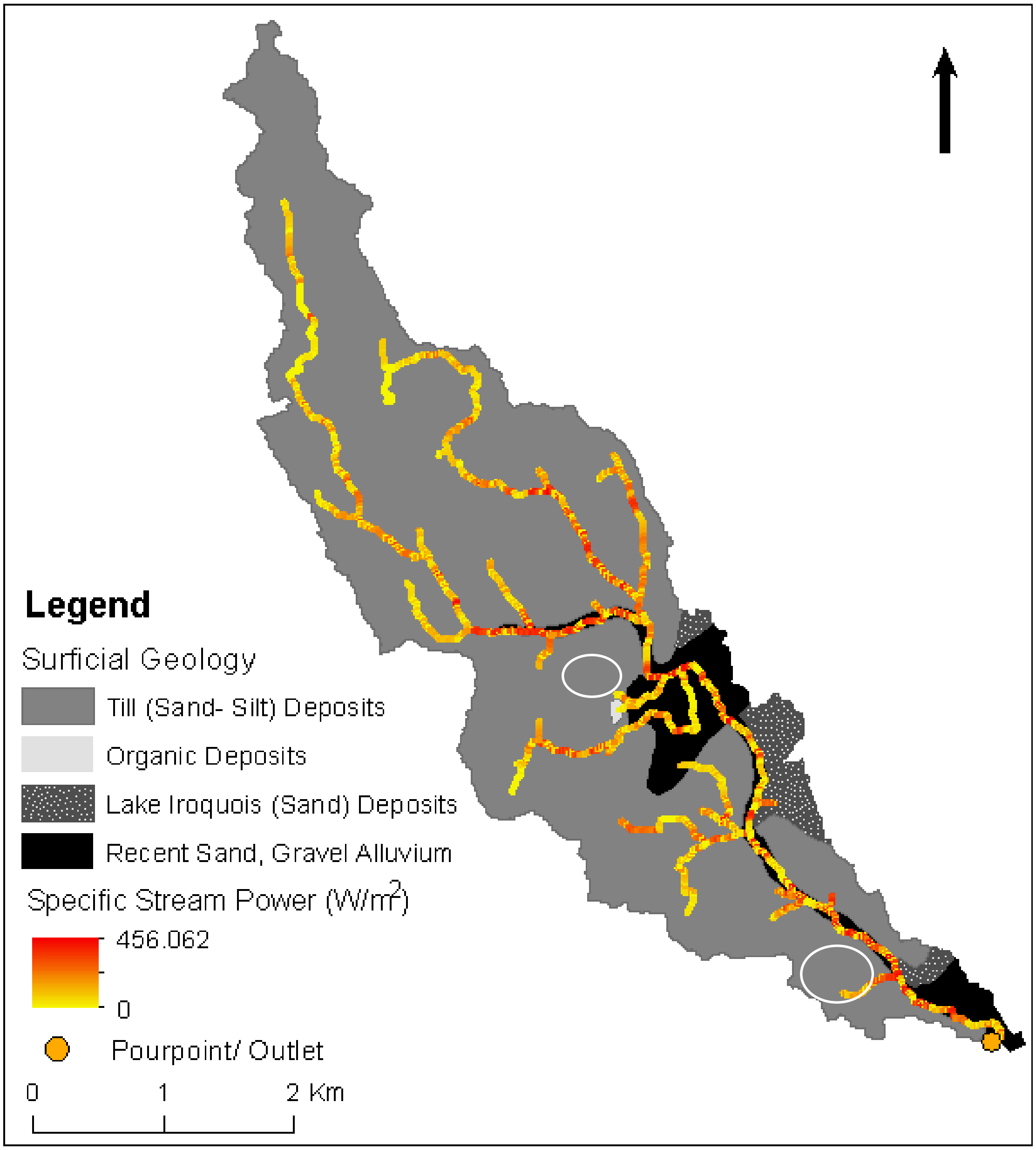


Figure 53: Sites of high specific stream power of Ganetsekaigon Creek for rural scenario whereby the stream network transitions between different types of surficial geology.

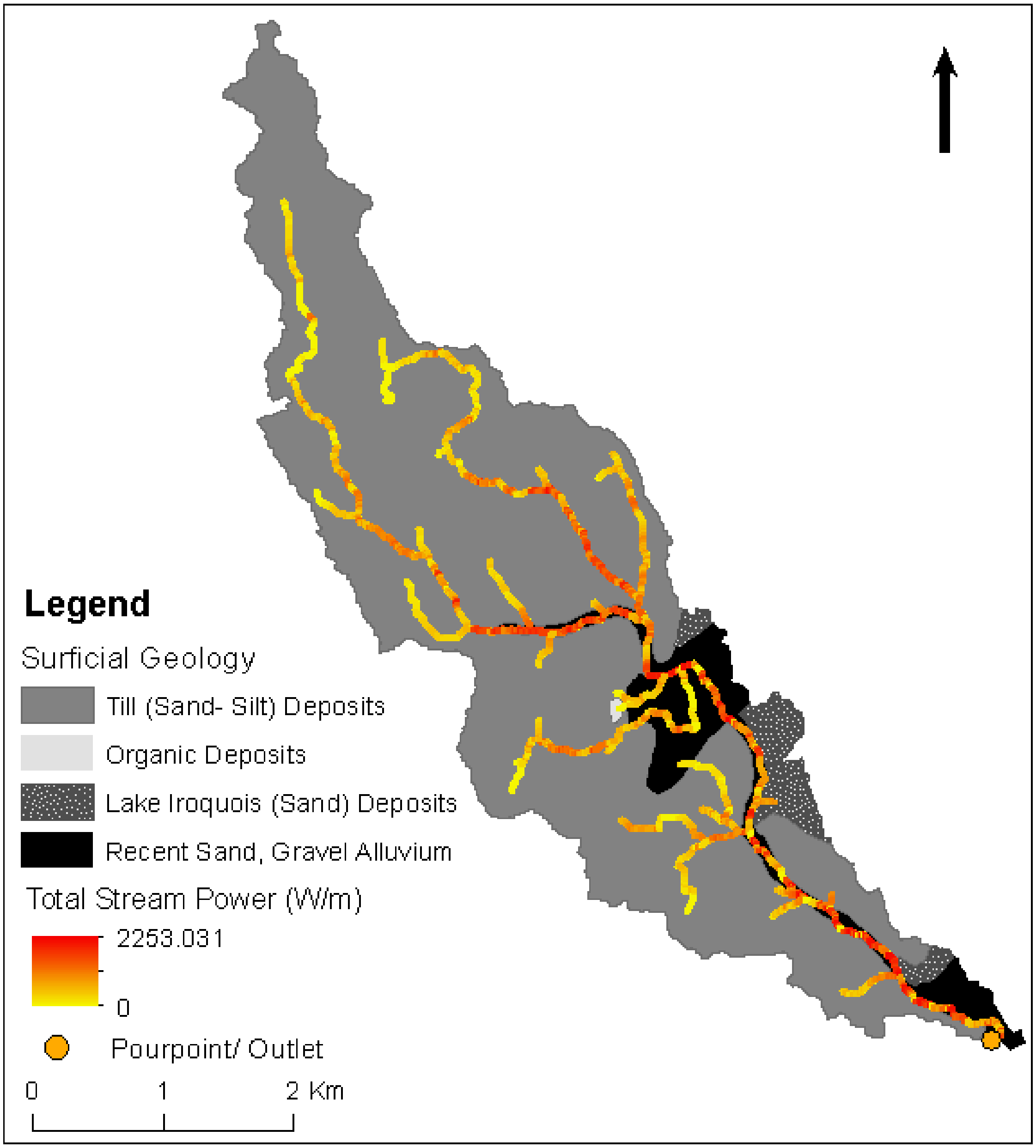


Figure 54: Total stream power of Ganetsekaigon Creek at the watershed scale for rural scenario using the discharge approach of Vocal Ferencevic and Ashmore, (2012).

Urban Scenarios: Total stream power increased by ~721W/m and specific stream power increased by ~170 W/m^2 from the rural scenario to the urban scenario when existing land use and cover was used to calculate discharge (Figures 55 and 56). Areas of total stream power and specific stream power increased in the lower section of the stream network whereby urban land developments increased discharge and consequently total stream power and specific stream power (Figures 55 and 56). The addition of a future land development with 95% imperviousness (Urban: Industrial) in the upper section of the stream network increased the total stream power by ~ 2435.731 W/m and the specific stream power by ~723.863 W/m^2 from the rural scenario (Figures 57 and 59). Areas of medium to high values of total stream power and specific stream power increased within the future industrial land parcel and downstream of it because the reaches received high discharges within its area thus, increasing total stream power and specific stream power. Urban land developments not only increased the total and specific stream power within their area but they also increased cumulative total and specific stream power along the stream network (Figures 55 to 58).

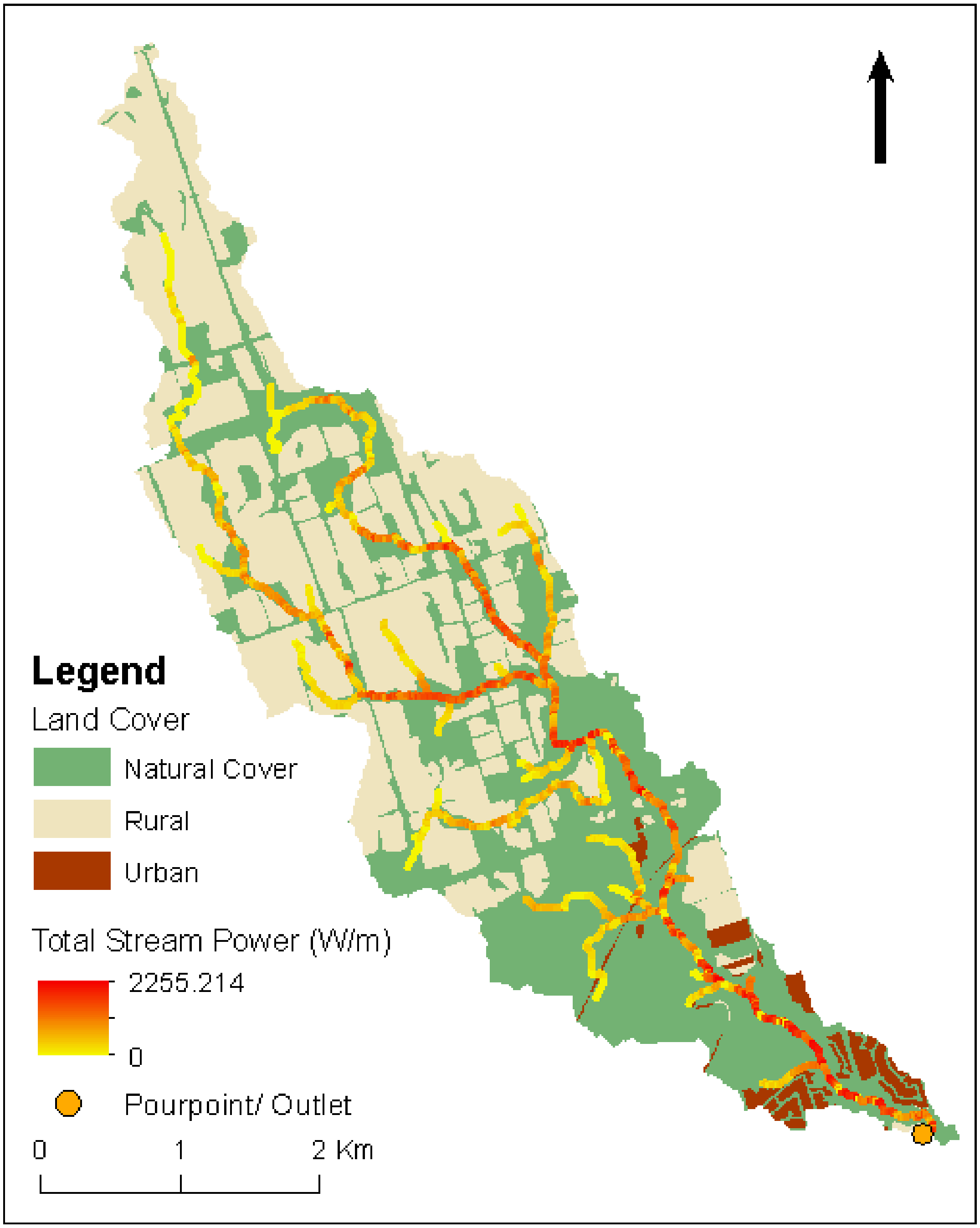


Figure 55: Total stream power of Ganetsekaigon Creek at the watershed scale for urban scenario using existing land use and cover data.

