The influence of contributing area on the hydrology of the prairie pothole region of North America

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Abstract

This thesis formulates a conceptual framework developed from field observations that describes the influence of surface depressions or potholes on runoff generation in the prairie pothole region of the North American prairies. The fill-and-spill of potholes results in intermittent surface water connectivity between potholes within the basin. The extent of connectivity between potholes is dependent on antecedent water levels. Dynamic connectivity between potholes results in dynamic contributing areas for runoff. The concept of connectivity is manifested in the conceptual curves presented in this thesis. These conceptual curves model the response of runoff events for landscape types found in the prairie pothole region, and capture the influence of the spatial distribution and extent of surface storage on contributing area. The conceptual curves differ due to variations in the spatial distribution and extent of surface storage volume.

An algorithm based on the conceptual framework proposed is presented. The algorithm, which uses the the D-8 drainage direction method, automates a methodology for identifying and quantifying runoff contributing area. The algorithm is applied in prairie pothole basins both to demonstrate its efficacy and to test the potential for using conceptual curves to describe the relationship between decreasing potential surface storage in the landscape and contributing area. The algorithm was applied to two digital elevation models (DEM) representative of the prairie pothole region. The first DEM was created using LiDAR elevation points at a 1 m resolution for the St. Denis watershed, and the second was created from orthophotos for the Smith Creek watershed at a 25 m resolution.

Fieldwork in the St. Denis watershed was carried out to both provide a basis for the conceptual framework proposed and to validate the results of the algorithm. The fieldwork involved gathering snow survey data, identifying and describing surface water conditions during a snow melt runoff event in 2006, and measuring pond levels from 2004 – 2007.

Results indicate that the proposed conceptual curves represent the non-linear relationship between potential surface storage and contributing area generated by the algorithm in the test basins. To test whether the underlying concepts of the algorithm were valid, the algorithm was used to model pond level depths measured in the St. Denis drainage basin after spring runoff in 2006 and 2007. An r^2 value over 0.9 was calculated for the relationship between measured and modeled pond levels in both years. Based on this work, it is clear that any hydrologic study or model applied in the prairie pothole region should consider the effect of dynamic contributing areas on runoff generation.

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A_{PS}	Pond surface area
CA_B	Basin contributing area (m^2)
CA_G	Gross contributing area (m^2)
CA_P	Pond contributing area (m^2)
CA_{PBND}	Pond contributing area boundary
CA_{POUT}	Pond contributing area outlet
D_Δ	Input depth change (cm)
D_I	Input depth (cm)
D_{MIN}	Minimum input depth (cm)
V_I	Input volume (m^3)
V_{SSA}	Volume of surface storage available (m^3)
V_{PMAX}	Maximum pond volume (m^3)
V_{BMAX}	Maximum basin volume (m^3)

CHAPTER 1

INTRODUCTION

1 Statement of Problem

The North American prairie pothole region encompasses approximately 775,000 km^2 of the north-central United States and south-central Canada (Figure 1-1). The unique topography of the prairie pothole region creates challenges for properly understanding hydrological processes within this area. Stichling and Blackwell (1957) were the first to identify the influence of large depressional storage on the fluctuation of contributing area in the prairie pothole region. The authors speculate that contributing area within these landscapes varies by season and year and that application of a variable contributing area concept would permit more accurate stream flow determination, particularly in areas where stream flow data is missing. However, Stichling and Blackwell (1957) were unable to quantify variable contributing areas.

The issue of variable or dynamic contributing area in the prairie pothole region has largely been ignored in the hydrological community. For example, Gray and Landine (1987) present a model for synthesizing streamflow in prairie pothole basins and discuss the performance of the model with only cursory mention of the topography and the effect depressional storage will have on the resulting hydrographs. Euliss et al. (2004)

propose a conceptualization of the horizontal movement of water in the prairie pothole region as entirely groundwater driven. Although this may be reasonable in some wetland complexes, other research in the prairie pothole region contradicts the importance of groundwater as a mechanism for lateral movement of water in the basin (van der Kamp and Hayashi, 1998; Conly and van der Kamp, 2001; van der Kamp and Hayashi, 2009). As presented in the literature review, subsequent studies have acknowledged surface water connectivity between depressions (potholes) in the region but have not presented a methodology for capturing and simulating the effect of fill-and-spill and the resulting connectivity between potholes (Rosenberry and Winter, 1997; Leibowitz and Vining, 2003).

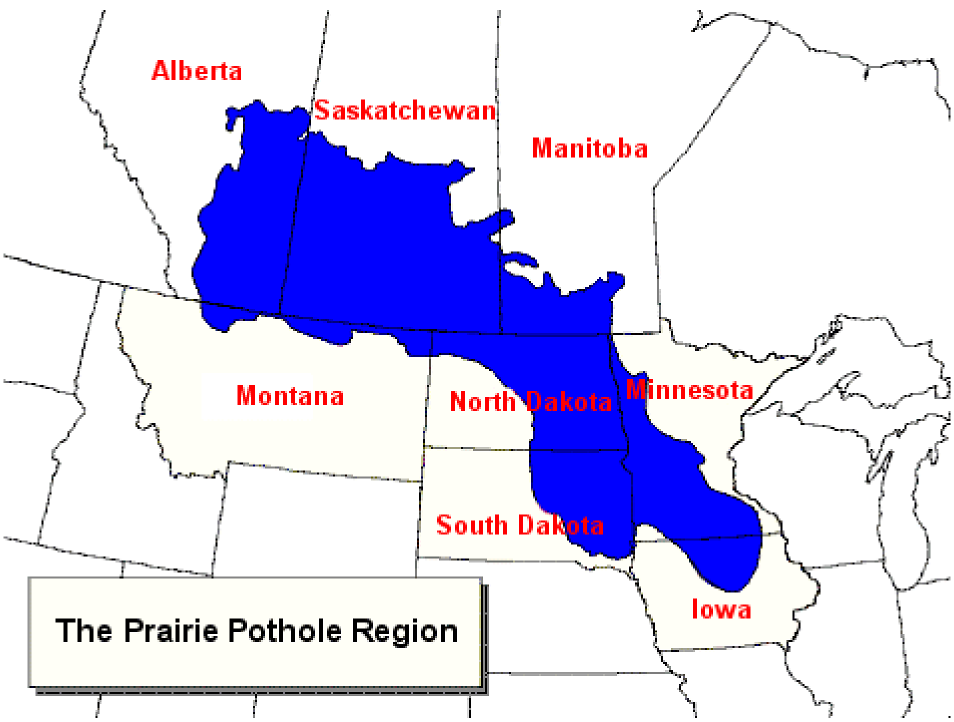


Figure 1-1. The prairie pothole region of North America.

Current hydrological practice often utilizes automated methods such as landscape analysis tools that can only calculate a threshold storage volume value that when satisfied, allows 100% of the basin to contribute. However, the large extent of non-contributing area defined by Agriculture and Agri-food Canada – Prairie Farm Rehabilitation Administration (see section 2.2.1) illustrate that most runoff events in the prairie pothole region are sub-threshold events that contribute only a portion of the total basin area to the outlet. Government agencies have developed methodologies for determining contributing areas for sub-threshold runoff events but these methodologies do not incorporate current technologies or incorporate antecedent basin conditions and, as a result, have limitations (see section 2.1).

The research presented in this thesis examines the spatial structure of drainage basins in the prairie pothole region and how topography and topology (the relationship between potholes and whether they receive or drain water to another pothole through surface water connections) control runoff response and basin contributing area within these basins. As such, this thesis approaches the concepts of connectivity and fill-and-spill from a geography-based rather than a physical hydrology-based perspective. However, this thesis acknowledges that the fill-and-spill of prairie pothole basins is not only influenced by topography and topology, but also by antecedent basin conditions that reflect the physical hydrology of the region (see section 2.2.3).

Potential surface storage in the basin decreases in response to input runoff and increases through loss of water through evaporation and groundwater seepage. This introduces a level of complexity for determining antecedent basin conditions such as the volume of potential storage in the basin. Unlike the fill of prairie potholes during runoff events, water losses from potholes are not influenced to a great degree by topography and topology. As a result, the relationship established between contributing area and basin topography and topology as a basin fills with runoff from an empty or dry state breaks down when water is removed from the basin. Thus, the prairie pothole region can be thought of as a hybrid system as the processes that control the filling and emptying of the basin are fundamentally different.

1.1 Rationale

The potential impacts of climate change combined with an ever increasing demand for water require that water resource managers have suitable tools to make informed decisions for both flood control and apportionment of water among the many competing interests of users. The seasonal and annual variability of rain and snowfall and antecedent basin conditions (Winter and Rosenberry, 1995) create unique challenges for correctly modeling river basin hydrology in the prairie pothole region. Excessive precipitation and runoff from snowmelt led to a disastrous flood of the Red River in 1997 (Macek-Rowland, 1997). Conversely, subsequent years of drought have placed a high demand on surface water for irrigation and livestock (Agriculture and Agri-Food Canada, 2003)..

The topography of the prairie pothole region of North America poses unique challenges for defining contributing areas. Although the drainage network is not well integrated into the landscape, when a runoff event fills a pothole and satisfies its potential storage, any further runoff will spill to downstream potholes. However, due to the irregular distribution and morphology of potholes, runoff does not follow a simple, cascading flow to the basin outlet. Instead, a complex cascade controlled by the connectivity of potholes in the basin occurs.

Hydrological models do not currently incorporate the influence of dynamic potential surface storage and the effect this dynamic storage has on contributing area in prairie pothole basins. Rather, many models simply assume that 100% of the basin contributes to the outlet. This assumption is satisfactory for runoff events that fill the potential storage within the basin. However, due to the semi-arid environment, such a threshold runoff event may occur infrequently in the prairie pothole region (Leibowitz and Vining, 2003). To improve hydrological models for the prairie pothole region, a methodology for determining contributing areas for runoff events that only partially satisfy the potential surface storage of a basin (sub-threshold runoff events) is required. Dynamic contributing areas, which are a function of the dynamic storage potential of the prairie pothole landscape, are critical for predicting the magnitude and timing of runoff events within and at the outlet of a prairie pothole drainage basin.

At present, software that models surface depression fill-and-spill and the resulting surface water connectivity is not available. Programs such as the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model many surface runoff processes but do not incorporate fill-and-spill. As such, there are no satisfactory algorithms for modeling the prairie pothole environment.

The effect of dynamic contributing area should be considered in any hydrologic study within the prairie pothole region. Dynamic contributing area should be included in both small and large-scale hydrological models and atmospheric models applied in the region.

1.2 Nature and Scope of Research

This thesis identifies the unsatisfactory state of hydrological modeling in the prairie pothole region due to poor contributing area delineation. The concept of variable or dynamic contributing areas as a foundation for parameterizing the complex impact of depression storage on the contributing areas is proposed: rather than basin contributing areas varying in time and space as a result of saturated ground conditions, prairie pothole region contributing areas will vary spatially and temporally as a result of antecedent basin conditions, potential surface storage and connectivity of potholes.

Fieldwork was undertaken on a small prairie pothole basin to conceptualize connectivity and fill-and-spill in the prairie pothole region. This involved data collection to identify and facilitate a better understanding of the hydrological processes involved in connectivity and fill-and-spill. Fieldwork was carried out over several years that included both wet and dry antecedent basin conditions during spring runoff events (see section 4.1). The effect of topography and topology on runoff events in the basin was noted. Results from the field studies were used to conceptualize the complexity of the topology and the influence of topography on connectivity in prairie pothole basins.

The relationship between decreasing potential storage in the landscape and contributing area at the basin outlet is hypothesized to be non-linear. Conceptual characteristic curves that illustrate the relationship between decreasing potential storage and contributing area for basins characteristic of the prairie pothole region are presented. The conceptual curves proposed in this thesis are similar to Snow Depletion Curves (SDC) in that they provide a basis for parameterizing large-scale models while capturing and simulating small-scale processes (Donald et al., 1995). The conceptual curves proposed provide a basis for calculating contributing area in a computationally efficient and repeatable manner. The conceptual curves are characterized by the landscape. The curves are differentiated by the location and extent of potential surface storage volume (V_{SSA}) that is available in surface depressions and wetlands. Thus both the topography and the topology of the basin is manifest in the curves.

A Simple Pothole terraIn anaLysis aLgorithm (SPILL) is presented for determining contributing area based on the surface water connectivity that results from the fill-and-spill of prairie potholes. The algorithm is used to understand the relationship between decreases in potential storage in the landscape and basin contributing area. Application of the algorithm to study basins located within the prairie pothole region allows for the examination of proposed conceptual curves that represent the relationship between potential storage and contributing area.

SPILL is based on a modification of traditional landscape analysis tool methods, using input hydrologic data and topographic information derived from a digital elevation model (DEM). Current landscape analysis models also calculate hydrologic and topographic information from a DEM. However, as noted, current methods artificially fill depressions in the DEM. This method is unacceptable as depressions are the predominant landscape feature in the prairie pothole region (Woo, 2002).

SPILL simulates the redistribution of input runoff by applying runoff depths consistently over the basin. The algorithm does not attempt to model the vertical water budgetof the runoff event, and assumes that runoff depth has been properly estimated prior to input by means of physically-based hydrological models. Decreasing runoff depth input into the algorithm can simulate additional hydrological processes such as infiltration.

Two study areas characteristic of prairie pothole basins are examined in this thesis. The St. Denis National Wildlife Area (SDNWA) basin is a small basin for which a DEM is available at a 1m resolution. A larger basin, the Smith Creek watershed, is a sub-basin of the Assiniboine River basin. A 25 metre DEM is available for Smith Creek basin.

Results produced by SPILL are used to examine the nature of the relationship between potential surface storage and contributing area for sub-threshold runoff events in the prairie pothole region. The results are also used to propose a methodology for parameterizing hydrological and atmospheric models.

1.3 Objectives

This thesis has two objectives. The first is to conceptualize and quantify the nature of the relationship between potential surface storage and contributing area for sub-threshold runoff events in the prairie pothole region. A large amount of study of the hydrology of individual prairie potholes has been already been completed (van der Kamp and Hayashi, 1998; LaBaugh et al., 1998). However, very little research focuses on how surface connections between prairie potholes vary spatially and temporally and how these connections effect contributing area size.

The second objective is to develop an automated landscape analysis algorithm that captures and simulates pothole connectivity in response to runoff events and can be used to parameterize hydrological and atmospheric models. There has been a strong research effort into resolving correct drainage directions for large-scale semi-distributed, gridded, hydrological models and atmospheric models (Olivera et al., 2002; Feteke et al., 2001; Shaw et al., 2004). However, the same effort has not yet been applied to the equally important calculation of contributing areas for each sub-grid. Proper drainage direction determination will be of little value if the contributing area for drainage directions are in error.

1.4 Hypotheses

1. Current landscape analysis tools are not sufficiently robust to deal with the complexity of the prairie pothole landscape.
2. The relationship between potential surface storage and contributing area in a prairie pothole basin is non-linear and hysteretic.
3. Connectivity between prairie potholes has a significant influence on runoff volumes at the outlet of prairie pothole basins.

4. Runoff volumes in the prairie pothole region can be satisfactorily modeled using a connectivity-based algorithm.
5. Methodologies that simply calculate runoff volume at the outlet as runoff volume minus the potential storage volume are unsatisfactory for properly modeling runoff volumes in prairie pothole basins.

CHAPTER 2

LITERATURE REVIEW

2 General Background

Retreating Pleistocene continental glaciers deposited a glacial till over much of the North American prairie that produced a hummocky terrain with numerous depressions, or potholes. These depressions have the potential to store runoff in the landscape. This *depressional storage* is defined in hydrology as the volume of water contained in natural depressions in the land surface (Linsley, 1949). Although potholes impound a great deal of runoff, potholes can fill-and-spill resulting in surface water connections between the potholes. Surface water connectivity varies spatially and temporally between prairie potholes and results in dynamic basin contributing area. Connectivity between potholes is influenced by meteorological, physiographic and antecedent basin conditions (Stichling and Blackwell, 1957).

Runoff events and the resulting runoff volumes at the outlet of a drainage basin in the prairie pothole region, are not only influenced by topography and the ability of the landscape to impound and store runoff, but also by hydrometeorological factors and the size and intensity of the snowmelt or runoff event (Mowchenko and Meid, 1983; Stichling and Blackwell, 1957). Antecedent conditions, such as the potential surface storage volume (V_{SSA}) available in the basin prior to a runoff event will also control runoff volumes at the basin outlet. V_{SSA} will vary due to the state of ponds in basin. Typically during dry climatic cycles ponds will be dry and the basin may be close to the maximum V_{SSA}. However, during wet climatic cycles the ponds may be filled and the V_{SSA} of the basin can be greatly reduced. Runoff events in the prairie pothole region can also be impacted by anthropogenic influences on the landscape such as draining potholes to increase agricultural area (Padmanabhan and Bengtson, 1999a).

Runoff volumes can change dramatically from year to year in prairie pothole basins (Stichling and Blackwell, 1957). This is due, in part, to wet and dry climatic cycles (Winter and Rosenberry, 1995). Wet climatic cycles can partially or completely satisfy V_{SSA} in the prairie pothole region and can result in larger runoff events such the disastrous flood of the Red River in 1997 (Macek-Rowland, 1997). Dry climatic cycles can result in the maximum V_{SSA} being available during runoff events. The lack of horizontal movement of surface water exacerbates drought condition such as the severe drought in parts of the prairie pothole region in 2001-2002 (Bonsal and Wheaton, 2005).

The maximum V_{SSA} in the basin can be thought of as *threshold storage*. When threshold storage is satisfied 100% of the basin will contribute runoff to the outlet. Currently, studies of surface runoff storage in the prairie pothole region, and in particular the role of surface storage in flood attenuation, focus on total storage available in the basin (Gleason et al., 2007). Calculations of V_{SSA} are made using techniques such as using an area-volume relationship (Bengtson and Padmanabhan, 1999b; Hayashi and van der Kamp, 2000; Wiens, 2001). Hydrological models typically calculate runoff at the outlet as total runoff volume minus the potential or threshold storage volume (Gleason et al., 2007).

It is hypothesized in this thesis that a methodology that simply calculates runoff volume at the outlet as input precipitation minus the V_{SSA} is unsatisfactory for properly modeling runoff volumes in prairie pothole basins. Although most drainage basins in the prairie pothole region are thought of as hydrologically closed (the basin does not contribute runoff downstream) (Su et al., 2000) surface water connections between potholes within the basin can occur. Surface water connections arise when the V_{SSA} of an individual pothole is satisfied allowing further runoff to cascade to an adjacent pothole (Rosenberry and Winter, 1997; Stichling and Blackwell, 1957). Runoff events that do not satisfy the V_{SSA} for the entire basin (sub-threshold storage runoff events) can have surface water connections that are intermittent (Leibowitz and Vining, 2003). Intermittent connections are a result of potholes connecting during spill events and disconnecting when potholes no longer spill. As a result, contributing area and the resulting runoff volume at the outlet are dynamic.

2.1 The concept of connectivity in the prairie pothole region

In the prairie pothole region, connected areas can be used as a conceptual basis for how contributing areas expand. The concept of variable contributing areas in the prairie pothole region builds upon research based on Horton's (1933) overland flow research work. Horton suggested that infiltration is the controlling barrier that determines the shape of the storm hydrograph. Horton also hypothesized that when the infiltration rate was exceeded by the rate of input precipitation, overland flow, which travels over the surface as a thin sheet of water, occurs. Runoff in the basin would be more-or-less uniform with 100% of the basin contributing to the outlet.

Further research by Hursh (1944) refined and revised Horton's hypothesis. Of particular importance was the proposal of a partial area concept by Betson (1964). Betson did not challenge the importance of infiltration in generating runoff, but proposed that within a watershed there is only a limited amount of area that can contribute runoff to the outlet. Betson's non-linear mathematical model predicts that runoff is restricted to defined areas and that the areas are static. Betson concluded that contributing area would not vary for 'normal' runoff events.

Hewlett and Hibbert (1967) advanced runoff research further by hypothesizing that during a storm event all precipitation infiltrated the soil. Throughflow and infiltration would raise the water table until water reached the surface. This return flow (water that returns to the surface from below ground) mixed with rainfall falling on the saturated areas and produced surface runoff. This type of runoff was called saturated overland flow. Hewlett and Hibbert suggest that the saturated areas adjacent to the stream function as extended channels that are temporally and spatially dynamic. They refer to this concept as variable source area. Their research adds variability to Betson's ideas of partial area response. Subsequent research done by Dunne and Black (1970) identified areas that produce saturated overland flow in areas other than those adjacent to the channel. Dunne (1978) also proposes subsurface stormflow, which again saturates the soil, as a fundamental hydrologic process that determines the dynamic location of overland flow in variable source areas.

Although the theoretical basis of the research presented in this thesis is the variable contributing area concept, it differs significantly in the way contributing area increases. In previous variable contributing area research, contributing area expands out from the channel depending on saturated ground conditions. As a result, the contributing area is fixed and always connected to the outlet. The concepts of dynamic contributing area in the prairie pothole region presented in this thesis can the thought of as parallel and complimentary to previous variable or dynamic contributing area research. This research builds on the idea of variable contributing area, but presents the concept of topographically controlled rather than saturated ground controlled variability.

2.2 Current methods for basin contributing area identification

2.2.1 Prairie Farm Rehabilitation (PFRA) contributing area identification

In 1970, the Hydrology Division of Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration (PFRA) began work on contributing areas in the Canadian prairie provinces of Alberta, Saskatchewan, and Manitoba (Mowchenko and Meid, 1983). PFRA proposed the concept of dividing drainage areas into two types; *gross* drainage area and *effective* drainage area. Gross drainage area is defined as the area enclosed in the drainage divide that is expected to contribute runoff under extremely wet conditions. It can simply be thought of as the entire area of the watershed or the basin area that contributes when surface storage has been completely satisfied. Effective drainage area, as defined by PFRA, is the portion of the basin that is expected to contribute runoff during a mean annual runoff event (Stichling and Blackwell, 1957). Effective drainage area does not include areas that impound runoff during an average runoff event. Figure 2-1 shows the extent of the prairie region defined by PFRA as non-contributing during an average runoff event.

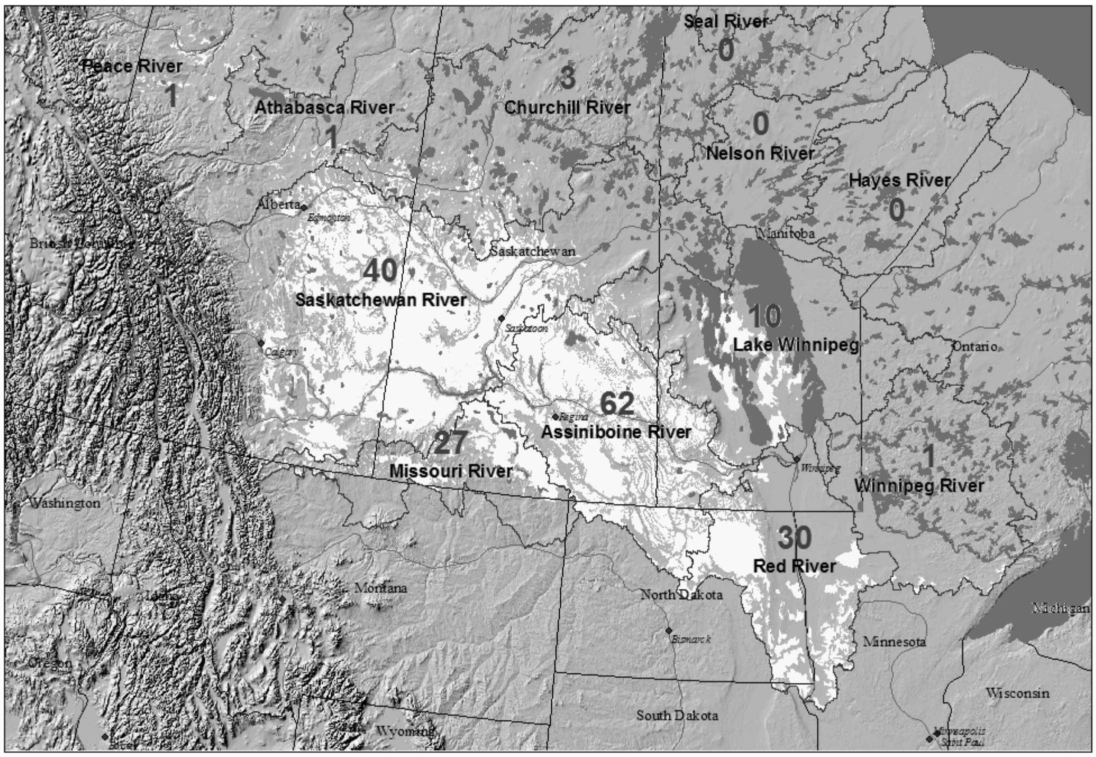


Figure 2-1. The white shaded area shows the extent of non-contributing areas defined by the Prairie Farm Rehabilitation Administration (P.F.R.A.). The numbers denote the percentage of the basin that is non-contributing. Source: Agriculture and Agri-Food Canada, P.F.R.A

PFRA defines "gross drainage" areas based upon topographic information supplied by 1:50,000 National Topographic Series (NTS) mapsheets. The height of the land measured from the NTS maps is used to determine the gross drainage area boundary for 1911 hydrometric stream gauging stations in Alberta, Saskatchewan, and Manitoba. For poorly drained areas, gross drainage areas are defined using physiographic characteristics such as slope, drainage pattern development and depressional storage in addition to topographical information. Depressions judged not to overflow during extremely high runoff conditions are excluded from the gross drainage area of the basin. Subjectivity is inherent in this process, however, as 'extremely high runoff conditions' are not quantified. This method determines a definite line for gross drainage area (Mowchenko and Meid, 1983). Because gross drainage area delineations require no assumptions about runoff magnitude it can be calculated solely by drainage directions determined by current landscape analysis models (see section 2.5).

Effective drainage, like gross drainage, is determined by the height of the land on topographic maps in the PFRA method. As with the gross drainage method, poorly drained areas are defined using physiographic characteristics, drainage patterns and depressional storage. A conceptual line that delineates the area that contributes runoff defines effective drainage area. A depression judged not to overflow in 50% of years is excluded from the effective drainage area. For mountainous and hilly areas this process is straightforward. However, in the prairie region several factors must be considered: the number of potholes in the basin; the size of potholes in the basin; and whether the pothole is small and connected to the mainstream by a channel. Field examinations of watersheds with poor drainage are required to determine runoff direction. Anecdotal evidence from local farmers is also used (Mowchenko and Meid, 1983). No automated or landscape analysis tools are available to calculate effective drainage.

To clarify terminology used in the remainder of this thesis, “effective drainage” will only be used when discussion is directly related to the PFRA methodology. Effective drainage, as it is defined above, refers to the drainage area that contributes flow during a *mean* runoff event. Effective drainage area is static and is defined by PFRA. The term “contributing area’ is variable and will be used to refer to the area that contributes runoff to the outlet during *any* runoff event.

$$\frac{\text{Area contributing runoff to basin outlet} * 100}{\text{Gross draiange area}} = \text{\% Contributing Area} \qquad \text{[Equation 1]}$$

“Non-contributing” area will refer to the area that does not produce runoff during a runoff event. It is influenced by topography, boundary conditions, and flood intensity. It should be noted that there are non-contributing areas on the prairies defined by PFRA as “dead drainage”. PFRA states that these areas will not contribute to the basin outlet even under extremely wet conditions (Mowchenko and Meid, 1983). An example of dead drainage is the tributaries of the Old Wives Lake in south-central Saskatchewan (Meid and Miller, 1978).

$$1 - \frac{\text{Contributing area} * 100}{\text{Gross drainge area}} = \text{\% Non-contributing area} \qquad \text{[Equation 2]}$$

2.2.2 United States Geological Survey (USGS) contributing area identification

The United States Geological Survey (USGS) has no formal methodology for determining contributing areas. It is left to individual states to define such methodology (Norbeck, 2003). Even within a state different areas may be treated as unique, resulting in a regional modification of the methodology. As a result, information on the methodology used to define non-contributing areas can only be collected through personal communication with field technicians.

In North Dakota, where prairie potholes heavily influence topography, non-contributing area is computed by using summary statistics such as average slope and average vegetation cover. Topographic information is supplied by maps with a 5-10 foot contour interval, depending on the relief of the landscape. This information is used to define areas that will contribute runoff to the outlet if water one inch, or more, in depth is applied consistently over the basin (Norbeck, 2003).

2.2.3 Shortcomings of current methods

An examination of PFRA and USGS methodologies reveals them to be highly subjective. Determination of contributing area is left to individual technicians. This subjectivity does not necessarily allow a repeatable process for defining effective runoff area by various operators or modelers. Further, both methods do not allow for variable runoff area determination on various landscapes at a variety of scales.

Another significant shortcoming of both methods is they do not incorporate antecedent basin conditions into the calculation of contributing area. The most significant antecedent condition for calculating contributing area in the prairie pothole regions is the V_{SSA} in the basin. When depressions in the basin are filled with water V_{SSA} in the basin can be partially or fully satisfied. When depressions have dried out and are empty, V_{SSP} will be maximum. A 'dry' basin will have significantly more V_{SSA} than a 'wet' basin that has V_{SSA} satisfied through previous filling of potholes in the basin. As such, both current methodologies for contributing area determination are only reasonable if the runoff event occurs in a basin that is dry (maximum V_{SSA}). As illustrated in Chapter 5, antecedent basin conditions must be incorporated into contributing area calculations for satisfactorily modeling runoff volumes at the outlet of a basin. Quantifying the identification of contributing areas based on input effective runoff and antecedent conditions should remove subjectivity from the process and allow repeatable results to be attained.

As described in section 4.3, a modified landscape analysis tool developed as part of this work provides a systematic and repeatable method for DEMs to be used to reflect antecedent surface storage conditions. Generating DEMs from remotely sensed sources such as **Li**ght **D**etection **a**nd **R**anging (LiDAR) allow pond levels and their effect of decreasing V_{SSA} to be included into the DEM data. This is because current remotely sensed methods cannot penetrate surface water and instead return the elevation of the pond surface rather than the elevation of the pond bottom. Thus, the resulting DEM is representative of the antecedent surface storage conditions as the LIDAR elevation data represents the 'filled' depressions rather than empty ones.

2.3 Prairie pothole hydrology

The complexity of prairie pothole hydrology is dominated by the connectivity between prairie potholes. The following section provides an overview of wetlands, examining relevant literature on prairie wetlands (prairie potholes) and identifying processes that are important for discerning how the prairie landscape generates and stores runoff.

2.3.1 Wetland and prairie pothole definitions

Wetlands can be defined as areas that are saturated long enough for poorly drained soils to form with establishment of hydrophytic vegetation and biological activity adapted to a wet environment (National Wetlands Working Group, 1997). There are five classes of wetlands: bog, fen, marsh, swamp, and shallow open water (National Wetlands Working Group, 1997). However, only shallow open water wetlands are relevant to this thesis.

The Canadian Wetland Classification System (National Wetlands Working Group, 1997) provide the following three descriptors of prairie potholes: 1) Prairie potholes are depressional wetlands that are primarily a type of fresh water marsh; 2) prairie potholes are better defined and deeper than marshes and 3) although potholes may receive some inflow of water through groundwater, the most important source of water is precipitation and runoff from surrounding areas. Prairie potholes were formed during the last glaciation (Late Pleistocene) when blocks of buried glacial ice melted, leaving saturated superglacial till to settle and created an inversion of the topography (Sloan, 1972). These depressions are found in the Canadian Prairie Provinces (Saskatchewan, Alberta, and Manitoba) and North Dakota, South Dakota, Wisconsin and Minnesota in the United States.

2.3.2 Wetland runoff processes

The following section outlines the physical hydrologic processes that influence fill-and-spill and basin connectivity. Of particular interest are three prairie hydrology overviews done by van der Kamp and Hayashi, (1998), Price et al., (2005) and LaBaugh et al., (1998). The amount of surface water that a pothole can store (which changes over time (LaBaugh et al., 1998)) can be answered by investigating the hydrological processes.

Filling prairie potholes with water is mainly accomplished through runoff of snowmelt over frozen ground (Hayashi et al., 2003; Li and Simonovic, 2002; Su et al., 2000) and blowing snow (Fang and Pomeroy, 2009) . However, even under frozen ground conditions, some runoff is lost to infiltration (Gray et al., 2001; Zhao and Gray, 1997).

The infiltration and movement of water into unfrozen soils are governed by the soil's hydraulic conductivity (a measure of the soil's ability to transmit water) and water-retention characteristics (the ability to store and release water) (Rawls et al., 1992). Hydraulic conductivity is influenced by the soil characteristics of soil porosity, pore-size distribution and pore continuity. During dry soil conditions, water moves into the soil column by gravity and capillary movement (Linsley et al., 1949)

Infiltration rates can vary according to:

1. the physical characteristics of the soil
2. the initial soil moisture content of the soil
3. the drop size and rainfall intensity
4. the hillslope
5. vegetation

Infiltration into frozen soil removes runoff from the landscape surface and has a large impact on the size of the spring snowmelt runoff. The infiltration potential of frozen soils can be grouped into three categories (Granger et al., 1984):

1. Restricted – an impermeable layer near the surface (such as an ice lense) impedes infiltration
2. Limited – infiltration is governed primarily by snow water equivalent and soil water content of the layer of soil 0-30 cm from the surface
3. Unlimited – the soil will infiltrate most or all of snowmelt due to macropores, cracks and air-filled noncapillary pores

A five-year study of frozen soil infiltration on the brown and dark brown prairie soils produced a simple equation for infiltration in soils with restricted or limited infiltrability (Granger et al., 1984). It is hardest to quantify the removal of surface water during limited infiltration conditions. Granger et al. (1984), observe that soil water content has the largest influence on the infiltrability of limited frozen soils, and formulate an equation that approximates infiltration using soil water content and snow water equivalent:

$$INF = 5(1-\theta_p)\ SWE^{0.584} \qquad \text{[Equation 3]}$$

Where INF = infiltration (mm)
SWE = snow water equivalent (mm)
θ_p = the degree of pore saturation in cubic cm per cubic cm.

Subsequent research has enhanced the Granger et al. (1984) equation and a parametric equation has been developed that describes the cumulative infiltration into limited frozen soils (Gray et al., 2001):

$$INF = CS_0^{\ 2.92}\ (1-S_I)^{1.64}\left(\frac{273.15-T_I}{273.13}\right)^{-0.45} t_0^{\ 0.44} \qquad \text{[Equation 4]}$$

Where C = coefficient

S_0 = surface saturation – moisture content at soil surface (%)
S_I = average soil saturation (water and ice) of 0-40 cm soil layer at start of infiltration (mm^3 / mm^3)
$S_I = \theta_I / \phi$
θ_I = average volumetric soil moisture (water + ice) at start of infiltration (mm^3 / mm^3)
ϕ = soil porosity (mm^3 / mm^3)
T_I = average temperature of 0-40mm at start of infiltration (K)
t_0 = infiltration opportunity time (h)

Soil water content

Soil water content in the prairies is important for infiltration calculations and varies both seasonally and spatially (De Jong and Bootsma, 1988). Several complex interactions between weather land-cover, soils and agricultural management effect SWC. In the prairie environment, evaporation exceeds precipitation during the growing season (van der Kamp et al., 2003). Even though near surface moisture increases after rains, soil moisture increases below 1.5 m are minimal (Woo and Rowsell, 1993; Chang et al., 1990). An assumed low SWC value simplifies the Granger infiltration and allows infiltration to be calculated for areas that do not have *in situ* SWC values.

Soil water content, which controls infiltration in unfrozen and frozen soil conditions can be calculated as a volume (Rawls et al., 1992):

$$\phi = \frac{V_w}{V_t} = \frac{Ws}{W_d}\frac{BD}{D} \qquad \text{[Equation 5]}$$

where ϕ = volumetric water content $cm^3\ cm^{-3}$
V_w = volume of water cm^3
V_t = total volume of soil, cm^3
BD = bulk density of soil, g cm-^{3}
Ws = weight of water, g
W_d = weight of dry soil
D = density of water (normally equal to 1 g cm^{-3})

Landcover

Landcover also has an impact on infiltration values during runoff events. Van der Kamp *et al.* (2003), found significantly different infiltration values for grassed and cultivated catchments. Their study determined that there was no measurable runoff from grassed areas adjacent to wetlands. It is surmised that the macropore structure in the permanent grass cover greatly increases infiltrability especially during snowmelt runoff events over frozen ground. Both landcover types are found in the St. Denis and Smith Creek basins used in this study.

Snow water equivalent (SWE) is the depth of water of a snowcover (in mm). It can be expressed as (Pomeroy and Gray, 1995):

$$SWE = .001\, d_s\, \rho_s \qquad \text{[Equation 6]}$$

Where: d_s = snowdepth in cm
ρ_s = density in kg/m^3

The snow cover is subjected to interception, ablation, evaporation, and redistribution by blowing snow before melt. The effect of vegetation and topography on the transport and redistribution of snow produces variable SWE values over the landscape. Prairie potholes and the willow rings that surround them effectively trap snow. Because of this, blowing snow effectively increases SWE in and around prairie potholes (Fang and Pomeroy, 2009). This will increase runoff into the pothole reducing the storage potential of the pothole to impound runoff from upland regions.

2.4 Surface water connectivity between prairie potholes

Although a great deal of work has been completed on the overland hydrological processes of individual prairie potholes (Woo and Rowsell, 1993; Hayashi and van der Kamp, 2000; Su et al, 2000.,; van der Kamp et al., 2003), very little work has examined how and when these potholes connect to downstream potholes. Although the drainage network is not well integrated into the landscape (Woo, 2002), runoff that overflows from a pothole will contribute to an adjacent downstream pothole. Leibowitz and Vining (2003) estimated that 28% of wetlands in a North Dakota field site were connected, or were at least temporarily connected by surface runoff. Anecdotal evidence of prairie potholes spilling exists in other studies Rosenberry and Winter, 1997; Stichling and Blackwell, 1957). Understanding the spatial and temporal connectivity of prairie wetlands plays a large part in determining the extent of contributing area in the river basin.

Several studies examine how wetland patterns and size influence surface runoff between wetlands (Dillon et al., 1991); (Waddington et al., 1993). These studies found a relationship between wetlands area and the amount of surface water connectivity between wetlands. However, these studies were carried out in humid areas of high relief. Studies within areas of low relief and semi-arid environments have found no such relationship between the size and distribution of wetlands and their connectivity (Devito et al., 2000).

Connected areas are a function of the fill-and-spill phenomenon of prairie potholes. Leibowitz and Vining (2003) found connectivity between wetlands through fill-and-spill and hypothesized that the connectivity between wetlands is a probability distribution over time and space. Other research that highlights the importance of the connectedness in the prairie pothole region includes the work of Spence (2007) that incorporates connectedness into a geophysically-based framework for converting catchment storage to runoff. Spence and Woo (2003) propose the concept of "fill-and-spill" in a sub-arctic basin where storage has to be satisfied before surface runoff could be observed. A fill-and-spill runoff system is proposed in which the valley physiography results in a series of units with varying V_{SSA}. As water is input to the valley, each unit has to be filled until its storage threshold for runoff is exceeded. Subsurface or surface flows will then be generated. However, these flows may be used to satisfy the storage requirements of the units downstream.

The concepts of fill-and-spill and connectedness are found in other similar hydrological research such as modeled outflow from a hillslope (Lehman et al., 2007) who proposed using percolation theory to model the non-linear relationship between rain input and hillslope outflow. When rainfall exceeded a threshold underlying elements (macropores) became connected and resulted in water flowing from the base of the hillslope. Tromp-van Meerveld and McDonnel, (2006a, 2006b) propose the concept of fill-and-spill for subsurface stromflow. They noted that only when a rainfall event exceeded 55 mm that that bedrock depressions filled and water spilled over microtopographic relief in the bedrock surface allowing subsurface areas to connect to the trench face.

The literature illustrates the importance of antecedent basin conditions on contributing area in the prairie pothole region as the ability of prairie potholes to impound and release water downstream, through wetland connections, has been of interest in recent years as a result of the Red River flood in 1997 and the subsequent wet climatological cycle that is occurring in North Dakota. There has been a research effort examining whether the practice of draining wetlands for agricultural purposes has exacerbated floods in North Dakota (Padmanabhan and Bengtson, 1999b; Vining, 2002; Simonovic and Juliano, 2001). The results of these studies show that prairie potholes do have an impact on the flood hydrograph for high frequency events. High frequency, low runoff volume events, which are called sub-threshold storage runoff events in this thesis, can be completely or partially attenuated through impoundment by landscape depressions. The size of the runoff event and the antecedent conditions during the event will determine where storage is overwhelmed and how much runoff is contributing to the basin outlet. During high frequency events with little or no V_{SSA} satisfied, storage attenuates most or all of the runoff in the basin. As a result, the prairie potholes have a significant impact on basin discharge. The water balance will therefore reflect a large change in storage with very little of the input precipitation producing runoff.