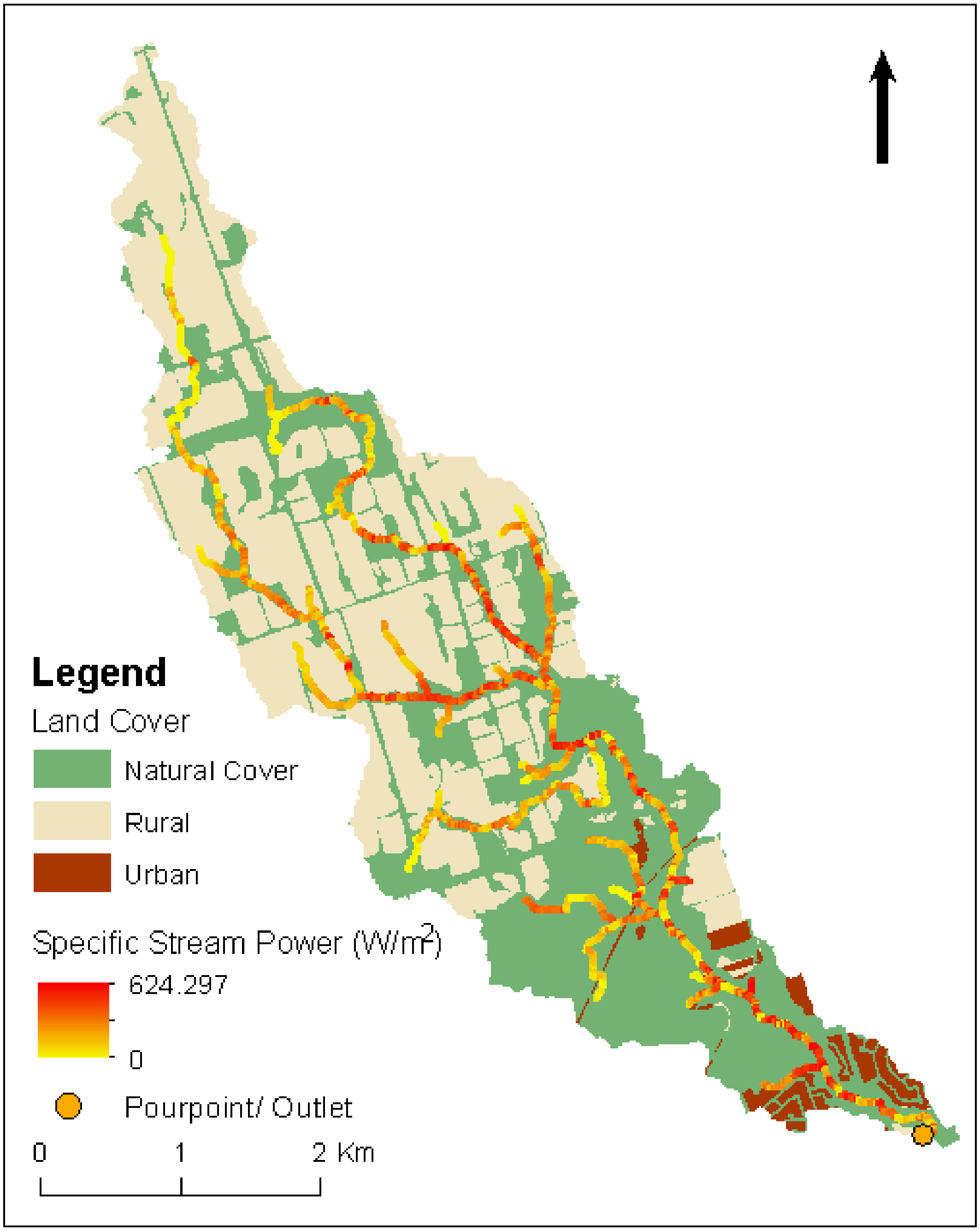


Figure 56: Specific stream power of Ganetsekaigon Creek at the watershed scale for urban scenario using existing land use and cover data.

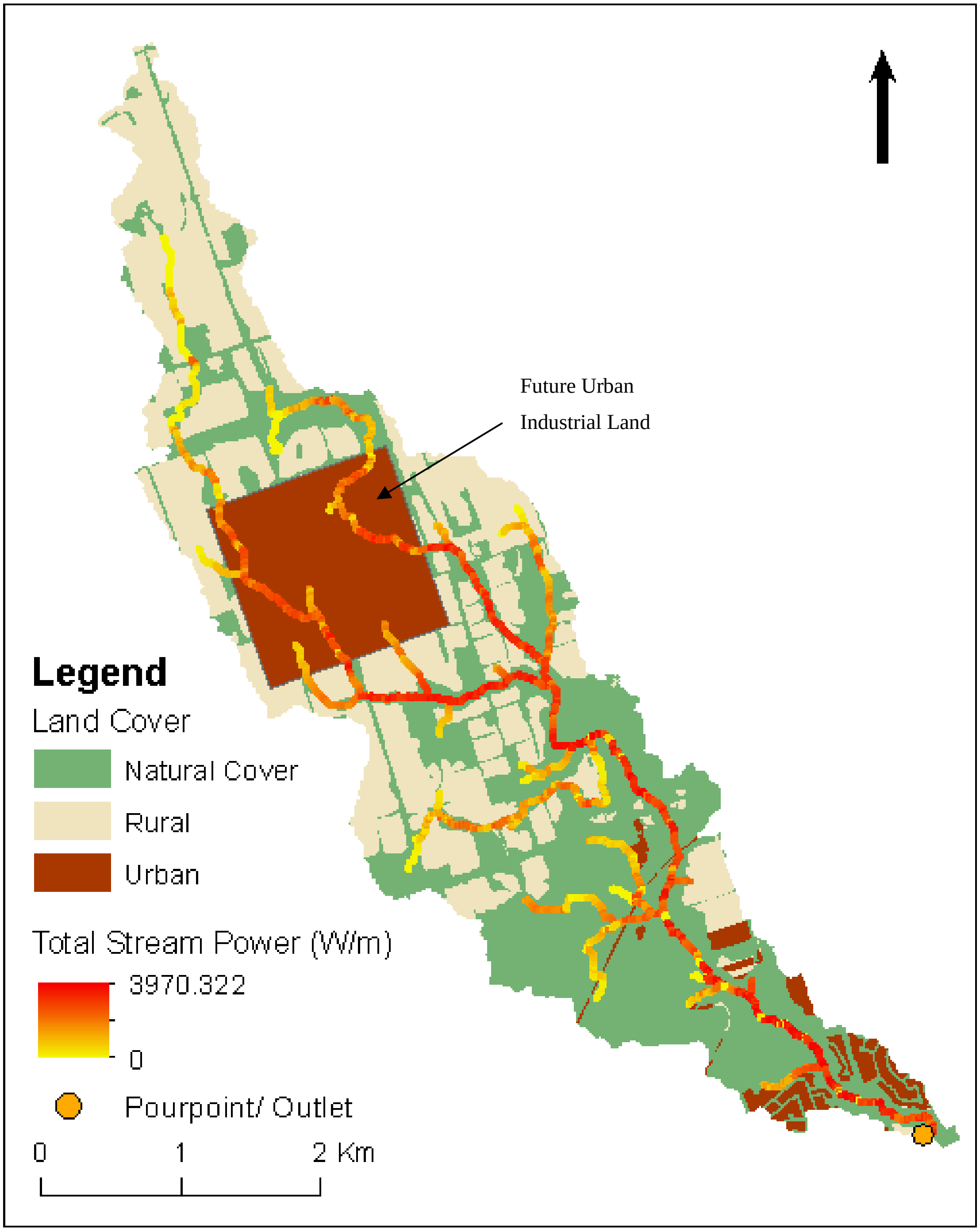


Figure 57: Total stream power of Ganetsekaigon Creek at the watershed scale for urban development scenario after updating existing land use and cover with a new urban development (industrial) using Future Land Use tool.