However, prairie potholes have very little impact on the severity of the flood during low frequency events (Padmanabhan and Bengtson, 1999b; Vining, 2002). During these low frequency, large runoff events it would seem that there is a threshold for impounding runoff that when exceeded, causes the contributing areas of the basin to dramatically increase. During low frequency runoff events, once threshold storage requirements are met, pothole connectivity is established throughout the basin and the entire basin contributes to the outlet. In this case, the hydrograph will reflect the initial lag where storage is being filled but after the storage requirements are met the entire basin will contribute flow and the rising limb of the hydrograph will rise sharply. Low frequency events will be characterized by runoff conditions that fill storage quickly by efficiently moving runoff to the potholes.

These studies, however, do not include antecedent basin conditions in their theory. While it is intuitive that high frequency runoff event will result in very little area contributing to the outlet because of V_{SSA} in the basin, what must be taken into account is the state of the basin V_{SSA} . Successive wet years may result in much of the V_{SSA} being filled prior to the runoff event. Antecedent basin conditions such as these may result in high frequency runoff events producing water volumes at the outlet similar to those of low frequency, high volume runoff events

2.5 Automated drainage area delineation

Part of the work undertaken in this thesis focuses on improving the manual, subjective methods of determining contributing area described earlier through the use of readily available computer programs and models using concepts developed in landscape analysis tools. It is well understood that landscape analysis tools can be incorporated into this new digital methodology and used to define gross drainage areas from an input DEM. The following section describes in greater detail some of the important concepts underlying landscape analysis tools. A review of landscape analysis tools is also provided below.

Digital Elevation Models

Digital Elevation Models (DEM)s are the elevation data that allow the automatic extraction of physiographic information about a drainage basin. DEMs can be understood as a digital representation of a portion of the earth's surface, and are represented by mathematically defined surfaces or by point or line images (Weibel and Heller, 1991). The point models or altitude matrix is the most common form of the DEM and can be produced by interpolation from irregularly or regularly spaced elevation points, and can be generated from stereoscopic aerial photographs made on analytical stereo-plotters (orthophotos).

Advantages of the altitude matrix include its ability to calculate contours, slope angles and aspects, hill shading, and automatic basin delineation images (Burrough, 1986). Disadvantages of the altitude matrix include a large amount of data redundancy in uniform areas, and an inability to adapt to areas of sharp relief without changing the grid size (Burrough, 1986).

Landscape analysis tools such as **TO**pographic **Pa**ramteri**Z**ation (TOPAZ) use a DEM as input to identify potholes and their contributing areas and to provide channel network information (Martz and Garbrecht, 1992). The foundation of TOPAZ and many landscape analysis tools is the D8 method for routing flow (Fairfield and Leymarie, 1991). This method evaluates each individual DEM raster cell by examining the elevation value of itself and the eight surrounding cells. Flow is assigned to the lowest neighbour cell (the steepest slope descent). The drainage pattern is then used to determine upstream drainage area for that cell.

In order for landscape analysis models to determine gross drainage area and delineate the drainage network, the input DEM must be free of cells that have no neighbours at a lower elevation. A sink, or DEM cell that has no neighbours with a lower elevation, presents a problem for all of the algorithms. The literature presents several different approaches to removing sinks in the DEM (Martz and Garbrecht, 1998); (Mark et al., 1984); (O'Callaghan and Mark, 1984). Each of these methods treat the sinks as spurious, however, and pre-process the DEM to remove sinks (Figure 2-2). It should be noted that although "DEMs commonly contain localized depressions and flat surfaces, most of which are artefacts of the horizontal and vertical DEM resolution, DEM generation method, and elevation data noise" (Martz and Garbrecht, 1998)**,** not all sinks are artefacts. There are landscapes such as the prairie pothole region where depressions or sinks are the dominant landscape features that naturally occur. As a result, TOPAZ and other landscape analysis models are not satisfactory tools for contributing area definition in the prairie pothole region.

Properly defining prairie potholes and identifying their contributing areas will be an important component of understanding the function of contributing areas in the prairie pothole region. Any algorithm that identifies potholes rather than filling them requires that drainage directions be determined by incorporating potholes rather than a single outlet as end points for flow patterns within the basin.

a) b)

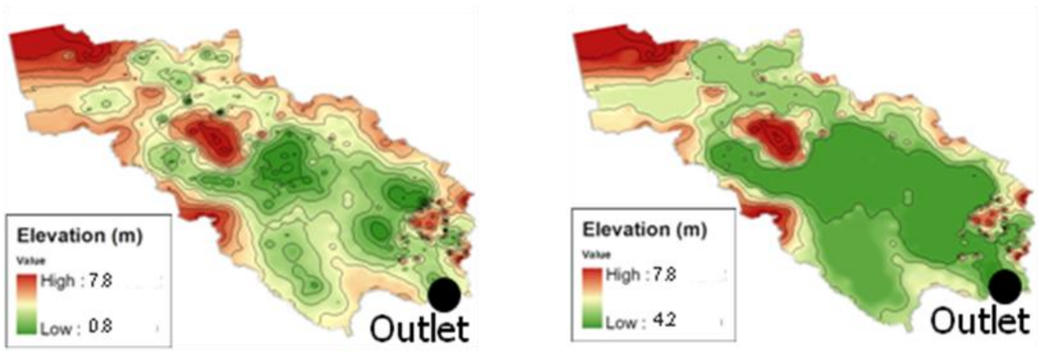


Figure 2-2. Example of pre-processing of a DEM required for landscape analysis algorithm: a) illustrates a DEM with sinks in the landscape; b) illustrates the DEM filled to allow all cells in the DEM to ultimately contribute flow to the outlet.

Three of the main algorithms proposed in the literature for routing flow and computing contributing areas from square-grid DEMs are the D-8 (deterministic eight-node) algorithm, the RHO-8 (random eight-node) algorithm, and the DEMON (digital elevation model networks) algorithm.

2.5.1 The D8 algorithm

The D8 algorithm was developed by O'Callaghan and Mark (1984). The algorithm evaluates each individual raster cell by examining the elevation value of itself and the eight surrounding cells. Flow is assigned to the lowest neighbour cell.

The main strength of the D-8 algorithm is its simplicity. The algorithm efficiently computes flow directions that are repeatable. Despite its limitations (see below), the algorithm provides a satisfactory representation of flow patterns, particularly in convergent flow conditions (Garbrecht and Martz, 1997). This algorithm produces consistent results for flow patterns, consistently calculated contributing areas and spatial representation of catchments. The D-8 algorithm is the most widely used of the automated drainage analysis algorithms (Tribe, 1992) and is used in the TOpographic PArameteriZation landscape analysis tool (TOPAZ).

A major limitation of the D-8 algorithm is that it does not deal with closed depressions or with flat areas. This limitation has been dealt with by pre-processing the DEM to eliminate the depressions and flat areas (Martz and Garbrecht, 1999).

The D8 algorithm is limited by its ability to assign only one flow direction to each grid cell. As a result, the algorithm can model flow convergence well in valleys but is not able to model flow divergence along ridges. Flow from upslope cells can flow into a single cell (converge) but flow diverging from ridges cannot have flow assigned in multiple directions (diverge). Further limiting this algorithm is that flow directions are constrained to one of eight flow directions. This results in the D-8 algorithm tending to produce parallel line flow that agrees with the aspect only when the aspect is a multiple of 45˚. For example if a surface has slope aspects that range from 0 – 22.5˚ the algorithm will always assign the flow direction to 0˚.

2.5.2 The RHO-8 algorithm

The RHO-8 algorithm was developed by Fairfield and Leymarie (1991). It is a stochastic version of the D-8 method that introduces a degree of randomness into flow direction derivation.

The D-8 method calculates slope (S_{D8}) as:

$$S_{D8} = \max \frac{Z9 - Zi}{h\phi(i)} \qquad \text{[Equation 7]}$$

$i = 1,8$ i is defined by the node numbering scheme (Figure 2-3)

where $\phi(i) = 1$ for north, south, east, west neighbours and
where $\phi(i) = \sqrt{2}$ for diagonal neighbours
where Z9 = elevation of the cell being processed
where Zi = elevation of neighbour cell

The RHO-8 modifies this equation and substitutes $2 - r$ for the diagonal neighbours. The variable r is a uniformly distributed random variable between 0 and 1 (Gallant and Wilson, 2000).

64 z_7	128 z_8	1 z_1
32 z_6	z_9	2 z_2
16 z_5	8 z_4	4 z_3

Figure 2-3. 3x3 subgrid for a DEM showing node numbers (blue) and flow direction numbering (black). Source: Gallant and Wilson (2000).

The effect of this change will be seen on hillslopes where slope values are similar. An example of how RHO-8 allows a closer approximation of the aspect of the surface begins with a DEM surface with an aspect of 15˚ east of north (Figure 2-4) . Using the D8 method all of the pixels will be assigned to either North (which is wrong by 15˚) or to North-East (which is wrong by 30˚). Using the RHO-8 algorithm, North and North-East will be randomly assigned and the flow directions will move toward a net movement of 15˚ (Figure 2-4). As a result the RHO-8 method properly identifies the proper directional flow (Figure 2-4).

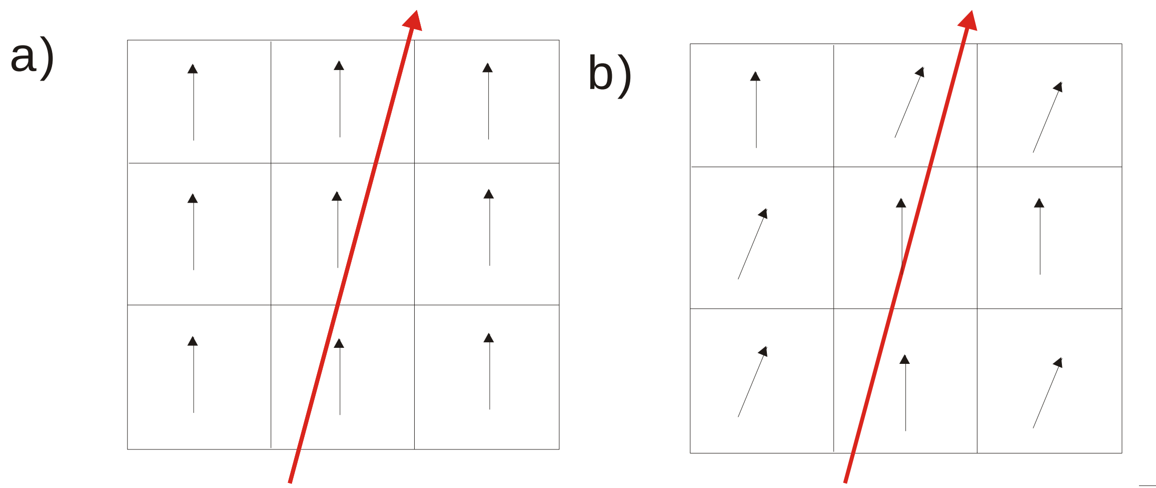


Figure 2-4. Two DEM surfaces with the correct aspect denoted by the red arrow a) illustrates the parallel grid-cell flow directions determined using the D-8 algorithm b) illustrates grid-cell flow directions values better representing a trend toward the aspect.

As with the D-8 method, the strength of RHO-8 is that it is a relatively simple algorithm that is not computationally expensive to apply. The RHO-8 algorithm simulates more "realistic" flow paths than those produced by the D8. Long parallel path flows are broken up and flow directions more closely match the aspect of the slope.

Like the D-8 method, RHO-8 can only assign flow to one direction from each grid cell and in only one of eight flow directions. Also similar to the D-8 is that the DEM needs to be pre-processed to remove cells which have no neighbouring cells with a lower elevation prior to applying the RHO-8 method.

The introduced randomness to the flow direction algorithm eliminates parallel flow directions but introduces a different flow direction error. Flow paths often converge laterally due to the randomness of flow directions in planar areas where flow paths are parallel. Because flow is directed to only one downstream grid cell there is no way for the flow paths to diverge again. The flow pattern becomes in error, and the contributing error for each grid-cell is compounded as the channel moves downstream.

The most significant weakness of this algorithm is that the generation of flow networks is not repeatable; changing each time the program is run. This is due to the stochastic nature of the algorithm. As a result, this algorithm is no longer considered as a satisfactory alternative to the D-8 algorithm (Gallant and Wilson, 2000).

2.5.3 The DEMON algorithm

The DEMON algorithm presented by Costa-Cabral and Burges (1994) is a completely different approach for flow accumulation. It is based on a concept of stream-tubes originally proposed by Lea (1992). The DEMON algorithm is also conceptually similar to the stream-tube approach used by Moore and Grayson (1991) on contour- based DEMs. Stream-tube algorithms "look" further downstream than the previous methods. They determine a fraction of flow by deriving the fraction of the area of the grid cell that will enter each downstream grid-cell as a function of aspect (Figure 2-5).

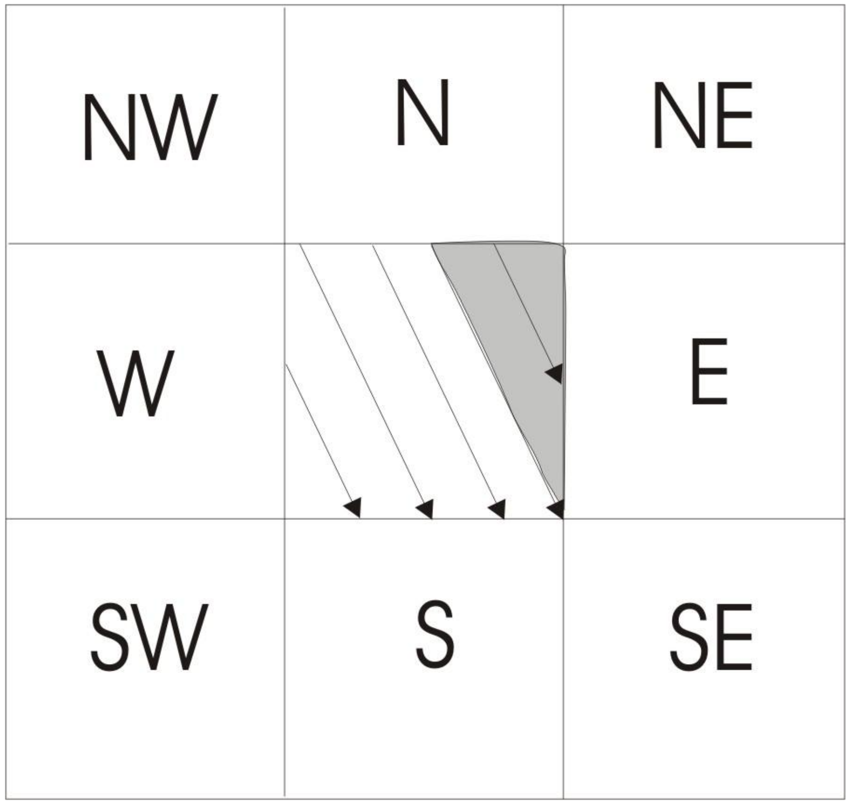


Figure 2-5. Illustrates how flow is partitioned from the source grid cell to the grid cells to the east and south based on the aspect (arrow directions). Grey shaded area in the centre cell (25% of cell area) is assigned to the East cell, while unshaded area in the centre cell (75% of cell area) is assigned to the South cell.

The DEMON generates flow areally (Costa-Cabral and Burges, 1994). Flow generated over a grid-cell is projected downslope over a two-dimensional strip (similar to a stream-tube). The width of stream-tubes increases over divergent surfaces and decreases over convergent surfaces.

Unlike the D-8 and RHO-8 methods, the DEMON algorithm allows multiple flow directions. This allows a much more realistic dispersion of flow in ridge areas of the DEM surface. The DEMON algorithm method also allows realistic flows in convergence areas as well. The drainage direction of flow is not constrained by a limited number of directions and is informed only by the aspect of the source grid cell's slope. Because flow directions are not constrained artificially, there are no problem with parallel flows in planar areas of the DEM surface.

The major weakness of the DEMON algorithm is its considerable complexity. As a result it is quite computationally inefficient. DEMON does not produce an explicit grid network with single flow direction that are preferred in practical applications (Chirico et al., 2005). As with the D-8 and RHO-8 flow direction algorithms, the DEM must be pre-processed to eliminate pits prior to application of the DEMON algorithm.

One of the stated objectives of this research project is to develop an algorithm that produces repeatable contributing area delineation for prairie pothole basins. This objective cannot be met using the RHO-8 method as randomness is incorporated into drainage direction determination. Due to the randomness built into the method there is potential for drainage directions to be different for each algorithm run. The main weakness of the DEMON algorithm is the heavy computational time requirement for drainage direction. High resolution or large-scale DEMs will require a computationally efficient method for determining drainage directions. Although the D-8 method has its own limitations, the computational efficiency and repeatable results make it best suited for developing a dynamic contributing area algorithm for the prairie pothole region.

2.6 Hydrological models

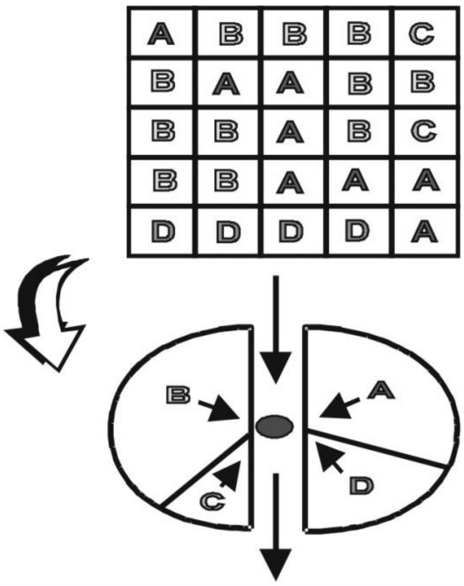
There has been a strong research interest in improving modeling in the prairie pothole region driven by interest in climatic variability in the region. The Drought Research Initiative (DRI) was developed in 2005, to better understand and predict droughts within the prairie pothole region by focusing on the severe drought of 1999- 2005. Also, the IP3 (Improved Processes and Parameterization for Prediction) is devoted to improving understanding surface water and weather systems. Central to both these research programs is an aim to improve model performance through coupling land surface hydrological process and the atmospheric system.

Dynamic contributing areas can be used to improve hydrological models and land–surface schemes applied in the prairie pothole region. Dynamic contributing areas should improve a hydrological model's ability to generate appropriate runoff volumes at a basin outlet. Although it will not be tested in this thesis, it is intuitive that appropriately redistributing surface water based on the topography and topology of the basin will also allow more satisfactory modelling of the vertical water budget within the basin.

Currently, semi-distributed models have been used to successfully model prairie wetland hydrology (Su et al., 2000). However, these models have not taken into account non-contributing areas in their runoff calculations. Semi-distributed models can satisfactorily model wetland streamflow because there are usually a number of representations of a watershed that can produce acceptable hydrographs or pothole water levels. This is because there are inherent limitations in the quality of input data and the model structures. This is the basis of the concept of equifinality put forward by Beven (2001). Equifinality assumes that even when only one model is applied to a basin with different parameter values, many acceptable simulations will be produced.

Semi-distributed or distributed hydrologic models divide a watershed into segments in an attempt to account for the spatial variability within the basin, and to allow more fundamental representations of the hydrological process (Kouwen et al., 1990). Over the last 20 years many distributed hydrologic models have been developed at a scale of the pixel of land cover imagery data or DEM data. The trend has been to develop methods that model areas of uniform hydrologic response at the pixel scale within the basin, such as the Hydrologic Response Unit (HRU) method (Kouwen, 2001). However, the HRU method can lead to a tremendous amount of segmentation within heterogeneous basins.

To apply hydrological models to large basins, areas with distinct hydrologic responses must be grouped within a segment. A grouped response unit (GRU) is presented by (Kouwen et al., 1993) that groups hydrological responses that are alike, regardless of location, and calculates the runoff for each response. The sum of runoff from each response region within the segment is the runoff that is available for routing downstream (Figure 2.6).



Land use map No. of Pixels:
A = 9
B = 10
C = 2
D = 4
Total = 25

Fraction of GRU in percent:
A = 36
B = 40
C = 8
D = 16

Figure 2-6. The grouped response unit (GRU)
Source: (Donald, Soulis et al., 1995)

The GRU provides a basis on which to improve hydrological modeling in the prairie pothole region by incorporating the concept of connectivity between depressions or wetlands. Each depression and its surrounding contributing area can be represented by a GRU in a hydrological model. A physically-based hydrological model can calculate the vertical water budget for each GRU (depression and contributing area) and an algorithm that incorporates connectivity between GRUs can appropriately move effective runoff calculated by the hydrological model horizontally.

The SPILL algorithm presented as part of this research is based upon existing landscape analysis tools such as TOPAZ. A characteristic of current landscape analysis tools, and the SPILL algorithm that is based on a landscape analysis tool, is that flow patterns generated do not incorporate the movement of water vertically in the basin. For example, infiltration is not taken into account; the tool simply determines drainage direction and flow patterns from topographic information. Coupling a physically-based hydrological model with a landscape analysis based algorithm has the potential to improve the performance of both. SPILL will improve both the calculation of contributing area of the basin and the movement and storage of water within the basin, which will refine the movement of water vertically by the land-surface scheme or hydrological model. Conversely, a land-surface scheme or hydrological model can be used to improve calculations of the magnitude and extent of effective runoff that is used as input into the SPILL algorithm.

2.7 Summary

This review of the literature has illustrated that there is very little theoretical basis for conceptualizing the nature and relationship between V_{SSA} and contributing area. This thesis will address this gap in current literature by undertaking fieldwork which will yield a theoretical framework for describing the horizontal movement of surface water in the prairie pothole region.

Further, the literature review also details state of the art for contributing area delineation are unsatisfactory due to the subjective and non-repeatable methods currently employed. The research presented in this thesis will present an algorithm which addresses these shortcomings and provides a method for quantifying contributing areas in the prairie pothole region using an automated method.

CHAPTER 3

- STUDY AREA, FIELD DATA COLLECTION AND SOFTWARE -

3 Overview

Due to the lack of literature on the behaviour of dynamic contributing areas in the prairie pothole region, field observations were made to better understand the processes which control surface water connections and fill-and-spill in order to conceptualize the system. A basin that characterizes the prairie pothole landscape was required for examination of the influence of connectivity on contributing area in a quantifiable way.

To automate an algorithm that quantifies dynamic contributing area based on the conceptualization of the prairie pothole surface runoff system, a DEM of the basin is also required. To provide the most topographically detailed representation of the basin a high resolution DEM (1 metre) was used in this study.

It is intuitive that the resolution of the DEM will have an impact on algorithm results. Although a detailed examination of this scale issue is important, it is outside the scope of this thesis. Nevertheless, a DEM with a 25 m cell size was also created. This resolution was chosen as it is more typically seen in operationalized hydrological models. The results obtained by the algorithm on both DEMs are compared to see whether the relationship between contributing area and V_{SSA} is similar between the 1m and 25m resolution DEMs.

3.1 St. Denis Wildlife Area

This research uses two study areas (Figure 3-1). The St. Denis National Wildlife Area (SDNWA) is located 45 km east of Saskatoon, at 106° 16' W, 51° 13' N. The topography is representative of a prairie pothole landscape. The topography is dominated by knob-and-kettle moraine with over 100 wetlands. The soils at SDNWA are described as an orthotic dark brown chernozem developed from fine textured to moderately unsorted glacial till (Miller et al., 1985). The SDNWA drainage basin is a sub-basin of the South Saskatchewan River watershed.

Mean annual precipitation measured at Saskatoon (approximately 40 km west of St. Denis) is 360mm. Approximately 85mm of this precipitation is snow (Atmospheric Environment Service, 2008). Due to air temperatures that reaches –30°C during the winter, soil frost penetrates as deep as 2m (Hayashi and van der Kamp, 2000).

In June 2003 two 128 point transects were established at SDNWA. The transects traversed three vegetated potholes as well as cultivated land that had been fallow since 2002 (Yates, 2006). Transect points were evenly spaced 5 metres apart along a straight line and overlaid representative landforms of the prairie pothole landscape. Three previous transects had been established for snow surveys. Two of these transects bisected a large permanent wetland and one of the transects were laid over an upland area of the basin (Schmidt, R., 2004) (Figure 3-2).

The SDNWA was chosen as the study site for several reasons. As a protected wildlife area the wetlands have not been drained for agricultural use. Extensive study of

Figure 3-1. The study area basins for Smith Creek and St. Denis Wildlife Area (SDNWA).

hydrological processes within the basin has already been completed (Su et al., 2000; Hayashi et al., 2003; Parsons et al., 2004). Therefore many of the hydrological processes in the basin are already well understood. Important data necessary for conducting hydrologic research has also been recorded in the basin. Snow surveys for consecutive years, including the years 1994, 1996-2008, have been obtained from sources at the University of Saskatchewan, the National Hydrologic Research Institute as well as snow survey data collected specifically for this thesis. The author was a member of a team comprised of soil science technicians and students that carried out snow surveys in 2004-206. Water levels are known for many prairie potholes in the basin since 1968 (Conly et al., 2004). As part of the research presented in this thesis the author was involved directly in measuring pond levels in St. Denis basin in the years 2004-2007. These water levels are invaluable as they allow a historical examination of the connectivity and fill-and-spill in the basin. Long term hydrographs developed using pond level data show that smaller ponds tend to be ephemeral, while larger ponds (wetlands) can retain water from one year to the next (Conly et al., 2004). Piezometer level data was also collected by the author for the St. Denis basin. Although piezometer data was not ultimately used in this thesis, it has been archived at the National Water Research Institute in Saskatoon, Saskatchewan.

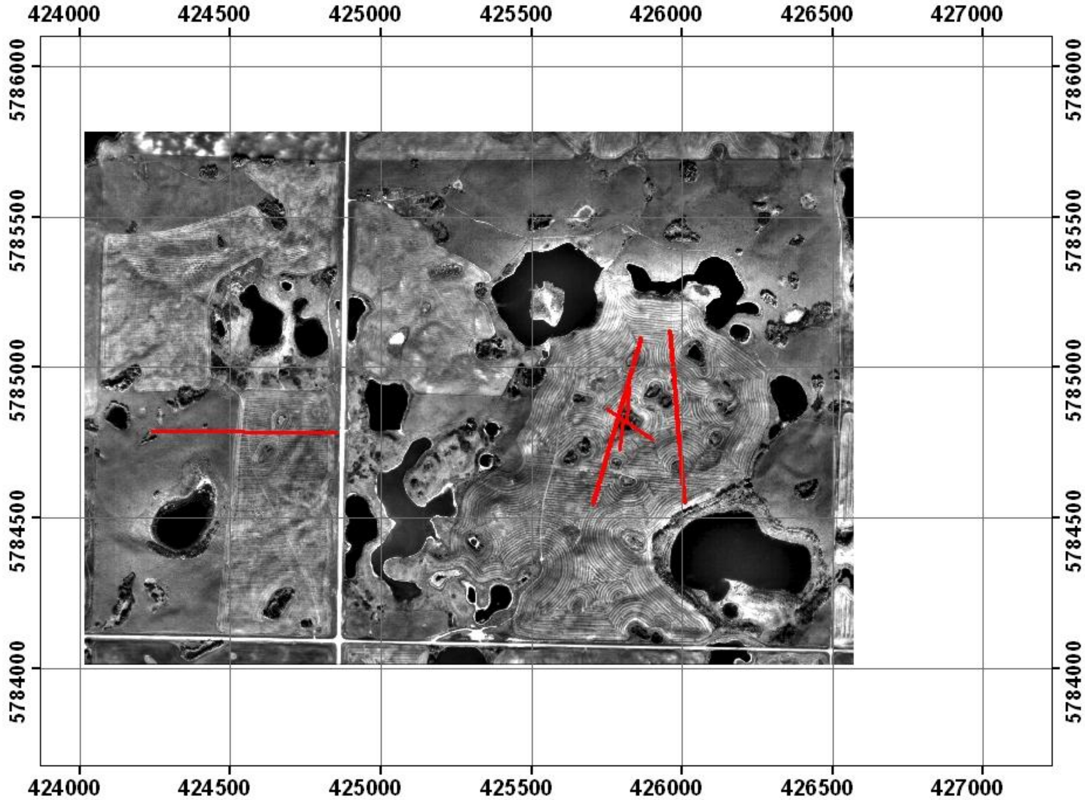


Figure 3-2. Snow survey transects (red lines) overlain on an airphoto of the St. Denis National Wildlife Area (SDNWA). Coordinates are UTM zone 13.

Finally, a **Li**ght **D**etection **a**nd **R**anging (LiDAR)-derived digital elevation model (DEM) was produced for the area encompassing and surrounding the SDNWA at a 1m resolution in the fall of 2005 (Toyra et al., 2008). Five sub-basins of the SDNWA basin have been chosen for application of the contributing area algorithm proposed in this thesis. The five sub-basins were chosen because they were approximately the same size and represent different areas of the basin (Figure 3-3). Figure 3-4 illustrates the elevations and slopes calculated for the five study basin DEMs. Area calculations for each basin are presented in Table 3-1.

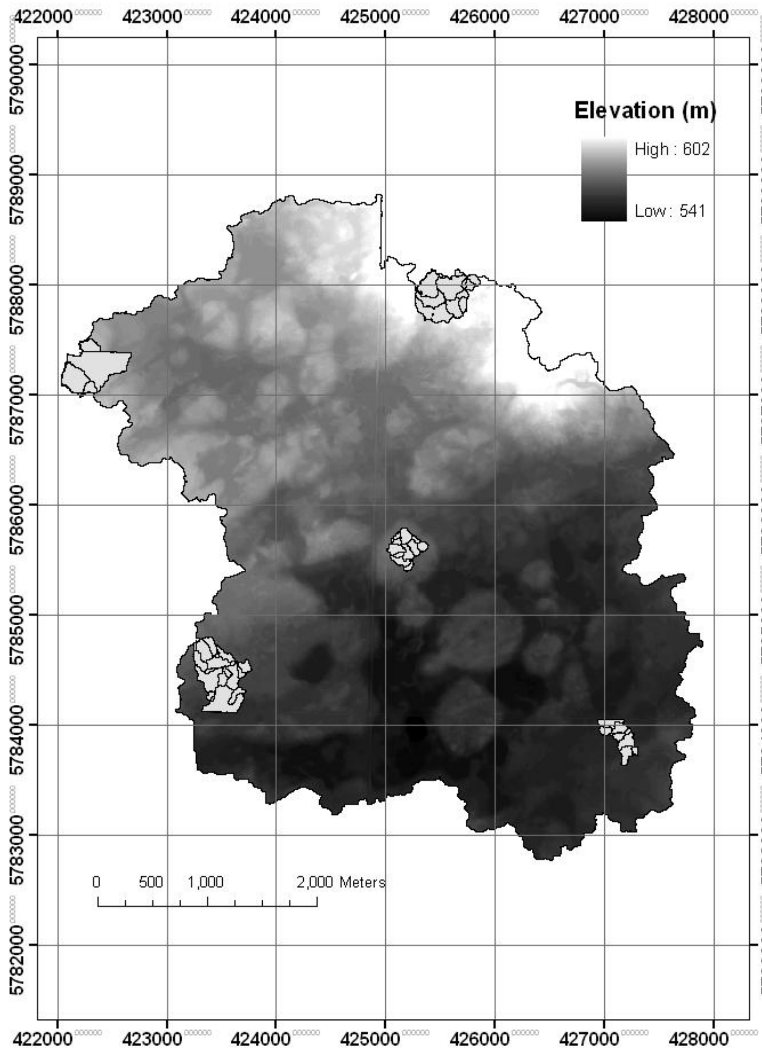
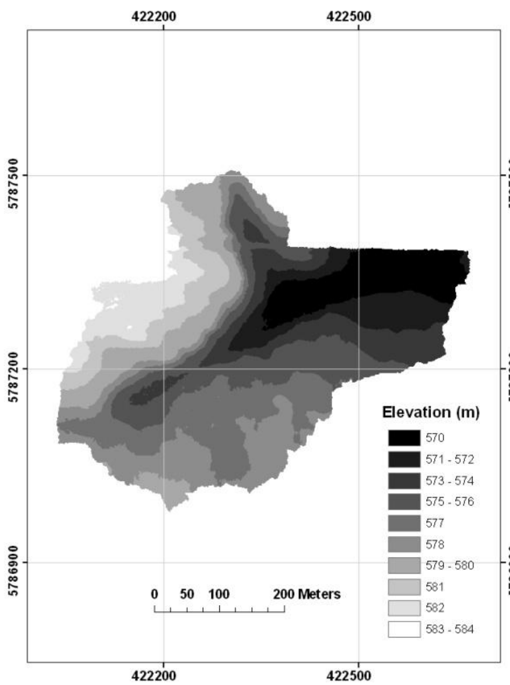


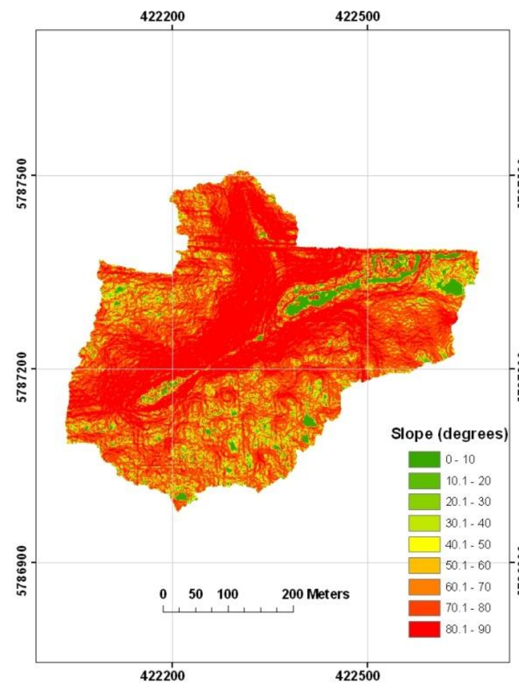
Figure 3-3. SDNWA DEM data overlain with sub-basin study areas.

St. Denis study basin 1

Elevation

Slope

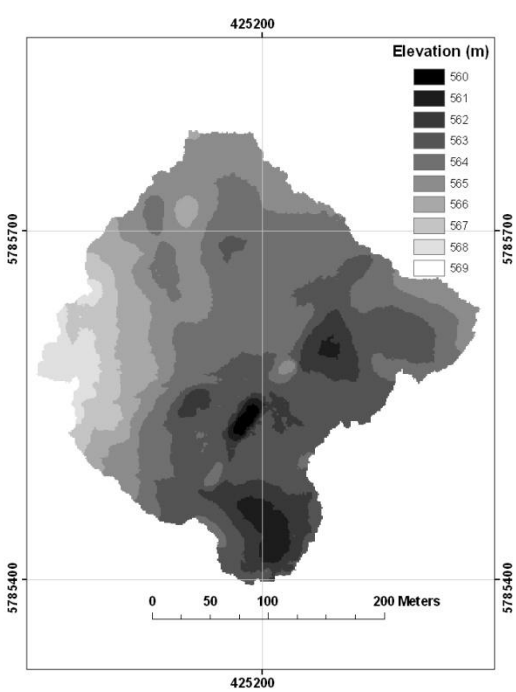


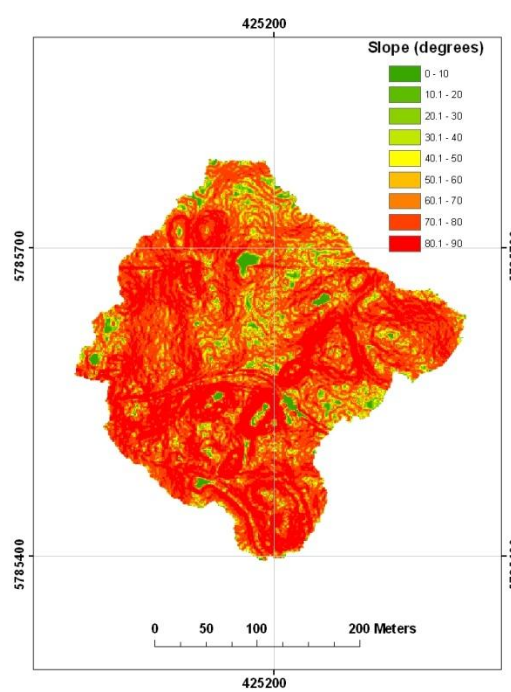


St. Denis study basin 2

Elevation

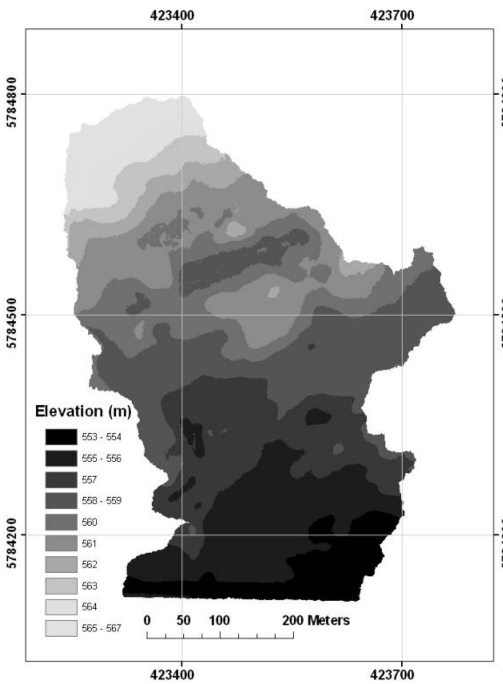
Slope

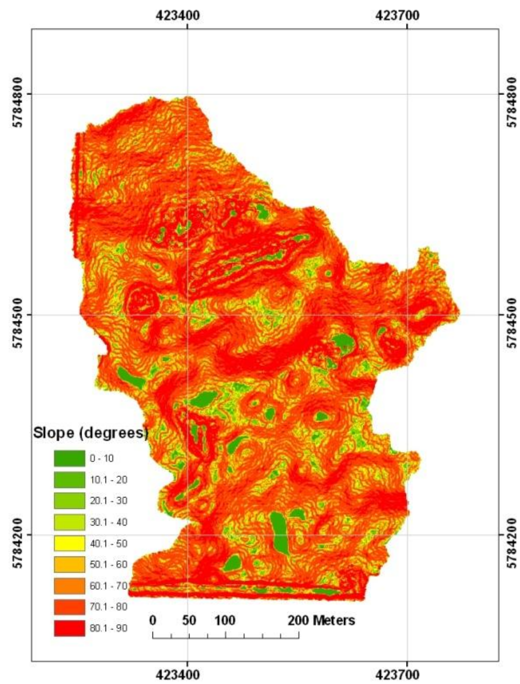




St. Denis study basin 3

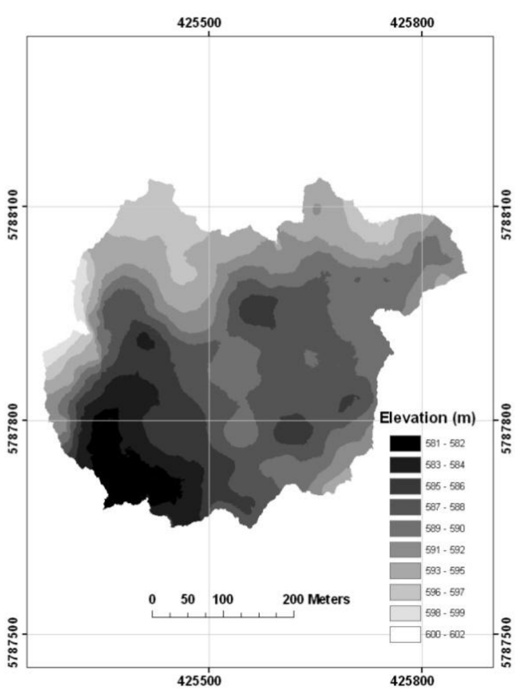
Elevation Slope

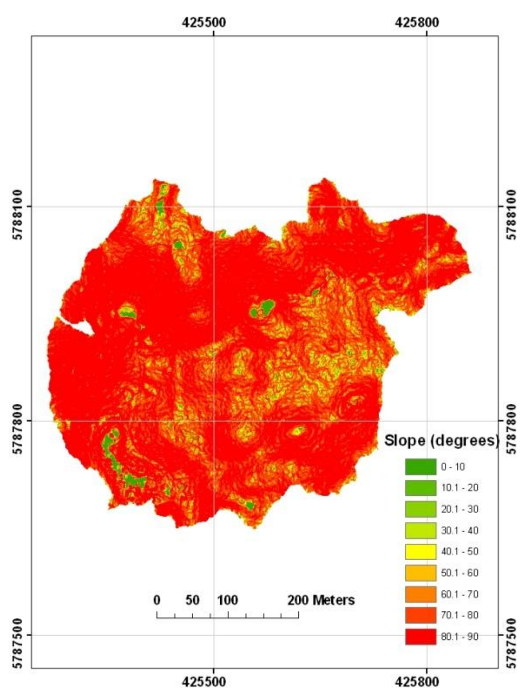




St. Denis study basin 4

Elevation Slope





St. Denis study basin 5

Elevation | Slope

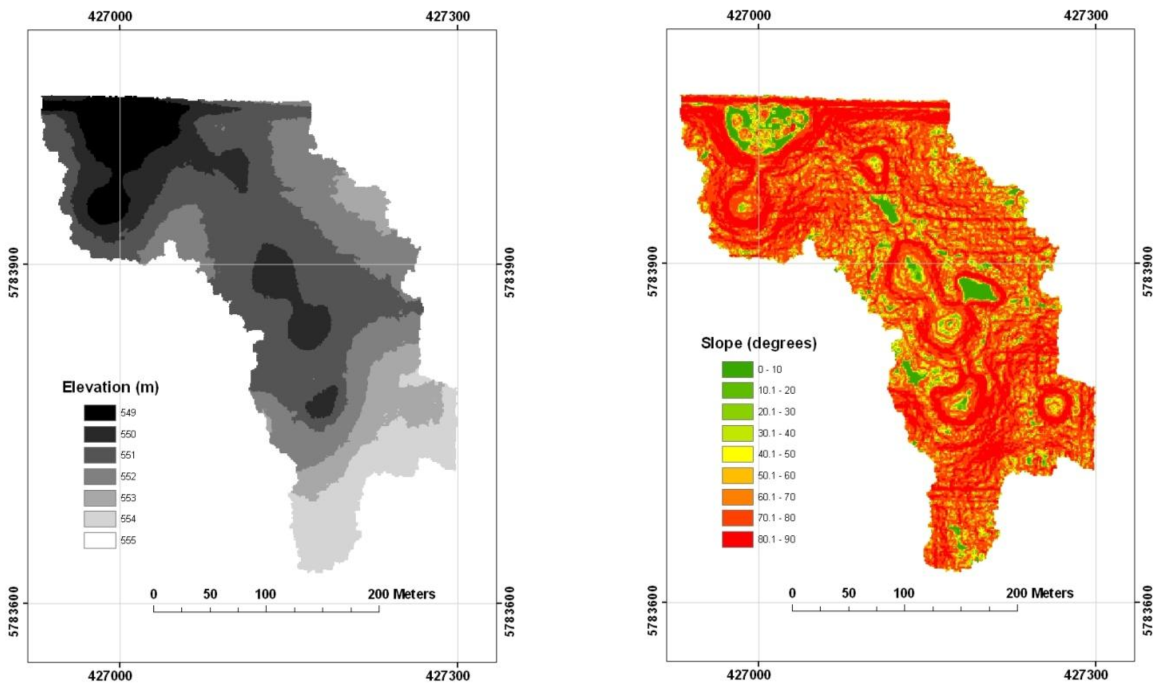


Figure 3-4. Basin DEM elevation and slope data determined for five study basins in the St. Denis basin.

Table 3-1. Area values (m^2) for DEM Study basins in St. Denis and Smith Creek.

Study basin (St. Denis)	Area (m^2)	Study basin (Smith Creek)	Area (m^2)
1.	187,791	1.	2,134,375
2.	79,919	2.	2,796,250
3.	229,829	3.	2,808,750
4.	189,719	4.	3,801,250
5.	72,888	5.	3,935,000

3.2 Smith Creek watershed

The second study area is the Smith Creek watershed (Figure 3-1). This watershed is also characteristic of the prairie pothole region. The landscape is hummocky with many depressions and potholes. Black chermozemic soils overlay most of the basin and have developed under native grassland vegetation. However, most of the native grassland has been cultivated.

The Smith Creek watershed is a sub-watershed of the larger Assiniboine River watershed and is located near the border of Saskatchewan and Manitoba. A 25m cell resolution DEM that encompasses the Smith Creek watershed was developed for Ducks Unlimited Canada. The Smith Creek watershed is comprised of approximately 80% cropland and 20% native grass (Boychuk, L., 2008). As with SDNWA, five sub-basins were chosen for application of the proposed contributing area algorithm (Figure 3-5). Figure 3-6 illustrates the elevations and slopes calculated for the five study basin DEMs. Area calculations for each basin are presented in Table 3-1.

The DEM created for the Smith Creek watershed was chosen for this study because it more approximated the cell resolution that would be used in operationalized hydrological modeling. Currently DEMs that are of a LiDAR type resolution (1 m) are available for only limited areas because of the cost of acquiring data at a high resolution.

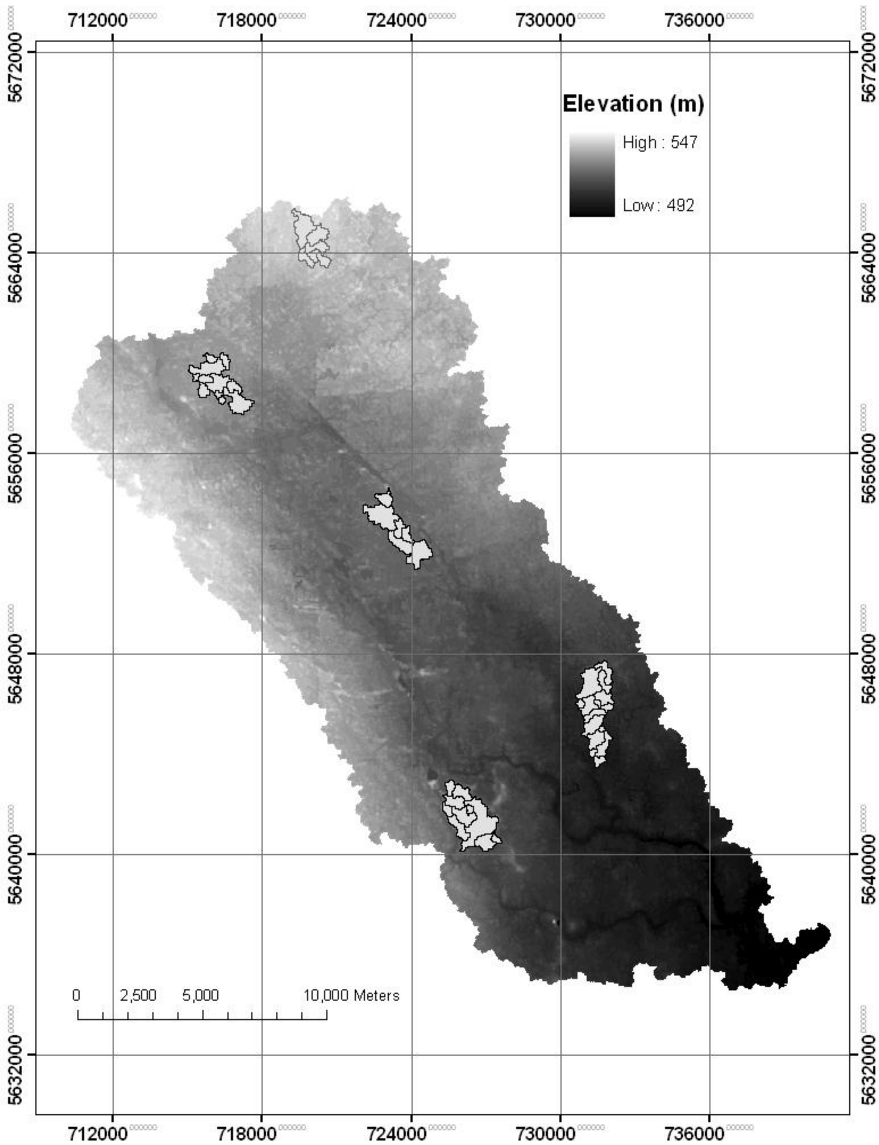
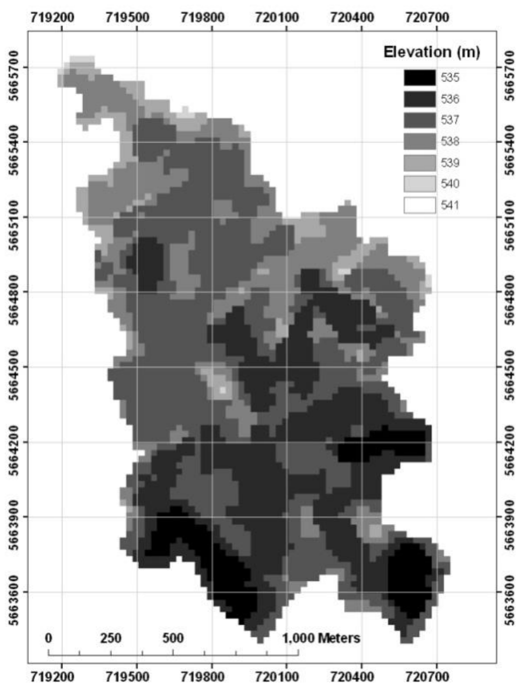


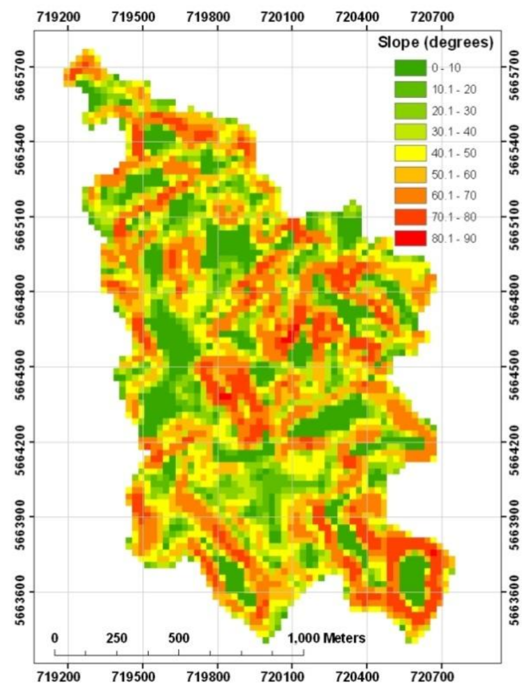
Figure 3-5. Smith Creek DEM data overlain with sub-basin study areas.

Smith Creek study basin 1

Elevation

Slope

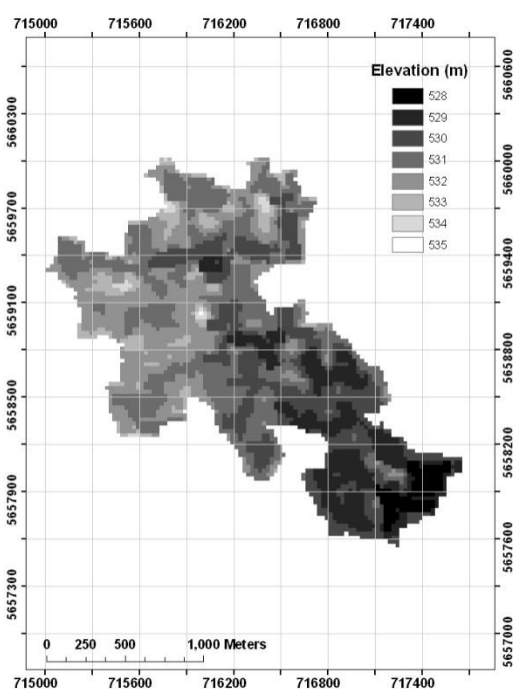


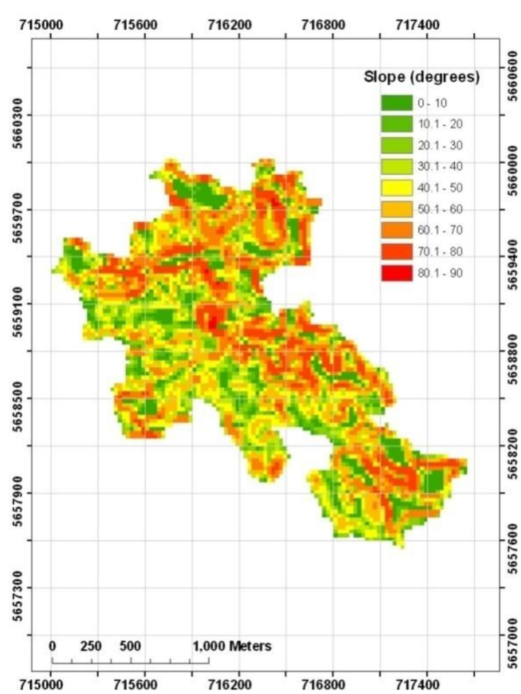


Smith Creek study basin 2

Elevation

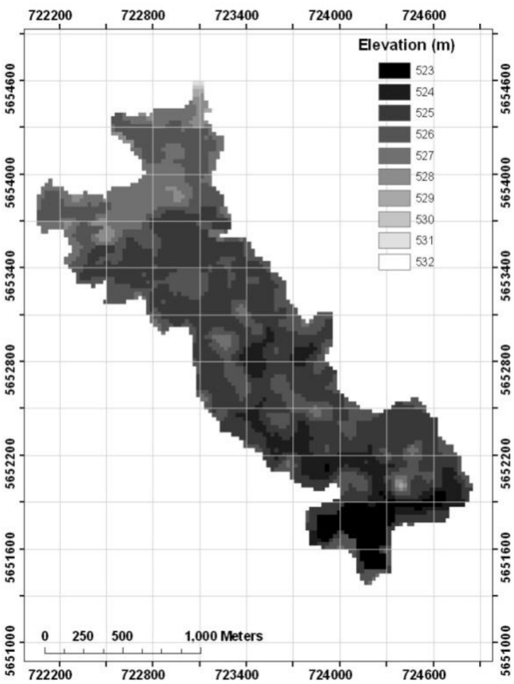
Slope

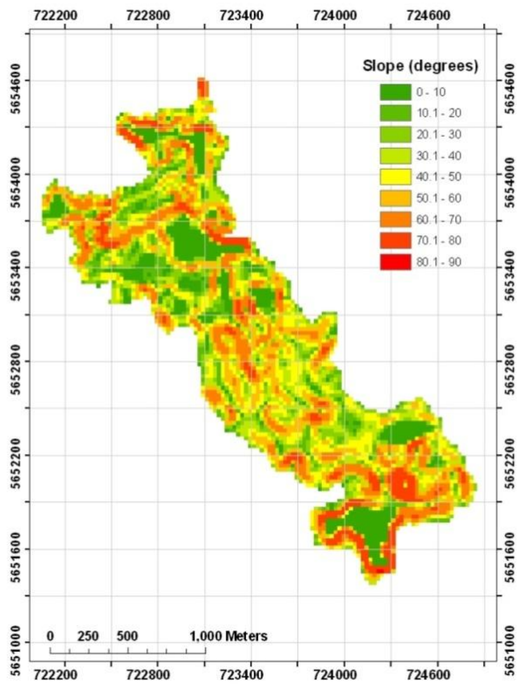




Smith Creek study basin 3

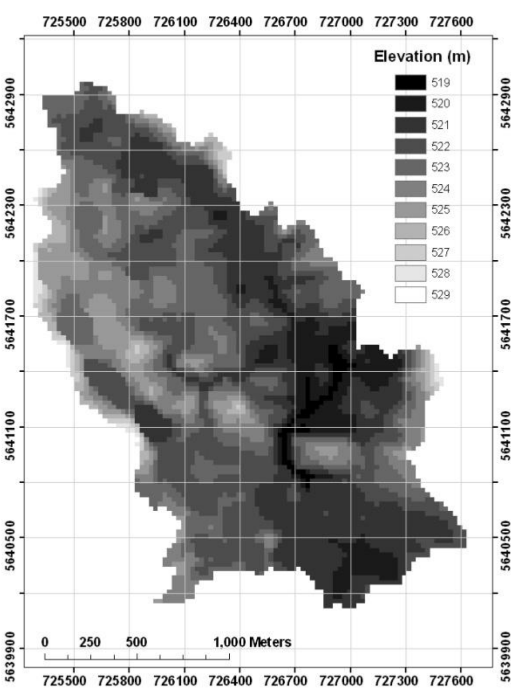
Elevation | Slope

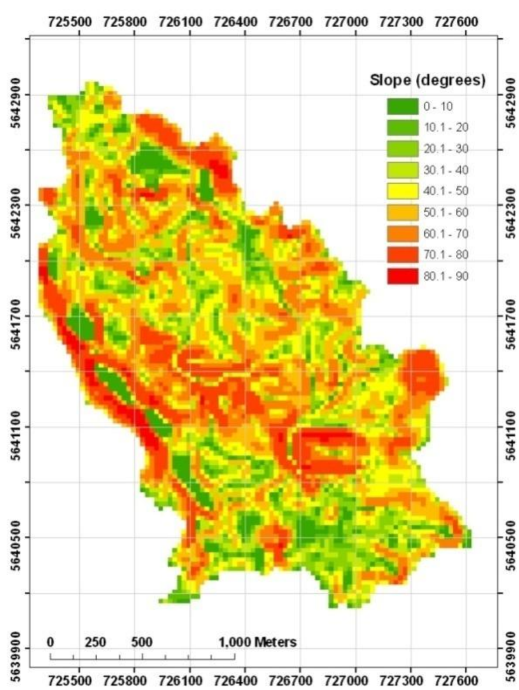




Smith Creek study basin 4

Elevation | Slope





Smith Creek study basin 5

Elevation Slope

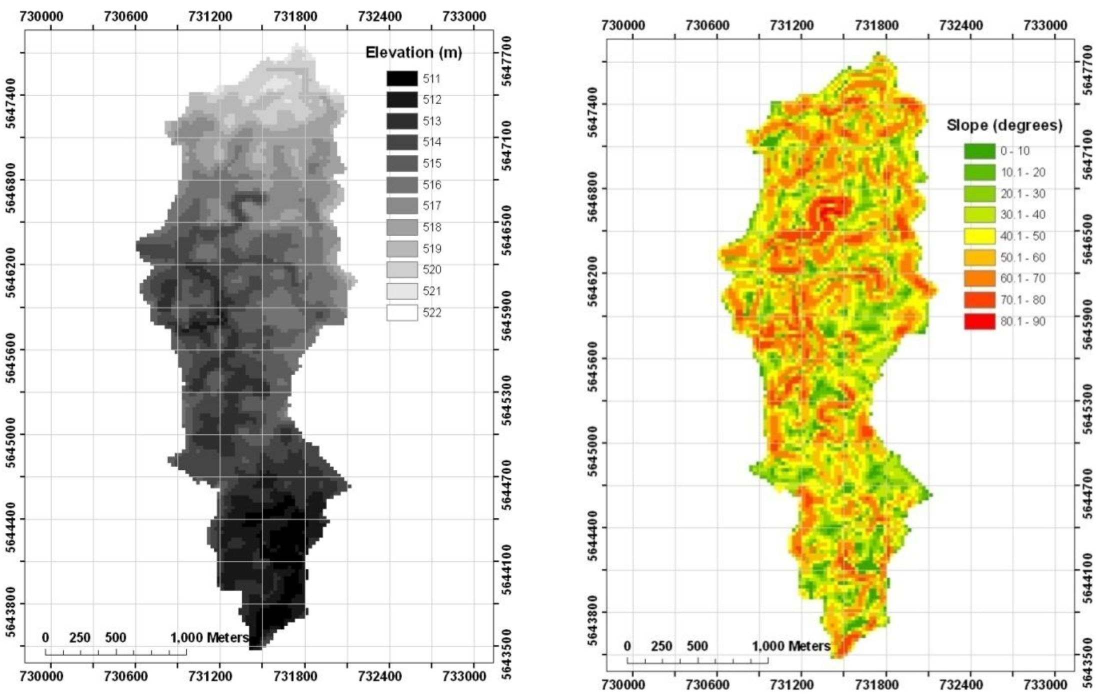


Figure 3-6. Basin DEM elevation and slope data determined for five study basins in the Smith Creek basin.

3.3 Data collection

3.3.1 Digital Elevation Models (DEM)

Airborne scanning LiDAR is an optical remote sensing technology that transmits near-infrared pulses and record the time and intensity of the return pulses. The coordinate and elevation of each LiDAR pulse are calculated based on the position of the aircraft, the scan angle and pointing direction of the laser, and the time it takes for the transmitted pulse to return from the reflecting surface.

The LiDAR accuracy reported by most manufacturers under ideal conditions (flat, hard and open surface) is 1/2,000 x aircraft altitude for horizontal error, while the vertical error is specified as 0.15m and 0.20m for aircraft altitudes of 1,200 and 1,500 meters above ground level (magl), respectively (Toyra et al., 2008).

The airborne scanner LiDAR data survey of the SDNWA watershed was conducted by Canadian Consortium for LiDAR Environmental Applications Research (C-CLEAR) on August 9, 2005. The SDNWA DEM was created through interpolation of ground data points using the Inverse Distance Weighted (IDW) algorithm(Toyra et al., 2008). The DEM is at a 1m resolution. All ponds in the SDNWA watershed were empty at the time of the LiDAR data survey except for Pond 1 and Pond 90 (see Figure 3-15 for location of these ponds).

Three different types of LiDAR verification data were collected to evaluate the generated LiDAR DEM: vegetation transects, wetland transects and long topographic transects. The LiDAR DEM was verified and adjusted using data points from the transects. The overall accuracy of the adjusted LiDAR DEM was estimated as 0.14m root mean square error (RMSE) with a positive bias of 0.03m and was judged to be an accurate representation of the basin topography (Toyra et al., 2008).

3.3.1.1 Photogrammetric Digital Elevation Model – Smith Creek

Ducks Unlimited created a DEM of the Smith Creek basin using aerial photography and photogrammetric mapping. Air photos at the scale of 1:40 000 were used for stereo digitizing the basin. At a scale of 1:40 000 the resulting data will have relative positional accuracy of 1.3m horizontally and 1m vertically (Boychuck, 2008). In order to accurately geo-reference the aerial photography and prepare it for the photogrammetric data acquisition, x,y,z coordinates were ground surveyed to 20 photo identifiable target positions. Existing Central Survey and Mapping Agency (CSMA) benchmarks and additional surveys performed by Ducks Unlimited were used (Boychuck, 2008). From the aerial photography a DEM was compiled from a dense network of three dimensional point data.

3.3.2 Pond levels

Pond depth levels for selected ponds in the SDNWA watershed basin have been measured since 1968 (Conly et al., 2004). Although the data are incomplete for some ponds, the data set is an invaluable resource for prairie pothole hydrology.

The method for measuring pond depth is straightforward. Ponds are staked at the lowest point in the depression or pothole. The lowest elevation in the pothole is easy to discern due to the ephemeral nature of most of the ponds. In more permanent ponds soundings were taken to determine the lowest point. Stakes were used to mark the lowest point in the pothole. Pond depths were acquired by measuring the depth of the pond at these stakes. Conly et al., (2004) provide a more detailed explanation of monitoring pond levels at SDNWA.

3.3.3 Snow surveys

Snow surveys have been carried out for several consecutive years at St. Denis. This includes the years 2006 and 2007 that are used to provide input data for an algorithm presented in this thesis. Snow surveys in 2004 and 2005 were a joint effort carried out by the author, and members of the Soil Science department of the University of Saskatchewan using transect points identified by the Soil Science department in 2004 and 2005. Snow surveys were also carried out in 1994, 1996 - 2003 and 2006 - 2008 by the staff of the National Hydrology Research Institute in Saskatoon and are used in this research to provide a context for assessing the magnitude of snow accumulations in 2006 and 2007 relative to the other snow survey years. There were five transects that encompassed treed areas, uplands, lowlands, and ponds in the SDNWA (Figure 3-2). The surveys were carried out using the snow water equivalent method (Pomeroy and Gray, 1995). Snow depths were measured at each transect point using a snow ruler. At every fifth depth measurement point a 7-cm diameter ESC-30 snowtube was used to take a snow core. Snow cores were preserved in sealed plastic bags and transported back to the University of Saskatchewan for snow water equivalent (SWE) calculations. SWE was calculated by weighing the snow core samples and plastic bag. After the bag was emptied, the plastic bag was weighed and this weight was subtracted from the first measurement to obtain a weight of only the snow core water . Figure 3-7 presents estimated SWE values calculated for the St. Denis basin from the snow survey data. See Appendix A for snow survey summary data.

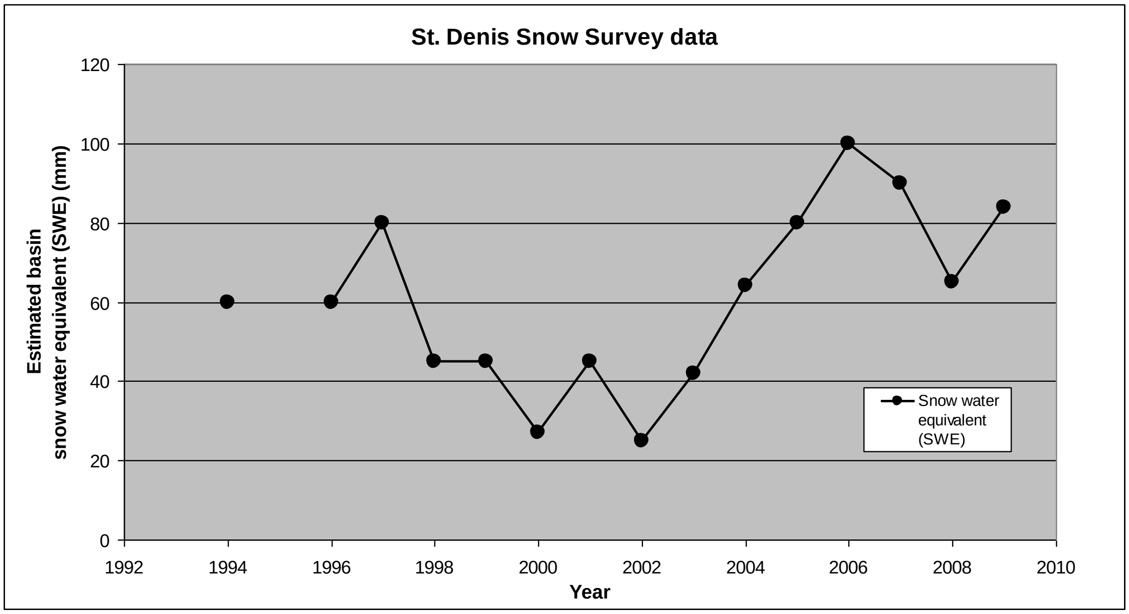


Figure 3-7. Estimated snow water equivalent (SWE) values for the entire St. Denis basin.

3.3.4 Channel network data

To examine the concept of connectivity in a prairie pothole basin proposed in this thesis, an extensive survey of overland flow at the SDNWA and surrounding area was carried out for the spring-melt of 2006. The 2006 runoff event was marked by higher than average of SWE available for spring-melt (110 mm). Snow surveys (see section 3.3.3) from 1994 - 2008 yield an mean SWE value of 60 mm.

Malcolm Conly of the National Water Research Institute (N.W.R.I.) developed the survey methodology. The author and staff of NWRI carried out the survey. The area surveyed was expanded out of the SDNWA to capture information for headwater areas for ponds within the SDNWA. The expanded study area encompassed approximately 12 km^2.

Air photos and DEM data were used to generate maps that would be used to direct field workers to assigned sites. The entire study area was divided into a 36 smaller square-cell sub areas of 500 x 500 m (Figure 3-8). Potential channels were identified on a DEM using a landscape analysis tool (see section 2.5) in order to better direct field workers to areas where surface runoff may be found (Figure 3-8). The channel network was determined using ArcInfo software based on the D-8 method (see section 2.5.1). However, these channels were used only as a guide. They were not used as the definitive location of surface runoff.

Surface runoff or pond water encountered within a sub-grid during the field-work period of April 5 to April 13 was noted. Daily re-surveys of each point of surface runoff were not possible because of the large survey area. Eight days were required to survey the entire basin. This results in an approximate state of the basin during these eight days rather than a continuous monitoring of the entire basin over the eight day time period. Surface runoff was delineated by walking the channel using a hand-held global positioning system (GPS) to mark the start and end of the channel as well as multiple waypoints along the length of the channel. The GPS unit was also used to provide a coordinate location for ponded water. Surface runoff was described as channel, rill, or sheet flow and a measure of the width of the flow was taken. GPS coordinate data and channel description data were assembled into points with both spatial and attribute information in ArcInfo. The field team, comprised of the author and staff of the NWRI, used the point data to re-create real-world channels and pond data in a modeled environment.

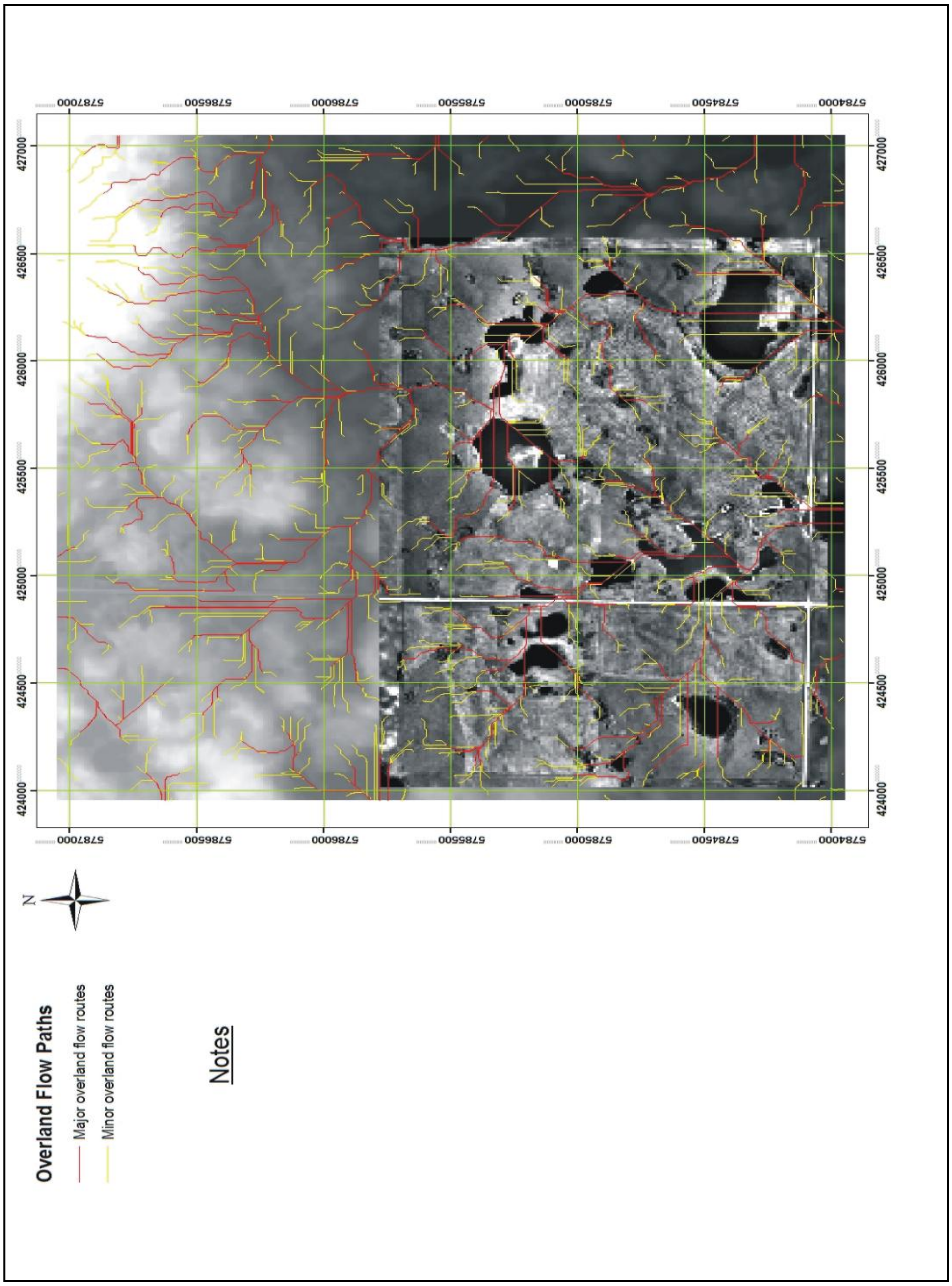


Figure 3-8. Example of maps used to organize the collection of channel network information at SDNWA. Green lines are mark the grid used to define and organize subsections of the area. Red and yellow lines are the channel structure determined by ArcInfo using a LiDAR DEM of the area.

3.4 Surface water observations at St. Denis Wildlife Area

A data set was prepared using a traditional landscape model that treats potholes in the DEM as depressional artefacts and pre-processes the depressions to remove them prior to landscape analysis (see section 2.5). Gross drainage area and channel structure were determined using the depression free DEM create by ArcInfo (see section 4.4.1) (Figure 3-9).

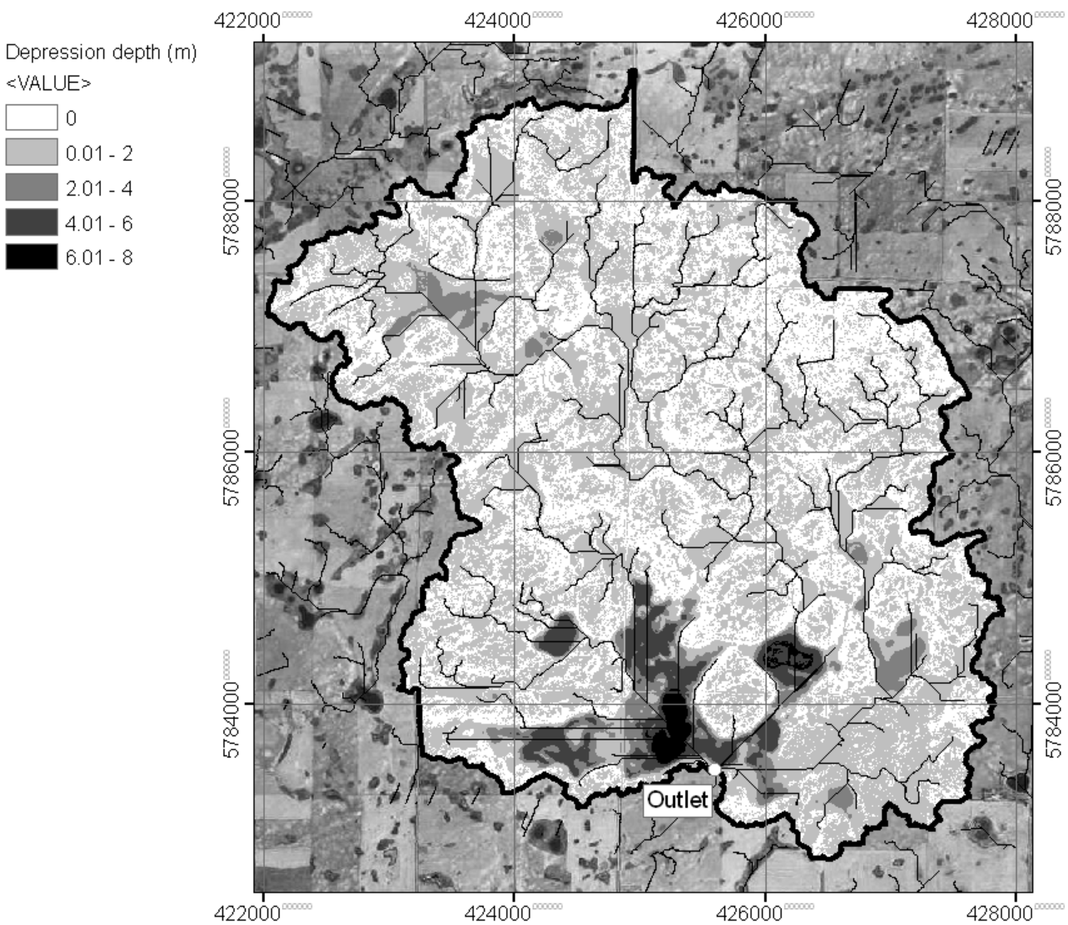


Figure 3-9. The watershed boundary and channel structure for the St. Denis drainage basin as determined by a ArcInfo GIS using an input LiDAR DEM. Basin coordinates are UTM zone 13.

During the 2006 snowmelt runoff information about the extent and spatial distribution of surface runoff was collected at the SDNWA basin (see section 3.3.4). Points that identified the location of surface water were overlain on an aerial photo of the basin (Figure 3-10). Using the collected surface water data, contributing area for pond 90 and connected areas within the basin were calculated for the snowmelt event in 2006. Because of time and resource limitations along with issues regarding access to some areas of the basin, the survey was refined to encompass only surface water for the areas that potentially contributed runoff to pond 90, rather than the outlet of the St. Denis. Because pond 90 did not spill runoff downstream to the outlet of the basin in 2006 . It is assumed that surveying only the basin area upstream of pond 90 was necessary.

Although attribute data was collected about each point identified as surface water, a specific methodology was not in place for consistently describing the attribute data for points collected. This resulted in a data set that was not consistently described throughout the basin and does not allow specific inferences about surface water connections to be made in all areas of the basin. However, the point data collected can be used to describe the general state of surface water in the basin and can be used to identify areas in which surface water was flowing or ponding on the surface. This data set was used to compare the actual basin contributing area that resulted from the runoff event with the contributing area calculated using currently accepted methods.

As expected, rather than a drainage basin that contributes 100% of upstream basin area for pond 90 and ultimately the basin outlet, as defined using the GIS (Figure 3-9), field research completed in the SDNWA drainage basin during the Spring 2006 snowmelt runoff event reveals a disconnected channel network. Figure 3-10 illustrates the approximate channel structure of the basin based on field observations. Plotting the observed points of surface water on an georeferenced image of the St. Denis basin, along with the channel network that is delineated using a current landscape analysis model, reveals the modelled channel network is not an accurate representation of the observed channel network during the runoff event in 2006. During the 2006 snowmelt event, regions of the basin were connected but these areas were not ultimately connected to pond 90 and would not connect to the basin outlet if pond 90 were spilling downstream (Figure 3-11). Thus, during the 2006 spring melt there may have been very local runoff to the basin outlet but it can be assumed that very close to 0% of the upstream potential contributing area connected to the outlet.

Figure 3-12 illustrates the sequence of sub-basins spilling and connecting in response to increasing the magnitude runoff events. A melt event that produces an effective runoff of 20 mm results in only local runoff to pond 90. However, a relatively minor increase in effective runoff to 27 mm results in much of the basin connecting to pond 90 (Figure 3-12c). However, it is not until an effective runoff depth of 130 mm is reached that the entire basin reaches threshold (Figure 3-12f).

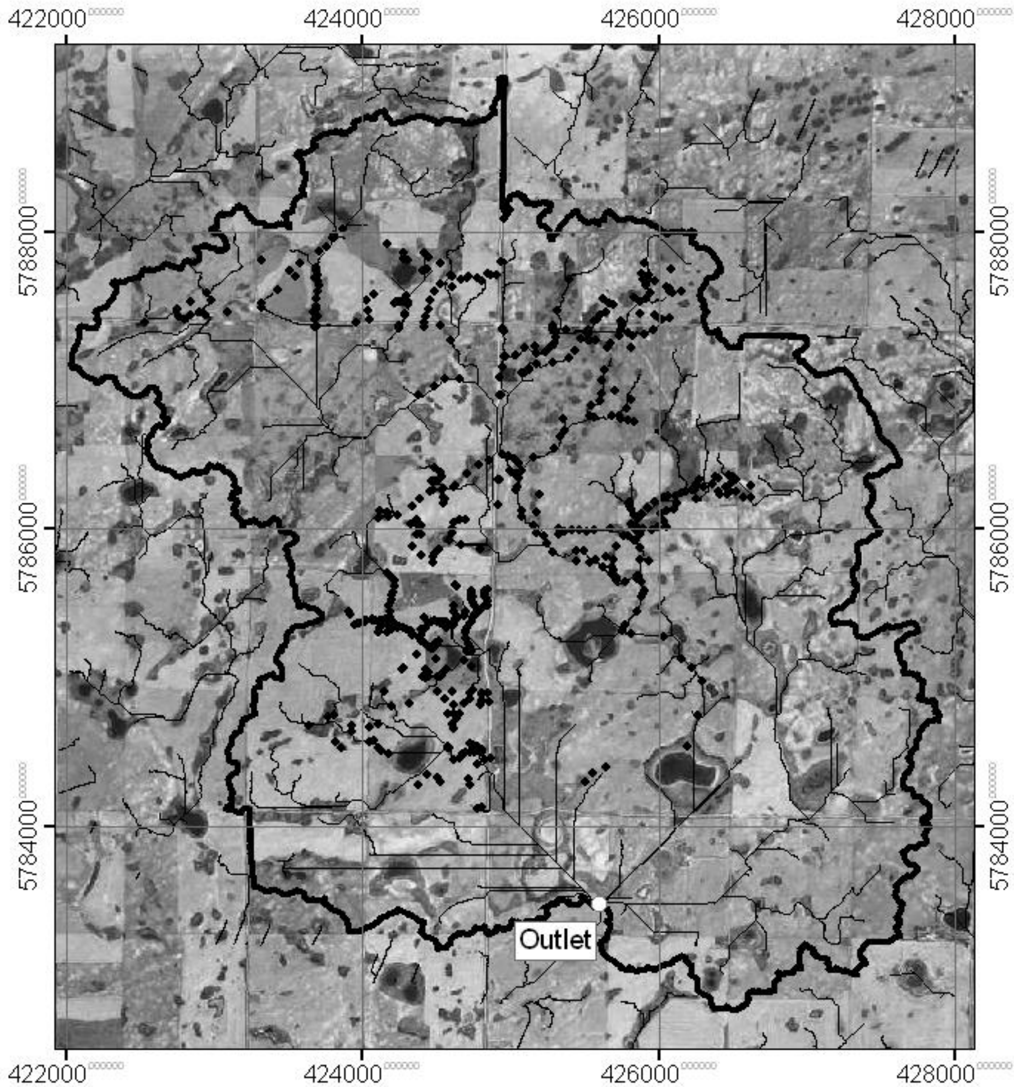


Figure 3-10. Points (black dots) show surface water mapped during the 2006 spring runoff event. Black lines show the channel network determined using a current landscape analysis tool.