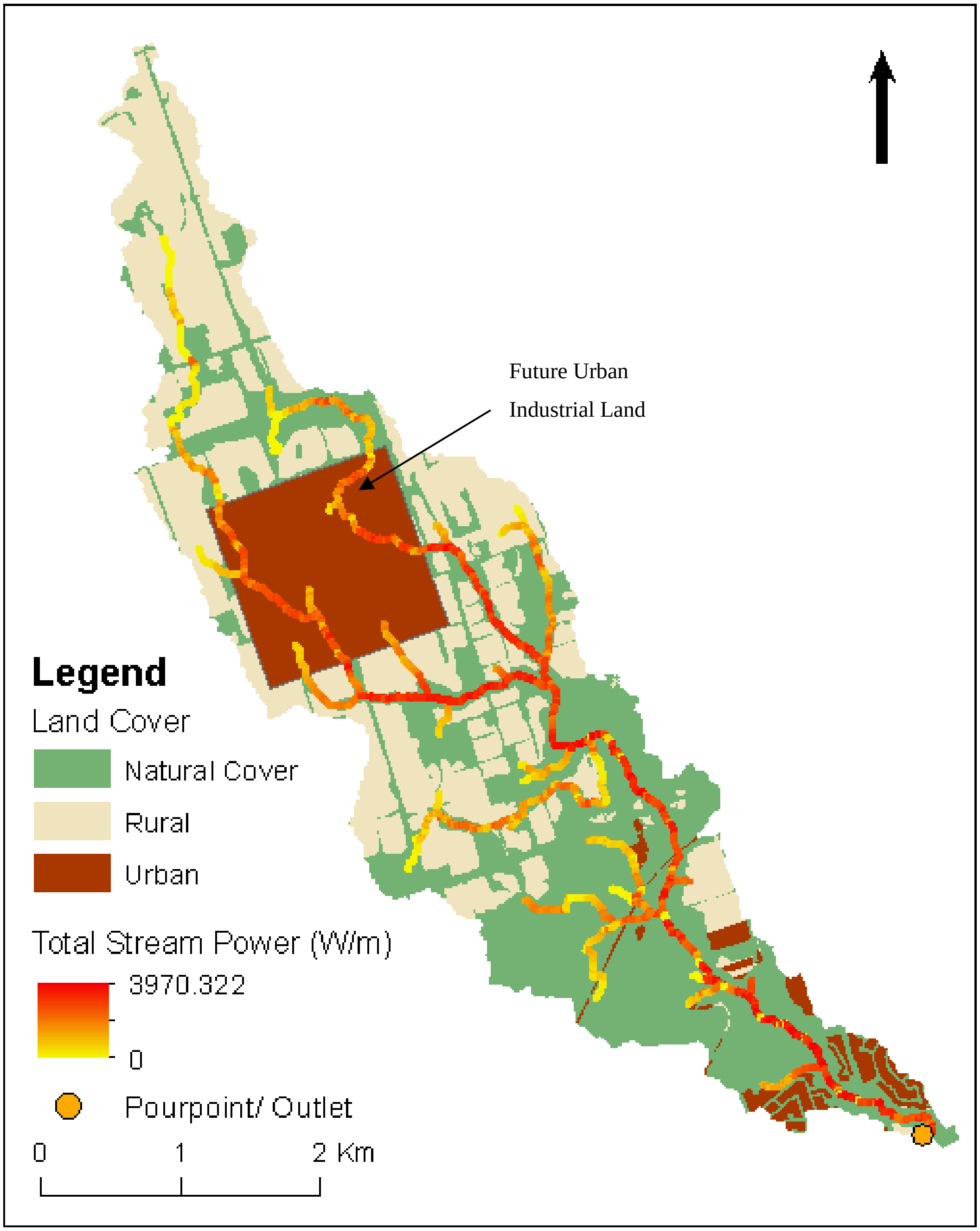


Figure 58: Specific stream power of Ganetsekaigon Creek at the watershed scale for urban development scenario after updating existing land use and cover with a new urban development (industrial) using Future Land Use tool.

4.5 Discussion

The SDSS was effective at generating fairly accurate information on discharge and slope to perform stream power calculations because the results of stream power for the rural scenario were comparable to other studies (i.e. Phillips and Desloges, 2014 and Vocal Ferencevic and Ashmore, 2012) of Southern Ontario despite using generalized empirical models. Visualization of the results as cartographic displays (Figures 51 to 58) placed the quantitative analysis of stream power within a spatial context to facilitate their interpretation in relation to their location within the landscape. Overlay of the specific stream power with the surficial geology showed spatial associations between specific stream power and types of geology (Figure 53). The increases in total and specific stream power along the stream network in urban scenarios can be explained by their proximity to the urban land developments (Figures 55 and 58). The thematic color scheme showing the scale of total and specific stream power values (Figures 51 to 58) can be useful for risk assessments of instability of the stream network. Visualizing risk areas of instability in Figures 55 and 56 can help in stream management efforts to control runoff, sediment sources and sediment transport processes for stream protection. New areas of concern which would not have been identified prior to having a visualization capability can also be identified. Most importantly, current stream management strategies can be more informed by considering impacts of urbanization on streams at the network scale and can be evaluated for effectiveness beyond the local scale. In addition to visualizing current susceptible areas of instability, future possible susceptible areas can also be identified (Figures 57 and 58). Applying the industrial land parcel to the existing land use and cover changed the spatial distribution of total and specific stream power by increasing discharge along the stream network and increasing total and specific stream power in areas which were already high in the rural scenario (Figures 57 and 58). Such comparative analysis of pre-development and post-development with the future land parcel on cumulative impacts can lead to better designs of stream management strategies which consider temporal changes in the stream network from urban growth. The future urban scenarios can also be useful to land use planners in evaluating the impact of their future development choices in decision making processes. They can change the configuration of the future land parcels to visualize the degree of their impact along the stream network to achieve a more sustainable decision. As a result, the design of communities can be better coordinated to ensure economic growth and a high quality of life while still protecting the environment. The cartographic displays are also of interest to fisheries managers because stream power can be used to assess habitat suitability. Given that an estimated 43.2% of urban land is anticipated from future land developments, the management of small riverine cold water species such as the redside dace and rainbow trout has been identified as high priority (TRCA, 2004). Their management zones are shown by pink lines in figure 59 which coincides with the areas of highest total stream power values in the rural scenario (Figure 52). Their key locations and spawning areas have been identified by Matrix Solutions during a collaborative meeting with the stakeholders involved in this research (Figure 59: black and purple circles). These areas are associated with high values of specific stream power (Figure 51). Future urban developments can increase specific stream power and influence the availability of sediments suitable for their habitat.

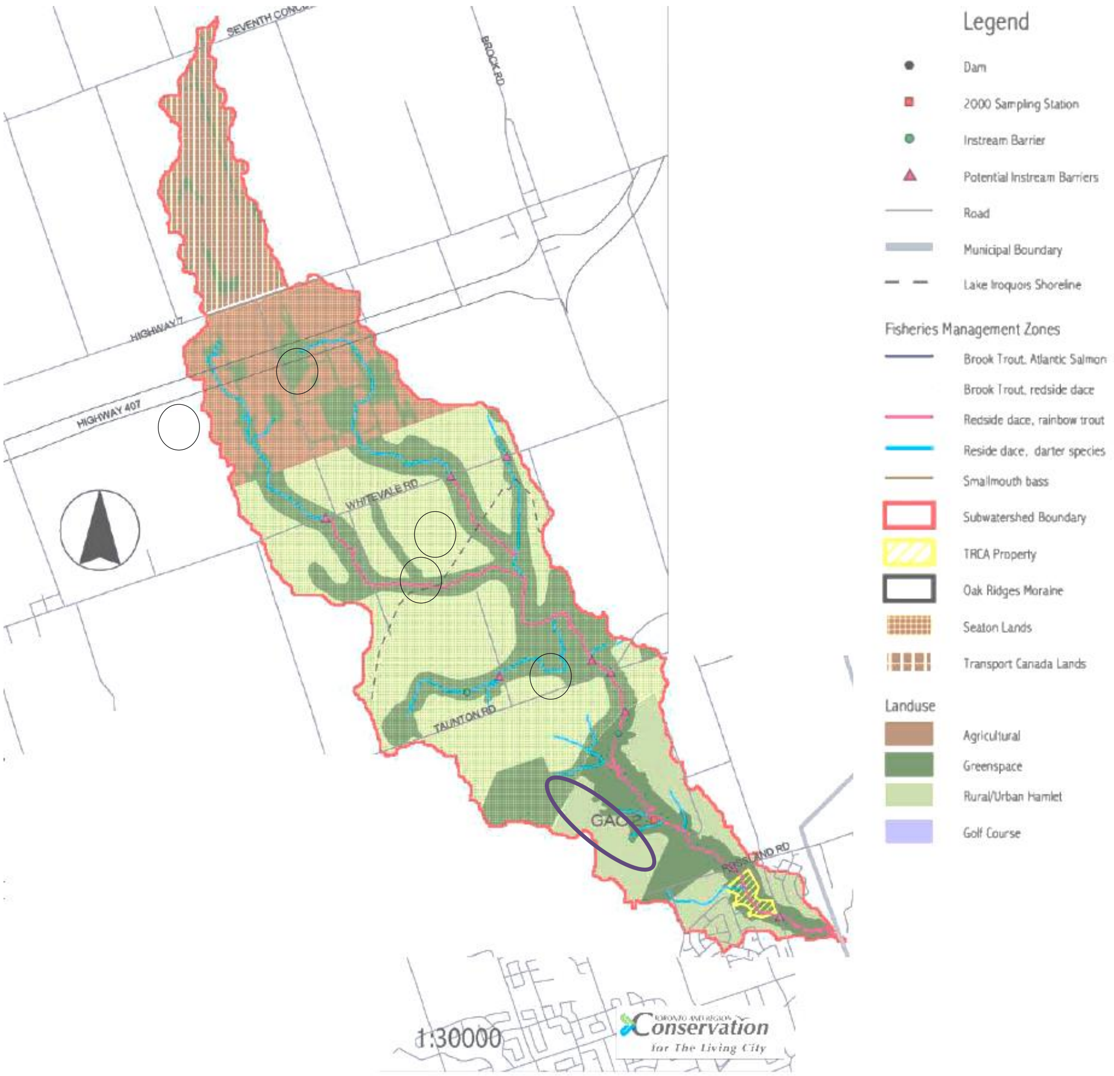


Figure 59: Recommended implementation strategies for Ganetsekaigon Creek (TRCA), 2004). Black circles represent key locations of redside dace and purple circle represents their spawning sites.

4.6 Conclusions

The SDSS produced representative results of total stream power and specific stream power for Ganetsekaigon Creek in comparison to other studies within the GTA which makes it suitable for assisting decision support processes in stream assessments. The cartographic displays facilitated visualization of meaningful spatial relationships of total stream power and specific stream power to surficial geology, fisheries management zones and urban land developments. The distribution and cumulative changes in total stream power and specific stream power with changes in land use and cover at the network scale for rural and urban scenarios were easily visualized. Current risk areas and future possible risk areas can be identified from the cartographic displays for risk communication in stream management, land use planning and fish habitat suitability.

Chapter 5: Conclusions

An adaptive and flexible SDSS was developed to assist decision makers responsible for protecting and rehabilitating streams affected by the 'urban stream syndrome'. Its current model framework was designed to address the lack of decision makers' capability to assess the spatial and temporal cumulative impact of urbanization along stream networks using a DEM and region specific empirical models. Application of the SDSS to the case study of Ganetsekaigon Creek demonstrated its effectiveness at using a DEM to delineate a stream network as a branching network of interconnected reaches which, in turn facilitated the visualization of the spatial and temporal changes in total stream power and specific stream power for different scenarios. The cumulative increases in total stream power and specific stream power were easily observed along the stream network when different land use and cover was applied for the urban scenario. Spatial relationships between stream power and geology, land use and cover and fisheries management zones were also visually evident despite the generalization of discharge, slope and width. Moreover, the results of the rural scenario closely matched results obtained from similar studies of Southern Ontario. Therefore, using DEMs and empirical models can be a reliable method for assessing stream networks and extracting topographic and information for model development.

The cartographic displays of total stream power and specific stream power along a stream network generated for Ganetsekaigon Creek have useful applications in risk communication and negotiation. They could be interpreted as risk susceptibility displays for land use planning, stream management and fish habitat suitability. Risk areas of stream instability can be identified and compared spatially and temporally to guide long term policies and plans which would encompass a range of possible scenarios which would have not been otherwise considered without a network scale analysis and visualization. It is evident that a knowledge-driven scenario analysis is advantageous to capitalize on the mutual needs of various stakeholders for integrated watershed management and support a decision-making process.

The SDSS allows stream stability assessments to be easily performed using DEMs, especially for remote locations where data is not available. Automated data extraction can increase processing efficiency and decrease cost and time in comparison to traditional methods of using topographic maps, field measurements and aerial imagery interpretations. However, their inaccuracy can lead to sources of errors in the model framework. Poor spatial resolution can lead to poor representation of topographic features. Inaccuracy in elevation values can affect the accuracy of slope extraction and drainage area delineation. Errors can also be introduced during conversion of raster grid cells to vector (points, lines and polygons) features and aggregation of different spatial data (e.g. overlay of drainage areas and land use and cover data) during geoprocessing. The regional empirical models for discharge and width can introduce errors because they are generalized over a large spatial scale and are based on methods which have assumptions, approximations and estimation.