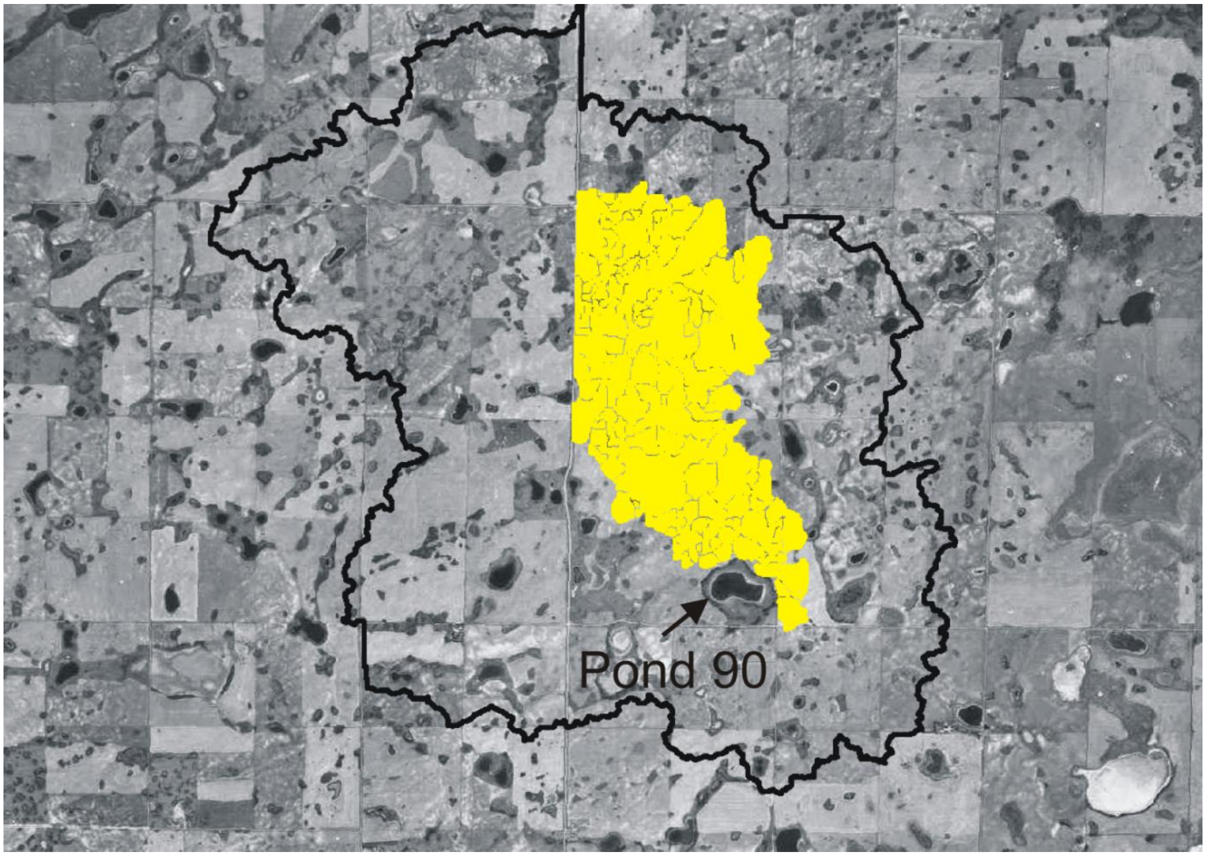


Figure 3-11. The yellow area shows the extent of connected areas contributing runoff to pond 90 during the spring melt in 2006.

These observations confirm the contol topography can have on connectivity in the basin and thus the timing and magnitude of runoff events both within and at the outlet of the basin. Moreover, it allows quantification of contributing area. Figure 3-13 illustrates that the upper 50% of the SDNWA basin contains only 14% (calculated from the DEM) of the total V_{SSA} of the basin. Thus, due to the low V_{SSA} of many of the potholes in this area, many of the potholes filled and overflowed and connected overland to downstream potholes. Thus during the 2006 runoff event much of the upper basin was connected. However the runoff event was not of a magnitude that allowed connections to occur in the middle and lower areas of the basin. Thus, the upper basin is disconnected from the basin outlet and therefore did not contribute to the outlet.

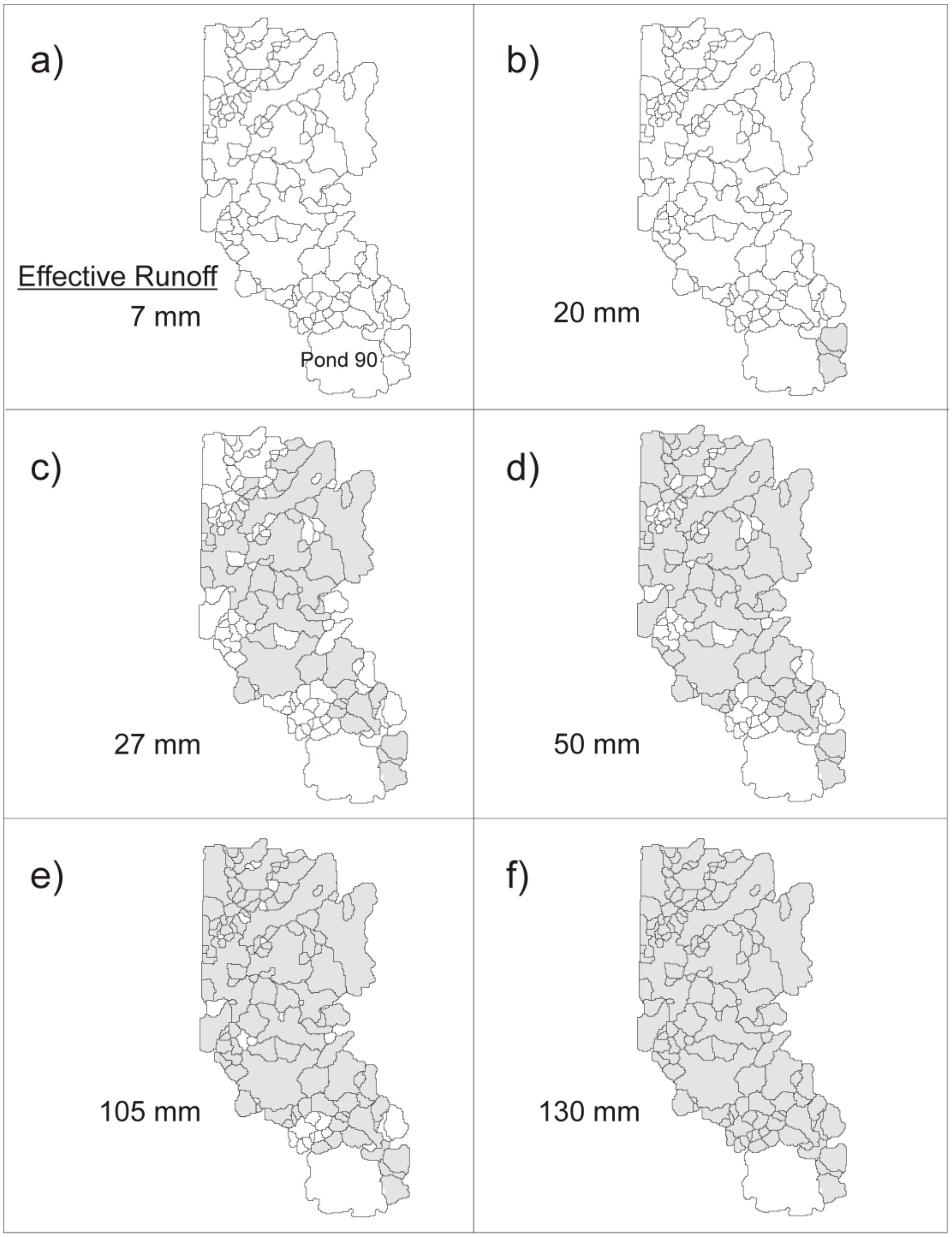


Figure 3-12. Grey areas identify areas of the St. Denis basin that are spilling in response to an effective runoff depth.

Measuring V_{SSA} in the basin can be done in a GIS by subtracting elevation values from a DEM (that represent pond surface elevations as well as land surface elevations) that has the landscape filled to the threshold storage volume from elevation values of a DEM of the basin in a dry state. The resulting DEM which will represent the volume that can be held by each depression in the basin can be used to examine the extent and distribution of V_{SSA}. It is apparent in SDNWA that the vast majority of storage capacity within the SDNWA basin is adjacent to the outlet (Figure 3-13). Thus, the entire V_{SSA} of the basin will need to be satisfied before there is runoff at the outlet. It is evident from the SDNWA 2006 runoff event that the spatial distribution of the surface storage volume (V_{SSA}) in the basin will influence the sub-threshold connectivity in the basin and will ultimately influence the contributing area of the basin at sub-threshold conditions.

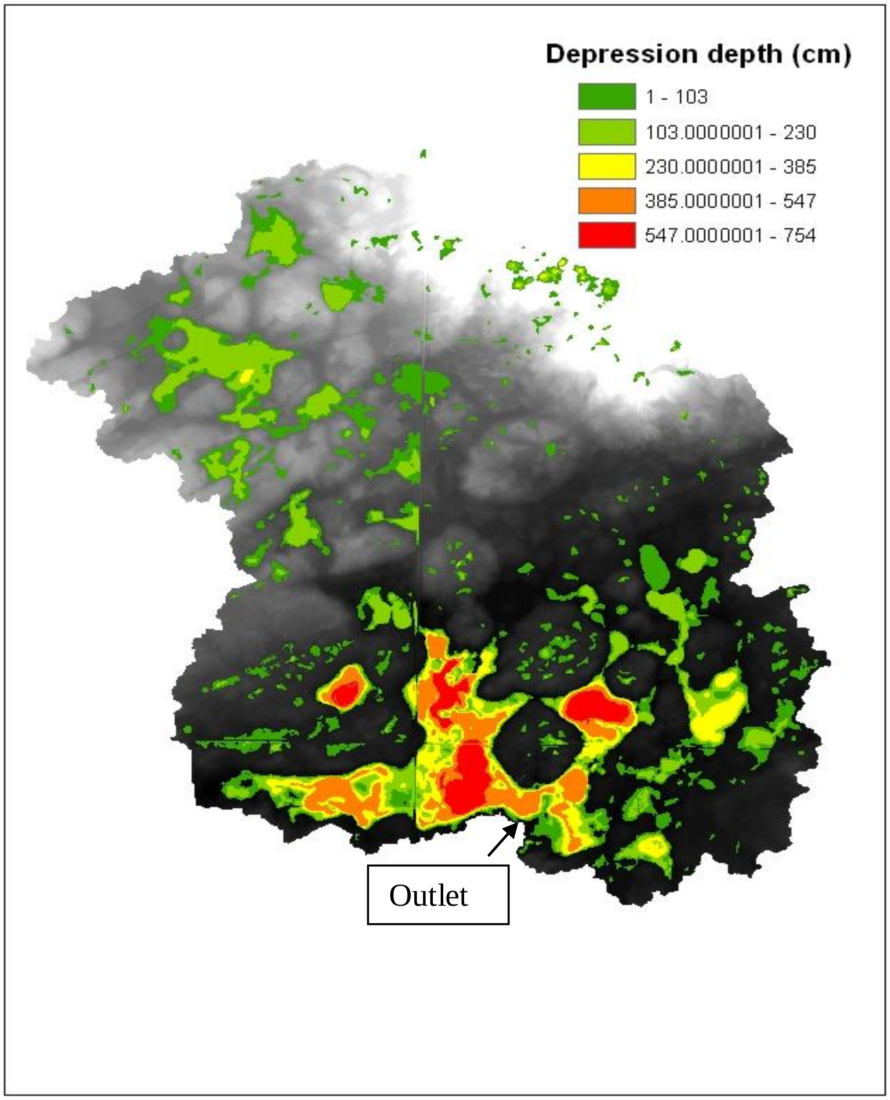


Figure 3-13. Illustrates areas of V_{SSA} in the St. Denis drainage basin.

The St. Denis drainage basin exhibits the runoff behaviour that is proposed for conceptual landscape C proposed in Chapter 4 (see Figure 4-6). There are connected areas in the basin's upstream area as a result of a runoff event but these connected areas ultimately do not overwhelm the available storage of pond 90 that is located near the outlet. As a result, there is no increase basin contributing area (CA_B) in the St. Denis basin for the 2006 spring runoff event. It is interesting to note in Figure 3-11 that contributing area for pond 90 is influenced by the road running through the basin. The road acts as a dam and is appropriately represented in the LiDAR DEM as an area of higher elevation relative to the surrounding area. This results in a contributing area shape for pond 90 that is straight along the road's edge. However, observations during runoff events at St. Denis revealed that there were two culverts that passed through the road allowing water to flow from one side of the road to the other. These observations illustrate the affect of anthropogenic influences on contributing area in the prairie pothole region. Although anthropogenic influences are an important consideration it is outside the scope of this thesis. However, identification of this issue in this thesis may guide future research on contributing areas in the prairie pothole region. Figure 3-14 illustrates the increase in contributing area that would occur if the culverts influence were incorporated into the DEM through lowering the elevation of the road to the culvert elevation from one side of the road to the other.

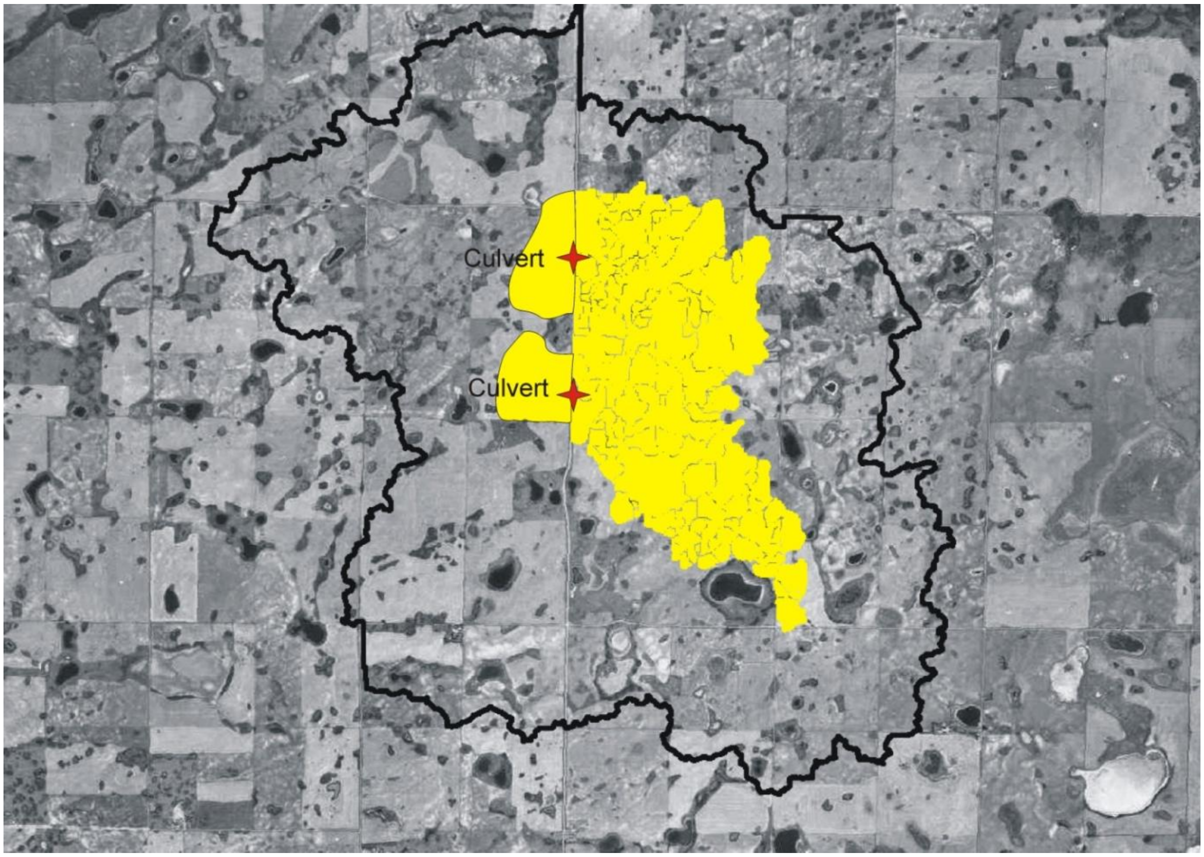


Figure 3-14. Increased contributing area for pond 90 if culverts are represented in the DEM.

The historical record of pond depth levels at the SDNWA offers an opportunity to examine the influence that connected areas have on the response of the basin to runoff events. Increases in pond depth and the resulting increase in pond volume in response to a runoff event can be used to quantify runoff. Using a pond as a method for measuring the runoff response to a spring-melt event is necessary as there are very few natural flow basins (347 in the Canadian prairie pothole region) with streams or stream-gauges in the prairie pothole region.

The study basin has two major ponds; pond 1 (p1), located approximately in the middle of the basin, and pond 90 (p90), situated downstream at the outlet of the basin (Figure 3-15). V_{PMAX} has been estimated for both potholes from the LiDAR DEM of the region. Due to the fact that both of these ponds were filled with water during the LiDAR data collection, bathymetry was calculated for both ponds using Hayashi and van der Kamp (2000) equations that represent the volume-area-depth relation of small wetland depressions. After bathymetry was determined and the DEM edited to reflect the bathymetry, maximum V_{SSA} for the ponds was calculated using the method of subtracting a DEM at threshold storage from one that is in a dry state that was outlined earlier. Maximum pond volume (V_{PMAX}) has been estimated for p1 as 84,000 m^3 and p90 has been estimated as 525,000 m^3. An examination of the historic pond levels for these two ponds was undertaken to determine whether evidence supportive of the concepts of fill-and-spill and connectivity as proposed in this thesis could be found.

Pond levels for p1 and p90 are shown in Figure 3-16a and Figure 3-16b. The data demonstrates a striking increase in pond levels in p90 in 2006 and 2007 due to connectivity in the basin. In the spring of 2007, p90 is approximately 3m deeper than any other time in the last 39 years. The dramatic increase in pond level in p90 occurs over a very short time. During the fall of 2004 the basin was very dry due to drought conditions that had persisted in the area since 1999 (Bonsal and Wheaton, 2005). Pond 90 (p90) was completely dry in the fall of 2004 while p1 has the lowest recorded depth since 1968.

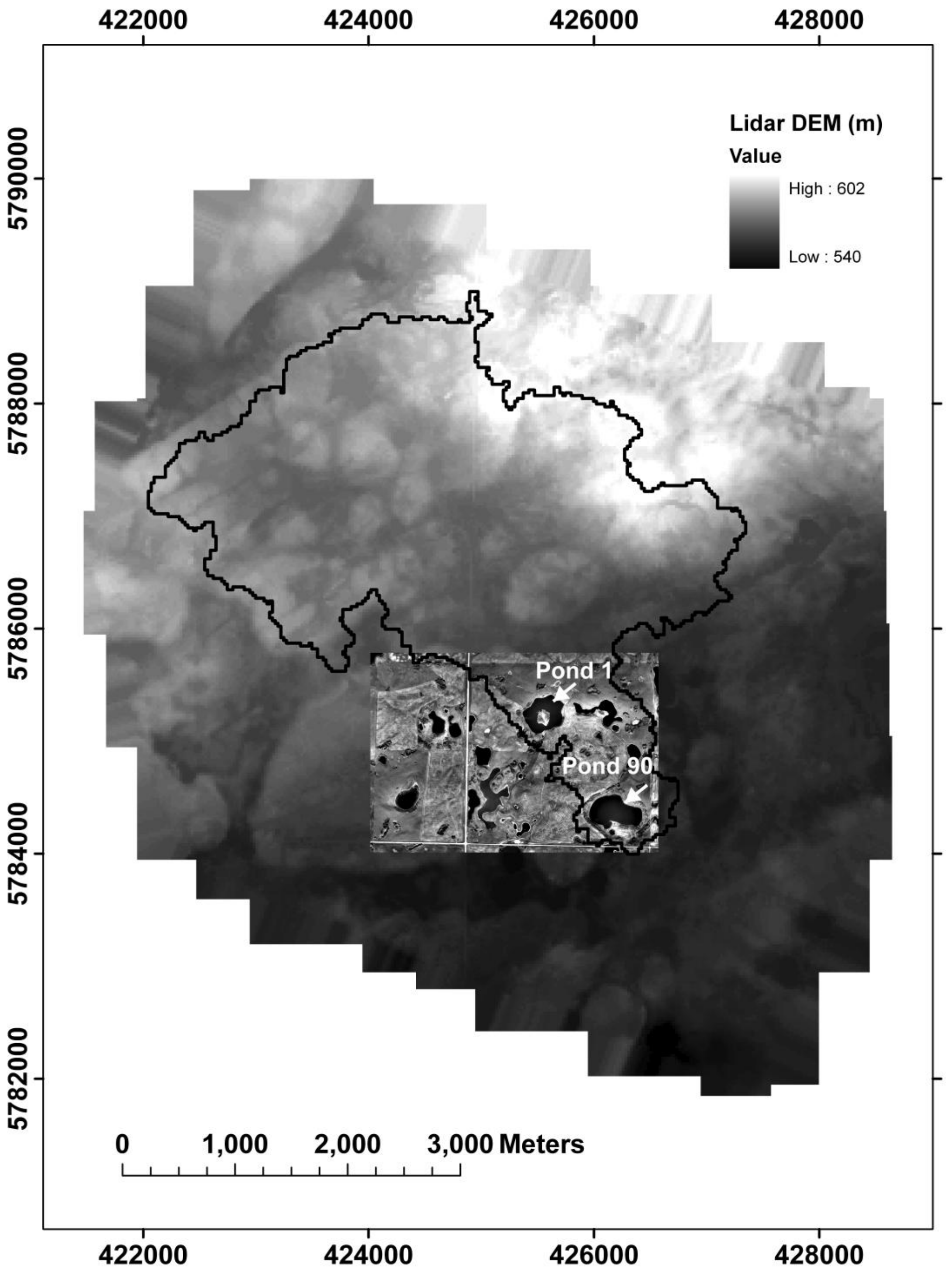
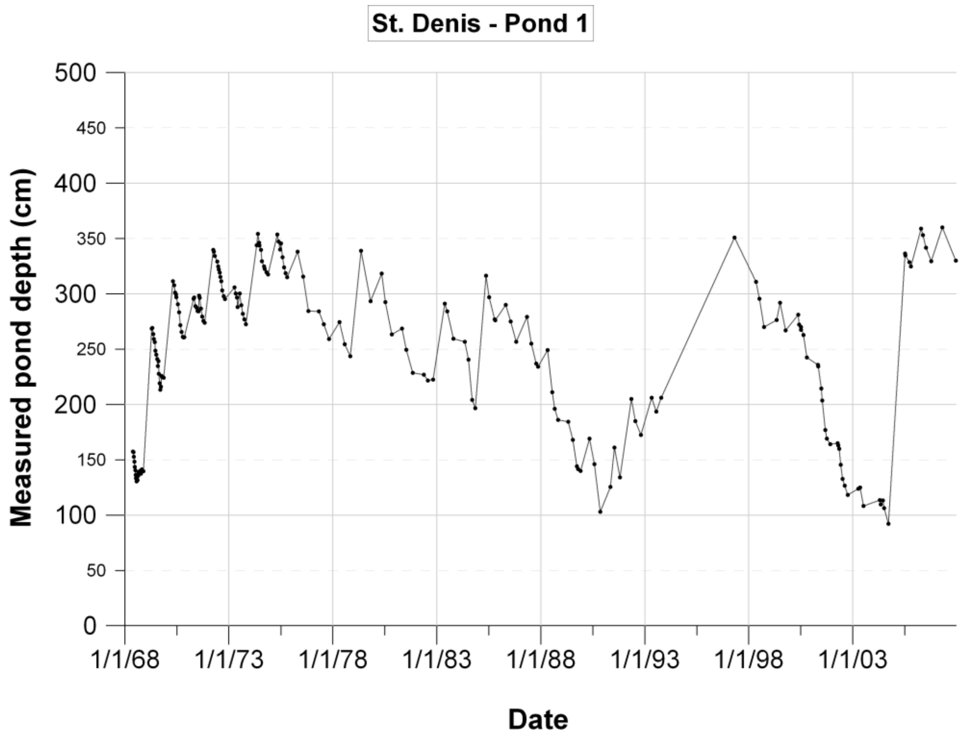


Figure 3-15 The main ponds (pond 1 and pond 90) of the St. Denis National Wildlife Area (SDNWA) are identified on an air photo with the surrounding area represented by a Lidar DEM. The black line denotes the boundary of the basin when spill point of pond 90 is identified as the basin outlet.

a)



b)

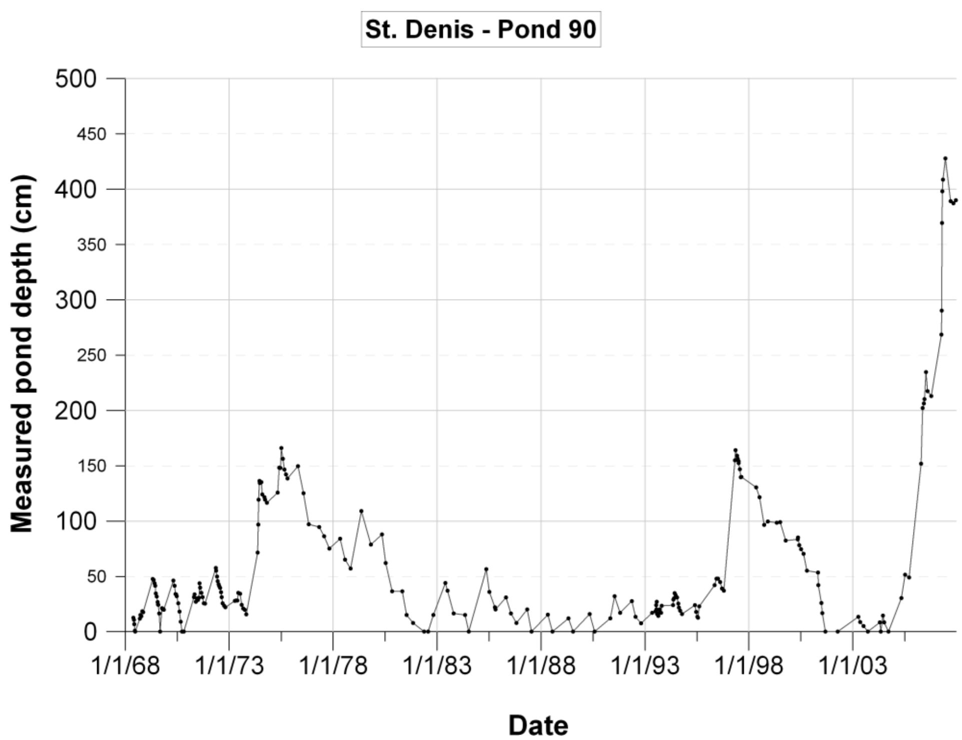


Figure 3-16. Pond levels for pond 1(p1) and pond 90 (p90) in the St. Denis Wildlife Area (SDNWA), 1968-2007.

Figure 3-17 illustrates the pond level increases for p1 and p90 for the 2005 spring runoff event. It is interesting to note that the p1 and p90 pond depth increases are dramatically different. The p1 pond level has increased over 2.5m to a depth of 3.51m. This is the depth at which p1is full and therefore spills downstream. However, in response to the exact same runoff event p90 pond level increases by only 0.25m. From an examination of pond levels in 2005 it could be concluded from looking at p1 that the drought in the region had been broken while examining p90 could lead to the conclusion that, although the pond level increased, drought persisted.

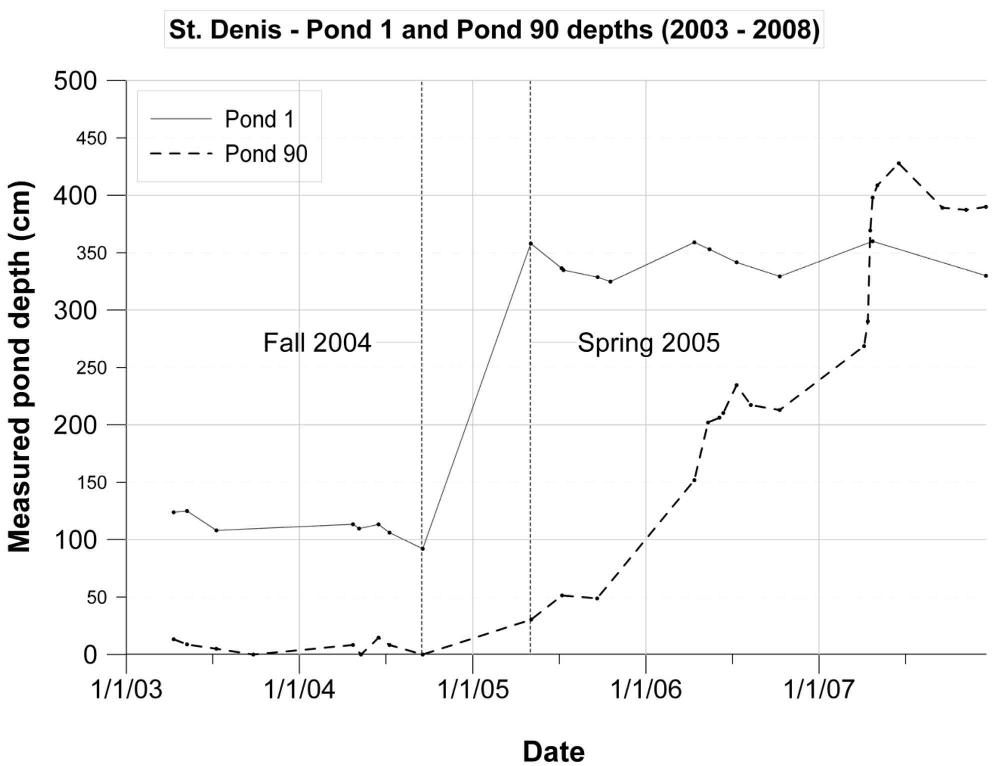


Figure 3-17. Illustrates the pond level increase for pond 1 and pond 90 during the spring melt event in 2005.

Snow water equivalent (SWE) values measured in the basin during the spring of 2006 were very similar to values measured in the spring of 2005 (Figure 3-18). However the response of the basins to similar SWE conditions differed dramatically between the two years. Because p1 remained very close to full in the fall of 2005, very little additional runoff was required to raise the pond level in the basin to the spill point. As a result, the connected area contributing to p90 dramatically increased very early in the 2006 spring melt runoff event subsequently increasing the pond level of p90 by 1.5m. This increase is 6 times the pond level increase measured in 2005 even though the SWE available for runoff in both years is comparable (Figure 3-19).

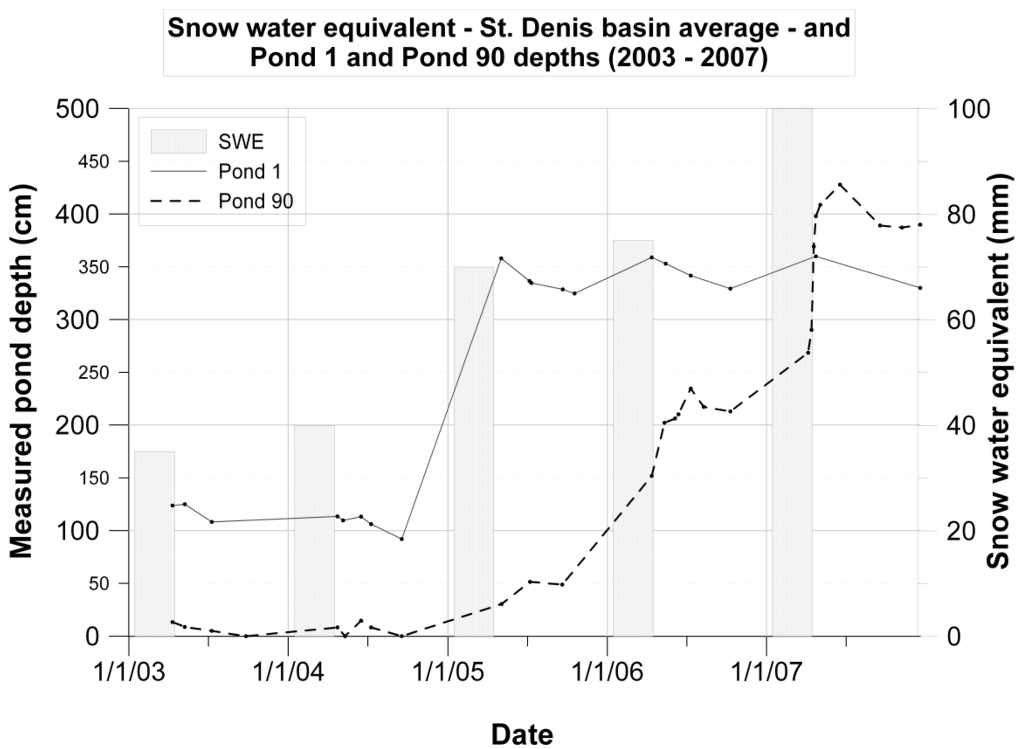


Figure 3-18. Snow water equivalent values at the St. Denis Wildlife Area for the years 2003-2007.

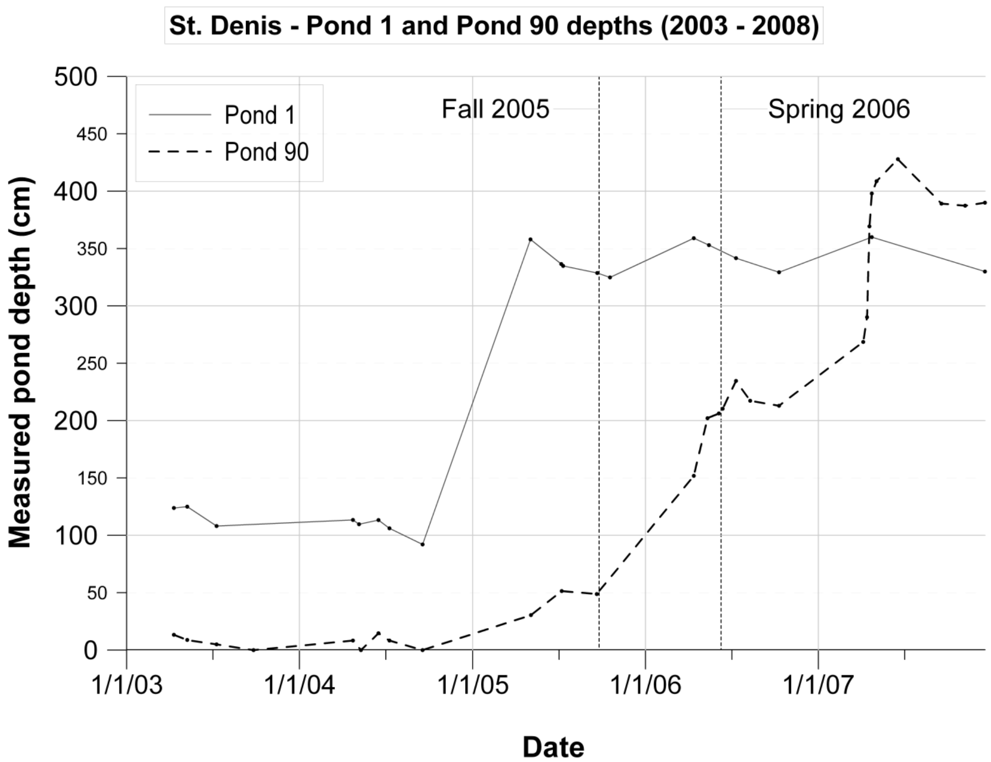


Figure 3-19. Illustrates the pond level increase for pond 1 and pond 90 during the spring melt event in 2006.

The spring snowmelt runoff event in 2007 again saw a dramatic rise in the pond depth level of p90. As in 2006, p1 filled and spilled early in the runoff event allowing the entire basin to connect to p90. This results in another 2.2m of pond depth added to p90. The measured increase in pond level of p90 is 0.7 m greater than in 2006. This increase may be attributed to 20% more SWE available for runoff in the spring of 2007 (Figure 3-20).

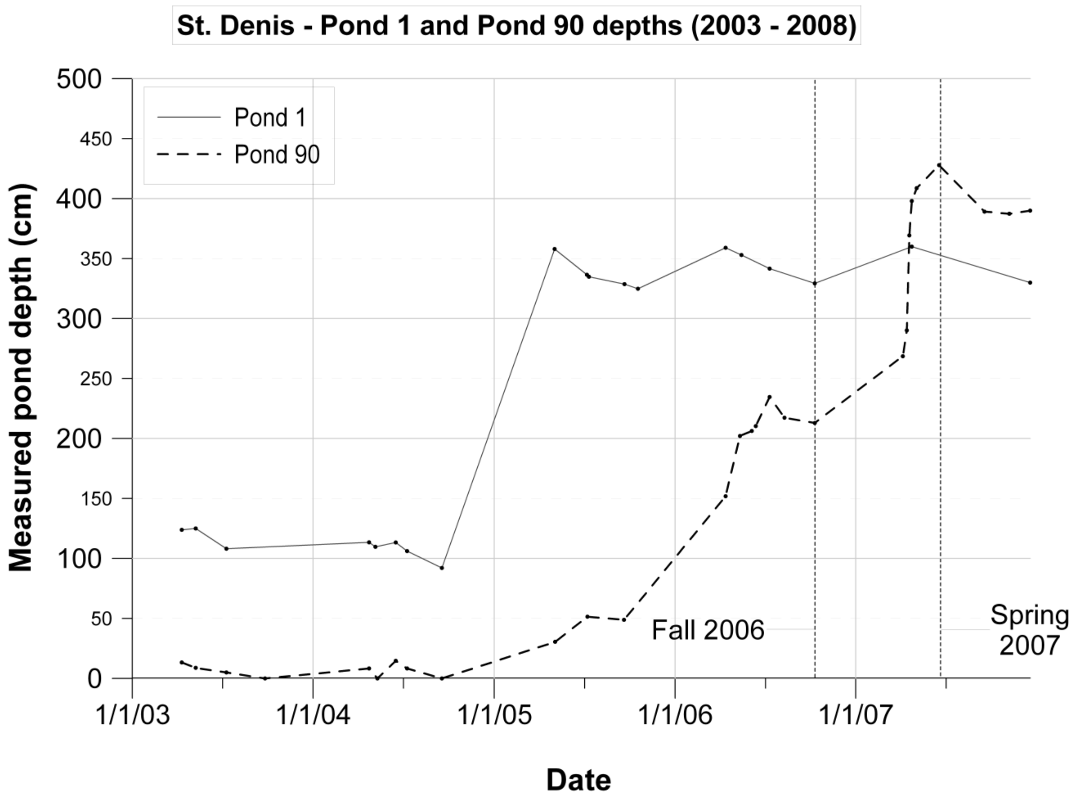


Figure 3-20. Illustrates the pond level increase for pond 1 and pond 90 during the spring melt event in 2007.

What the response of p90 illustrates is the importance of connected areas in modeling the hydrology of the prairie pothole region. The fill-and-spill of potholes influences the extent of connected area and can influence the CA_B. What the pond level data at SDNWA reveals is that basin storage can be satisfied in such a manner that minor runoff events, can cause a tremendous increase in CA_B. Water resource managers in the prairie pothole region would benefit greatly from an algorithm that accurately and reliably determines the state of basin storage and how close the basin is to being connected in a manner that dramatically increases CA_B. The algorithm will help water resource managers with flood forecasting and water apportionment.

CHAPTER 4

PRAIRIE POTHOLE LANDSCAPE ANALYSIS

4 Overview

This chapter describes a conceptual framework for dynamic contributing areas in the prairie pothole region based on field observations described in the previous chapter. The concepts are used to develop an algorithm that automates a method of quantifying contributing area for prairie pothole basins. The resulting algorithm provides a methodology for calculating contributing area in a way that captures and simulates the processes identified in Chapter 4 as important for drainage area calculation.

4.1 Concepts

Figure 4-1 shows a pothole that is connected to both upstream and downstream potholes at the SDNWA, Saskatchewan, Canada. In the prairie pothole region a snowmelt or rainfall event may produce runoff in various areas of the drainage basin (Figure 4-2).

Figure 4-1. A prairie pothole (B) receiving surface water (A) from an upstream pothole and spilling downstream (C).

Figure 4-2. . Surface runoff at SDNWA during 2006 snowmelt runoff.

Each pothole in the basin fills with runoff from the surrounding pothole contributing area (CA_P) (Figure 4-3). All potholes will have a maximum pothole volume (V_{PMAX}), which is defined as the amount of *surface* water volume each pothole can hold before the pothole spills (Figure 4-3). When the V_{PMAX} of a pothole is reached, the V_{SSA} has been satisfied and any further runoff input into the area is spilled to downstream potholes. However, downstream potholes may completely impound the runoff before it reaches the outlet. As a result, there can be runoff- producing areas that contribute to downstream potholes but that may not ultimately connect to the outlet of the basin. The term proposed for this concept is *connected area* (Figure 4-3). These connected areas may be found throughout the basin. However, as seen in the St. Denis basin (section 3.4) only when these connected areas ultimately runoff to the outlet of the basin will they be classified as basin contributing area (CA_B) (Figure 4-3). When the V_{SSA} in the entire basin is completely satisfied and thus the maximum volume of runoff is stored, (V_{BMAX}), the basin will be completely connected and 100% of the basin will contribute runoff to the outlet. This basin state will be referred within this thesis as *threshold*.

It is important to note that only V_{SSA} is addressed in this research. It is acknowledged that there are other forms of water storage in the basin, but this thesis is only concerned with surface water storage.

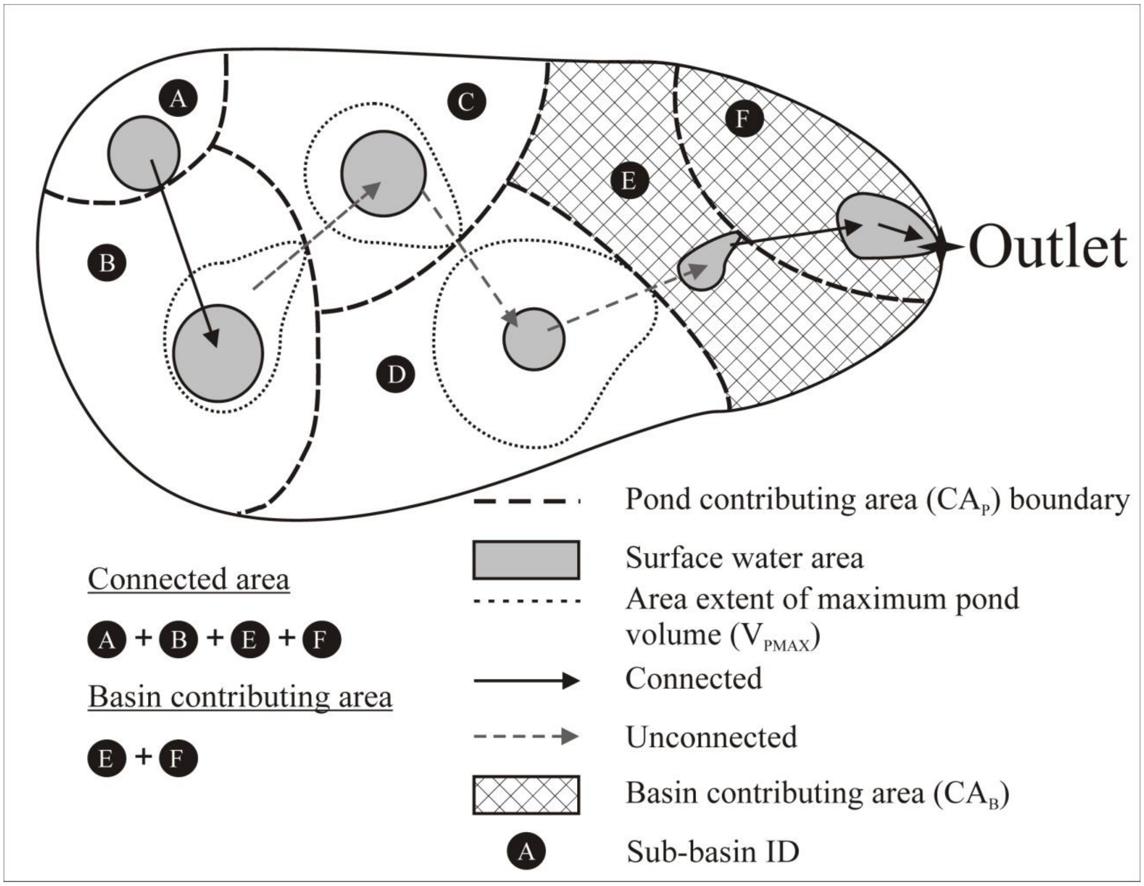


Figure 4-3. Illustrates terminology used to describe the response of a prairie pothole region basin to a runoff event.

The volume of water required to fill the basin to the V_{BMAX} value is a function of the connectivity of individual prairie potholes within the basin. However, it is very important to note that the V_{BMAX} is not always equal to the sum of all V_{PMAX}. This is due to nested sub-basins and ponds within the basin. Figure 4-4a illustrates a basin in which runoff has filled each pond to its V_{PMAX}. Each of the ponds in the sub-basins has filled to their spill point. However, Figure 4-4b illustrates that more water volume is required in order for the entire basin to reach a threshold state. This is an important consideration when determining total surface storage in the basin. Methods that simply determine storage from simply summing individual pond volumes (see section 2.0) in the basin will underestimate storage volume required to reach threshold storage. Sub-basins are frequently nested in a prairie pothole basin. A simple cascade of sub-basins (storage) spilling to lower elevation basins and ultimately to the outlet that are generally described in traditional hydrology literature (Nash, 1957; Dooge, 1959) are not representative of the complex interactions between sub-basins in the prairie pothole region.

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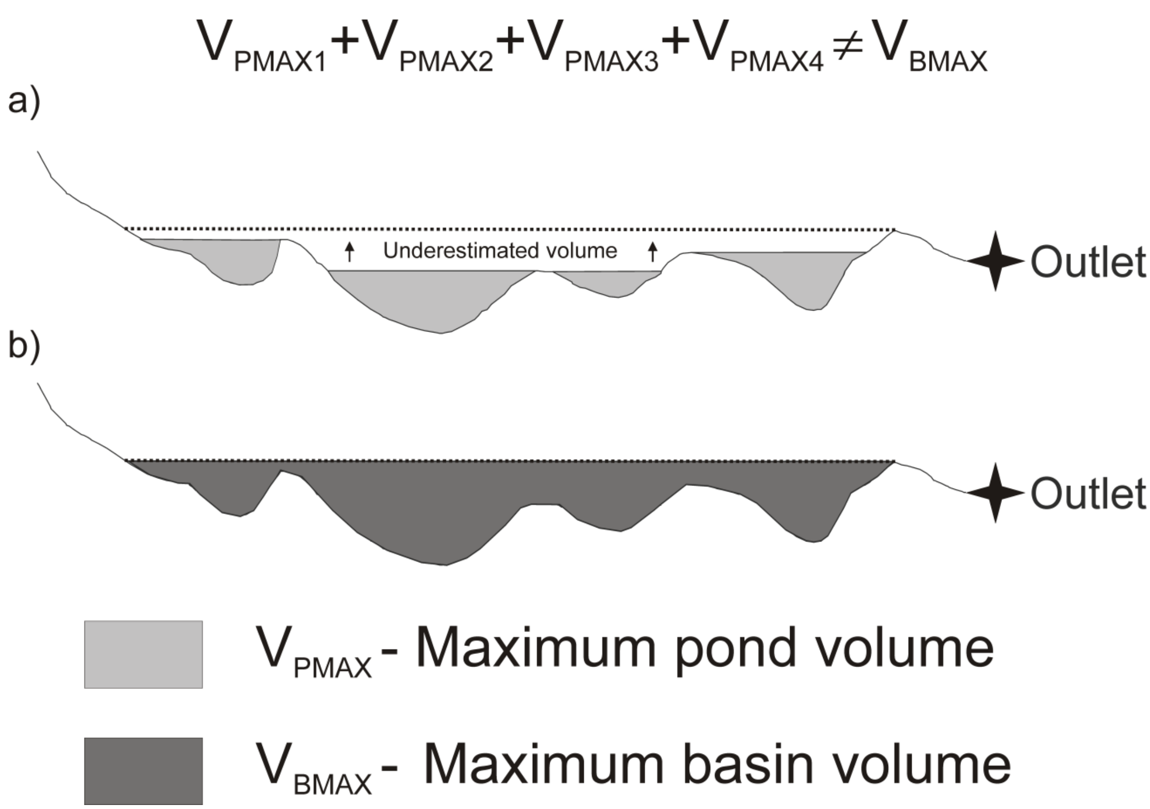


Figure 4-4. The sum of maximum pond volume (V_{PMAX}) in the basin may not be equal to the total maximum water volume a basin can store (V_{BMAX}).

Figure 4-5 illustrates the complex interaction between ponds that have reached V_{PMAX} and are spill 'upstream' of the outlet before ultimately cascading runoff towards the outlet after upstreams ponds have reached their V_{PMAX}.

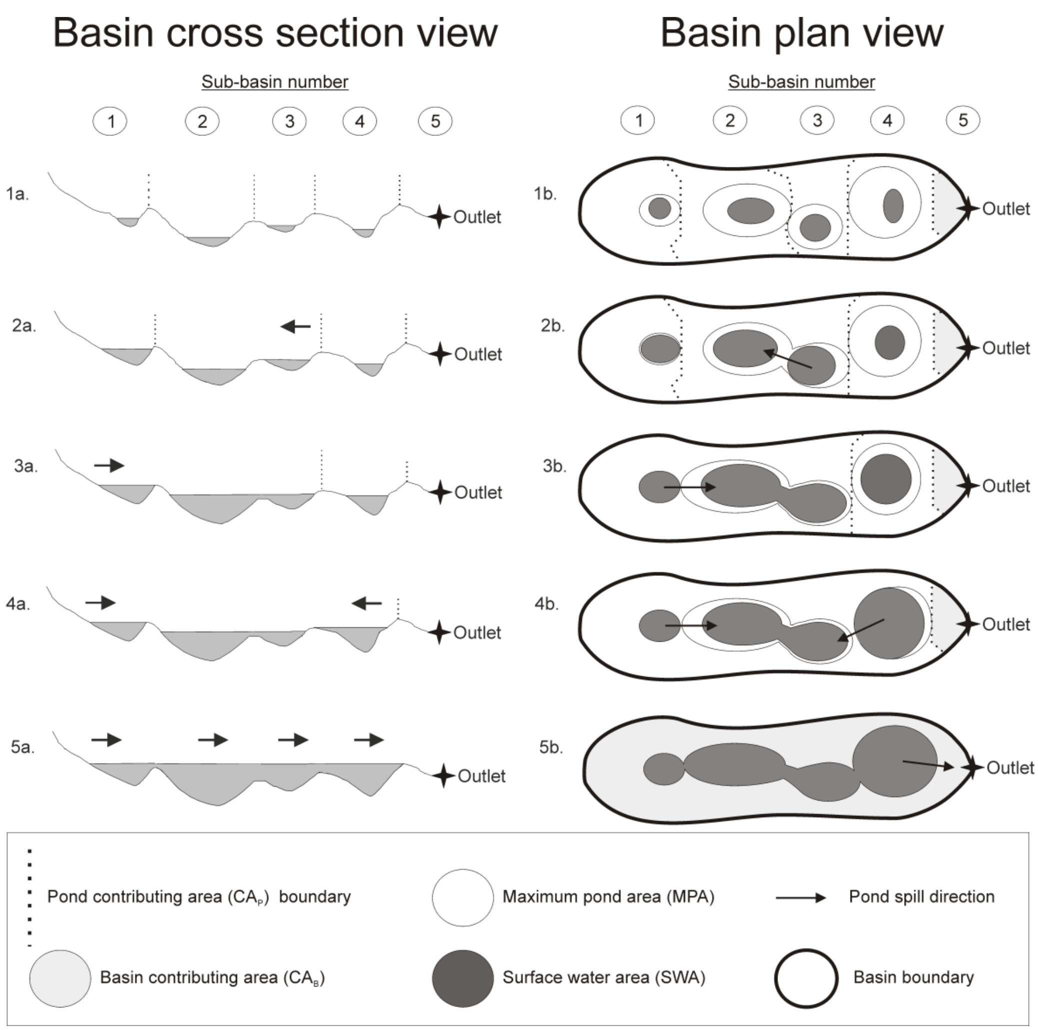


Figure 4-5. Illustrates the complex cascade of runoff as ponds fill-and-spill in the prairie pothole region.

4.2 Conceptual landscapes

It is intuitive that the spatial distribution of storage capacity in the basin will influence the sub-threshold connectivity in the basin, ultimately influencing the contributing area of the basin at sub-threshold conditions. Figure 4-6 presents a set of conceptual curves for four types of landscapes with the same V_{SSA} within the basin. These curves illustrate the relationship between a basin's contributing area in relation to the amount and distribution of storage in the landscape that has been satisfied. The conceptual basins will achieve a threshold storage value at the same point. However, the relationship between storage and contributing area at sub-threshold levels will differ dramatically according to the distribution of storage. Basins which are located inside the prairie pothole region can have three spatial distribution patterns: storage predominantly in the upper area of the basin (landscape/curve A), evenly distributed storage (landscape/curve B), or storage predominantly in the lower area of the basin (landscape/curve C). A basin that combines potholes with defined channels (landscape/curve D) would be found in areas where the prairie pothole region transitions to a landscape with an integrated channel structure.

Figure 4-7 illustrates the relationship between contributing area and decreasing available storage volume for landscape B shown in Figure 4-6. The step-wise increase in contributing area is controlled by the fill-and-spill and resulting connectivity of potholes. Landscape B illustrates a simple cascade of potholes connecting back upstream from the outlet. As each pothole fills to a point in which V_{SSA} is satisfied, the pothole spills and connects through surface runoff to a downstream pond that is connected to the outlet. As a result, CA_B is increased by the CA_P for each instance of pond fill-and-spill.

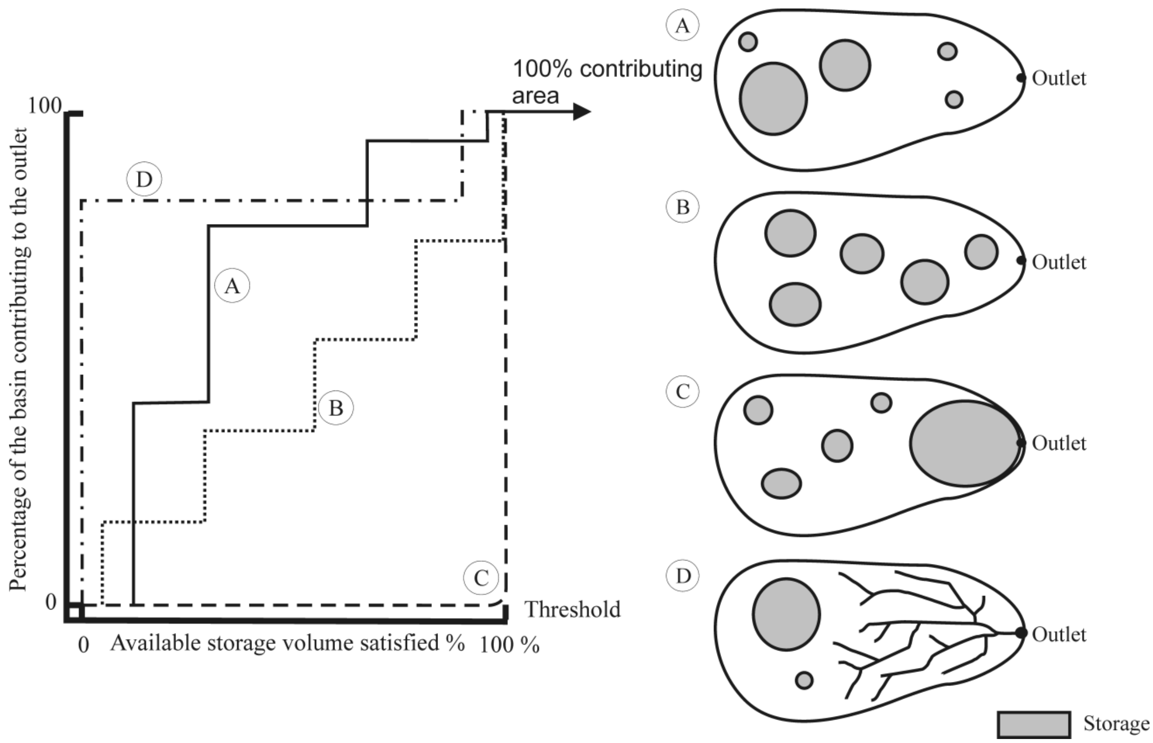


Figure 4-6. Conceptual curves expressing the relationship between basin storage and contributing area in a prairie pothole landscape.

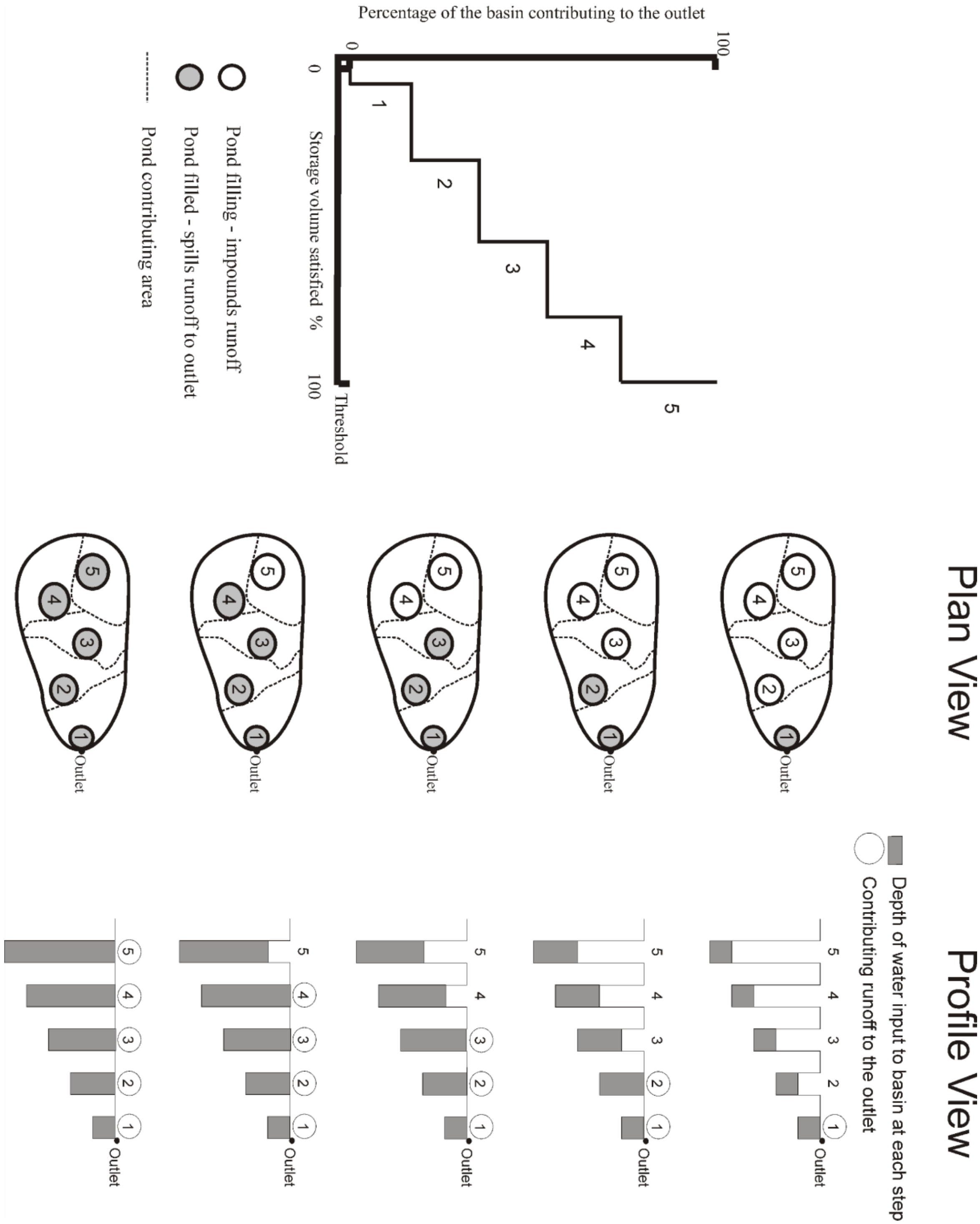


Figure 4-7. The relationship between decreasing available basin storage volume and increasing contributing area for conceptual landscape B presented in Figure 4-6.

4.3 SPILL Algorithm

4.3.1 Algorithm assumptions

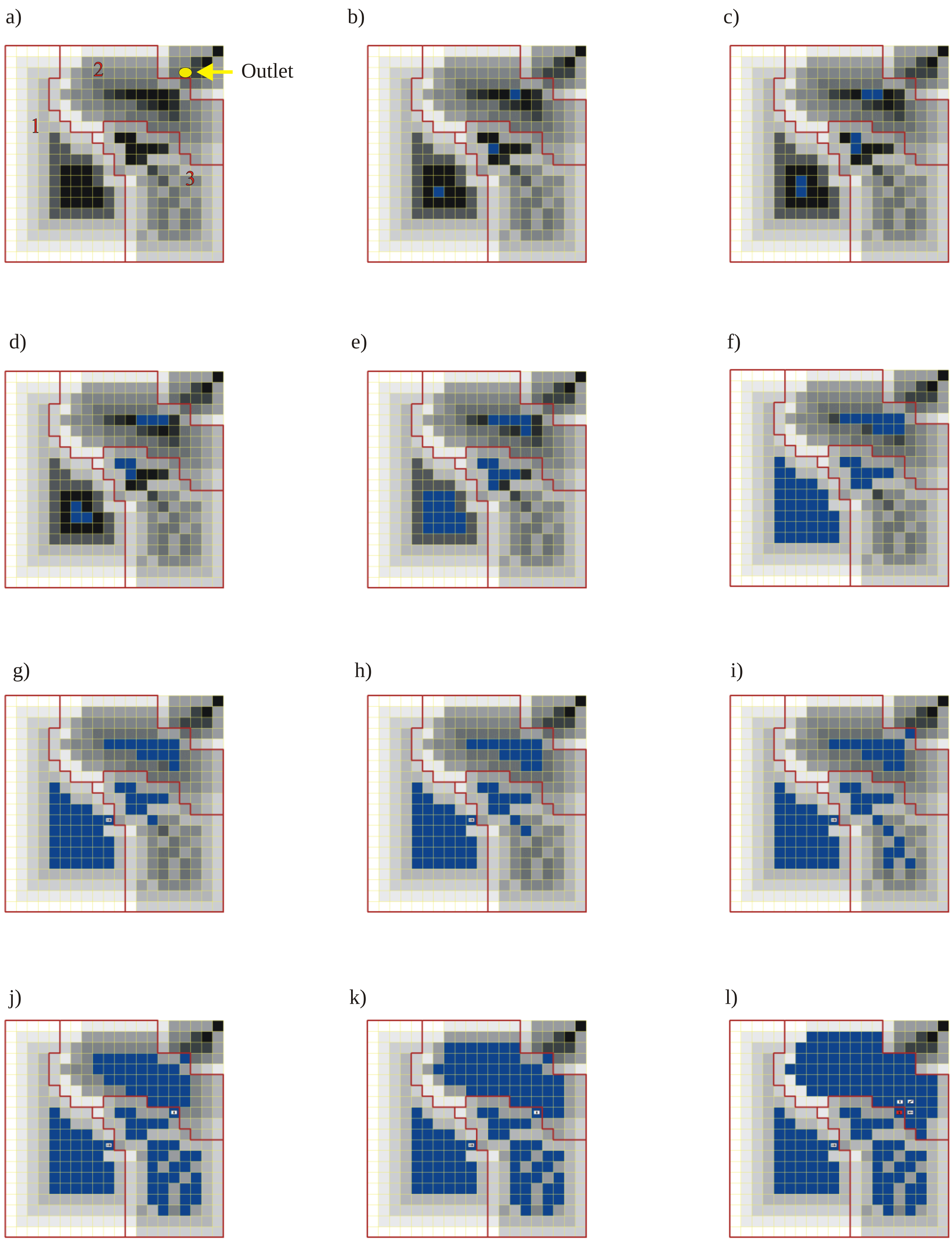
In developing the Simple Pothole terraIn anaLysis aLgorithm (SPILL) for use in the prairie pothole region there are several general assumptions to be considered.

1. The algorithm models the connectivity and resulting CA_B in the basin for spring melt runoff events not summer storms.
2. The attenuation of runoff through hydrologic processes is represented by adjustments of input SWE values. The model does not attempt to model the magnitude of the runoff event, assuming that the magnitude of the runoff event has been attenuated prior to input. Extensive hydrology research on infiltration, (Su et al., 2000) snow redistribution (Pomeroy et al., 1993), and snowmelt runoff (van der Kamp et al., 2003) in the prairie pothole region can refine the magnitude of the runoff depth value input into the model.
3. SPILL redistributes over what is assumed to be an impervious surface. This is a reasonable assumption for snowmelt runoff events under restricted infiltration conditions (see section 2.3.2). However, for limited and unlimited infiltration conditions (see section 2.3.2) the SWE input value into the algorithm can be adjusted to reflect increased infiltration.
4. The input DEM represents current basin conditions with respect to available V_{SS}.

4.3.2 Limitations of a cell-based methodology

The SPILL algorithm models the redistribution of input runoff events over the landscape. It allows sub-basins to connect based on a spill point that is determined solely by the elevations of the unfilled DEM. The spill point is a cell identified as the lowest elevation of boundary cells that have been identified for each sub-basin. This allows more realistic modeling of the complex connectivity between the potholes. Preliminary algorithms revealed that it was necessary for the algorithm to be robust to handle the complexity of the fill-and-spill of the prairie landscape. However, this complexity has to be addressed in a manner that is computationally efficient. A cell by cell model proved to be unsatisfactory as processing times were unreasonably long. Basin 2 in the SDNWA (Figure 3-3) required 7 days of processing in the GIS ArcInfo to complete. While the LiDAR DEM of the SDNWA basin is relatively small (24 km^2), due to its high resolution, the DEM is comprised of over 50 million cells at a DEM resolution of 1 m.

Although the cell-based version of SPILL was ultimately rejected, its development revealed many issues inherent in developing a robust and computationally efficient method. The cell-based version of spill is an iterative method of filling a DEM with synthetic runoff events. This method applied a runoff depth consistently over the entire basin in increments. The first increment depth was applied and allowed to runoff according to drainage directions for each cell that were defined during pre-processing of the DEM. Each cell moved water, which was either applied to it in the initial runoff depth or input into the cell from an upstream cell, to a neighbouring cell with the lowest elevation. This process was carried out until all cells had moved water to a lower elevation. In cases where the cell had no adjacent neighbours water depth was allowed to accumulate. This process simulated runoff moving from upland regions to lowland pond areas. Subsequent increment depths were applied using the same method until the entire synthetic runoff depth had been input into the DEM landscape. Figure 4-8a-t illustrates a synthetic basin filling from empty to filling. This synthetic basin impounds all effective runoff until a large area of V_{SSA} is ultimately overwhelmed adjacent to the outlet resulting in an increase in contributing area from 0% to 100%. This is an example of the conceptual curve ‘C’ presented in section 4.2.


a)
Outlet
2
1
3
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)

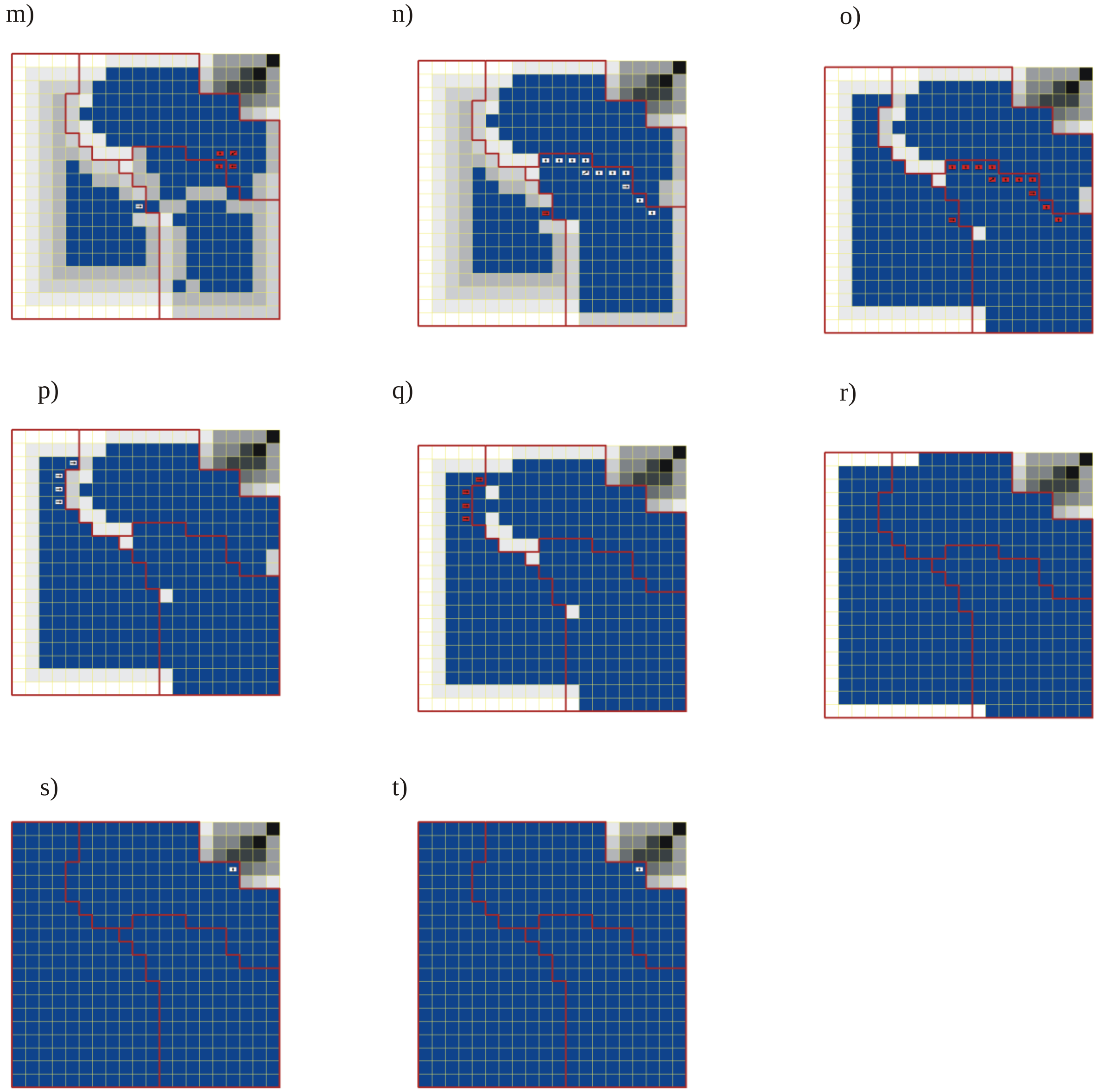


Figure 4-8. Illustrates the fill of a synthetic watershed from empty to full spilling using the finite difference algorithm. Black arrows in white boxes show the direction of spill from an actively spilling sub-basin. Black arrows in red squares illustrate when the downstream sub-basin pond depth reaches an equal depth and does not allow further spilling from the upstream basin. DEM elevations are indicated by cells ranging from black (lowest) to light grey (highest). Blue cells denote cells that are filling or have been filled.

The complexity of the algorithm was the result of each cell requiring multiple variables to properly move water through the basin. For instance a cell could move from a state in which it was accumulating runoff to a state in which it became an outlet and was required to spill to a downstream sub-basin all within one iteration of an increment runoff volume being added. Further, the downstream basin is required to provide the upstream outlet cell with a constant feedback of the pond depth for the sub-basin. This was necessary in order for the outlet to stop spilling downstream when the downstream pond depth reached an equal depth of the upstream outlet depth. The upstream and downstream ponds were now linked as one with pond depth common to both.

The constant feedback and relationship changes between cells as the basin filled resulted in a very computationally expensive method. Even very small basins required long processing times on the order of days or weeks. Although the methodology was sound, the processing times made it impractical. A GIS (ArcInfo) was used to develop spatial relationships between each cell as it filled or spilled. It is acknowledged that processing in the ArcInfo environment increases processing time in relation to a high level programming language such as Fortran or C+. However, the suite of functions inherent in the ArcInfo environment allowed algorithms to be more easily developed and tested. The more robust and computationally efficient algorithm that resulted from development of this cell-based method is outlined below.

4.3.3 SPILL description

SPILL has been developed to automate the calculation of contributing area for a basin at its sub-threshold state. SPILL captures and simulates surface water connectivity and is designed to fill a DEM in a manner that reflects the topography and the connectivity between potholes that occurs in the prairie pothole region when infiltration is restricted. The algorithm is based on hypotheses that resulted from a review of the literature and the concept of variable contributing area as outlined in section 2.2.1.

Inherent in landscape analysis models is the capability to fill depressions in a DEM (see section 2.5). The filling of individual potholes in the DEM characterizes removal of V_{SSA} by filling potholes with surface runoff. However, the SPILL algorithm differs significantly from many landscape analysis models in that it fills potholes in a basin in a manner that is proportional to each pothole's contributing area. The relative rate of fill is proportional to CA_P and basin geometry. Currently most landscape analysis models fill depressions in a DEM to a specified level. If a user specifies depression filling by 0.5 metres, all depressions in the basin will be raised this depth. Consistently raising pond levels a set amount does not satisfactorily model the response of the basin to input runoff events because neither the contributing area for each pothole or the fill-and-spill that occurs between potholes is reflected.

The importance of blowing snow on the redistribution of SWE in the basin before spring runoff is presented in Fang and Pomeroy, (2009). However, the SPILL model simulates this process by assuming runoff from the pond contributing area is over restricted soil infiltration conditions. The result of both these processes is to move snow within the sub-basin to the pond without abstraction.

Any algorithm that determines sub-threshold contributing area, must allow the DEM to be filled in an incremental manner. This will simulate increasing pond levels, and the resulting decrease in available storage in the basin, in response to runoff events. The SPILL algorithm is an iterative solution that increases the magnitude of input runoff events and records the decreasing change in available surface storage and the increase in contributing area until the storage threshold is reached and the contributing area reaches 100%.

Figure 4-9 shows the response of potholes in cross section using the SPILL algorithm and a synthetic input runoff event on a sub-watershed in SDNWA. In Figures 4-9-c pond levels rise and ponds spill within the basin but the outlet sub-basin does not reach a level that will allow it to spill. Thus CA_B remains at 0%. In Figure 4-9d V_{SSA} for the sub-basin closest to the outlet is satisfied, therefore, the basin contributes. The basin contributes runoff from the area of the sub-basin closest to the outlet and the sub-basin immediately upstream. However, the connectivity within the basin does not extend to basins further upstream as a sub-basin in the middle of the basin still has V_{SSA}. Figure 4-9e shows the sub-basin with V_{SSA} fulfilled and spilling downstream. This produces a sharp rise in CA_B as the entire basin, except for a small sub-basin, is now contributing. The threshold storage value is reached in Figure 4-9f as the last sub-basin is filled and CA_B for the basin is 100%.

Figure 4-10 illustrates the response of the basin to the synthetic events illustrated in Figure 4-9 in plan view. Figure 4-10a shows that pond 4 is the first pond to spill. It is interesting to note that the pond spills before the V_{PMAX} is reached. As is seen in Figure

4-9 pond 4 is nested within a larger depression that includes pond 3. As a result, pond 4 can spill during a low intensity runoff event but a much greater runoff event is required to fill pond 4 to the V_{PMAX} value. As the downstream pond 3 fills but does not spill, the pond level in pond 4 will continue to increase until pond 3 ultimately spills. To reach the V_{PMAX} value for pond 4, the storage in both pond 3 and 4 must be satisfied (Figure 4-9e).

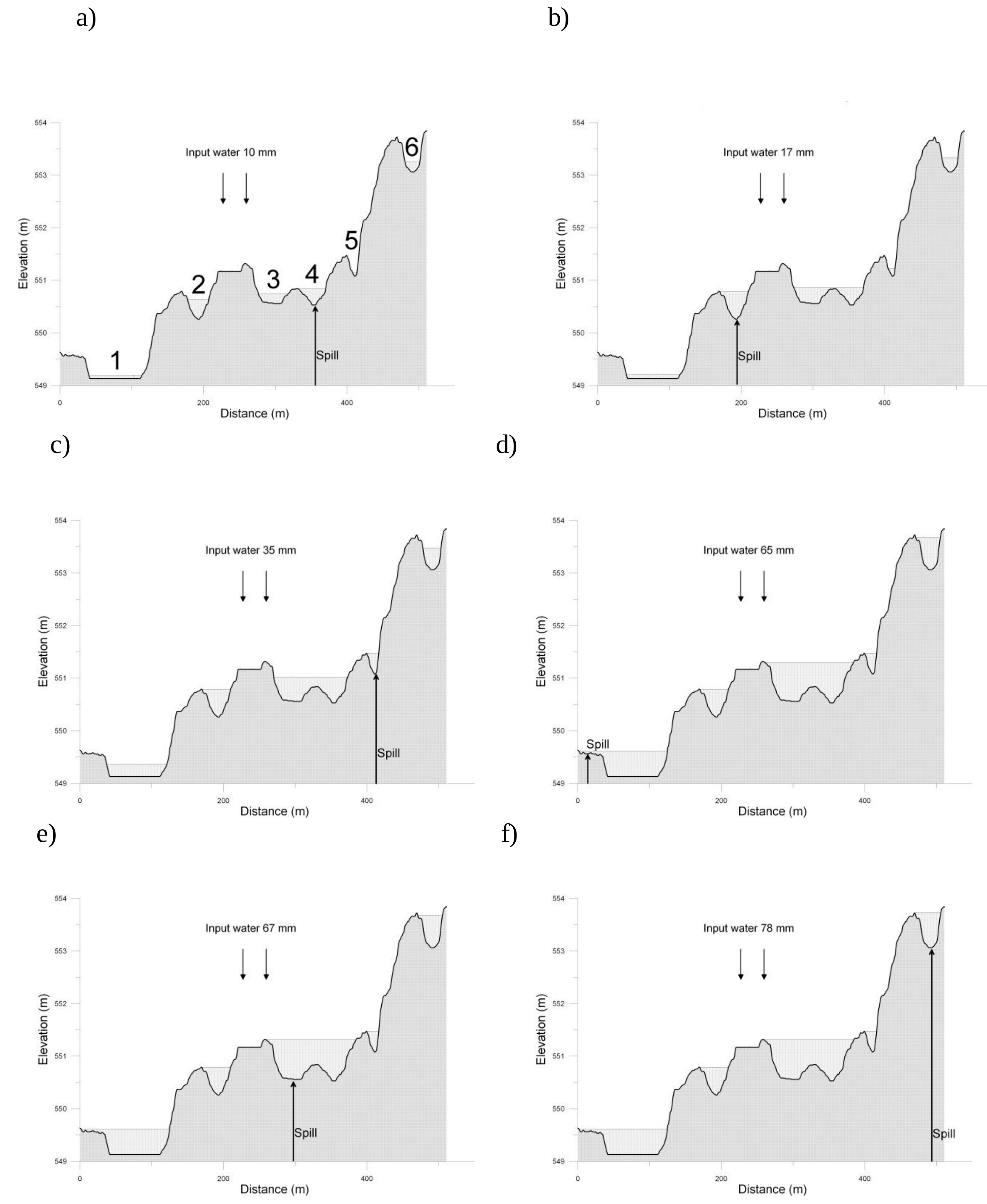


Figure 4-9. A cross section illustrating the fill-and-spill of a sub-watershed in the St. Denis basin using the SPILL algorithm. Ponds are numbered in 4-9a.