The described SDSS adopts a framework largely based on available DEMs and empirical models. Such data is readily available and allowed the SDSS to be developed to match existing published research. It should be understood, however, that the system can continue to be developed to improve the physical realism of the results. For example, researchers working parallel to the SDSS development project are collecting field data for Ganatsekaigon Creek and other watersheds that could be used to calibrate the models for better accuracy. Longitudinal stream profiles, channel section surveys, sediment particle sizes, surveys of sediment sources, sediment transport tracking, and discharge measurements could all be used to assess and adjust the predictions. Other work to automatically extract key information from continuous hydrological models, for example the U.S. Environmental Protection Agency's Stormwater Management Model (SWMM), is ongoing to obtain stability predictions based on cumulative metrics such as excess stream power that are tied to a physically-based understanding of sediment dynamics in rivers. Such an approach would also allow users to assess the impact of stormwater management techniques on stability predictions. Finally, the FWIS database is being adapted to allow direct comparison between model predictions and field results by the Computer Systems Group at the University of Waterloo. Stakeholders including the TRCA, Centre for Community Mapping (COMAP), and the City of Toronto are sharing their knowledge and experience related to the formalization of database systems, model frameworks and structured decision support processes to directly contribute to a robust and adaptable SDSS for urban stream management.

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Appendix A

Table 1: Codes of land use and cover types as provided by City of Toronto and also found in Wet Weather Flow Management Guidelines (WWFM) of the City of Toronto (City of Toronto, 2006).

Class	**Category**	**Code**
Residential	Low-Density	RLD
	Medium-Density	RMD
	High-Density	RHD
	High-Rise	RHR
Commercial	DownTown commercial	CDT
	Big Box Commercial	CBB
	Strip Malls	CSM
Educational / Institutional	Universities	EIU
	local Schools/churches	EIS
Open Space	Park Lands	OPL
	Valley Lands	OVL
	Hydro Corridor	OHC
	Golf course/Cemetery	OGC
Transportation	Highway Corridor	THC
	Rail Yards	TRY
	AirPorts	TAP
Industrial	Prestige	IPR
	Big Box Industrial	IBB
Agricultural	Tilled	AGT
	Pasture/Fallow	AGP

Table 2: Imperviousness (%) for land use and cover types as provided by City of Toronto and also found in Wet Weather Flow Management Guidelines (WWFM) of the City of Toronto (City of Toronto, 2006). Details of Class Code are provided in Appendix-Table 1.

Class Code	Measured Land Surface-Type Breakdown									Consulting Team Responsible
	Impervious Category					Pervious Category		Totals		
	Roofs	Roads	Parking	Driveways	Sidewalks / Patio	Lawns	Open	Impervious	Pervious	
	(%)	*(%)*	*(%)*	*(%)*	*(%)*	*(%)*	*(%)*	*TIMP (%)*	*TPER (%)*	
RLD	13	9	0	7	1	70	0	30	70	TSH, ABL
RMD	24	13	0	10	3	50	0	50	50	XCG
RHD	32	17	0	11	5	35	0	65	35	MMM
RHR	9	9	27	5	0	50	0	50	50	XCG
CDT	52	38	0	5	0	5	0	95	5	ABL
CBB	29	12	57	0	0	2	0	98	2	ABL
CSM	17	19	62	0	0	2	0	98	2	ABL
EIU	5	8	40	2	0	45	0	55	45	XCG
EIS	9	9	14	0	0	68	0	32	68	TSH
OPL	0	5	5	0	0	0	90	10	90	ABL
OVL	0	3	0	0	0	0	97	3	97	ABL
OHC	0	5	5	0	0	0	90	10	90	ABL
OGC	0	5	5	0	0	0	90	10	90	ABL
THC	0	60	0	0	0	0	40	60	40	TSH
TRY	site specific									n/a
TAP	site specific									n/a
IPR	30	7	43	0	0	20	0	80	20	MMM
IBB	45	6	42	0	0	7	0	93	7	ABL
AGT	0	0	0	0	0	0	100	0	100	TSH
AGP	0	0	0	0	0	0	100	0	100	TSH

Appendix B

Stream Network Tool

```
##Python script: This script delineates the stream network from a DEM.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#---------------------------------------------------------------------------#
#Import the Arc Package
import arcpy
import os
from arcpy import *
from arcpy import env
from arcpy.sa import *
arcpy.CheckOutExtension("Spatial")
#Enable the Spatial Analyst Extension license
arcpy.CheckOutExtension("Spatial")
#Allow overwrite of files
arcpy.env.overwriteOutput = True
#Set the current workspace for geoprocessing
workspace_folder = GetParameterAsText(0)
env.workspace= workspace_folder
#Ask User Input for Folder Path and Geodatabase name
out_folder_path = workspace_folder
# Importing DEM as a parameter
dem=GetParameterAsText(1)
#Other inputs
thres=GetParameterAsText(2)
# Process: Fill and Save
fill=arcpy.gp.Fill_sa(dem)
dem_fill=arcpy.Raster(fill)
dem_fill.save(str(out_folder_path) +"\\flow_fill")
AddMessage("Creating fill raster where holes/sinks in the DEM are corrected.")
# Process: Flow Direction and Save
direction= arcpy.gp.FlowDirection_sa(dem_fill)
dem_flow_direction=arcpy.Raster(direction)
dem_flow_direction.save(str(out_folder_path) + "\\flow_dir")
AddMessage("Creating flow direction raster to define direction of flow to steepest downslope cell")
# Process: Flow Accumulation and Save
```

```
accumulation= arcpy.gp.FlowAccumulation_sa(dem_flow_direction)
dem_accum=arcpy.Raster(accumulation)
dem_accum.save(str(out_folder_path) + "\\flow_accum")
AddMessage("Creating flow accumulation raster to define the accumulated flow in each cell.")
# Process: Extract Stream by Drainage Threshold and Save
#thres=GetParameterAsText(2)
accum_path= str(out_folder_path) + "\\flow_accum"
expression= "Value >=" + str(thres)
applied_thres=arcpy.gp.ExtractByAttributes_sa(accum_path, str(expression))
strm_thres=arcpy.Raster(applied_thres)
strm_thres.save(str(out_folder_path) + "\\strm_thres")
AddMessage("Creating flow accumulation raster to define the stream by a threshold accumulated flow." +
str(expression) + "in m^2.")
# Process: Stream Link and Save
link= arcpy.gp.StreamLink_sa(strm_thres, dem_flow_direction)
strm_link=arcpy.Raster(link)
strm_link.save(str(out_folder_path) + "\\strm_link")
AddMessage("Creating stream network raster with values assigned to each tributary.")
#Process: Stream Order and save
strm_order= str(out_folder_path) + "\\strm_order"
order = arcpy.gp.StreamOrder_sa(strm_thres, dem_flow_direction,strm_order, "SHREVE")
AddMessage("Creating stream order raster with values assigned to each tributary.")
# Process: Raster Stream to Polyline feature
strm_network=arcpy.gp.StreamToFeature_sa(strm_link, dem_flow_direction, "strm_net.shp" )
AddMessage("Creating final stream network polyline called strm_net.shp.")
## Process: Converting the raster cells into polygons
# Round up elevation values
roundupdempath= str(workspace_folder) + "\\roundeddem"
arcpy.gp.RoundUp_sa(dem, roundupdempath)
# Truncate rounded decimal elevation values to integers
intdempath= str(workspace_folder) + "\\intdem"
intdem=arcpy.gp.Int_sa(roundupdempath, intdempath)
# Save integer dem as raster file.
dem_int=arcpy.Raster(intdem)
dem_int.save(str(workspace_folder) +"\\dem_int")
# Save raster as tiff
intdemtiff=arcpy.RasterToOtherFormat_conversion(dem_int, workspace_folder, "TIFF")
```

```
# Obtain extent of fishnet
intdemtiffraster= Raster(str(workspace_folder) + "\\dem_int")
xmax= intdemtiffraster.extent.XMax
ymax= intdemtiffraster.extent.YMax
xmin= intdemtiffraster.extent.XMin
ymin= intdemtiffraster.extent.YMin
xyorigin= str(xmin) + " " + str(ymin)
yaxis= str(xmin) + " " + str(ymax)
xyend= str(xmax) + " " + str(ymax)
# Process: Create Fishnet
fishnetpath= str(workspace_folder) + "\\fishnetpolyline.shp"
cellwidth = GetParameterAsText(5)
cellheight = GetParameterAsText(6)
arcpy.CreateFishnet_management(fishnetpath, str(xyorigin), str(yaxis), "10" , "10", "", "",
str(xyend),"NO_LABELS",intdemtiffraster, "POLYLINE")
# Create Polygons from the fishnet
fishnetpolygonpath = str(workspace_folder) + "\\demcellspolygon.shp"
arcpy.FeatureToPolygon_management(fishnetpath, fishnetpolygonpath, "", "ATTRIBUTES", "")
AddMessage("Converting the raster cells into polygons called demcellspolygon.shp.")
```

Pourpoint/ Outlet Tool

```
##Python Script: This script creates a point feature to represent the pourpoint/outlet of the stream network. The flow accumulation raster is converted to a point feature class and the point with the maximum value is selected as the pourpoint location.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
from arcpy import *
from arcpy.sa import *
import arceditor
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
#Import flow accumulation raster
f_accum = GetParameterAsText(1)
flow_accum = Raster(f_accum)
# Process: Convert raster into point and Save as acc_points.shp
arcpy.RasterToPoint_conversion(flow_accum, "acc_points")
# Process: Find maximum point and Save as table
accum_points_path= str(workspace_folder) + "\\acc_points.shp"
arcpy.Statistics_analysis(accum_points_path,"maxaccum_value", [["GRID_CODE", "MAX"]])
AddMessage("Finding maximum flow accumulation.")
# Process: Use maximum point as variable
maxaccum_tbl= str(workspace_folder) + "\\maxaccum_value"
#Select maxaccumulation value from table
cursor=arcpy.da.SearchCursor(maxaccum_tbl, ["MAX_GRID_CODE"])
for row in cursor:
        maxaccum= "{0}".format(row[0])
        maxaccum_flt= str(maxaccum)
#Save maxaccumumulation point as point feature
expression= "GRID_CODE =" + str(maxaccum_flt)
arcpy.MakeFeatureLayer_management (accum_points_path, "pourpoint")
arcpy.gp.SelectLayerByAttribute_management("pourpoint","NEW_SELECTION",expression)
```

```
arcpy.CopyFeatures_management("pourpoint", "pour_point")
# Process: Snap
pourpt= str(workspace_folder) + "\\pour_point.shp"
cell_size = GetParameterAsText(2)
strmnet= GetParameterAsText(3)
cell_info = str(cell_size) + " Meters"
vertex_type= "END"
strmnet_info = [str(strmnet), str(vertex_type), str(cell_info)]
arcpy.Snap_edit(pourpt, [strmnet_info])
AddMessage("Creating final pourpoint point called pour_point.shp.")
```

Stream Elevation Tool

```
## Python Script: This script finds the elevation points along the stream network.
## Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#-----------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import arceditor
import arcinfo
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
#Import elevation fill sink data
edemflowfill = GetParameterAsText(1)
# Import flow accumulation (threshold applied) data
faccumthres = GetParameterAsText(2)
# EXtract stream elevation cells by mask (overlaying with flow accumulation thresholded raster representing the stream)
strmfillpath= str(workspace_folder) + "\\strmedemfill"
edemfillextract = arcpy.gp.ExtractByMask_sa(edemflowfill, faccumthres,strmfillpath)
# Process: Raster to Point - Converting elevation cells into points
strmfillpts= str(workspace_folder) + "\\strmfillpts.shp"
arcpy.RasterToPoint_conversion(strmfillpath, strmfillpts, "Value")
AddMessage("Converting elevation cells to points.")
# Import raster cell polygon shapefile
cellpoly = GetParameterAsText(3)
#Create feature layer of raster cells polygon
fishnetpolygonlyr=arcpy.MakeFeatureLayer_management(cellpoly,"fishnetpolygonlyr")
# Process: Select Layer By Location
strmcells=str(workspace_folder) + "\\strmcells.shp"
```

```
strmcell_select= arcpy.SelectLayerByLocation_management(fishnetpolygonlyr, "intersect",
strmfillpts,"","NEW_SELECTION", "NOT_INVERT")
arcpy.CopyFeatures_management(strmcell_select, strmcells)
AddMessage("Selecting stream cells.")
# Join flow fill points to cell polygons
cellswithfillpts= str(workspace_folder) + "\\cells_fill.shp"
arcpy.SpatialJoin_analysis(strmcells, strmfillpts, cellswithfillpts)
AddMessage("Join elevation points to stream cells.")
# Import stream network shapefile
strm_net = GetParameterAsText(4)
# Make a copy of stream network shapefile
strm_net_path = str(workspace_folder) + "\\strm_netcopy.shp"
strm_netcopy =arcpy.CopyFeatures_management(strm_net, strm_net_path)
#Create feature layer of raster cells polygon
cells_filllyr=arcpy.MakeFeatureLayer_management(cellswithfillpts,"cells_filllyr")
# Process: Select Layer By Location - cells with fill data intersecting the stream network
strmpolygoncells=str(workspace_folder) + "\\strmnetpolygon.shp"
strmpolygon_select= arcpy.SelectLayerByLocation_management(cells_filllyr, "intersect",
strm_net_path,"","NEW_SELECTION", "NOT_INVERT")
arcpy.CopyFeatures_management(strmpolygon_select, strmpolygoncells)
AddMessage("Selecting stream cells overlaying stream network.")
# Convert strmnetpolygons into points - Process: Feature To Point
strm_elevpts = str(workspace_folder) + "\\strm_elevpts.shp"
arcpy.FeatureToPoint_management(strmpolygoncells, strm_elevpts, "CENTROID")
AddMessage("Converting selected stream cells to elevation points.")
#Process: Snap- aligning elevation fill points on the edge of the stream network
elevcell_size= GetParameterAsText(5)
dist_snap= str(elevcell_size) + " Meters"
snapenv=[[strm_netcopy, "EDGE", str(dist_snap)]]
arcpy.Snap_edit(strm_elevpts, snapenv)
AddMessage("Creating final elevation points of the stream network called strm_elevpts.shp.")
```

Stream Slope Tool

```
##Python Script: This script calculates the slope between elevation points for each stream segment in a stream network.The first point of the segment has a slope of zero and between two points, the second point holds the slope value upstream of it.
## Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#----------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import csv
import domainvalues
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
# Import stream network shapefile
strm_net = GetParameterAsText(1)
# Make a copy of stream network shapefile
strm_net_path = str(workspace_folder) + "\\strm_netcopy.shp"
arcpy.CopyFeatures_management(strm_net, strm_net_path)
# Import elevation point data
elev_pts = GetParameterAsText(2)
# Make a copy of stream network shapefile
elevpt_path = str(workspace_folder) + "\\elevptcopy.shp"
arcpy.CopyFeatures_management(elev_pts, elevpt_path)
# Process: Integrate- It is used to maintain integrity of shared feature boundaries, i.e. the stream network is modified to contain the elevation points as its vertices.
outintegrate= str(strm_net_path)
withintegrate= str(elevpt_path)
arcpy.Integrate_management([[outintegrate],[withintegrate]], "")
AddMessage("Elevation points are integrated as the vertices of the stream network.")
```

```
# Process: Split Line at Point- split lines based on the intersection or proximity of slope points(note: both slope points and discharge points must coincide).
splitstrmpath=str(workspace_folder) + "\\slope_reaches.shp"
arcpy.SplitLine_management(strm_net_path,splitstrmpath)
AddMessage("The stream network is split into reaches.")
##Saving the result to a file geodatabase to allow for the management of the attribute table.
#Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\strmslope.gdb"
arcpy.Delete_management(gdb_name)
arcpy.CreateFileGDB_management(str(workspace_folder), "strmslope.gdb")
#Save shapefile to file geodatabase
arcpy.FeatureClassToGeodatabase_conversion(splitstrmpath,gdb_name)
slopereachgdb= gdb_name + "\\slope_reaches"
#Save shapefile to file geodatabase
arcpy.FeatureClassToGeodatabase_conversion(elevpt_path,gdb_name)
elevptgdb= gdb_name + "\\elevptcopy"
# Add Fields to slope_reach to obtain the first x,y coordinates.
arcpy.AddField_management(slopereachgdb,"xstartr", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(slopereachgdb,"ystartr","DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(slopereachgdb,"x_ystartr", "TEXT")
arcpy.CalculateField_management(slopereachgdb, "xstartr", "!SHAPE.firstPoint.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(slopereachgdb, "ystartr", "!SHAPE.firstPoint.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(slopereachgdb, "x_ystartr", "str(float(!xstartr!))+\",\"+ str(float(!ystartr!))", "PYTHON_9.3", "")
# Add Fields to slope_reach to obtain the last x,y coordinates.
arcpy.AddField_management(slopereachgdb,"xendr", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(slopereachgdb,"yendr","DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(slopereachgdb,"x_yendr", "TEXT")
arcpy.CalculateField_management(slopereachgdb, "xendr", "!SHAPE.lastPoint.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(slopereachgdb, "yendr", "!SHAPE.lastPoint.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(slopereachgdb, "x_yendr", "str(float(!xendr!))+\",\"+ str(float(!yendr!))", "PYTHON_9.3", "")
# Add Field to slope_reach to calculate length of line in metres
```

```
arcpy.AddField_management(slopereachgdb,"lengthr_m", "FLOAT", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(slopereachgdb, "lengthr_m", "!SHAPE.length@meters!", "PYTHON_9.3", "")
#Add Fields to elevation points to obtain the x,y coordinates.
arcpy.AddField_management(elevptgdb,"xelev", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.AddField_management(elevptgdb,"yelev","DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.AddField_management(elevptgdb,"x_yelev", "TEXT")
arcpy.CalculateField_management(elevptgdb, "xelev", "!SHAPE.CENTROID.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(elevptgdb, "yelev", "!SHAPE.CENTROID.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(elevptgdb, "x_yelev", "str(float(!xelev!))+\",\"+ str(float(!yelev!))",
"PYTHON_9.3", "")
# Add join field upelev and down elev to slope reaches based on their respective coordinates
arcpy.JoinField_management(slopereachgdb, "x_ystartr", elevptgdb, "x_yelev", "GRID_CODE")
arcpy.AlterField_management(slopereachgdb, "GRID_CODE_1", "upelev", "", "", "", "NON_NULLABLE",
"false")
arcpy.JoinField_management(slopereachgdb, "x_yendr", elevptgdb, "x_yelev", "GRID_CODE")
arcpy.AlterField_management(slopereachgdb, "GRID_CODE_1", "downelev", "", "", "", "NON_NULLABLE",
"false")
# Add Field to calculate slope
arcpy.AddField_management(slopereachgdb,"S_mperm", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionslope= "(!downelev!-!upelev!)/!lengthr_m!"
arcpy.CalculateField_management(slopereachgdb, "S_mperm", str(expressionslope), "PYTHON_9.3", "")
AddMessage("The calculated slope is saved as slope_reaches.")
```

Summary Table Tool

```
##Python script: This script creates a summary table for final data.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#--------------------------------------------------------------------------#
#Import the Arc Package
import arcpy
import os
from arcpy import *
from arcpy import env
from arcpy.sa import *
arcpy.CheckOutExtension("Spatial")
#Enable the Spatial Analyst Extension license
arcpy.CheckOutExtension("Spatial")
#Allow overwrite of files
arcpy.env.overwriteOutput = True
# Import inputs
workspace_folder= GetParameterAsText(0)
flow_dir = GetParameterAsText(1)
strm_order = GetParameterAsText(2)
flow_accum= GetParameterAsText(3)
#Create file geodatabase to store final results
#Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\summary.gdb"
arcpy.Delete_management(gdb_name)
#Create a table with stream order
arcpy.CreateFileGDB_management(str(workspace_folder), "summary.gdb")
#Create stream with order
summarypath=str(workspace_folder) +"\\summarydata.shp"
summary=arcpy.gp.StreamToFeature_sa(strm_order, flow_dir, summarypath )
# Copy features to geodatabase for summary
arcpy.FeatureClassToGeodatabase_conversion(summarypath,gdb_name)
summarygdb= gdb_name + "\\summarydata"
# Edit field "GRIDCODE" to OrderID
arcpy.AlterField_management(summarygdb, "GRID_CODE", "OrderID", "", "", "", "NON_NULLABLE", "false")
#Find subwatersheds
# Add Fields to summary table to obtain the last x,y coordinates.
```

```
arcpy.AddField_management(summarygdb,"xend", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(summarygdb,"yend","DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.CalculateField_management(summarygdb, "xend", "!SHAPE.lastPoint.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(summarygdb, "yend", "!SHAPE.lastPoint.Y!", "PYTHON_9.3", "")
#Make an x y event layer given the identified coordinates
desc = arcpy.Describe(summarypath)
spatial_ref = desc.spatialReference
outletslyr= arcpy.MakeXYEventLayer_management(summarygdb, "xend", "yend", "outletslyr",spatial_ref, "")
outlyrpath = str(workspace_folder)+"\\outletslyr.lyr"
arcpy.SaveToLayerFile_management(outletslyr, outlyrpath)
outletptspath = str(workspace_folder)+"\\outletpoints.shp"
arcpy.CopyFeatures_management(outlyrpath, outletptspath)
# find duplicate outlet points
arcpy.AddField_management(outletptspath,"x_yend", "TEXT")
arcpy.CalculateField_management(outletptspath, "x_yend", "str(float(!xend!))+\",\"+ str(float(!yend!))",
"PYTHON_9.3", "")
outletswoduplicates = str(workspace_folder)+ "\\outletpointswoduplicates.shp"
# Process: Dissolve
arcpy.Dissolve_management(outletptspath, outletswoduplicates, "x_yend", "", "MULTI_PART",
"DISSOLVE_LINES")
# Create subwatersheds
subws = str(workspace_folder)+ "\\subwatersheds.shp"
snappour= SnapPourPoint(outletswoduplicates, flow_accum, "10", "FID")
wshed= Watershed(flow_dir, snappour, "Value")
arcpy.RasterToPolygon_conversion(wshed,subws,"NO_SIMPLIFY","Value" )
# Copy subwatersheds to geodatabase for summary
arcpy.FeatureClassToGeodatabase_conversion(subws,gdb_name)
swshedgdb= gdb_name + "\\subwatersheds"
#Spatial Join subwatershedid with summary table based on length of stream polyline.
summarytableswshed= str(gdb_name) + "\\summarytable"
arcpy.SpatialJoin_analysis(summarygdb, swshedgdb, summarytableswshed, "JOIN_ONE_TO_ONE",
"KEEP_ALL", "", "HAVE_THEIR_CENTER_IN", "", "")
arcpy.AlterField_management(summarytableswshed, "ID", "Swshed_ID", "", "", "", "NON_NULLABLE", "false")
# Create a reach base summary file
spatial_reference = arcpy.Describe(summarygdb).spatialReference
```

```
arcpy.CreateFeatureclass_management(gdb_name, "summary_reach", "POLYLINE", summarygdb,
"SAME_AS_TEMPLATE", "SAME_AS_TEMPLATE", spatial_reference)
summaryreach= str(gdb_name) + "\\summary_reach"
#Delete all fields in summary_reach
desc = arcpy.Describe(summaryreach)
fieldslist=arcpy.ListFields(summaryreach)
fieldnames = []
for field in fieldslist:
        if not field.required:          # only list nonrequired fields
                fieldnames.append(field.name)
if desc.dataType in ["ShapeFile", "DbaseTable"]: ##Retain an extra field
    fieldnames = fieldnames[1:]
# Execute DeleteField to delete all fields in the field list.
arcpy.DeleteField_management(summaryreach, fieldnames)
```