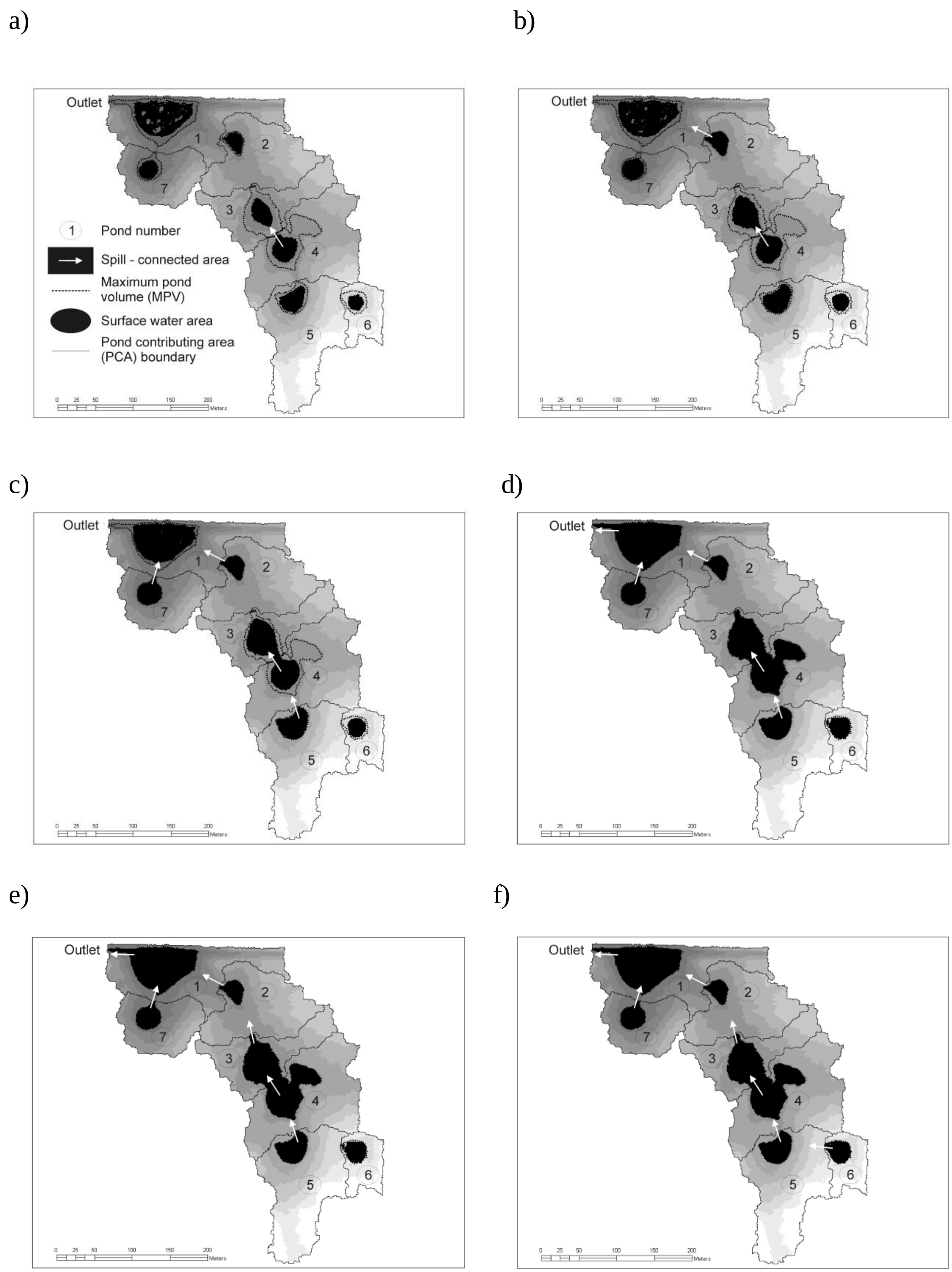


Figure 4-10. Plan view illustrating the fill-and-spill of a sub-watershed in the St. Denis basin using the SPILL algorithm.

SPILL begins with the function FLOWDIRECTION in ArcInfo to determine drainage directions for each cell in the DEM. FLOWDIRECTION calculates flow direction (fd) for the processed cell by examining the elevation (z) of neighbours and determining drainage direction as the neighbouring cell with the steepest elevation descent:

$s = \Delta z / d * 100$
s = slope
d = distance between cell centres

$fd = max(s)$ [Equation 8]

If the cell has no neighbours with a lower elevation it is identified as a sink (see section 2.5) The user then identifies a basin outlet cell in the DEM. Using the identified outlet cell ArcInfo delineates the gross contributing area (CA_G) using the WATERSHED function to identify cells that ultimately flow into the outlet cell. ArcInfo, like all landscape analysis models fills sinks in the DEM in order to define CA_G (see section 2.5). The filled DEM is only used to define CA_G and is not used in any further algorithm functions.

SPILL defines CA_P using sinks identified by FLOWDIRECTION function. Each sink is used as a synthetic outlet. In this way the WATERSHED function can be used to determine which cells are upstream of each sink thus identifying contributing area for each sink (pond). The result of this process is a drainage basin with ponds and CA_P that can be thought of as sub-basins.

To determine pond depths required to spill ponds downstream for each CA_P cells are first identified that sit on the boundary of each CA_P area (CA_{PBND}). From these cells the lowest elevation is identified (CA_{POUT}) and is used as a spill point.

$$CA_{POUT} = \min(z) \in CA_{PBND} \qquad \text{[Equation 9]}$$

The value of CA_{POUT} is then examined to determine whether the boundary elevation of the downstream cell from the adjacent CA_P area is lower. This check is required due to a limitation of the D8 method. Drainage direction is assigned to one of the eight adjacent cells with the steepest down-slope path. Figure 4-11 illustrates the problem that can arise on sub-basin boundaries.

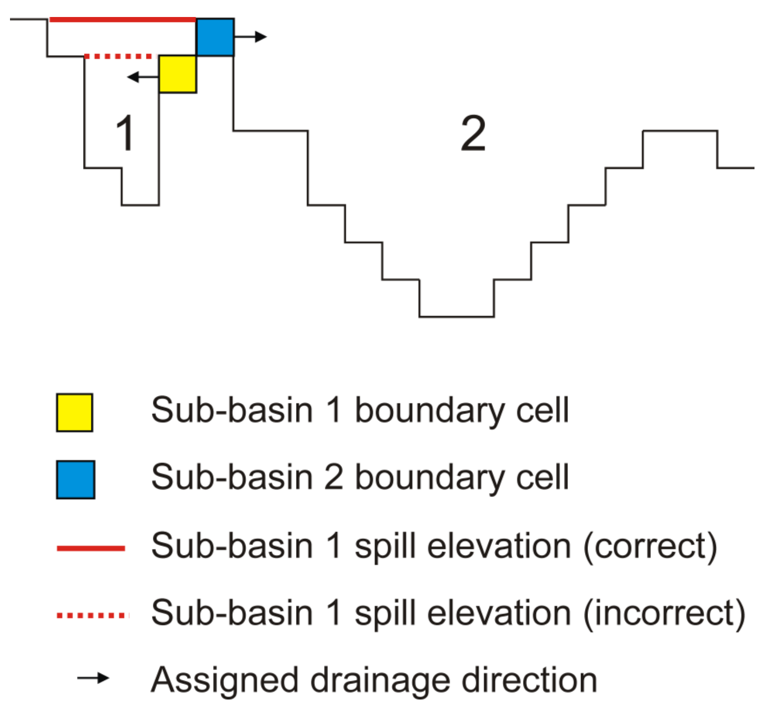


Figure 4-11 Illustrates the problem of determining spill elevations that results from using the D8 method of determining drainage directions.

The yellow cell shown in Figure 4-11 is assigned by the D8 method to sub-basin 1 because the blue cell is at a higher elevation. The yellow cell becomes a sub-basin boundary cell for sub-basin 1. The D8 method assigns the blue cell to sub-basin 2 because there is a steeper slope to an adjacent cell in sub-basin 2. As a result, raising the pond elevation of sub-basin 1 to the lowest cell on the basin boundary (yellow cell) is not sufficient to spill sub-basin 1 to sub-basin 2. This causes an error in the SPILL algorithm as sub-basin 1 is identified as full and is therefore not further processed even though the pond level has not been raised to a sufficient depth to spill to sub-basin 2. The algorithm requires a routine that checks for this situation and when found, assigns either the elevation of the boundary cell or the elevation of the cell outside the sub-basin. The proper cell elevation is identified and assigned as the spill point for the sub-basin.

For each sub-basin in the basin the following calculation is made:

$$D_I = V_I / CA_P \qquad \text{[Equation 10]}$$

Where: $D_I =$ Water depth required to spill a sub-basin
V_I = Water volume that can be stored by a sub-basin before it spills
CA_P = Pond contributing area

The D_I required to spill each sub-basin are compared and the minimum D_I value is identified. The minimum D_I (D_{IMIN}) is then applied to the entire basin and the depth each sub-basin will be filled is calculated. The depth of filling for each sub-basin is calculated as:

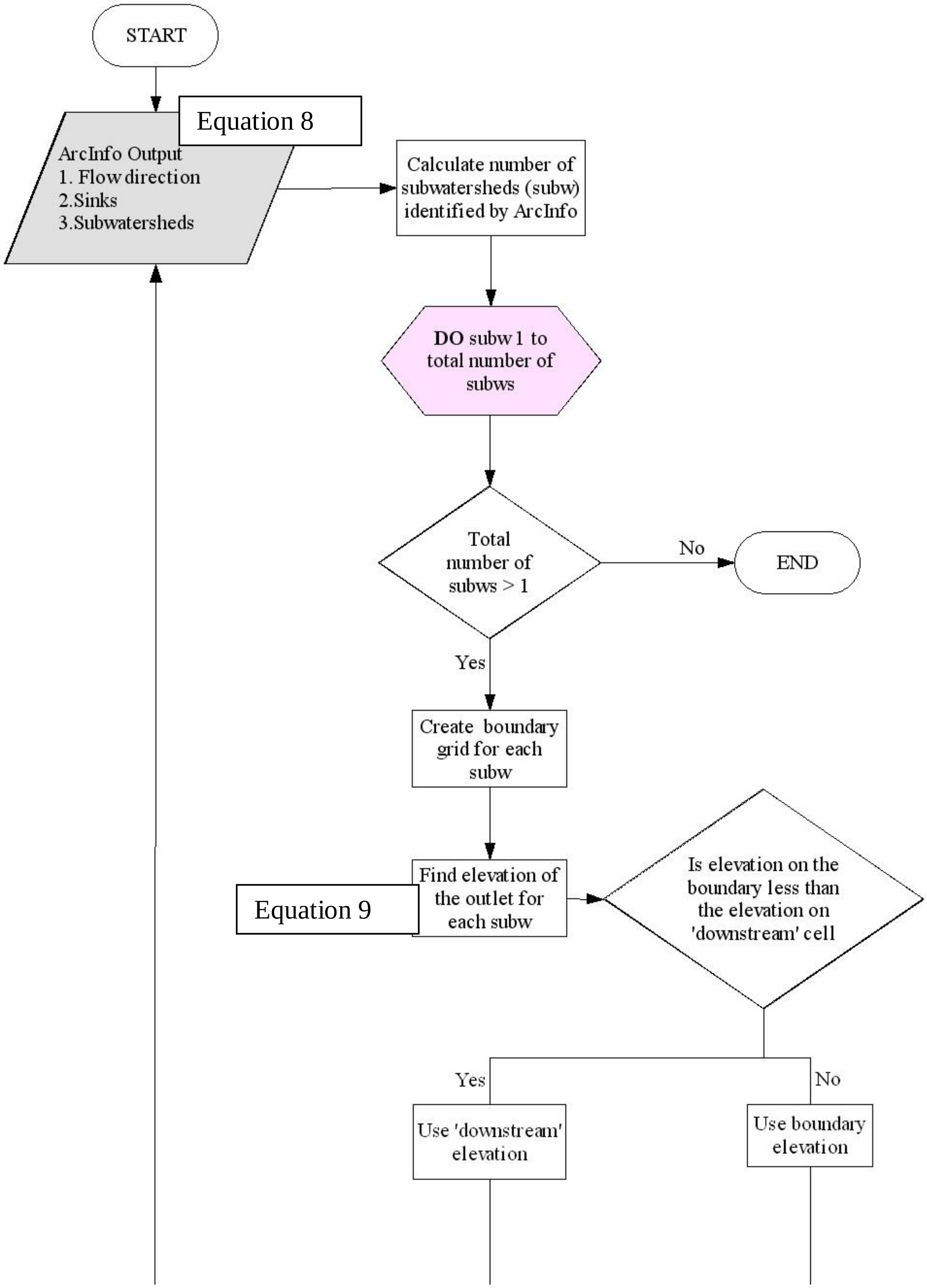
$D_{\Delta} = D_{IMIN} / CA_P$ [Equation 11]

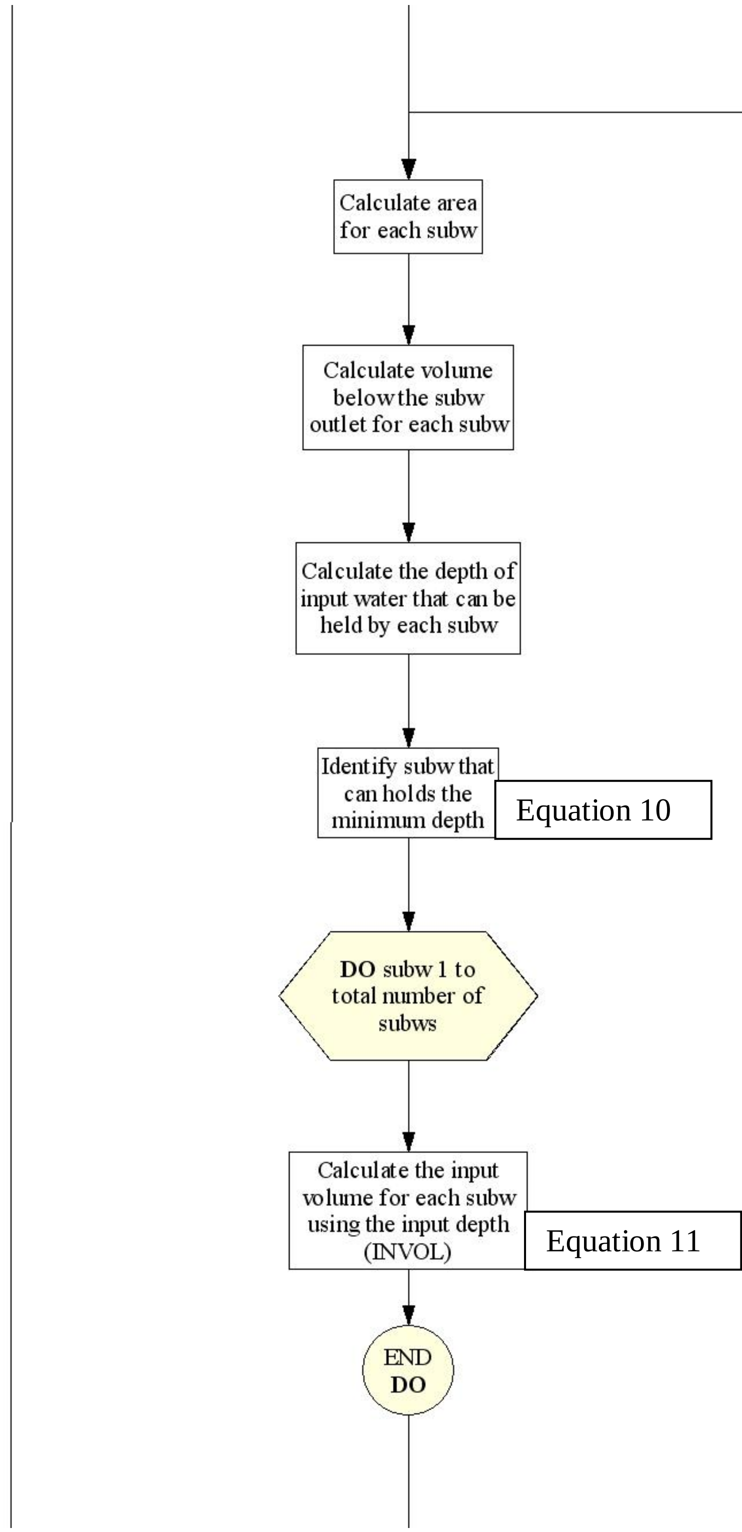
Where: D_{Δ} = Pond level depth increase (m)
D_{IMIN} = Minimum input water depth (m)
CA_P = Pond contributing area (m^2)

The DEM is then edited by the algorithm to 'raise' DEM elevation values so as to simulate filling each pond by D_{Δ}. This is done to reflect the loss of surface storage potential available in the landscape due to increased water volume in the potholes. Drainage directions are again determined for the newly filled DEM. Cells in the DEM that drain to the outlet of the basin are identified. Contributing area is calculated as the area of cells identified as draining to the outlet. The SPILL algorithm outputs three variables to a text file after every iteration of basin filling. The output variables are: 1) CA_B, 2) D_{IMIN} and 3) Fractional pond surface area (A_{PS}) calculated as:

$A_{PS}(\%)$ = Pond surface area (m^2) / CA_G (m^2) [Equation 12]

Plotting these allows an examination of the relationship between the variables as the basin is filled from empty to threshold storage. Figure 4-12 is a flow chart that shows procedure used by SPILL to calculate the relationship between CA_B, A_{PS} and V_{SSA}.


START
Equation 8
ArcInfo Output
1. Flow direction
2.Sinks
3.Subwatersheds
Calculate number of subwatersheds (subw) identified by ArcInfo
DO subw 1 to total number of subws
Total number of subws > 1
No
END
Yes
Create boundary grid for each subw
Find elevation of the outlet for each subw
Equation 9
Is elevation on the boundary less than the elevation on 'downstream' cell
Yes
No
Use 'downstream' elevation
Use boundary elevation


Calculate area for each subw
Calculate volume below the subw outlet for each subw
Calculate the depth of input water that can be held by each subw
Identify subw that can holds the minimum depth
Equation 10
DO subw 1 to total number of subws
Calculate the input volume for each subw using the input depth (INVOL)
Equation 11
END DO

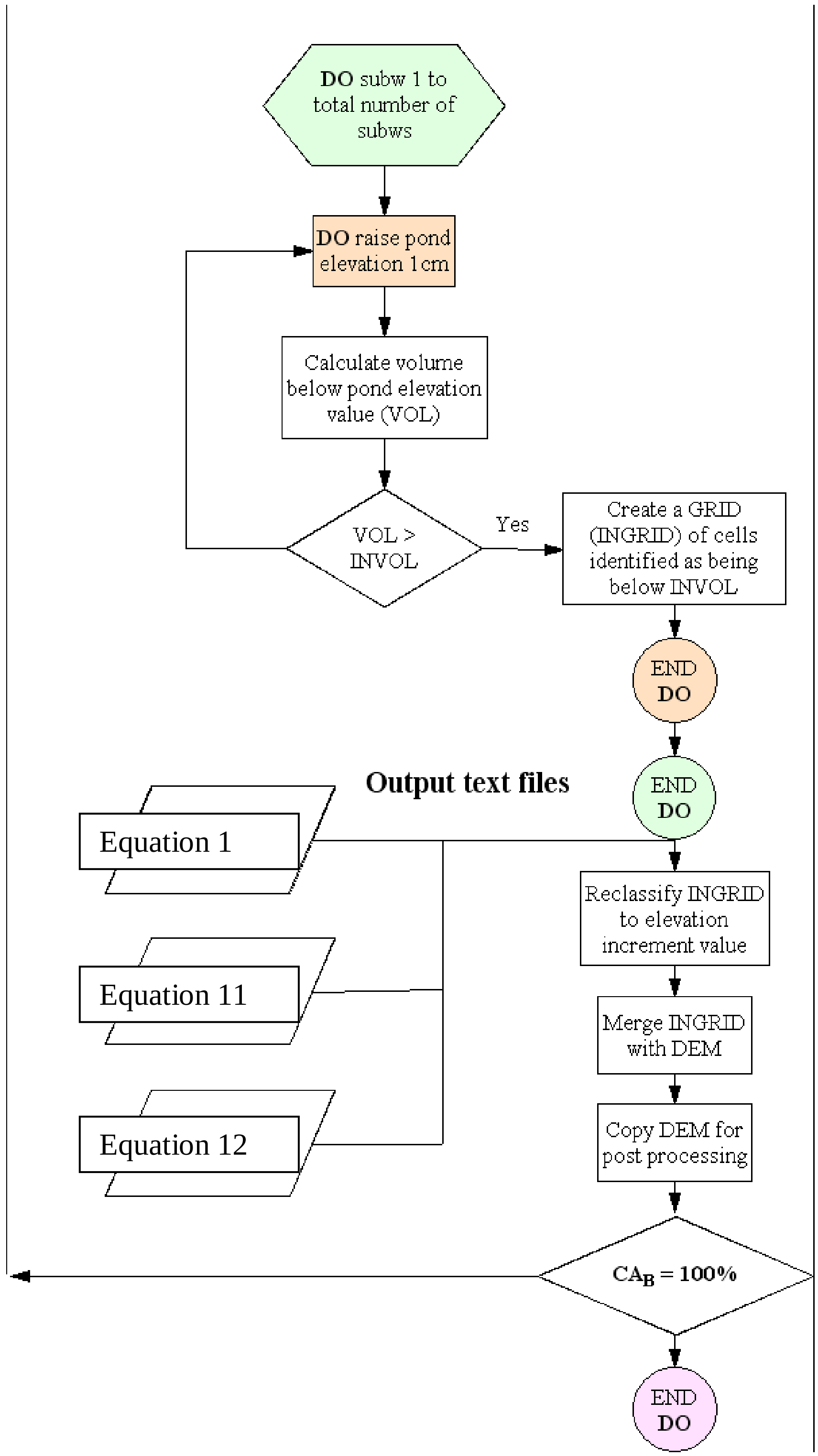


Figure 4-12. Flowchart for SPILL

4.4 Software

4.4.1 ArcInfo

The SPILL algorithm presented in this thesis uses input hydrologic and topographic information derived from a DEM using a GIS (ArcInfo). ArcInfo can be described as "a system of computer software, hardware, data and personnel to manipulate, analyze and present information that is tied to a spatial location" (Environmental Systems Research Institute, 2002a). ArcInfo provides a set of functions and directives that are used to manipulate and display spatial data. These functions and directives can be accessed using the Arc Macro Language (AML). Because AML is part of ArcInfo, it recognizes ArcInfo objects such as grids (see section 4.4.2) and provides information about these objects, as well as, information about specific ARC environments. Source code for the SPILL algorithm can be found in Appendix B.

4.4.2 ArcInfo GRID environment

The ArcInfo environment that handles cell-based processing is called GRID. As such there can be confusion between the ArcInfo environment GRID, and the data sets produced by the GRID environment called *grids*. *Grids* are based on a combined raster-based spatial model and a relational attribute model. Subsequent references to the *grid* relational attribute models will be italicized to avoid confusion with the GRID environment. In GRID, the inherent power of the grid-modeling structure is coupled with the capabilities of a relational database that manages all attributes associated with the cell values. Each categorical *grid* has an associated value attribute table (VAT) that is stored in the INFO relational database (Environmental Systems Research Institute, 2002b).

GRID is based on a hierarchical tile-block structure. A *grid* is first divided into uniform square units called tiles. Each tile represents an actual portion of geographic space. A tile is divided into blocks. A block is made up of cells arranged in a Cartesian matrix consisting of rows and columns. Cells are square (Figure 4-13). The tile-block structure allows GRID to support random access to data and rapid retrieval of information maintained from any subsection of a grid, regardless of the size of the database.

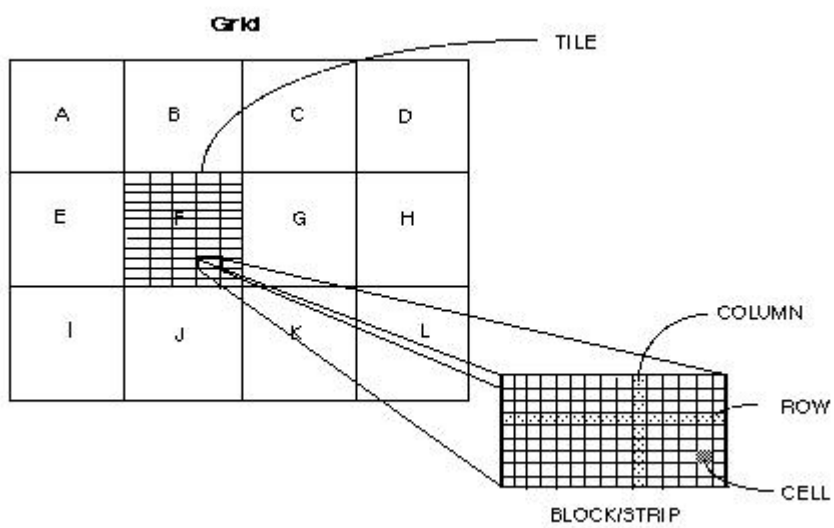


Figure 4-13. GRID data structure

Source: ArcInfo online help manual (Environmental Systems Research Institute, 2001)

CHAPTER 5

RESULTS AND DISCUSSION – SPILL

5 Contributing area / surface storage relationship

SPILL was applied to five sub-basins in SDNWA (Figure 3-4) and five sub-basins in Smith Creek DEMs (Figure 3-6). For each sub-basin variables describing the CA_B and the V_{SSA} available in the landscape were output to a text file. These variables, describing the relationship between CA_B and the V_{SSA} available at each iteration of the basin filing, were plotted.

Figure 5-1a-f demonstrates the relationship between CA_B and V_{SSA} for SDNWA. However, rather than plotting a V_{SSA} value, the V_{SSA} value is expressed as the percentage of V_{BMAX}. This conversion normalizes the x-axis for plots for all study area basins. For each of these plots the spill of each sub-basin is identified on the curve. A complimentary plot of the spill sequence of each sub-basin in plan view is presented in Figure 5-1aa-ff

The results show that two distinct types of basin storage topology are represented. Figure 5-1a-c illustrates the relationship between the sub-threshold V_{SSA} and CA_B found in a basin where a large portion of V_{SSA} is located adjacent to the outlet. As the SPILL algorithm iteratively filled V_{SSA} and spilled sub-basins, connectivity within the basin is achieved. However, it is not until almost all sub-threshold V_{SSA} is satisfied that CA_B occurs. CA_B increases from less than 1% of total area to 100% of total area once 95% of V_{BMAX} is satisfied. These basins can be represented conceptually by landscape C in figure 4-6. Figure 5-1d illustrates the CA_B response that matches the conceptual landscape B (Figure 4-6). There is a more even distribution of V_{SSA} within this basin with 35% and 46% of the basin contributing with 20% and 50% of V_{BMAX} satisfied in basin 3. Basin 4 (Figure 5-1e) can be represented by landscape A in Figure 4-6. Over 50% of the basin contributes to the outlet when only 15% of V_{SSA} is filled.

Figure 5-2 presents the relationship between CA_B and V_{SSA} for Smith Creek. Again, the V_{SSA} value is expressed as the percentage of V_{BMAX}. Figure 5-2a demonstrates the response of a basin that immediately contributes runoff to the outlet. It is similar to the conceptual landscape A (Figure 4-6). There is very little V_{SSA} near the outlet. This allows the basin to immediately contribute 13% of total area. The majority of the basin's V_{SSA} is in the upper portion of the basin. As a result CA_B remains constant while the remaining V_{SSA} fills until it ultimately spills, allowing 100% of the basin to contribute.

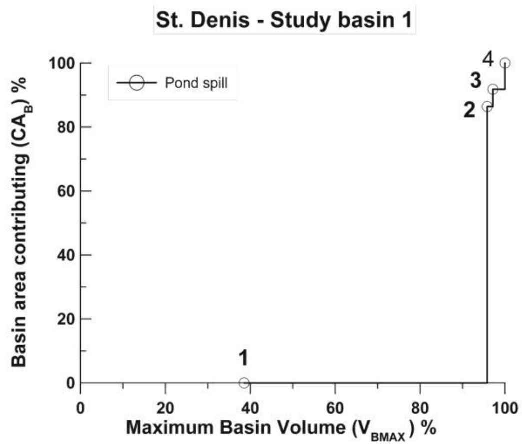
Sub-basin 2 (Figure 5-2b) has a contributing area of 23% with 27% of V_{SSA} satisfied. CA_B remains constant until it starts to increase dramatically after 90% of V_{BMAX} is filled.

Figure 5-2c-e again illustrates basins that require almost all of V_{BMAX} to be satisfied before the CA_B becomes greater than 1%. Sub-basin 3 behaves similarly to the SDNWA basins as this landscape storage pattern has CA_B increase dramatically once 95% of V_{BMAX} is filled. However, sub-basins 4 and 5 demonstrate earlier increases in CA_B, occurring at 85% of V_{BMAX}.

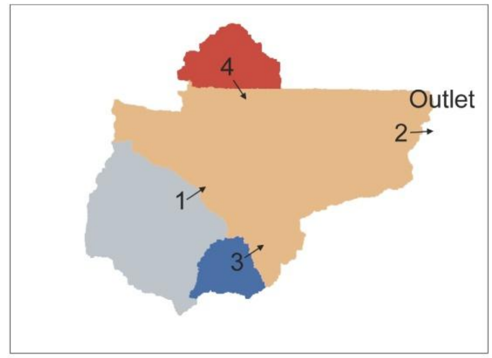
The results illustrate the relationship between CA_B and V_{SSA} in the prairie pothole region is non-linear. The results also illustrate the complexity of modeling sub-threshold contributing areas. There is no consistent increase in CA_B as V_{SSA} within the basin is satisfied. Instead, the connectivity of the wetlands that result from the fill-and-spill of individual potholes produce the non-linear relationship shown in both SDNWA and Smith Creek basins. Significantly different CA_B and sub-threshold V_{SSA} relationships can be found within the same landscapes.

The results also show an agreement with the conceptual curves proposed in this thesis that describe the relationship between V_{SSA} and CA_B. Three of the four landscapes presented in the conceptual curves were apparent in the results in SDNWA and Smith Creek. The exception is the transitional landscape. This was to be expected because both study watersheds are located well within the boundaries of the prairie pothole region. Also, each sub-basin was chosen to end at a spill point from a depression, thereby avoiding transitional landscapes that are defined by channels adjacent to the outlet.

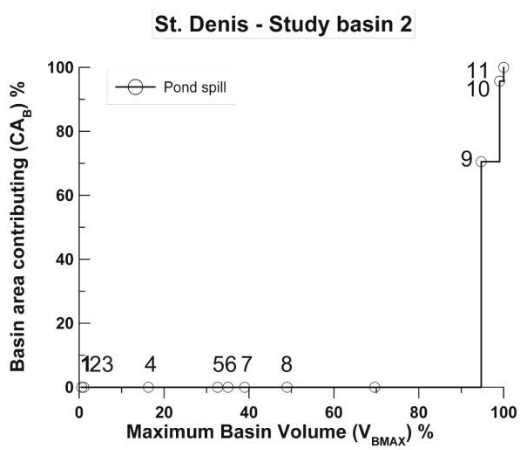
a)


St. Denis - Study basin 1
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
1
2
3
4

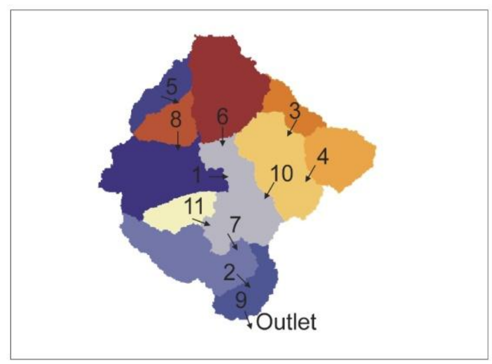
aa)


Outlet
1
2
3
4

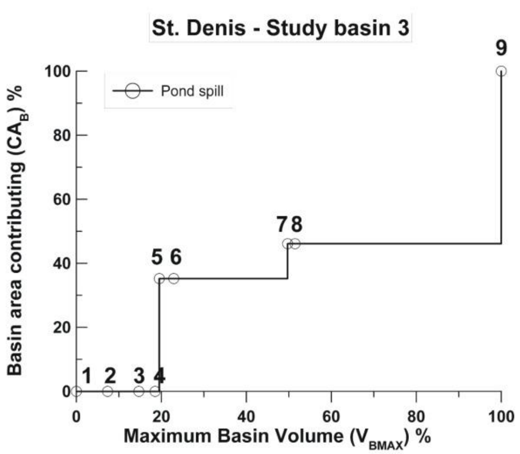
b)


St. Denis - Study basin 2
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
123
4
56 7
8
9
10
11

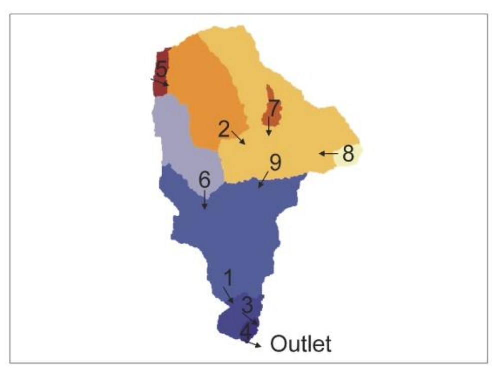
bb)


Outlet
1
2
3
4
5
6
7
8
9
10
11

c)


St. Denis - Study basin 3
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
1 2 3 4
5 6
7 8
9

cc)


Outlet
1
2
3
4
5
6
7
8
9

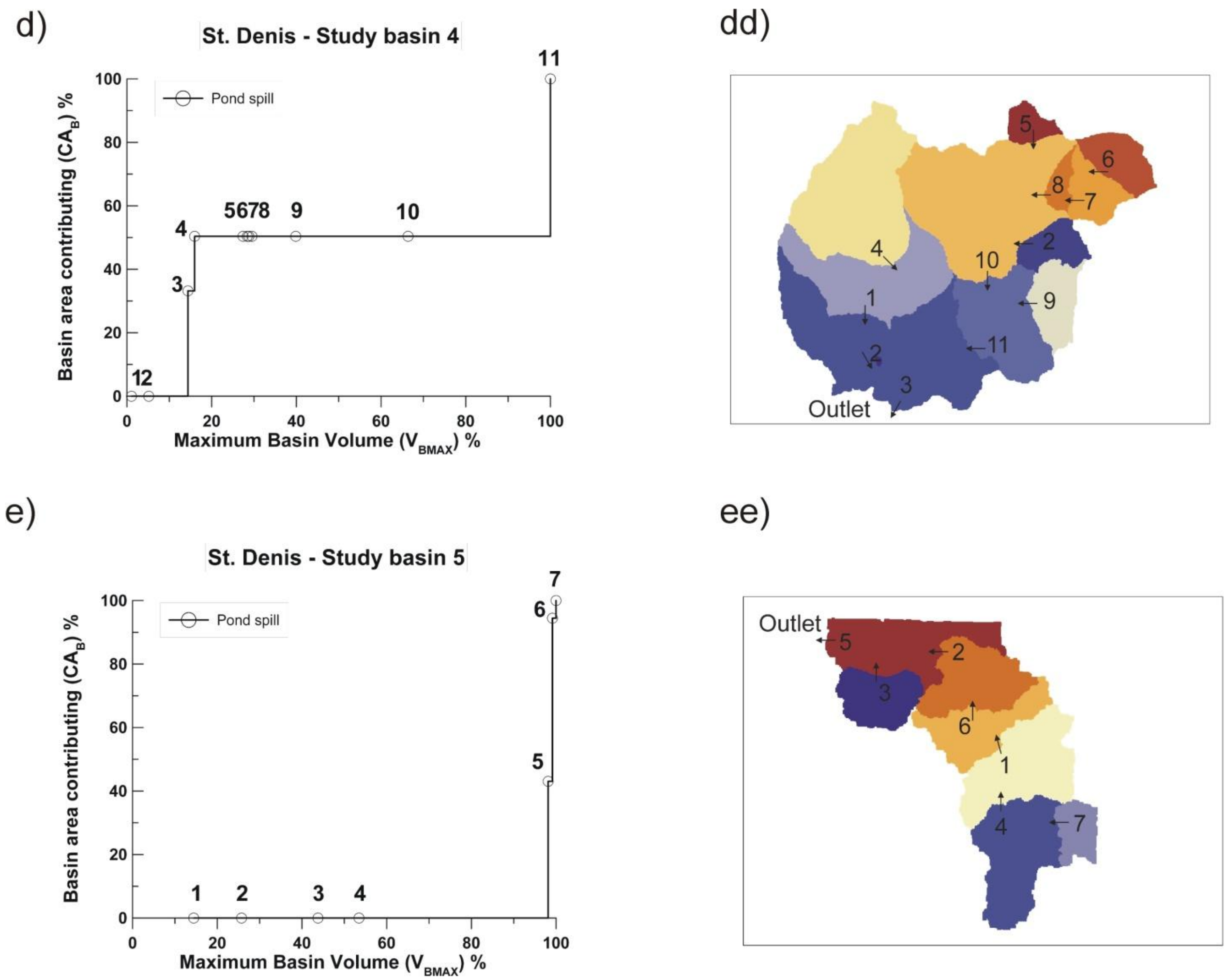
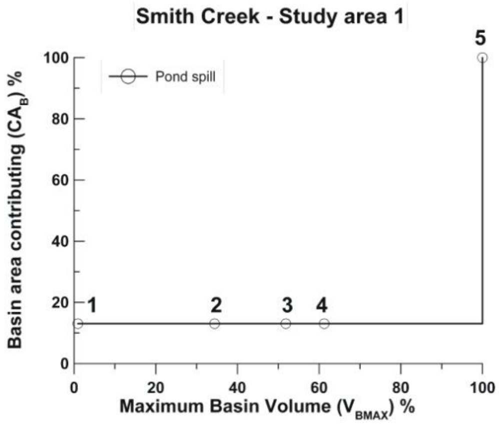
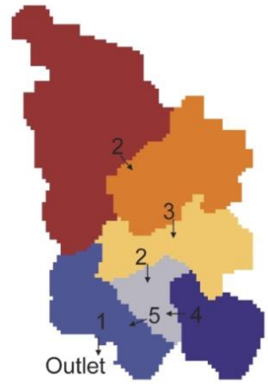


Figure 5-1.The resulting relationship between contributing area (CA_B) and threshold storage (V_{BMAX})as calculated by the SPILL algorithm for sub-basins within the SDNWA watershed.