Rural Discharge Tool

```
## Python Script: This script finds the discharge points for each reach in a stream network.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#-------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import arceditor
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
# Import stream network shapefile
strm_net = GetParameterAsText(1)
# Make a copy of stream network shapefile
strm_net_path = str(workspace_folder) + "\\strm_netcopy.shp"
strm_netcopy =arcpy.CopyFeatures_management(strm_net, strm_net_path)
# Import flow accumulation (threshold applied) data
facthres = GetParameterAsText(2)
# Process: Raster to Point - Converting  cells into points
facthres_pts= str(workspace_folder) + "\\facthres_pts.shp"
arcpy.RasterToPoint_conversion(facthres, facthres_pts, "Value")
# Import raster cell polygon shapefile
cellpoly = GetParameterAsText(3)
#Import coefficient c and x in Q= cA^x.
coeff_c = GetParameterAsText(4)
coeff_x = GetParameterAsText(5)
#Create feature layer of raster cells polygon
fishnetpolygonlyr=arcpy.MakeFeatureLayer_management(cellpoly,"fishnetpolygonlyr")
# Process: Select Layer By Location
strmcells=str(workspace_folder) + "\\strmcells.shp"
strmcell_select= arcpy.SelectLayerByLocation_management(fishnetpolygonlyr, "intersect",
facthres_pts,"","NEW_SELECTION", "NOT_INVERT")
```

```
arcpy.CopyFeatures_management(strmcell_select, strmcells)
AddMessage("Selecting flow accumulation cells of the stream network.")
# Join flow fac thres points to cell polygons
cellswithfacpts= str(workspace_folder) + "\\cells_fac.shp"
arcpy.SpatialJoin_analysis(strmcells, facthres_pts, cellswithfacpts)
AddMessage("Joining flow accumulation cells to stream cells.")
#Create feature layer of raster cells polygon
cells_faclyr=arcpy.MakeFeatureLayer_management(cellswithfacpts,"cells_faclyr")
# Process: Select Layer By Location - cells with fac data intersecting the stream network
strmpolygoncells=str(workspace_folder) + "\\strmnetpolygon.shp"
strmpolygon_select= arcpy.SelectLayerByLocation_management(cells_faclyr, "intersect",
strm_net_path,"","NEW_SELECTION", "NOT_INVERT")
arcpy.CopyFeatures_management(strmpolygon_select, strmpolygoncells)
# Convert strmnetpolygons into points - Process: Feature To Point
strm_facpts = str(workspace_folder) + "\\discharge_pts.shp"
arcpy.FeatureToPoint_management(strmpolygoncells, strm_facpts, "CENTROID")
AddMessage("Converting stream cells to discharge points.")
# Process: Snap- aligning discharge points on the edge of the stream network
faccell_size = GetParameterAsText(4)
dist_snap= str(faccell_size) + " Meters"
snapenv=[[strm_netcopy, "EDGE", str(dist_snap)]]
arcpy.Snap_edit(strm_facpts, snapenv)
#Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\strmdischarge.gdb"
arcpy.Delete_management(gdb_name)
arcpy.CreateFileGDB_management(str(workspace_folder), "strmdischarge.gdb")
# Copy features to geodatabase for drainage area calculation
arcpy.FeatureClassToGeodatabase_conversion(strm_facpts,gdb_name)
strmdischargepgdb= gdb_name + "\\discharge_pts"
# Add field to calculate drainage area
arcpy.AddField_management(strmdischargepgdb, "drainarea_km2", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
# Calculate drainage area based on 10x10m cell(given by elevation cell dimension)
cell_area= math.pow((float(faccell_size)),2)
expressiondarea= "([GRID_CODE]/1000000)*" + str(cell_area)
arcpy.CalculateField_management(strmdischargepgdb, "drainarea_km2", str(expressiondarea), "VB", "")
# Add Field to calculate discharge using Q=cA^x where c and x are coefficcients and A is the drainage area
```

```
arcpy.AddField_management(strmdischargepgdb,"totalimp_percnt", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(strmdischargepgdb, "totalimp_percnt", "0" , "VB", "")
arcpy.AddField_management(strmdischargepgdb,"c", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(strmdischargepgdb, "c", "0.248" , "VB", "")
arcpy.AddField_management(strmdischargepgdb,"x", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(strmdischargepgdb, "x", "0.91" , "VB", "")
arcpy.AddField_management(strmdischargepgdb,"Q_m3pers", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionq= "!c!*(!drainarea_km2!**!x!)"
arcpy.CalculateField_management(strmdischargepgdb, "Q_m3pers", str(expressionq), "PYTHON_9.3", "")
# Add field to discharge points to obtain the x,y coordinates of the points.
arcpy.AddField_management(strmdischargepgdb,"xp", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(strmdischargepgdb,"yp","DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(strmdischargepgdb,"x_yp", "TEXT")
arcpy.CalculateField_management(strmdischargepgdb, "xp", "!SHAPE.CENTROID.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(strmdischargepgdb, "yp", "!SHAPE.CENTROID.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(strmdischargepgdb, "x_yp", "str(float(!xp!))+\",\"+ str(float(!yp!))",
"PYTHON_9.3", "")
# Creating reaches with the upstream discharge points as attributes.
# Process: Integrate- It is used to maintain integrity of shared feature boundaries, i.e. the stream network is modified
to contain the discharge points as its vertices.
outintegrate= str(strm_net_path)
withintegrate= str(strmdischargepgdb)
arcpy.Integrate_management([[outintegrate],[withintegrate]], "")
# Process: Split Line at Point- split lines based on the intersection or proximity of slope points(note: both slope
points and discharge points must coincide).
splitstrmpath=str(workspace_folder) + "\\disch_reaches.shp"
arcpy.SplitLine_management(strm_net_path,splitstrmpath)
# Copy features to geodatabase for drainage area calculation
arcpy.FeatureClassToGeodatabase_conversion(splitstrmpath,gdb_name)
strmdischargergdb= gdb_name + "\\disch_reaches"
# Add Fields to discharge_reaches to obtain the first x,y coordinates.
```

```
arcpy.AddField_management(strmdischargergdb,"xstartr", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(strmdischargergdb,"ystartr","DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(strmdischargergdb,"x_ystartr", "TEXT")
arcpy.CalculateField_management(strmdischargergdb, "xstartr", "!SHAPE.firstPoint.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(strmdischargergdb, "ystartr", "!SHAPE.firstPoint.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(strmdischargergdb, "x_ystartr", "str(float(!xstartr!))+\",\"+ str(float(!ystartr!))",
"PYTHON_9.3", "")
# Join discharge values based on x,y coordinates of discharge points and start x,y of discharge reaches
arcpy.JoinField_management(strmdischargergdb, "x_ystartr", strmdischargepgdb, "x_yp", ["drainarea_km2",
"totalimp_percnt", "Q_m3pers"])
AddMessage("The calculated rural discharge is saved as disch_reaches.")
```

Stream Power Tool

```
## This script calculates the stream power. width and critical stream power using discharge and slope values for reaches in the stream network.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#-----------------------------------------------------------------------------------------------------------------------
#import Arc Packages
import arcpy
from arcpy import *
from arcpy.sa import *
import arcinfo
import os
import sys
import math
#Allow overwrite of results
arcpy.env.overwriteOutput = True
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
# Import slope reach feature class from geodatabase
slopergdb = GetParameterAsText(1)
# Import discharge reach feature class and point feature class from geodatabase
disch_rgdb = GetParameterAsText(2)
##Inputs
coeff_a=GetParameterAsText(3)
coeff_b=GetParameterAsText(4)
d84predict =GetParameterAsText(5)
summary = GetParameterAsText(6)
summarytable=GetParameterAsText(7)
type= GetParameterAsText(8)
number= GetParameterAsText(9)
# Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\strmpower.gdb"
arcpy.Delete_management(gdb_name)
arcpy.CreateFileGDB_management(str(workspace_folder), "strmpower.gdb")
# Copy features to geodatabase for streampower calculation
#arcpy.FeatureClassToGeodatabase_conversion(pow_path,gdb_name)
```

```
# Intersect discharge and slope reaches to join their attributes
strmpowergdb= gdb_name + "\\strmpower_reach"
arcpy.Intersect_analysis([[disch_rgdb],[slopergdb]], strmpowergdb, "ALL", "", "INPUT")
# Add Field with specific weight of water(9810 N) and strmpower
arcpy.AddField_management(strmpowergdb,"Wg_Nperm3", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(strmpowergdb, "Wg_Nperm3", "9810" , "VB", "")
arcpy.AddField_management(strmpowergdb,"Power_Wperm", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionpow="!S_mperm!*!Q_m3pers!*!Wg_Nperm3!"
arcpy.CalculateField_management(strmpowergdb, "Power_Wperm", str(expressionpow), "PYTHON_9.3", "")
# Add Field with width and specific stream power
arcpy.AddField_management(strmpowergdb,"a", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.CalculateField_management(strmpowergdb, "a", str(coeff_a) , "VB", "")
arcpy.AddField_management(strmpowergdb,"b", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.CalculateField_management(strmpowergdb, "b", str(coeff_b) , "VB", "")
arcpy.AddField_management(strmpowergdb,"Width_m", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionwidth="!a!*(!drainarea_km2!**!b!)"
arcpy.CalculateField_management(strmpowergdb, "width_m", str(expressionwidth), "PYTHON_9.3", "")
arcpy.AddField_management(strmpowergdb,"SPower_Wperm", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionspow="!Power_Wperm!/!width_m!"
arcpy.CalculateField_management(strmpowergdb, "SPower_Wperm", str(expressionspow), "PYTHON_9.3", "")
if d84predict == "true":
        ##Calculate d84 based on Ferguson (2005) particle mobility model. Model fitting uses Annable (1996)
        #data.
        #Add field for d84 prediction
        arcpy.AddField_management(strmpowergdb,"D84_mm", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
        #Equation 16 from Ferguson (2005) Assumption: Di = Db
        #constants for d84 prediction
        gamma = 9790 # N/m3
        kappa = 0.41 # constant from Ferguson 2005 - works for D in mm, power in W/m2
        R = 1.65 # submerged specific gravity
```

```
	rho = 1000 # density of water
	theta_cb = 0.045 # shear stress threshold
	m =2.80 # roughness multiplier for D84 from Lopez and Barrangan e.g. Hey 1979
	gee = 9.81 #acceleration by gravity
	#C = log10(30*theta_cb*R/(e*m*!S_mperm!))"
	#expressionDb =
"(kappa*!SPower_Wperm!/(2.30*rho*log10(30*theta_cb*R/(exp*m*!S_mperm!))))**(2/3)/(theta_cb*R*gee)"
	expressionlogC= "math.log10(30*0.045*1.65/(math.exp(1)*2.80*(abs(!S_mperm!))))"
	expressionDb = "(((0.41*abs(!SPower_Wperm!))/(2.30*1000*" + str(expressionlogC) +
"))**(2.0/3)/(0.045*1.65*9.81))*1000"
	arcpy.CalculateField_management(strmpowergdb, "D84_mm", str(expressionDb), "PYTHON_9.3", "")
#Update summary table
if summary =="true":
	# import summary data containing orderid
	#summarytable=GetParameterAsText(3)
	summarygdb=os.path.dirname(summarytable)
	# intersect summary table with strm reaches
	intersectsummarygdb= str(summarygdb) + "\\sumdata_r"
	arcpy.Intersect_analysis([summarytable, strmpowergdb], intersectsummarygdb, "ALL", "", "INPUT")
	# Copy summary table with strm reaches to gdb
	#intersectsummarygdb= str(summarygdb) + "\\sumdata_r"
	#arcpy.FeatureClassToGeodatabase_conversion(intersectsummarygdb, summarygdb)
	# path for summary reaches
	summaryreachgdb= str(summarygdb) + "\\summary_reach"
	arcpy.AddMessage("If number already exists, program will end.")
	# Check if the label already exist
	checklabel= str(type) + str(number) + "Q"
	list_field = arcpy.ListFields(summaryreachgdb)
	for field in list_field:
		checklabel= str(type) + str(number) + "Q"
		if field.name == str(checklabel):
			arcpy.AddMessage("Number already exists. Please, Enter a different number.")
			sys.exit(0)
	if d84predict == "true":
		list= ["OrderID"]
		list_fields = arcpy.ListFields(summaryreachgdb)
		fieldname = [f.name for f in list_fields]
```

```
for field in list:
    if field in fieldname:
        #field name is adjusted based on labels
        new_da = str(type) + str(number) + "DA"
        new_imp = str(type) +str(number) + "Imp"
        new_slope = str(type) + str(number)+ "S"
        new_weight = str(type) + str(number)+ "W"
        new_q = str(type) + str(number)+ "Q"
        new_power = str(type) + str(number)+ "P"
        new_width= str(type) + str(number)+ "Wi"
        new_spower= str(type) + str(number)+ "SP"
        new_Db= str(type) + str(number)+ "Db"
        #add field to join reaches data to table
        arcpy.JoinField_management(summaryreachgdb, "OBJECTID",
strmpowergdb,"OBJECTID",["drainarea_km2","totalimp_percnt","S_mperm","Wg_Nperm3","Q_m3pers","Power_
Wperm","Width_m","SPower_Wperm", "D84_mm"])
        arcpy.AlterField_management(summaryreachgdb, 'drainarea_km2', new_da)
        arcpy.AlterField_management(summaryreachgdb, 'totalimp_percnt', new_imp)
        arcpy.AlterField_management(summaryreachgdb, 'S_mperm', new_slope)
        arcpy.AlterField_management(summaryreachgdb, 'Wg_Nperm3', new_weight)
        arcpy.AlterField_management(summaryreachgdb, 'Q_m3pers', new_q)
        arcpy.AlterField_management(summaryreachgdb, 'Power_Wperm', new_power)
        arcpy.AlterField_management(summaryreachgdb, 'Width_m', new_width)
        arcpy.AlterField_management(summaryreachgdb, 'SPower_Wperm',
new_spower)
        arcpy.AlterField_management(summaryreachgdb, 'D84_mm', new_Db)
    else:
        cursor1 = arcpy.SearchCursor(intersectsummarygdb)
        cursor2 = arcpy.InsertCursor(summaryreachgdb)
        for row1 in cursor1:
            cursor2.insertRow(row1)
        del row1
        del cursor1
        del cursor2
        #Add order number
        arcpy.JoinField_management(summaryreachgdb, "OBJECTID",
intersectsummarygdb, "OBJECTID",["OrderID", "Swshed_ID"])
```

```
                        #field name is adjusted based on labels
                        new_da = str(type) + str(number) + "DA"
                        new_imp = str(type) +str(number) + "Imp"
                        new_slope = str(type) + str(number)+ "S"
                        new_weight = str(type) + str(number)+ "W"
                        new_q = str(type) + str(number)+ "Q"
                        new_power = str(type) + str(number)+ "P"
                        new_width= str(type) + str(number)+ "Wi"
                        new_spower= str(type) + str(number)+ "SP"
                        new_Db= str(type) + str(number)+ "Db"
                        #add field to join reaches data to table
                        arcpy.JoinField_management(summaryreachgdb, "OBJECTID", strmpowergdb,
"OBJECTID",["drainarea_km2","totalimp_percnt","S_mperm","Wg_Nperm3","Q_m3pers","Power_Wperm","Widt
h_m","SPower_Wperm","D84_mm"])
                        arcpy.AlterField_management(summaryreachgdb, 'drainarea_km2', new_da)
                        arcpy.AlterField_management(summaryreachgdb, 'totalimp_percnt', new_imp)
                        arcpy.AlterField_management(summaryreachgdb, 'S_mperm', new_slope)
                        arcpy.AlterField_management(summaryreachgdb, 'Wg_Nperm3', new_weight)
                        arcpy.AlterField_management(summaryreachgdb, 'Q_m3pers', new_q)
                        arcpy.AlterField_management(summaryreachgdb, 'Power_Wperm', new_power)
                        arcpy.AlterField_management(summaryreachgdb, 'Width_m', new_width)
                        arcpy.AlterField_management(summaryreachgdb, 'SPower_Wperm',
new_spower)
                        arcpy.AlterField_management(summaryreachgdb, 'D84_mm', new_Db)
    else:
        list= ["OrderID"]
        list_fields = arcpy.ListFields(summaryreachgdb)
        fieldname = [f.name for f in list_fields]
        for field in list:
            if field in fieldname:
                        #field name is adjusted based on labels
                        new_da = str(type) + str(number) + "DA"
                        new_imp = str(type) +str(number) + "Imp"
                        new_slope = str(type) + str(number)+ "S"
                        new_weight = str(type) + str(number)+ "W"
                        new_q = str(type) + str(number)+ "Q"
```

```
new_power = str(type) + str(number)+ "P"
new_width= str(type) + str(number)+ "Wi"
new_spower= str(type) + str(number)+ "SP"
#add field to join reaches data to table
arcpy.JoinField_management(summaryreachgdb,"OBJECTID",strmpowergdb,"OBJECTID",["drainarea_km2","totalimp_percnt","S_mperm","Wg_Nperm3","Q_m3pers","Power_Wperm","Width_m","SPower_Wperm"])
arcpy.AlterField_management(summaryreachgdb, 'drainarea_km2', new_da)
arcpy.AlterField_management(summaryreachgdb, 'totalimp_percnt', new_imp)
arcpy.AlterField_management(summaryreachgdb, 'S_mperm', new_slope)
arcpy.AlterField_management(summaryreachgdb, 'Wg_Nperm3', new_weight)
arcpy.AlterField_management(summaryreachgdb, 'Q_m3pers', new_q)
arcpy.AlterField_management(summaryreachgdb, 'Power_Wperm', new_power)
arcpy.AlterField_management(summaryreachgdb, 'Width_m', new_width)
arcpy.AlterField_management(summaryreachgdb, 'SPower_Wperm', new_spower)
else:
    cursor1 = arcpy.SearchCursor(intersectsummarygdb)
    cursor2 = arcpy.InsertCursor(summaryreachgdb)
    for row1 in cursor1:
        cursor2.insertRow(row1)
    del row1
    del cursor1
    del cursor2
    #Add order number
    arcpy.JoinField_management(summaryreachgdb, "OBJECTID", intersectsummarygdb, "OBJECTID",["OrderID", "Swshed_ID"])
    #field name is adjusted based on labels
    new_da = str(type) + str(number) + "DA"
    new_imp = str(type) +str(number) + "Imp"
    new_slope = str(type) + str(number)+ "S"
    new_weight = str(type) + str(number)+ "W"
    new_q = str(type) + str(number)+ "Q"
    new_power = str(type) + str(number)+ "P"
    new_width= str(type) + str(number)+ "Wi"
    new_spower= str(type) + str(number)+ "SP"
    #add field to join reaches data to table
```

```
arcpy.JoinField_management(summaryreachgdb, "OBJECTID",
strmpowergdb,"OBJECTID",["drainarea_km2","totalimp_percnt","S_mperm","Wg_Nperm3","Q_m3pers","Power_
Wperm","Width_m","SPower_Wperm"])
arcpy.AlterField_management(summaryreachgdb, 'drainarea_km2', new_da)
arcpy.AlterField_management(summaryreachgdb, 'totalimp_percnt', new_imp)
arcpy.AlterField_management(summaryreachgdb, 'S_mperm', new_slope)
arcpy.AlterField_management(summaryreachgdb, 'Wg_Nperm3', new_weight)
arcpy.AlterField_management(summaryreachgdb, 'Q_m3pers', new_q)
arcpy.AlterField_management(summaryreachgdb, 'Power_Wperm', new_power)
arcpy.AlterField_management(summaryreachgdb, 'Width_m', new_width)
arcpy.AlterField_management(summaryreachgdb, 'SPower_Wperm',
new_spower)
```