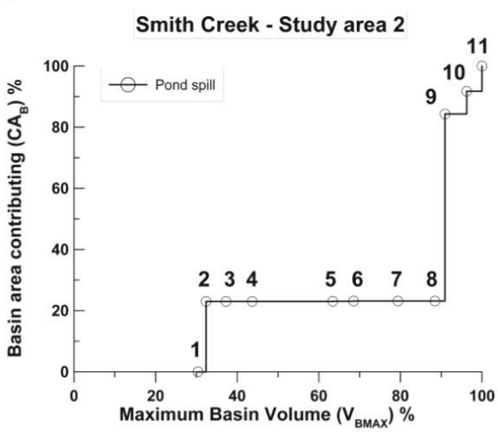
a)


Smith Creek - Study area 1
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
0
20
40
60
80
100
1
2
3
4
5

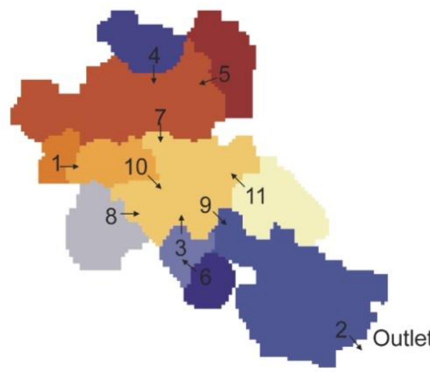
aa)


2
3
2
5
4
1
Outlet

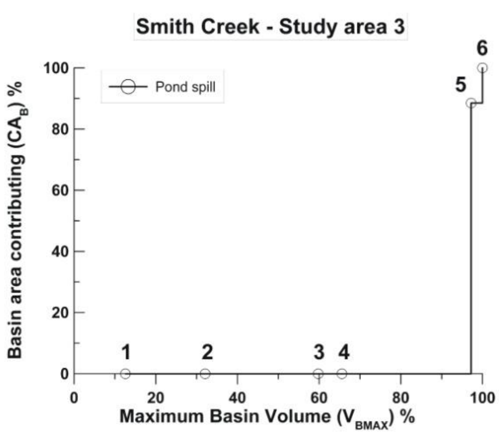
b)


Smith Creek - Study area 2
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
0
20
40
60
80
100
1
2
3
4
5
6
7
8
9
10
11

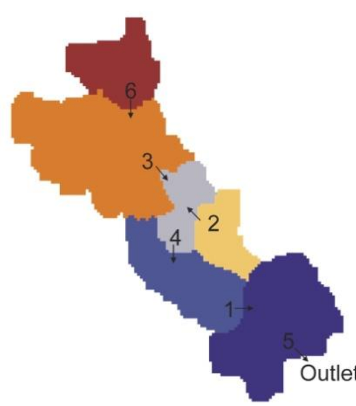
bb)


4
5
7
1
10
11
9
8
3
6
2
Outlet

c)


Smith Creek - Study area 3
Pond spill
Basin area contributing (CA_B) %
Maximum Basin Volume (V_{BMAX}) %
0
20
40
60
80
100
1
2
3
4
5
6

cc)


6
3
2
4
1
5
Outlet

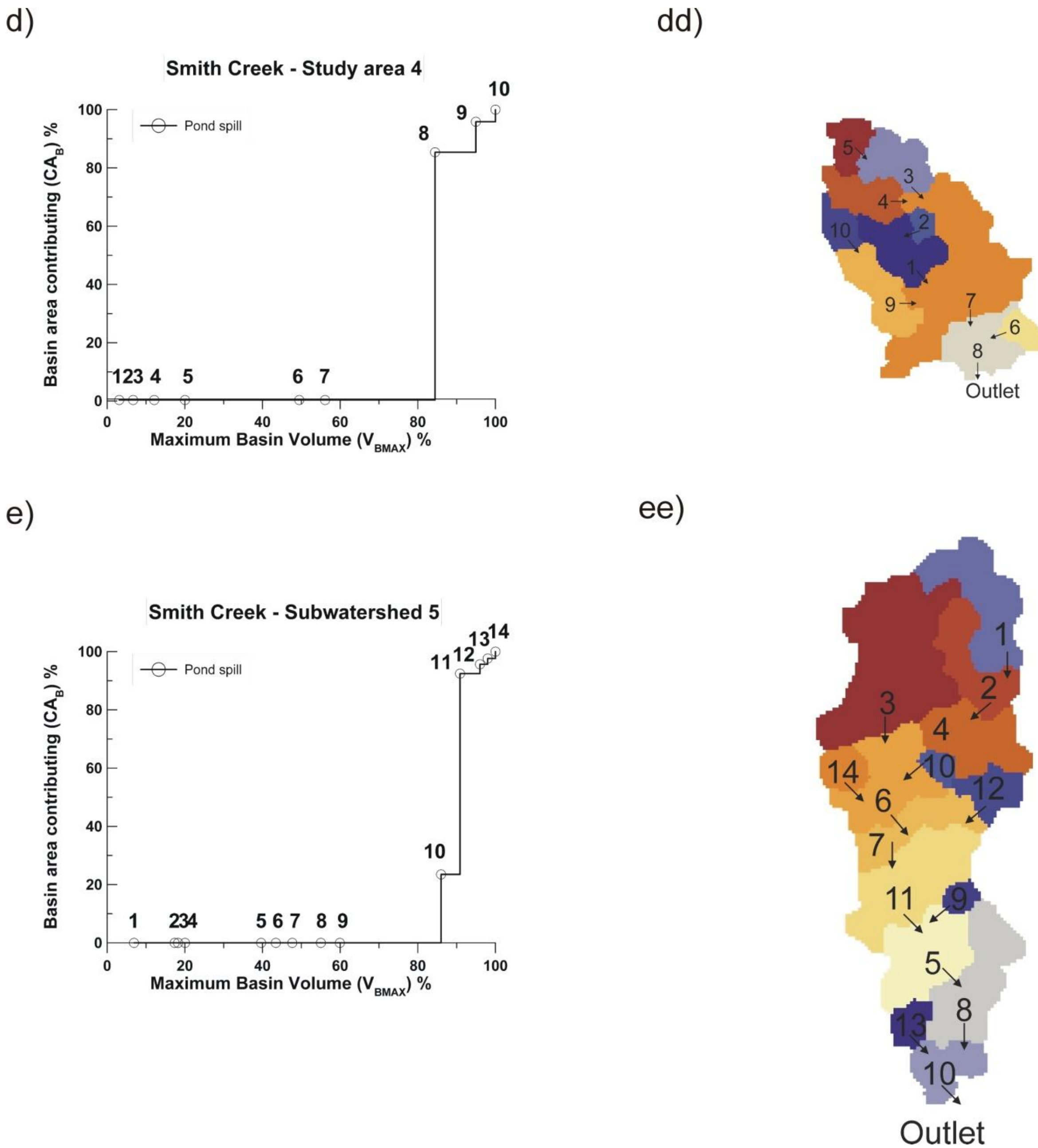


Figure 5-2 The resulting relationship between contributing area (CA_B) and threshold storage (V_{BMAX}) as calculated by the SPILL algorithm for sub-basins within the Smith Creek watershed.

5.1 Contributing area / surface storage potential / surface water area relationship

This research examines the relationship between CA_B, V_{SSA} and surface water area (A_{PS}) as a basin fills with runoff. The SPILL algorithm was modified to calculate the surface water area at each iteration of the fill process. Sub-basins 1,2 and 5 in SDNWA are similar in that only as the percentage V_{BMAX} approaches 95% is there any increase in CA_B (Figure 5-3a,b,d). This type of basin reflects the importance of knowing the state of connected areas and V_{SSA} in the basin. There is not a gradual increase of flow to the outlet as the V_{SSA} fills over days or over years. Runoff will be completely impounded until the V_{BMAX} is approached. A small or high frequency runoff event in these basins has the potential to increase the contributing area from 0-100%. For basins 1,2 and 5 the point in which CA_B dramatically increases is when the A_{PS} as a percentage of the total basin approaches 10.5%, 19% and 16.5% respectively.

Sub-basin 3 illustrates a basin that contributes runoff to the outlet with a more linear relationship between decreasing V_{SSA} and increasing CA_B (Figure 5-3c). However, like sub-basins 1, 2, and 5 there is also a sharp increase in CA_B as the V_{BMAX} reaches 100%. CA_B increases from 40% of the basin to 100% when the A_{PS} is approximately 15.5% of the total basin area.

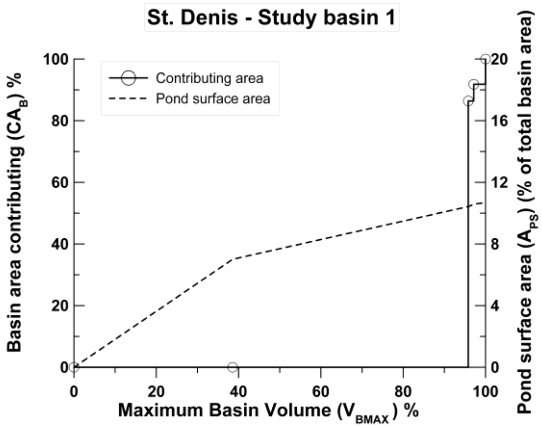
Sub-basin 4 shows an increase in CA_B with very little V_{SSA} satisfied (Figure 5-3d). The basin is representative of one in which storage near the outlet is very small. The V_{PMAX} of the pond closest to the outlet is overwhelmed by small runoff events and the basin starts to contribute flow to the outlet early in the runoff event. CA_B increases to approximately 50% very early in the runoff event and stays constant until the threshold is reached and the other 50% of the basin area contributes. The point at which this threshold is reached is when the A_{PS} is 14.5%.

Although the Smith Creek DEM has a more coarse resolution and the study basins are located further east in the prairie pothole region, many of the trends found in the SDNWA basins are apparent. In sub-basin 1, there is a small increase in CA_B with little of the basin V_{SSA} satisfied (Figure 5-4a). However, the CA_B remains constant until the A_{PS} in the basin reaches 26% of total basin area. CA_B increases from approximately 15% to 100% at this point.

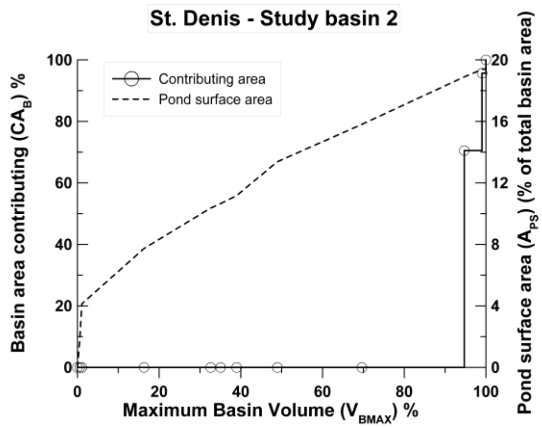
Sub-basin 2 in the Smith Creek basin illustrates a sub-basin that CA_B in a more incremental manner than the other basins (Figure 5-4b). However, as V_{BMAX} reaches 90% and A_{PS} is 14% of total basin area there is a sharp 60% increase in CA_B.

Study sub-basins 4 and 5 are similar in that, like three basins in SDNWA, CA_B increases dramatically as the basin approaches V_{BMAX} (Figure 5-4d,e). In both basins CA_B increases from 0% to over 80% as basin V_{BMAX} reaches 85%. Sub-basin 3 has a more dramatic increase, as 97% of V_{BMAX} must be satisfied to have runoff connect to the outlet. As the V_{BMAX} for the basin approached, CA_B increases from 0% to almost 90%. Sub-basins such as 3, 4 and 5 illustrate the importance of knowing where on the CA_B / V_{BMAX} curve a runoff event begins.

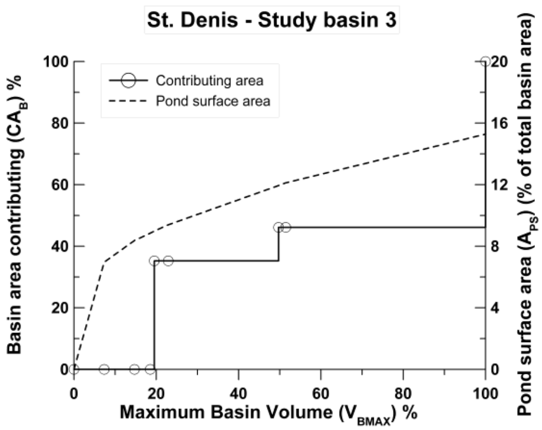
a)



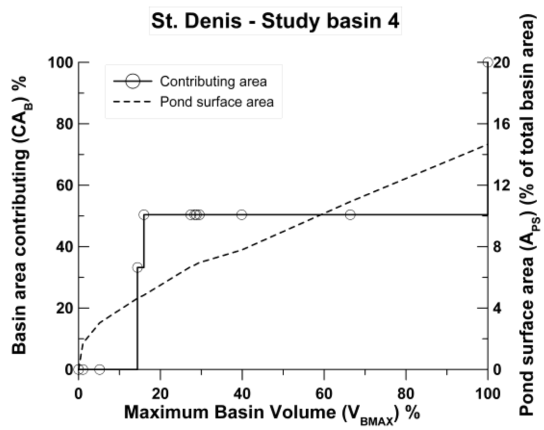
b)



c)



d)



e)

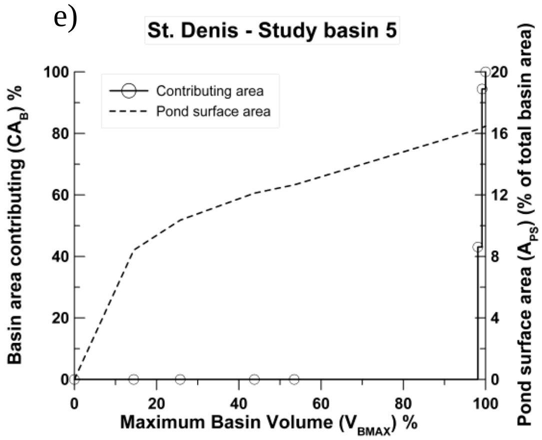
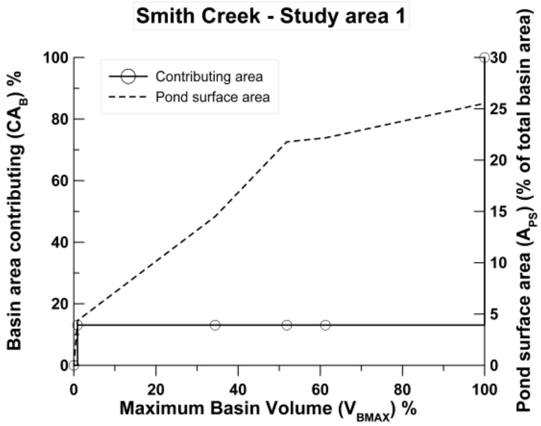
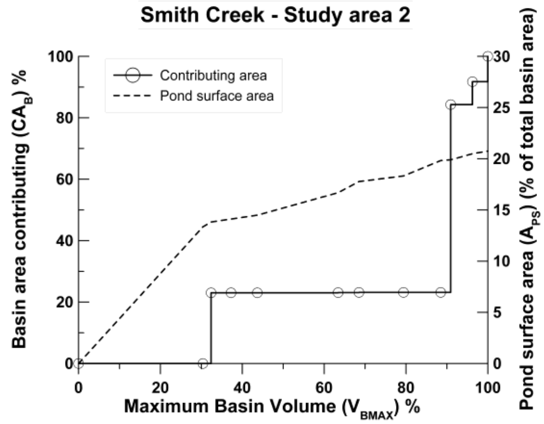


Figure 5-3 The resulting relationship between contributing area (CA_B), threshold storage (V_{BMAX}) and pond surface water area (A_{PS}) calculated by the SPILL algorithm for sub-basins within the SDNWA watershed.

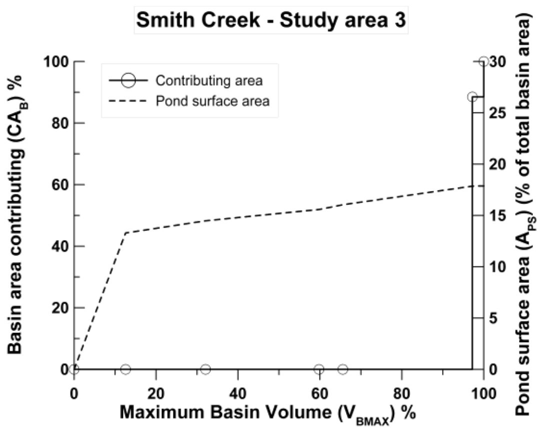
a)



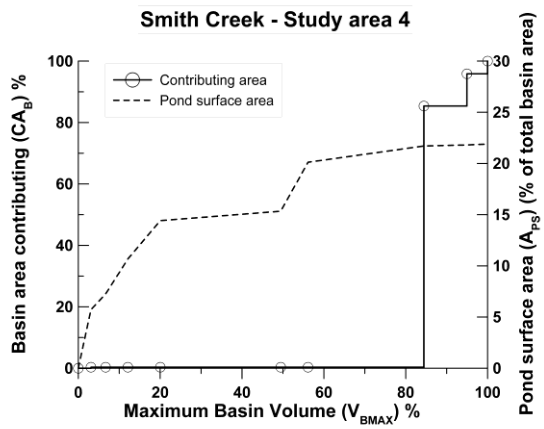
b)



b)



d)



e)

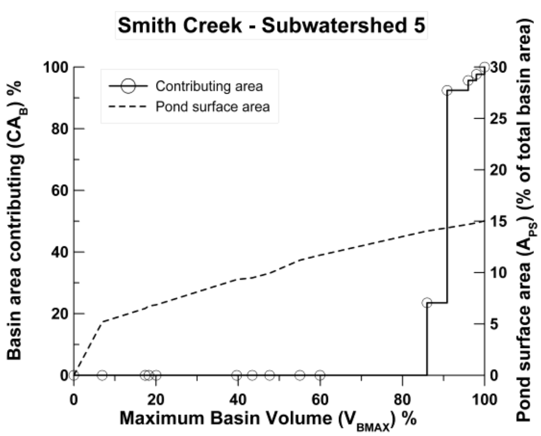


Figure 5-4. The resulting relationship between contributing area (CA_B), threshold storage (V_{BMAX}) and pond surface water area (A_{PS}) calculated by the SPILL algorithm for sub-basins within the Smith Creek watershed.

5.2 Evaluating three methods for modeling pond levels in SDNWA

This section examines how effectively two current contributing area methods and SPILL can model pond levels at SDNWA. Because the SDNWA does not have a stream gauge a pond level is used to quantify how well the runoff response from the basin is modeled. Pond levels are compared to measured pond levels for the 2006 and 2007 spring melt event.

For 2006 and 2007 measure SWE values were not attenuated prior to input into the algorithm. This was a reasonable assumption due to the winter conditions both years. In both 2006 and 2007 temperature rose above freezing during the winter months allowing the snowpack to melt (Figure 5-5). This could result in snowpack melt water reaching the soil and saturating the top layer of soil before it was frozen. As a result of these melt events it is reasonable to assume that snowmelt runoff was over restricted infiltration conditions (see section 2.3.2).

The years 2006 and 2007 were chosen for two reasons. The first is that there was LiDAR data available for the area in the fall of 2005 (see section 3.3.1). As such, the antecedent conditions of the basin were known for the spring 2006 runoff event. Because LiDAR can not ‘see’ through water, LiDAR pulses will reflect back from pond surfaces and generate elevation data for the pond levels rather than the pond bathymetry for potholes that did not dry out completely during 2005. Because the DEM essentially ‘fills’ ponds up to elevations determined by LiDAR, the state of pond levels and thus V_{SSA} in the basin reflected in the DEM. The second reason is that 2006 was an interesting runoff year in the St. Denis basin. When the long-range pond level data are examined it can be seen that there are sharp increases in pond levels in the basin in 2006 and 2007. Figure 5-6 illustrates the dramatic increase in pond level for these two years. It was thought that because these years were unique in the recorded 39 year time period that modeling pond levels for these years would provide an interesting and complex case in which to test various techniques for determining runoff volumes.

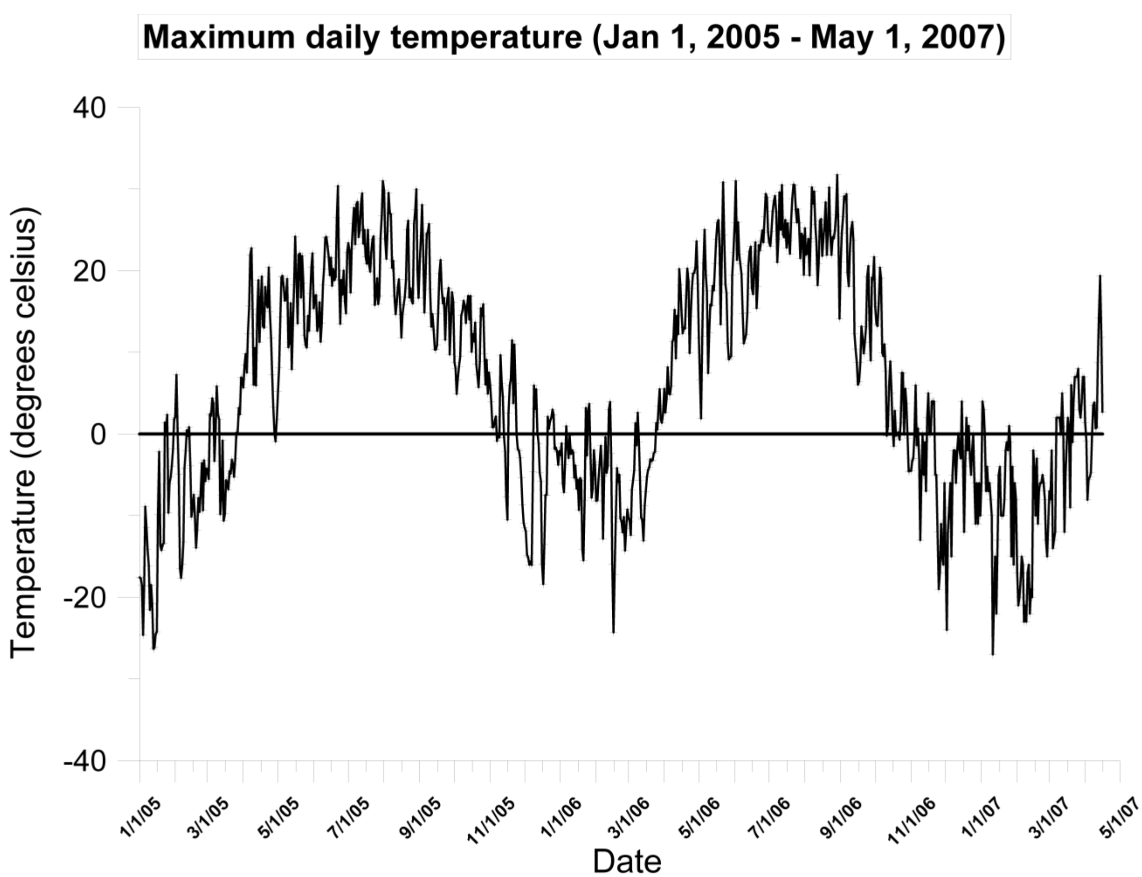


Figure 5-5 Daily maximum temperatures for the period January 1, 2005 to May 1, 2007 show winter melt events. Temperature data was recorded at the Saskatoon weather station.

5.2.1 Modeled pond levels in a prairie pothole basin using 100% basin contributing area

Table 5-1 presents modeled pond level depths in SDNWA basin, using current landscape analysis models that assume CA_B of 100%, and measured pond levels for the 2006 and 2007 spring melt event. Measured SWE for 2006 and 2007 was applied consistently over the basin and assumed to runoff completely to the outlet. The modeled pond level for p90 is overestimated by almost 100% (280 cm) in 2006 rather than the measured value of 150 cm (Table 5-1). The overestimation of this pond depth value is further compounded during the runoff event of 2007. In 2007 V_{SSA} for p90 has been decreased by the overestimation of runoff volume received in 2006 and rather than p90 impounding runoff from the basin entirely, which is the measured result in 2007, modeled results produce runoff at the outlet of the basin as V_{SSA} in p90 is satisfied and is spilling. As a result, modeling the basin using a simple 100% CA_B not only results in incorrect pond level values, but also cause the basin to erroneously contribute runoff to the outlet which in turn will lead to increased overestimation of pond levels downstream of the outlet.

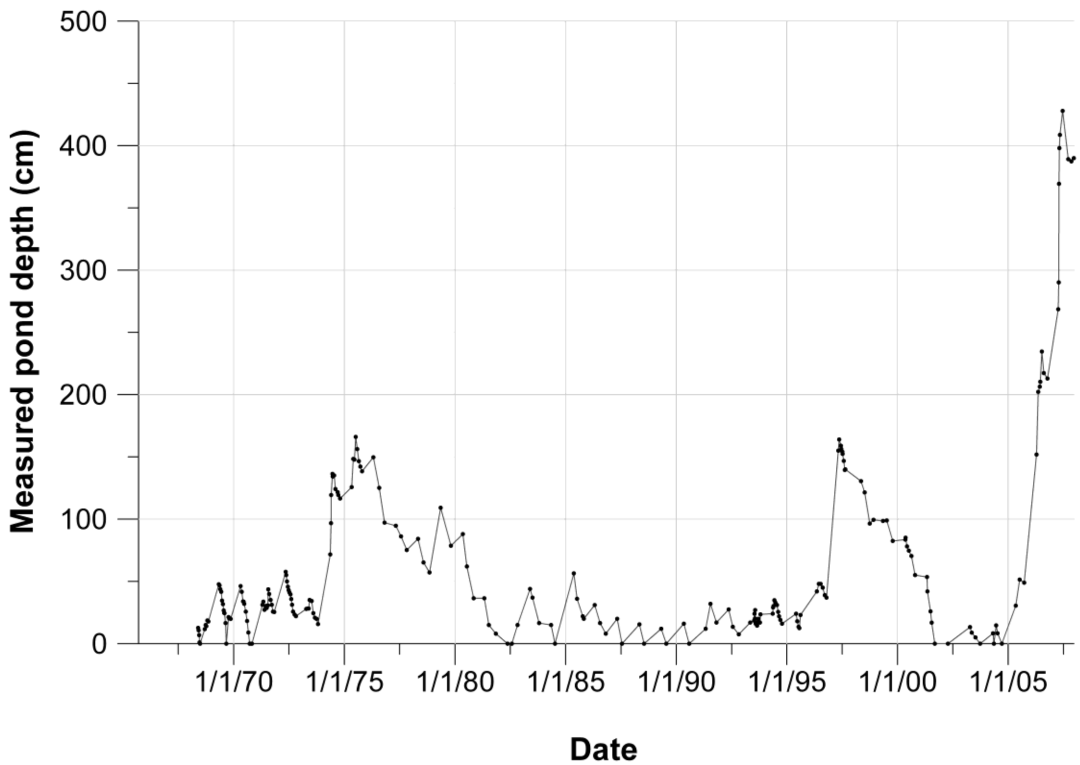


Figure 5-6 Measured pond levels for St. Denis pond 90 (1968 – 2007).

Table 5-1. Measured pond level for Pond 90 (p90) are compared to modeled pond levels levels for p90.

Method	2006 Pond 90 pond depth (cm)	2007 Pond 90 pond depth (cm)	2006 +/- error in pond level (cm)	2007 +/- error in pond level (cm)
Measured pond level	150	408	-	-
100% of basin contributes	280	430	+130	+22
Basin runoff volume - V_{BMAX}	65	150	-85	-258
SPILL algorithm	149	413	-1	+5

5.2.2 Modeled pond levels in a prairie pothole basin using a runoff volume – V_{BMAX} equation

As seen in Table 5-1 a method that simply subtracts V_{BMAX} from the potential runoff volume produced by measured SWE values significantly underestimates the pond level for p90. In 2006 the modeled pond depth value is 65 cm. This pond depth is 43% of the measured pond level for p90. Again in 2007 the pond level for p90 is underestimated. Only 31% of the measured pond depth is modeled using this approach.

What these results illustrate is that a simple attenuation of runoff volume from the V_{BMAX} value is not satisfactory when modeling runoff volumes in the prairie pothole region. This method does not include the fill-and-spill of potholes and the resulting connectivity between these potholes. As a result, areas in the basin that are connected to the outlet and contribute runoff volume are not represented. Thus, runoff volumes at the outlet are underestimated.

5.2.3 Modeled pond levels in a prairie pothole basin using SPILL

Including connectivity and the fill-and-spill of V_{SSA} when modeling pond levels for p90 results in dramatically improved results than those presented in Table 5-1 for methods presented in sections 5.2.1 and 5.2.2. Modelling pond levels using only the SPILL algorithm allows an examination of how satisfactorily the algorithm redistributes input water.

At each iteration of the SPILL algorithm water depth is added that results in one sub-basin spilling. The V_{BMAX} will be reached if the algorithm is allowed to complete all iterations. However, the response of input events of a known magnitude can be simulated. This is accomplished by simply stopping the algorithm when the required input depth has iteratively been reached.

The resulting pond depths can be calculated by subtracting the DEM that has been filled with the desired runoff event from the original empty DEM. The DEM that results from this procedure represents pond depths as modeled by the SPILL algorithm. These modeled pond depths can be compared to measured pond depths collected at the SDNWA (see section 3.3.2).

The outlet pond (p90) experiences a dramatic increase in pond depth for the year 2006 (Figure 5-6). As Table 5-1 illustrates, the SPILL model produces a very satisfactory result of modeling the pond depth increases. Using the SWE value measured in the SDNWA (80 mm) results in a pond depth of depth 149 cm for p90. The measured depth for p90 at the end of the 2006 snowmelt event was 150 cm.

As in 2006, p90 pond depth rises dramatically. Pond depth rises over 200% higher than pond depths measured for p90 in the previous 40 years (Figure 5-6). Using an input SWE value of 100 mm results in a modeled pond depth of 408 cm for p90. Again the modeled pond depth is satisfactory as the measured pond depth for 2007 was 413 cm (Table 5-1).

Examination of ponds depths upstream of p90 again shows good agreement with measured pond depths for 2006 and 2007 (Figure 5-7, 5-8). Good agreement between upstream modeled pond depths and measured pond depths illustrate the capability of the SPILL algorithm to simulate the processes of fill-and-spill and connectivity within the basin.

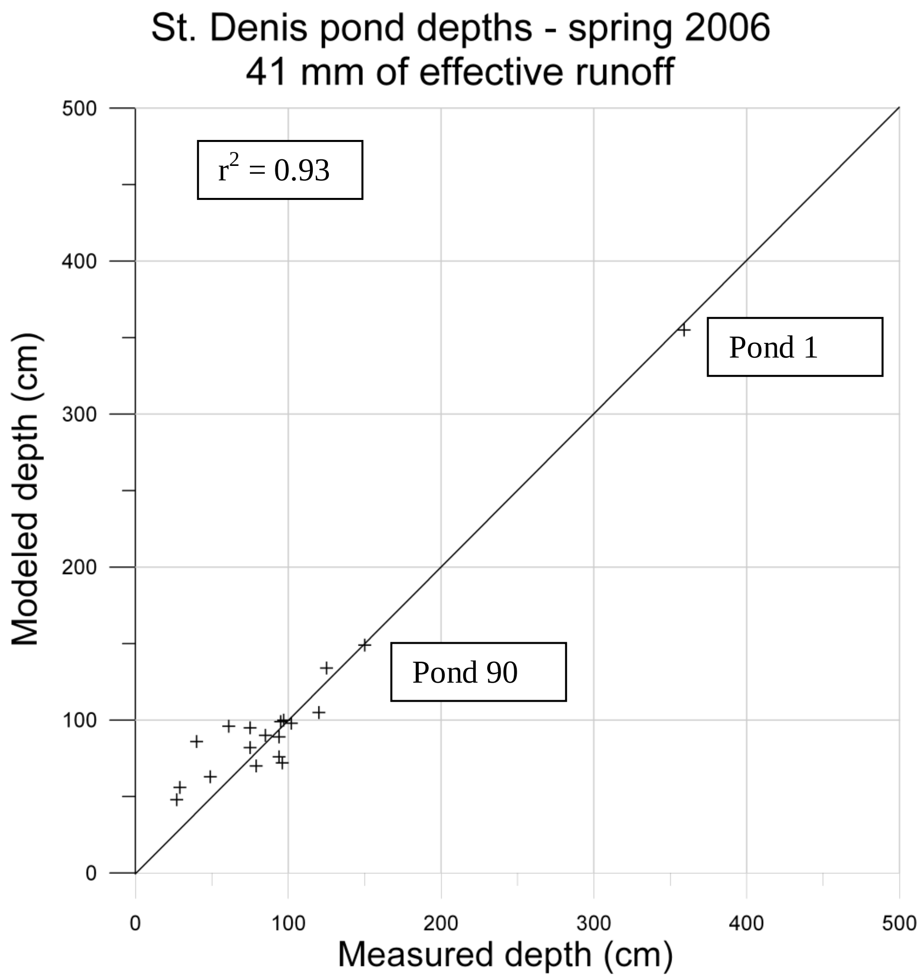


Figure 5-7. Modeled vs. measured pond depths at SDNWA in April, 2006.

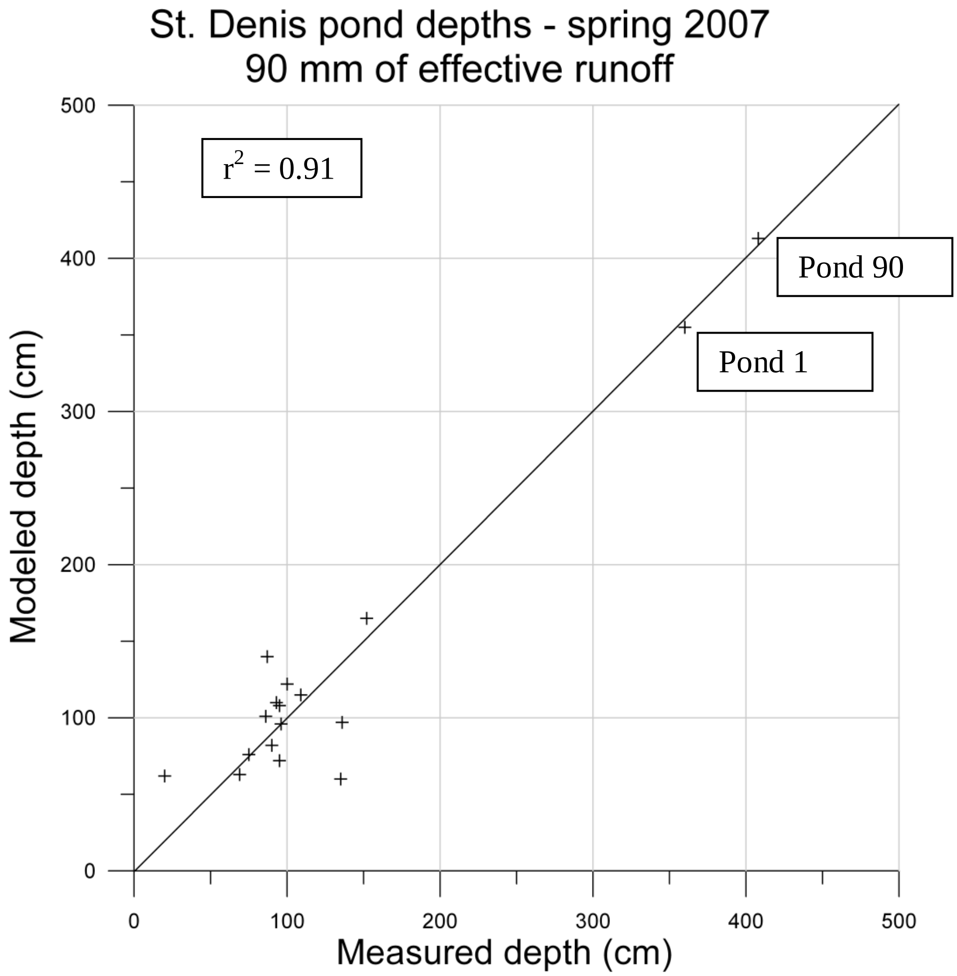


Figure 5-8. Modeled vs. measured pond depths at SDNWA in April, 2007.

5.3 Limitations of consecutive year SPILL runs

To run the SPILL algorithm on consecutive years, The DEM must be annually updated to reflect the pond levels changes that result from hydrological processes between snowmelt runoff events such as water loss in order to run the SPILL algorithm on consecutive years. Research was completed to determine whether a relationship could be found between a variable such as water loss and the variables CA_B, V_{SSA}, and A_{PS} so as to avoid 'forcing' basin storage conditions for each year. The goal of this research was to simulate movement up and down the A_{PS} curve as water is either added or removed from the basin (Figure 5-9).

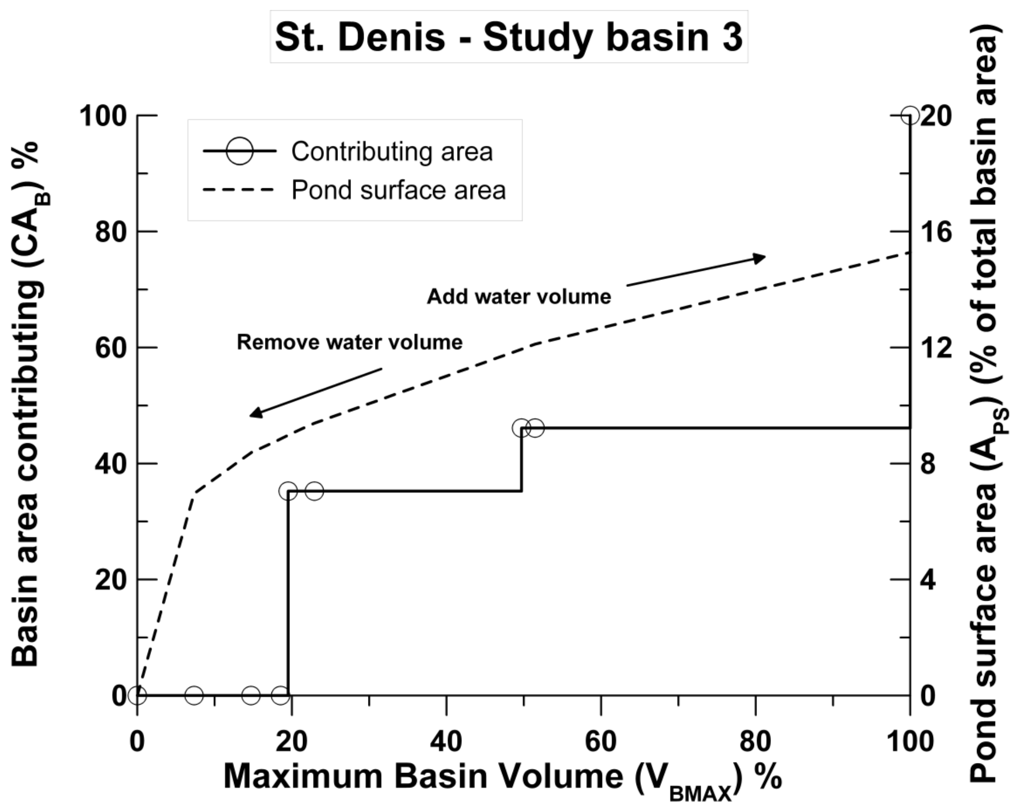


Figure 5-9 Illustrates the theory of moving up and down the A_{PS} curve in response to adding or removing water volume from the basin to determine CA_B.

Figures 5-10, Figure 5-11 and Figure 5-12 illustrate an attempt to relate evaporation to CA_B, V_{SSA}, and A_{PS}. The SPILL algorithm was applied to sub-basin 3 (Figure 5-10). It is acknowledged that many factors are involved in evaporating water from ponds. However, in order to simplify water removal from ponds, water loss was simulated by removing incremental depths from the ponds by lowering the elevations of the identified ponds in the DEM. Incremental depths were removed until the basin was 'dry' (Figure

5-11). Figure 5-11 illustrates that CA_B drops to 0% immediately after any water is removed from the system. This is because lowering the pond depth at the outlet immediately stops spill from the basin. Pond surface area and water volume in the basin follow an approximately linear relationship as the basin empties.

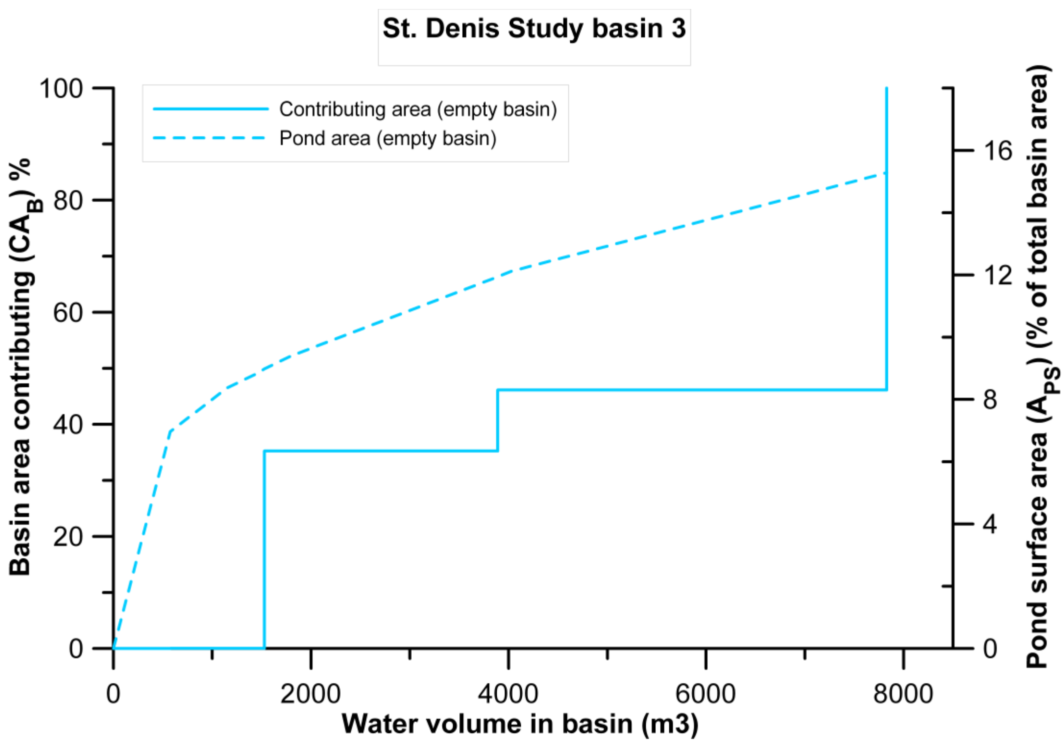


Figure 5-10. The relationship between CA_B, V_{SSA}, and A_{PS} for sub-basin 3 in the SDNWA is presented.