Drainage Area Tool

```
## Python Script: This script delineates the cumulative drainage area as polygons for each discharge point.
##Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#-----------------------------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import csv
import domainvalues
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
# Import discharge points shapefile
dischargepts = GetParameterAsText(1)
# Make a copy of discharge points shapefile
pointspath = str(workspace_folder) + "\\pointscopy.shp"
arcpy.CopyFeatures_management(dischargepts, pointspath)
arcpy.DeleteField_management(pointspath, ["Join_Count","TARGET_FID","Id","GRID_CODE", "ORIG_FID"])
#Import flow accumulation raster
flow_accum= GetParameterAsText(2)
#Import flow direction raster
flow_dir= GetParameterAsText(3)
# Create a folder to store the point shapefiles and use the shapefiles to create their drainage area polygons
arcpy.CreateFolder_management(str(workspace_folder), "pointshp")
arcpy.CreateFolder_management(str(workspace_folder), "dashp")
pointshppath= str(workspace_folder)+ "\\pointshp"
dashppath= str(workspace_folder)+ "\\dashp"
AddMessage("Creating folders to store discharge points and drainage area polygons.")
cursor= arcpy.da.SearchCursor(pointspath, ["FID"])
for row in cursor:
```

```
        attribute=row[0]
        point_name = str(pointshppath) + "\\" + str(attribute) + u".shp"
        da_name = str(dashppath) + "\\" + str(attribute) + u".shp"
        where = "\"FID\" = " + str(attribute)
        arcpy.Select_analysis(pointspath, point_name, where)
        snappour= SnapPourPoint(point_name, flow_accum, "10", "POINTID")
        wshed= Watershed(flow_dir, snappour, "Value")
        arcpy.RasterToPolygon_conversion(wshed, da_name, "NO_SIMPLIFY", "Value")
# Merge all watershed shapefiles together
arcpy.env.workspace = dashppath
dashplist=arcpy.ListFeatureClasses()
arcpy.Merge_management(dashplist, os.path.join(dashppath, 'all_dashps.shp'))
AddMessage("Merging all drainage areas together.")
# Some drainage areas need to be dissolved
alldapath= str(dashppath)+ "\\all_dashps.shp"
alldapathlyr= str(dashppath)+ "\\all_dashpslyr"
final_da = str(dashppath)+ "\\final_da.shp"
arcpy.MakeFeatureLayer_management(alldapath, alldapathlyr)
arcpy.Dissolve_management(alldapathlyr, final_da, ["GRIDCODE"])
AddMessage("Dissolving drainage area polygons together.")
#Create file geodatabase to store final results
#Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\drainagearea.gdb"
arcpy.Delete_management(gdb_name)
arcpy.CreateFileGDB_management(str(workspace_folder), "drainagearea.gdb")
# Copy final drainage area polygons to geodatabase
arcpy.FeatureClassToGeodatabase_conversion(final_da,gdb_name)
dischdagdb= gdb_name + "\\final_da"
# Edit field "GRIDCODE" to PointID
arcpy.AlterField_management(dischdagdb, "GRIDCODE", "POINTID", "", "", "", "NON_NULLABLE", "false")
AddMessage("The final drainage area polygons are saved in final_da.")
```

Future Land Use Tool

```
## This script updates the old land use cover with the new land use polygons.
## Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#------------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import arceditor
import arcinfo
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
#Import old land use shapefile
oldlu = GetParameterAsText(1)
#Import the new land use shapefile
newlu = GetParameterAsText(2)
# Update old land use with new land use
updatedlu= str(workspace_folder) + "\\modifiedlu.shp"
arcpy.Update_analysis(oldlu, newlu, updatedlu)
```

Urban Discharge Tool

```
## This script finds the  discharge along the stream network by relating it to imperviousness.
## Written by Kimisha Ghunowa, River Hydraulics Research Group, University of Waterloo.
#-----------------------------------------------------------------------------------------#
#import Arc Packages
import arcpy
import numpy as np
from arcpy import *
from arcpy.sa import *
import os
import arceditor
import arcinfo
#Set workspace folder
workspace_folder = GetParameterAsText(0)
env.workspace= str(workspace_folder)
#Allow overwrite of results
arcpy.env.overwriteOutput = True
#Import discharge points
disch_pt = GetParameterAsText(1)
#Import drainage area polygons shapefile
dischpolygdiss = GetParameterAsText(2)
#Define following variables
lu_path = GetParameterAsText(3)
#coeff_c=GetParameterAsText(4) Note:hardcoded
#coeff_x=GetParameterAsText(5) Note:hardcoded
#coeff_b=GetParameterAsText(6) Note:hardcoded
disch_reach= GetParameterAsText(7)
#Create file geodatabase to store final results
#Process: Delete geodatabase with same name and create new file geodatabase
gdb_name=str(workspace_folder)+ "\\imperviousness.gdb"
arcpy.Delete_management(gdb_name)
arcpy.CreateFileGDB_management(str(workspace_folder), "imperviousness.gdb")
# Copy discharge drainage area polygons to geodatabase
arcpy.FeatureClassToGeodatabase_conversion(dischpolygdiss,gdb_name)
dischpt_dagdb= gdb_name + "\\final_da"
```

```
# Add field to calculate drainage area
arcpy.AddField_management(dischpt_dagdb, "drainarea_km2", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
# Calculate drainage area based on 10x10m cell(given by elevation cell dimension)
arcpy.CalculateField_management(dischpt_dagdb,"drainarea_km2","!shape.area@squarekilometers!","PYTHON_9.
3","#")
# Copy discharge points to gdb
disch_ptgdb= str(gdb_name) + "\\disch_ptcopy"
arcpy.CopyFeatures_management(disch_pt, disch_ptgdb)
arcpy.DeleteField_management(disch_ptgdb, ["Join_Count","TARGET_FID","Id","ORIG_FID"])
# Copy landuse imperviousness polygons to geodatabase
#Already defined at the beginning: lu_path = GetParameterAsText(3)
#lu_path = "C:\GIS_Research\Masters_Thesis\Ganet_ModelBuilding\Scripts\Test\imp_ganet.shp"
arcpy.FeatureClassToGeodatabase_conversion(lu_path,gdb_name)
lu_pathname=os.path.splitext(os.path.basename(str(lu_path)))[0]
lu_gdb= gdb_name + "\\" + str(lu_pathname)
# Intersect landuse with drainage area to find which landuse types each contain
dischda_lugdb=gdb_name+"\\dischda_lu"
#arcpy.Intersect_analysis([dischpt_dagdb,lu_gdb], dischda_lugdb, "ALL","", "INPUT")
# Copy drainage area with landuse to gdb
#dischda_lugdb= str(gdb_name) + "\\dischda_lu"
#arcpy.CopyFeatures_management(dischdalupath, dischda_lugdb)
# Add field to calculate drainage area
arcpy.AddField_management(dischda_lugdb, "luarea_km2", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
# Calculate drainage area based on 10x10m cell(given by elevation cell dimension)
arcpy.CalculateField_management(dischda_lugdb,"luarea_km2","!shape.area@squarekilometers!","PYTHON_9.3",
"#")
# Add field to calculate imperviousness for each land use type
arcpy.AddField_management(dischda_lugdb, "impervOfluarea_km2", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
# Calculate drainage area based on 10x10m cell(given by elevation cell dimension)
percent= "((!imper_pcnt!)/100)"
arcpy.CalculateField_management(dischda_lugdb,"impervOfluarea_km2",percent+"*(!luarea_km2!)","PYTHON_9
.3","#")
```

```
#Create summary stats table for calculating the sum of imperviousness for each drainage area
sumimperv = str(gdb_name) + "\\sumimper_da"
# Process: Summary Statistics
arcpy.Statistics_analysis(dischda_lugdb, sumimperv, "impervOfluarea_km2 SUM", "FID_final_")
# Join sum of imperviousness area to drainage areas
# Process: Join Field
arcpy.JoinField_management(dischpt_dagdb, "OBJECTID", sumimperv, "FID_final_",
"SUM_impervOfluarea_km2")
# Add field to calculate total imperviousness (=sum imperviousness area/ drainage area) for each drainage area
arcpy.AddField_management(dischpt_dagdb, "totalimp_percnt", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
# Calculate total imperviousness (=sum imperviousness area/ drainage area)
ratio= "((!SUM_impervOfluarea_km2!)/(!drainarea_km2!))"
arcpy.CalculateField_management(dischpt_dagdb,"totalimp_percnt",ratio +"*100","PYTHON_9.3","#")
# Process: Join Field of drainage area total imp and drainage_area_km2 with discharge points
arcpy.JoinField_management(disch_ptgdb, "POINTID",dischpt_dagdb, "POINTID", "totalimp_percnt")
arcpy.JoinField_management(disch_ptgdb, "POINTID",dischpt_dagdb, "POINTID", "drainarea_km2")
## Add Field to calculate discharge using Q=cA^x(IA^b) where c, x and b are coefficcients, A is the drainage area
and IA is total imperviousness percentage.
coeff_c=GetParameterAsText(4)
coeff_x=GetParameterAsText(5)
coeff_b=GetParameterAsText(6)
arcpy.AddField_management(disch_ptgdb,"urban_c", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(disch_ptgdb, "urban_c", "0.52" , "VB", "")
arcpy.AddField_management(disch_ptgdb,"urban_x", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(disch_ptgdb, "urban_x", "0.7" , "VB", "")
arcpy.AddField_management(disch_ptgdb,"urban_b", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.CalculateField_management(disch_ptgdb, "urban_b", "0.3" , "VB", "")
arcpy.AddField_management(disch_ptgdb, "Q_m3pers", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
expressionuq= "!urban_c!*(!drainarea_km2!**!urban_x!)*(!totalimp_percnt!**!urban_b!)"
arcpy.CalculateField_management(disch_ptgdb,"Q_m3pers",str(expressionuq),"PYTHON_9.3","#")
```

```
# Add field to discharge points to obtain the x,y coordinates of the points.
arcpy.AddField_management(disch_ptgdb,"xp", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.AddField_management(disch_ptgdb,"yp","DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED",
"")
arcpy.AddField_management(disch_ptgdb,"x_yp", "TEXT")
arcpy.CalculateField_management(disch_ptgdb, "xp", "!SHAPE.CENTROID.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(disch_ptgdb, "yp", "!SHAPE.CENTROID.Y!", "PYTHON_9.3", "")
arcpy.CalculateField_management(disch_ptgdb, "x_yp", "str(float(!xp!))+\",\"+ str(float(!yp!))",  "PYTHON_9.3",
"")
##Creating reaches for urban discharge
#Already defined at the beginning: disch_reach= GetParameterAsText(7)
# Copy dischreaches to gdb
disch_reachesgdb= str(gdb_name) + "\\disch_reaches"
arcpy.CopyFeatures_management(disch_reach, disch_reachesgdb)
#Delete all fields in dischreaches (including previously calculated discharge)
desc = arcpy.Describe(disch_reachesgdb)
fieldslist=arcpy.ListFields(disch_reachesgdb)
fieldnames = []
for field in fieldslist:
        if not field.required:          # only list nonrequired fields
                fieldnames.append(field.name)
if desc.dataType in ["ShapeFile", "DbaseTable"]: ##Retain an extra field
    fieldnames = fieldnames[2:]
# Execute DeleteField to delete all fields in the field list.
arcpy.DeleteField_management(disch_reachesgdb, fieldnames)
# Add Fields to discharge_reaches to obtain the first x,y coordinates.
arcpy.AddField_management(disch_reachesgdb,"xstartr", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(disch_reachesgdb,"ystartr","DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")
arcpy.AddField_management(disch_reachesgdb,"x_ystartr", "TEXT")
arcpy.CalculateField_management(disch_reachesgdb, "xstartr", "!SHAPE.firstPoint.X!", "PYTHON_9.3", "")
arcpy.CalculateField_management(disch_reachesgdb, "ystartr", "!SHAPE.firstPoint.Y!", "PYTHON_9.3", "")
```

```
arcpy.CalculateField_management(disch_reachesgdb, "x_ystartr", "str(float(!xstartr!))+\",\"+ str(float(!ystartr!))",
"PYTHON_9.3", "")
# Join discharge values based on x,y coordinates of discharge points and start x,y of discharge reaches
arcpy.JoinField_management(disch_reachesgdb, "x_ystartr", disch_ptgdb, "x_yp", ["drainarea_km2",
"totalimp_percnt", "Q_m3pers"])
```