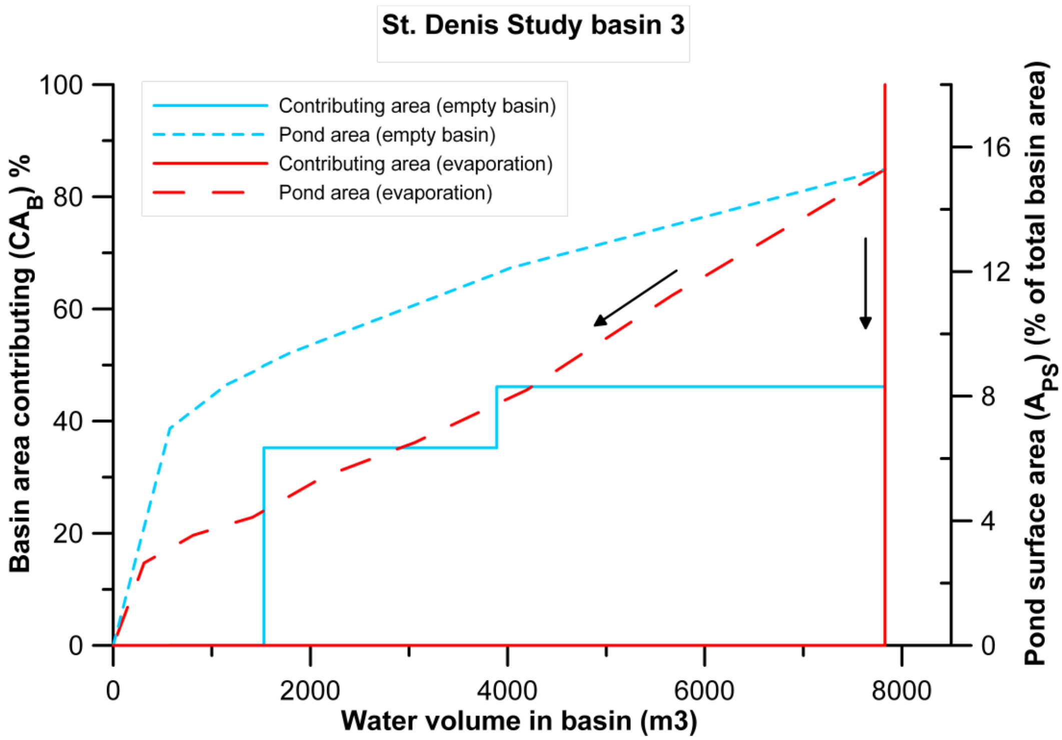


Figure 5-11 Water loss is added to the relationship between CA_B, V_{SSA}, and A_{PS} for sub-basin 3 in the SDNWA is presented.

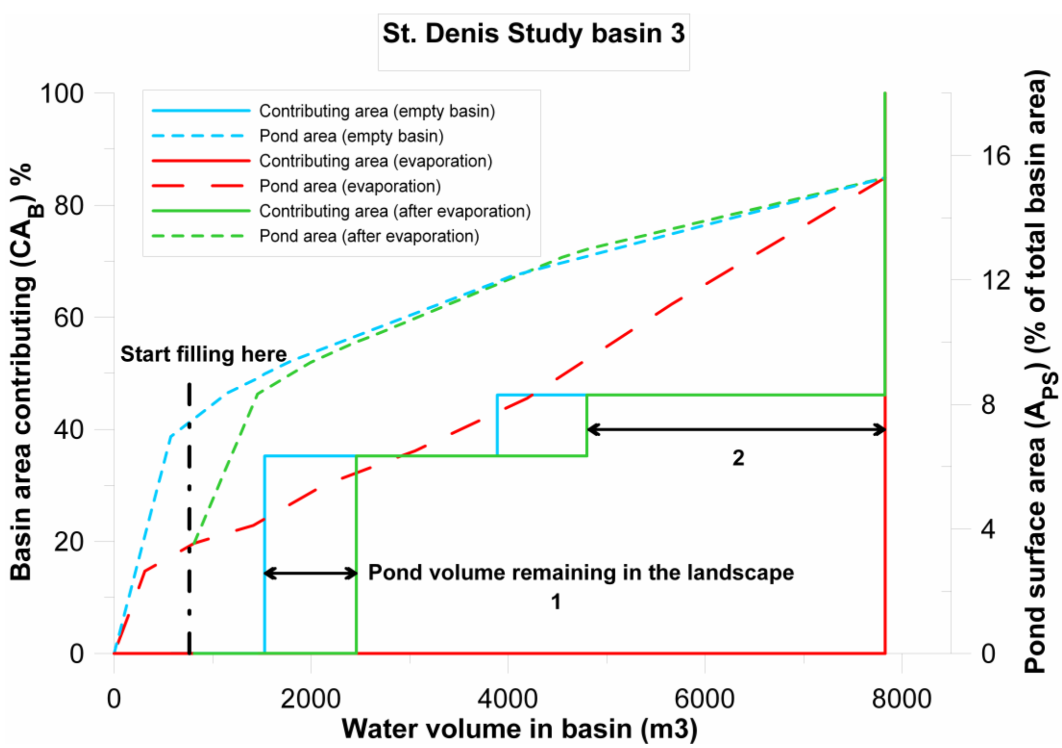


Figure 5-12. Illustrates the relationship between CA_B, V_{SSA}, and A_{PS} as sub-basin 3 fills after water loss removes all but 1000 m3 of V_{SSA}.

Figure 5-12 illustrates the relationship between variables when water loss is stopped prior to the basin becoming completely dry. This reflects basins with ponds that do not dry out during the intervening period between snowmelt runoff events. The SPILL algorithm is run from the nearly dry state and the relationships between CA_B, V_{SSA}, and A_{PS} are again plotted.

Figure 5-12 illustrates that less additional water is needed for CA_B to increase. It is reasonable to assume that contributing area will occur earlier when there is more water volume in the basin. However, Figure 5-13, Figure 5-14 and Figure 5-15 illustrate why the contributing area does not occur earlier with antecedent water volume. Figure 5-13 shows pond areas for a basin at a full state. All ponds are connected and 100% of the basin is contributing. Figure 5-14 illustrates water loss dries out the smaller ponds in the basin leaving only the large pond in the headwater of the basin with remaining water volume. As the basin fills (Figure 5-15) the small ponds start to fill-and-spill, thus connecting with surface water. However, the antecedent water volume present in the landscape before the fill does not connect until late in the basin fill. This is because although antecedent water volume is present, the V_{SSA} for this sub-basin is still largest in the basin at the beginning of the fill. As such, the antecedent water volume in the sub-basin is in the landscape but does not affect CA_B until the basin is almost full resulting in the sub-basin spilling and ultimately connecting to the outlet. This fill sequence can be seen in figure 5-12. The water volume required to fill the last pond and reach threshold basin volume is less during the fill with antecedent water volume than that of the fill from an empty basin.

This demonstrates that the relationship between CA_B, V_{SSA}, and A_{PS} is not constant for both the filling of a basin with runoff and emptying due to water loss. The break down of the relationship of the variables is due to the water loss process resulting in distribution of pond area and pond volumes that do not adhere to the CA_B, V_{SSA}, and A_{PS} relationship established during basin fill. Thus, the A_{PS} cannot be used to determine CA_B after water loss has occurred because the relationship between prairie pothole system variables is different when the basin is drying out or filling up.

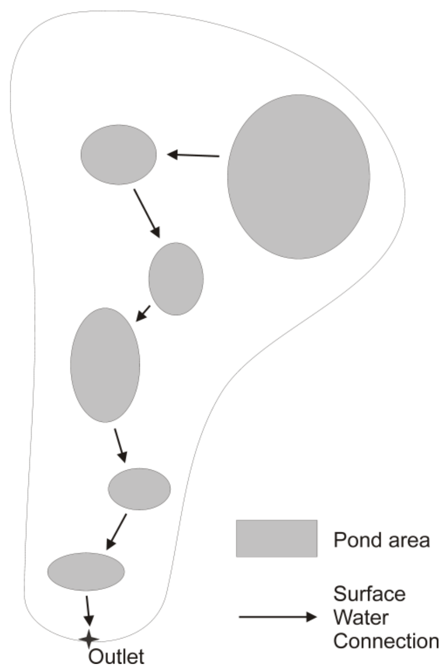


Figure 5-13. Illustrates a fully connected basin with 100% contributing area.

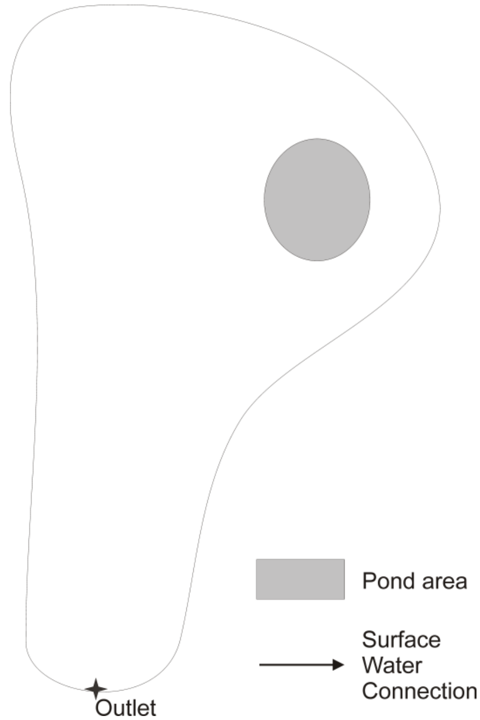


Figure 5-14. Illustrates a basin after water loss has removed most of surface storage and pond area.

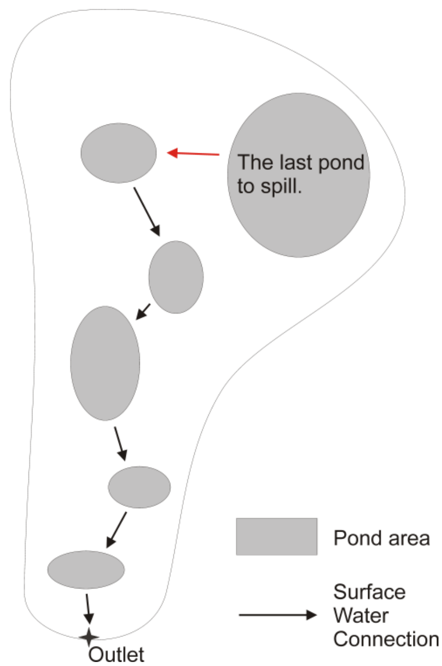


Figure 5-15. Illustrates fill of a basin with larger $\mathbf{V_{SSA}}$ in the headwater of the basin. Small ponds fill-and-spill and connect first, while the larger pond is last to spill.

CHAPTER 6

- SUMMARY AND CONCLUSIONS -

6 Summary

The development of an algorithm (SPILL) that captures and simulates pothole connectivity in response to runoff events allows the relationship between variables in the prairie pothole system to be examined. Landscape tools such as TOPAZ currently can calculate threshold storage volume. When this threshold storage volume is assumed to be satisfied, 100% of the basin can contribute runoff to the basin outlet. However, for runoff events of magnitudes that do not reach threshold volume (sub-threshold events) calculation of contributing area is more complex. Sub-threshold runoff events will have dynamic contributing area due to dynamic basin conditions, such antecedent storage, that impact surface water connectivity between potholes. Surface water connectivity, controlled by the fill-and-spill of potholes, determines the percentage of the basin that can contribute to the outlet. The SPILL algorithm is used to quantify contributing area for these sub-threshold runoff events.

The theoretical basis for the SPILL algorithm is dynamic contributing area. However unlike historical dynamic contributing area theories that are founded on the concept that contributing area varies in time and space as a result of saturated ground conditions, this thesis quantifies the extent of varying contributing area spatially and temporally as a result of the antecedent basin conditions, V_{SSA}, and connectivity of potholes. This is manifest in the filling and spilling of runoff between potholes.

The relationship between the landscape's decreasing V_{SSA} and the contributing area to the basin outlet is non-linear. The fill-and-spill behaviour inherent in the prairie pothole region produces large step functional increases in contributing area. Application of the SPILL algorithm to prairie pothole sub-basins demonstrates that the conceptual curves presented in this thesis properly represent the non-linear step functional relationship between decreasing V_{SSA} and contributing area.

6.1 Operationalizing SPILL

Although this thesis will not operationalize the SPILL algorithm into an existing hydrological model, this section will suggest a method of doing so. Shaw, et, al. (2004) proposed a method for parameterizing hydrological models using physiographic data. This method (WATPAZ) provided an interface between the TOpographic PArameteriZation (TOPAZ) software and the WATFLOOD hydrological model. The interface uses output raster data created by TOPAZ (i.e. drainage identification) to supply physiographic parameters required by WATFLOOD to move water horizontally in the basin.

WATFLOOD is a semi-distributed model that sub-divides the watershed into square grids or segments. The strength of the WATPAZ interface is the ability to preserve segment variability while determining physiographic parameters for the WATFLOOD model. The WATPAZ interface greatly improved drainage direction determination for WATFLOOD segments by incorporating segment variability (Shaw et al., 2004).

However, contributing areas are always assumed to be 100% for each segment in the WATFLOOD basin. The SPILL algorithm offers an opportunity to improve the performance of the WATFLOOD model by incorporating dynamic contributing area into the model.

Both WATFLOOD and the SPILL algorithm require square-grid input. As such, there is an opportunity to interface the programs through remotely sensed data. Remotely sensed images can be used to supply both the topographic information and antecedent pond level information for a modeled basin. The WATFLOOD model divides a watershed into a number of Grouped Response Units with runoff from each grid-square routed down the river network to the basin outlet. Gross drainage area can be determined for each segment by identifying the lowest point each grid-square boundary and identifying each cell in the basin that flows to the outlet. With gross area determined and an initial input water volume, the SPILL algorithm can be run for each grid-square. A contributing area parameter for each grid-square can be determined by the SPILL algorithm using runoff volumes input into each grid square and antecedent pond levels in the basin. This contributing area parameter will be used determine effective runoff volume for the grid-square. As a result, SPILL will improve modeling of horizontal movement of water through the basin.

WATFLOOD can also be interfaced with CLASS, the Canadian Land Surface Scheme, which is a tool used to model the vertical and water energy budget. The vertical water budget calculations in CLASS can be used to determine the volume of water available for runoff from each segment in the basin and refine the volume used as an input for the SPILL algorithm. An interface between SPILL, WATFLOOD and WATCLASS will provide a method for improved modeling of prairie pothole region hydrology.

6.2 Conclusions

One of the objectives of this thesis was to produce an algorithm that quantifies dynamic contributing area in the prairie pothole region and is scale-independent. Scale-independence is important as hydrological and atmospheric models are applied over a wide range of scales. While this research focused on potholes, the SPILL algorithm can also be applied on larger depressions that fill with lakes. The fill-and-spill of lakes will be similar to what has been observed in potholes but with larger water volumes. Recent research examining long-term lake levels in the prairie pothole region (van der Kamp et al., 2008) illustrates the opportunity to scale up the research presented in this thesis.

It is necessary to run the SPILL algorithm using antecedent basin conditions for each spring snowmelt runoff event for multiple year hydrological model runs. As outlined within this thesis, the loss of pond depth due to water loss between spring runoff events cannot be correlated to the relationship established in this thesis between contributing area, volume of storage available in the landscape, and pond water area in the SPILL algorithm. As a result, the input DEM reflect the basin storage conditions at the start of each year's snowmelt runoff event.

SPILL validates the conceptual prairie pothole contributing area/potential surface storage relationships proposed in the thesis. The algorithm identified three of the four proposed conceptual landscapes. The fourth conceptual landscape which transitions between the prairie pothole region and a landscape where the channel structure is well defined was not found. This was to be expected given that all basins examined in this study lie well within the prairie pothole region.

This research illustrates the tremendous impact of connectivity and fill-and-spill on prairie hydrology. Validating the SPILL model through the prediction of pond levels illustrated that the SPILL algorithm modeled pond levels very well while incorporating no hydrological physical processes. These results are tempered, however, by the fact that restricted infiltration conditions occurred in both years that the algorithm modeled pond depths. These circumstances match very well with the assumption that the algorithm redistributes runoff over an impervious surface. Further examination of model performance over a variety of infiltration conditions should be completed.

Although a conceptual method of incorporating the SPILL algorithm into the WATFLOOD hydrological model is proposed, future research should focus on operationalizing this concept in hydrologic or atmospheric models.

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APPENDIX A

Snow survey data

St. Denis snow survey summaries.

Archived data: Randy Schmidt National Water Research Institute – Saskatoon, SK.

				Transect			
Spring (Year)	Date of survey	Overall landscape SWE (mm) estimate	Average sample density	S50 brome grass SWE (mm)	S50 field average SWE (mm)	S109 SWE (mm)	S109 pond centre SWE (mm)
1994	Mar 3	60				64	111
1995	n/a						
1996	Mar 13	60				40	84
1997	Mar 22, Mar 21	80		88	35	80	101
1998	Mar 17, Mar 19	45	0.19	30	44	45	49
1999	Mar 22, Mar 15	45	0.23	20	8	74	74
2000	Feb 26	27	0.21	25	22	30	32
2001	Mar 1, Mar 2	45	0.2	48	20	45	52
2002	Mar 25, Mar 22	25	0.2	12	19	28	41
2003	Mar 14	42	0.22	45	33	50	65
2004	nd	64	0.22			70	
2005	nd	80					
2006	Mar 23	100	0.27	100	98	110	146
2007	Mar 18, Mar 20	90	0.28	85	50	125	136
2008	Mar 8, Mar 10	65	0.23	58	40	80	80
2009	Mar 30	84	0.21	81	50	91	91

APPENDIX B

Source code

/* MAIN BODY

```
&r cleanup
/* &messages &off
&sv closestat = [close -all]
/* Input DEM
&sv in_dem = in_dem

/* Input variables
&sv cellsize = 1
&sv done = 0
&sv count = 1
&sv .count = 1
&sv orig_increment = 1
precision double

grid
shedfull = reclass(in_demo, reclassfile3.txt)
q

/* START 1
&do &while %done% = 0

         grid
         fldir%count% = flowdirection(%in_dem%%count%)
         sink%count% = sink(fldir%count%)
         &if not [exists sink%count%.vat -info] &then
        &do
          &type done
          &return
        &end
         shed%count% = watershed(fldir%count%, sink%count%)
          shedfull%count% = merge(shed%count%, shedfull)
         q



         /* Find out how many subw's to be processed
         /* This has to be fairly involved because
         /* error watersheds are defined using gridpoly
         /* command

         gridpoly shed%count% shedp%count%
         dropitem shedp%count%.pat shedp%count%.pat use
         additem shedp%count%.pat shedp%count%.pat use 1 1 n 0


         tables
         sel shedp%count%.pat
         &sv shedtotalsel = [show number select]
         q

         /* START 2
              &do shedsel = 1 &to %shedtotalsel% &by 1
              &type shedtotalsel is %shedtotalsel%
              &type WORKING ON LOOP %shedsel%
              tables
              sel shedp%count%.pat
              resel grid-code = %shedsel%
              &sv numbsel = [show number select]
              &if %numbsel% = 0 &then
                     &do
```

```
                &type No subwatershed selected
                &end
          &if %numbsel% = 1 &then
                &do
                calc use = 1
                &end
          &if %numbsel% > 1 &then
                &do
                copy shedp%count%.pat subwcount%shedsel%.dat
                &DATA arc
                statistics subwcount%shedsel%.dat subwcount%shedsel%.stat
                max area
                end
                q
                &END
                sel subwcount%shedsel%.stat
                &sv maxarea%shedsel% = [show record 1 max-area]
                sel shedp%count%.pat
                resel grid-code = %shedsel% and area = [value
maxarea%shedsel%]
                calc use = 1
                &end
          q
          &end
      /* END 2

      /* Find the maximum number for grid-code
      additem shedp%count%.pat shedp%count%.pat gridid 10 10 n 0
      tables
      sel shedp%count%.pat
      calc gridid = grid-code
      q

      statistics shedp%count%.pat shedp%count%.stat
      max gridid
      end

      tables
      sel shedp%count%.stat
      &sv tmp_gridcode = [show record 1 max-gridid]
      q

      &sv max_gridcode = [truncate %tmp_gridcode%]
      &sv .max_gridcode = [truncate %tmp_gridcode%]

     &type maxgridcode = %max_gridcode%


     /* end maximum number
     /* ************************************

 /* Create a mask grid for each subw


     &do mincount = 1 &to %max_gridcode% &by 1
          ae
          ec shedp%count%
          ef poly
          sel grid-code = %mincount%
          resel use = 1
          put p%mincount%
          q
          build p%mincount%
```

```
       &end


     /* make the boundary grid
   &do mincount = 1 &to %max_gridcode% &by 1

        &sv halfcellsize = %cellsize% / 2

        linegrid p%mincount% grd%mincount%
        %cellsize%
        y
        ~

        grid
        re%mincount% = resample(grd%mincount%, %halfcellsize%)      /*
        q

        build p%mincount%

        polygrid p%mincount% msk%mincount%
        %cellsize%
        y
        ~

        grid
        setmask msk%mincount%
        bnd%mincount%tmp = re%mincount%

        rew%mincount% = reclass(bnd%mincount%tmp, reclassfile.txt)
        ex%mincount% = expand(rew%mincount%,1,list,1)

        bndtmp%mincount% = ex%mincount%

        rez%mincount% = reclass(bndtmp%mincount%, reclassfile2.txt)
        rex%mincount% = reclass(msk%mincount%, reclassfile.txt)
        q

        gridpoly rez%mincount% rez%mincount%tmp
        polygrid rez%mincount%tmp rey%mincount%
        %cellsize%
        y

        grid
        bndmin%mincount%tmp = merge(rey%mincount%, rex%mincount%)
        bndmin/bndmin%mincount% = reclass(bndmin%mincount%tmp,
reclassfile1.txt)

        setmask rez%mincount%
        bnd%mincount% = in_dem%.count%
        q

         statistics bnd%mincount%.vat bnd%mincount%.stat
         min value
         end

        tables
        sel bnd%mincount%.stat
        &sv bndmino%mincount% = [show record 1 min-value ]
        q


        grid
```

```
        outlt/outlt%mincount% = select(bnd%mincount%, [quote value = [value
bndmino%mincount%]])
        q

        kill bnd%mincount% all          /*** REALLY?


       /* new part that gets pit elevation of each subw
       grid
       setmask msk%mincount%
       pitelev%mincount% = in_dem%count%
       q

       statistics pitelev%mincount%.vat pitelev%mincount%.stat
       min value
       end

       tables
       sel pitelev%mincount%.stat
       &sv pitelev%mincount% = [show record 1 min-value]
       q

        /* cleanup
        kill (!p%mincount%, grd%mincount%, re%mincount%, msk%mincount%,
bndmin%mincount%tmp, bnd%mincount%tmp, rew%mincount%, ex%mincount%!) all
        kill (!bndtmp%mincount%, rez%mincount%, rex%mincount%, rey%mincount%,
rez%mincount%tmp pitelev%mincount%!) all
        tables
        kill *.stat noprompt
        kill *.dat noprompt
        q

  &end

  /*
  /*
  /****************************************
  /****************************************
  /* Elevation of the outlet for each subw
  /****************************************
  /****************************************

  /* START 3


  &do idcount = 1 &to %max_gridcode% &by 1

  gridpoly outlt/outlt%idcount% outp%idcount%
  buffer outp%idcount% outbf%idcount% # # %cellsize% .001 line flat

  polygrid outbf%idcount% outbg%idcount%
  %cellsize%
  y

  grid
  setmask outbg%idcount%
  tvel%idcount% = in_dem%count%
  setmask off

  bsmsk%idcount% = select(shedfull%count%, [quote value ne %idcount%])

  setmask bsmsk%idcount%
  idbnd%idcount% = tvel%idcount%
```

```
  q

  &if [exists idbnd%idcount%.vat -info] &then
  &do

  /* Cleanup files generated above


    &if [exists outp%idcount% -poly] &then
    &do
    kill outp%idcount% all
    &end

    &if [exists outbf%idcount% -cover] &then
    &do
    kill outbf%idcount% all
    &end

    &if [exists outbg%idcount% -grid] &then
    &do
    kill outbg%idcount% all
    &end

    &if [exists tvel%idcount% -grid] &then
    &do
    kill tvel%idcount% all
    &end

    &if [exists bsmsk%idcount% -grid] &then
    &do
    kill bsmsk%idcount% all
    &end

    &if [exists bndchk%idcount% -grid] &then
    &do
    kill bndchk%idcount% all
    &end

  statistics idbnd%idcount%.vat idbnd%idcount%.stat
  min value
  end
  &type ok here!
  tables
  sel idbnd%idcount%.stat
  &type wtf
  &sv bndminn%idcount% = [show record 1 min-value]
  &type wtf2
  q

  kill idbnd%idcount% all

/*******************************************************************************
*************************************************************

  /* type calculates which bndmin to use
       &type idcount is %idcount%
       &type outer bnd value is  [value bndminn%idcount%]
       &type real boundary value is [value bndmino%idcount%]
       &type pitelev is  [value pitelev%idcount%]

  &sv delta = 0
```

```
  &if [value bndminn%idcount%] > [value bndmino%idcount%] & [value
bndminn%idcount%] < 99998 &then  /* new May 13, 2008
  &do
  &sv bndmin%idcount% = [value bndminn%idcount%]
  &end

  &if [value bndminn%idcount%] > [value bndmino%idcount%] & [value
bndminn%idcount%] >= 99998 &then  /* new May 13, 2008
  &do
  &sv bndmin%idcount% = [value bndmino%idcount%]
  &sv delta = 1
  &end

  &if [value bndmino%idcount%] >= [value bndminn%idcount%] & %delta% ne 1 &then
  &do
  &sv bndmin%idcount% = [value bndmino%idcount%]
  &end

  /*new
  &if [value bndmino%idcount%] = [value pitelev%idcount%] &then
  &do
  &type Doing the right thing
  &sv bndmin%idcount% = [value bndminn%idcount%]
  &end



  /****************************************

         &if [exists inc%count%.txt -file] &then
             &do

             &sv unit = [open inc%count%.txt openstat -append]
             &sv writestat = [WRITE %unit% %idcount%,[value bndmin%idcount%]]
             &sv closestat [close %unit%]
             &end

           &else
             &do

             &sv unit = [open inc%count%.txt openstat -write]
             &sv writestat = [WRITE %unit% %idcount%,[value bndmin%idcount%]]
             &sv closestat [close %unit%]
             &end

   &end
   &else
   &do
   &type this outlet drains out of the basin

  grid
  setmask outlt/outlt%idcount%
  outel%idcount% = in_dem%count%
  q

  tables
  sel outel%idcount%.vat
  &sv bndmin%idcount% = [show record 1 value]
  q

   &if [exists inc%count%.txt -file] &then
             &do
```

```
          &sv unit = [open inc%count%.txt openstat -append]
          &sv writestat = [WRITE %unit% %idcount%,[value bndmin%idcount%]]
          &sv closestat [close %unit%]
          &end

        &else
          &do

          &sv unit = [open inc%count%.txt openstat -write]
          &sv writestat = [WRITE %unit% %idcount%,[value bndmin%idcount%]]
          &sv closestat [close %unit%]
          &end

  &if [exists outp%idcount% -poly] &then
  &do
  kill outp%idcount% all
  &end

  &if [exists outbf%idcount% -cover] &then
  &do
  kill outbf%idcount% all
  &end

  &if [exists outbg%idcount% -grid] &then
  &do
  kill outbg%idcount% all
  &end

  &if [exists tvel%idcount% -grid] &then
  &do
  kill tvel%idcount% all
  &end

  &if [exists bsmsk%idcount% -grid] &then
  &do
  kill bsmsk%idcount% all
  &end

  &if [exists bndchk%idcount% -grid] &then
  &do
  kill bndchk%idcount% all
  &end

  &if [exists idbnd%idcount% -grid] &then
  &do
  kill idbnd%idcount% all
  &end

  &if [exists outel%idcount% -grid] &then
  &do
  kill outel%idcount% all
  &end



 &end
&end


/* END 3
```

```
  /* START 6
  /* Gets area for each subw (m2)
       &do areacount = 1 &to %max_gridcode% &by 1
       tables
       sel shedp%count%.pat
       resel grid-code = %areacount%
       resel use = 1
       copy shedp%count%.pat temp.dat
       sel temp.dat
       &sv area%areacount% = [show record 1 area]
       &type areacount is %areacount% and area = [value area%areacount%]
       kill temp.dat
       q
       &end
  /* END 6


    /*********************************


  /************************************

  /* Calculate the volume (cm3) of the cells below the outlet for all subws

/* START 6a
  &do getvolcount = 1 &to %max_gridcode% &by 1


       grid
       setmask bndmin/bndmin%getvolcount%
       tempminvol2 = select(in_dem%count%, [quote value <= [value
bndmin%getvolcount%]])
       tempminvol1 = [value bndmin%getvolcount%] - tempminvol2        /* NO
grid tvol
       tempminvol = int(tempminvol1)
       q

       additem tempminvol.vat tempminvol.vat vol 10 10 n 0

       tables
       sel tempminvol.vat
       calc vol = value * count
       calc vol = vol * %cellsize% * %cellsize%
       q

       statistics tempminvol.vat tempminvol.stat
       sum vol
       end

       tables
       sel tempminvol.stat
       &sv totvolcm%getvolcount% = [show record 1 sum-vol]
       &sv totvolm%getvolcount% = [value totvolcm%getvolcount%] * 0.01
       &type totalvolcm for count %getvolcount% is [value
totvolcm%getvolcount%]
       &type totalvolm for count %getvolcount% is [value totvolm%getvolcount%]
       q

       &if [exists getvol%count%.txt -file] &then
       &do
```

```
       &sv unit = [open getvol%count%.txt openstat -append]
       &sv writestat = [WRITE %unit% %getvolcount%,[value
totvolm%getvolcount%],[value area%getvolcount%]]
       &sv closestat [close %unit%]
       &end

     &else
       &do

       &sv unit = [open getvol%count%.txt openstat -write]
       &sv writestat = [WRITE %unit% %getvolcount%,[value
totvolm%getvolcount%],[value area%getvolcount%]]
       &sv closestat [close %unit%]
       &end


       kill tempminvol all
       kill tempminvol1 all
       kill tempminvol2 all

  &end
/* END 6a


/*    Write getvol.txt to .dat file to find the lowest volume

       tables
       define getvol%count%.dat
       subw
       6
       6
       n
       0
       volume
       15
       15
       n
       3
       area
       15
       15
       n
       3
       ~
       add from getvol%count%.txt
       q

       additem getvol%count%.dat getvol%count%.dat depth 10 10 n 5

       tables
       sel getvol%count%.dat
       calc depth = volume / area
       q


       statistics getvol%count%.dat getvol%count%.stat
       min depth
       end

       tables
       sel getvol%count%.stat
       &sv minvol%count% = [show record 1 min-depth]
       &sv indepth%count% = [value minvol%count%]
```

```
        q

        &type [value minvol%count%]
        &type [value depth%count%]

        /* CHECK - can be removed
        tables
        sel getvol%count%.dat
        resel depth = [value minvol%count%]
        copy getvol%count%.dat temp.dat
        sel temp.dat
        &sv subw%count% = [show record 1 subw]
        kill temp.dat
        q

        &type Minimum volume/depth subw is [value subw%count%]
        &sv subwuse = [value subw%count%]


        /************************************
        /* Create the minimum grid
        grid
        setmask bndmin/bndmin%subwuse%
        tempminvol2 = select(in_dem%count%, [quote value <= [value
bndmin%subwuse%]])
        &type bndmin is [value bndmin%subwuse%]
        tempminvol1 = [value bndmin%subwuse%] - tempminvol2
        tempminvol = int(tempminvol1)
        q

        &sv test = '0 100000 : '
        &sv unit = [open reclass_id.txt openstat -write]
        &sv writestat = [WRITE %unit% %test%[value bndmin%subwuse%]]
        &sv closestat [close %unit%]

        grid
        mincellf/mincl%count%_%subwuse% = reclass(tempminvol, reclass_id.txt)
        q
        &sys erase reclass_id.txt
        kill tempminvol all
        kill tempminvol2 all
        kill tempminvol1 all
        /************************************



    /* Write out the input depth in (m) for each iteration

    &if [exists inputvolume%count%.txt -file] &then
        &do

        &sv unit = [open inputvolume%count%.txt openstat -append]
        &sv writestat = [WRITE %unit% [value indepth%count%]]
        &sv closestat [close %unit%]
        &end

      &else
        &do

        &sv unit = [open inputvolume%count%.txt openstat -write]
        &sv writestat = [WRITE %unit% [value indepth%count%]]
        &sv closestat [close %unit%]
        &end
```

```
  /***************************************

  /* START 7
  /* Calculate input volumes (m3) for each subw
       &do involcount = 1 &to %max_gridcode% &by 1
       &sv invol%involcount% = [value indepth%count%] * [value
area%involcount%]
       &type input volume for subw %involcount% = [value invol%involcount%]


 &if [exists tempvol%count%.txt -file] &then
       &do

       &sv unit = [open tempvol%count%.txt openstat -append]
       &sv writestat = [WRITE %unit% %involcount%,[value invol%involcount%]]
       &sv closestat [close %unit%]
       &end

     &else
       &do

       &sv unit = [open tempvol%count%.txt openstat -write]
       &sv writestat = [WRITE %unit% %involcount%,[value invol%involcount%]]
       &sv closestat [close %unit%]
       &end

       &end
  /* END 7


       tables
       define tempvol%count%.dat
       id
       5
       5
       n
       0
       volume
       10
       10
       n
       3
       ~
       add from tempvol%count%.txt
       q


 /**********************************************************
 /**********************************************************
 /* Iterative calculation of volume starting from the top
 /**********************************************************

/*******************************************************************************
************************************************************************


 /* START 8
 &do subwnumber = 1 &to %max_gridcode% &by 1
 &if %subwnumber% ne %subwuse% &then
/* START 8_1a
```

```
       &do
       &sv loopcount = 1
       &sv check = 1
       &sv increment = %orig_increment%
/* START 8a
       &do &until %check% = 0
       &sv iteration = %subwnumber%_%loopcount%
       &sv loopcount1 = %loopcount% - 1
       &sv iteration1 = %subwnumber%_%loopcount1%
       &sv skipcheck%iteration% = 1

       &if %loopcount% = 1 &then
       &do
       grid
       setmask bndmin/bndmin%subwnumber%
       tempelev = in_dem%count%
       q

       statistics tempelev.vat tempelev.stat
       min value
       end

       tables
       sel tempelev.stat
       &sv minelev%subwnumber% = [show record 1 min-value]
       q
       &type MINIMUM ELEVATION IS [value minelev%subwnumber%]

       &sv incelev%iteration% = [value minelev%subwnumber%] + %orig_increment%

       /* cleanup
       kill tempelev all

       &end

       &if %loopcount% > 1 &then
       &do

       &sv incelev%iteration% = [value incelev%iteration1%] + %orig_increment%
/*****************************************
       &end



       &type loopcount = %loopcount%
       &type incelev = [value incelev%iteration%]
       &type skipcheck iteration = [value skipcheck%iteration%]

       grid
       setmask bndmin/bndmin%subwnumber%
       tempminvol2 = select(in_dem%count%, [quote value < [value
incelev%iteration%]])  /* for volume calc
       tempminvol3 = select(in_dem%count%, [quote value > [value
incelev%iteration%]])  /* check to see if this is the overflow pt.


       /*
       &if not [exists tempminvol3.vat -info] &then
       &do
       &type runnning the new section
       &sv incelev%iteration% = [value incelev%iteration%] - %orig_increment%

       kill tempminvol2 all
```

```
	setmask bndmin/bndmin%subwnumber%
	tempminvol2 = select(in_dem%count%, [quote value <= [value
incelev%iteration%]])
	&sv skipcheck%iteration% = 0

	&end
	/*

	&if [exists tempminvol3 -grid] &then
	&do
	kill tempminvol3 all
	&end

	tempminvol1 = [value incelev%iteration%] - tempminvol2

	tempminvol = int(tempminvol1)
	q

	additem tempminvol.vat tempminvol.vat vol 10 10 n 0

	tables
	sel tempminvol.vat
	calc vol = value * count
	calc vol = vol * %cellsize% * %cellsize%
	q

	statistics tempminvol.vat tempminvol.stat
	sum vol
	end

	tables
	sel tempminvol.stat
	&sv subwiterationcm%subwnumber% = [show record 1 sum-vol]
	&sv subwiterationm%subwnumber% = [value subwiterationcm%subwnumber%] *
0.01
	&sv runvol%iteration% = [value subwiterationm%subwnumber%]

	&type subwiterationcm for count %subwnumber% is [value
subwiterationcm%subwnumber%]
	&type subwiterationm for count %subwnumber% is [value
subwiterationm%subwnumber%]
	&type runvol = [value runvol%iteration%]
	q


	kill tempminvol1 all
	kill tempminvol2 all
	&sv temp = [value runvol%iteration%]
	&sv temp1 = [value invol%subwnumber%]
	&type %temp%
	&type %temp1%
	&sv runvola%iteration% = [truncate %temp%]
	&sv involа%subwnumber% = [truncate %temp1%]
	&type runvol is [value runvola%iteration%]
	&type invol is [value invola%subwnumber%]

			&if [value runvola%iteration%] < [value invola%subwnumber%]
&then
			&do
			&sv check = 1
			&end
			&if [value runvola%iteration%] > [value invola%subwnumber%]
OR [value skipcheck%iteration%] = 0 &then
```

```
                    &do
                    &type doing skipcheck = 0
                    &sv check = 0
                    &end

                    &if %check% = 1 &then
/* START 12
             &do
                    &type [value runvola%iteration%] is LESS than [value
invola%subwnumber%] and keep FILLING volume
                    &sv loopcount = %loopcount% + 1
                    kill tempminvol all
                    &type done the < loop
             &end

&else

             &do
                    &type [value runvola%iteration%] is MORE THAN or EQUAL to
[value invola%subwnumber%] and is stopping
                    &type The calculated volume can hold the input
                    /* New June 1, 2008
                    &if [value incelev%iteration%] = [value bndmin%subwnumber%]
&then
                    &do
                    &sv incelev%iteration% = [value incelev%iteration%] -
%orig_increment%
                    &end
                    &type NEW PART IS BEING DONE




                    &sv test = '0 100000 : '
                    &sv unit = [open reclass_id.txt openstat -write]
                    &sv writestat = [WRITE %unit% %test%[value
incelev%iteration%]]
                    &sv closestat [close %unit%]

                    grid
                    mincellf/mincl%count%_%subwnumber% = reclass(tempminvol,
reclass_id.txt)
                    q
                    &sys erase reclass_id.txt
                    /*

                    kill tempminvol all

             &end
/* END 13
       &end
/* END 8a
       &end
/* END 8_1a
     &else
/* START 8_1b
       &do
       &type the subw has already been done because its the min
       &end
/* END 8_1b

&end
```

```
 /* END 8



/* Creates an updated in_dem from the original in_dem and merged volume grids

/* START 13a
       &do nextdemcount = 1 &to %max_gridcode% &by 1
       &sv nextdemcount1 = %nextdemcount% - 1
       &if %nextdemcount% = 1 &then
              &do
              grid
              indema%nextdemcount% =
merge(mincellf/mincl%count%_%nextdemcount%, in_dem%count%)
              kill mincellf/mincl%count%_%nextdemcount% all
              q
              &end
        &else
              &do
              grid
              indema%nextdemcount% =
merge(mincellf/mincl%count%_%nextdemcount%, indema%nextdemcount1%)
              q
              kill mincellf/mincl%count%_%nextdemcount% all
              &end
       &end
/* END 13a

       kill in_dem%count% all
       /****************************

       copy indema%max_gridcode% in_dem%count%

/******************************************************************************
**



/* cleanup temp grids
/* START 13b
       &do nextdemcount = 1 &to %max_gridcode% &by 1
       &if [exists indema%nextdemcount% -grid] &then
              &do
              kill indema%nextdemcount% all
              &end
       &end
/* END 13b

/* Cleanup last iteration data sets

/* START 15
&do cleancnt = 1 &to %max_gridcode% &by 1
kill bndmin/bndmin%cleancnt% all
kill outlt/outlt%cleancnt% all
&end
/* END 15



kill fldir%count% all
```

```
kill sink%count% all
kill shedfull%count% all
tables
kill *.stat noprompt
q
&sys erase runvol*.txt

/* Check to see if entire watershed has been processed

tables
sel shedp%count%.pat
&sv donecheck = [show number select]
q
&type donecheck = %donecheck%
&if %donecheck% > 1 &then
       &do
       &type end of the loop %count% - donecheck is greater than 2
       &sv count = %count% + 1
       &sv .count = %.count% + 1
       &sv countminus = %count% - 1
       kill shedp%countminus% all
       copy in_dem%countminus% in_dem%count%
       &sv done = 0
       &end
     &else
       &do
       &type doing wrong loop - donecheck = 2
       &sv done = 1
       kill shedp%count% all
       &end

&end
/* END 1
```