A combined field data and empirical modeling approach to precipitation-runoff analysis in an agro-forested Prairie watershed

by

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ABSTRACT

Low relief, heavily human-impacted landscapes like those of the Prairies in south-central Canada have received little attention in previous hydrological research. Here, the rainfall-runoff relationship in the context of both a field-based investigation and an empirical model is examined in an effort to provide insight into Prairie hydrology. Rainfall and water level data were collected for nested sub-watersheds of the Catfish Creek watershed, a 642 km^2, near-level, mixed land use and engineered Prairie watershed. First, the dataset is examined for runoff controls. Second, the history of the United States Curve Number Method is reviewed and its initial abstraction ratio examined against collected field data to determine the applicability of a single, constant ratio to Prairie landscapes. Overall, the results indicate that Prairie runoff generation processes differ significantly from those of humid, pristine catchments of higher relief and a conceptual model is proposed with that regards.

Keywords: hydrograph analysis, thresholds, runoff generation, watershed characteristics, antecedent moisture conditions, curve number, US-SCS CN method, initial abstraction, Prairie watersheds.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1.

INTRODUCTION

1.1 General introduction

The discipline of Hydrology seeks to understand the dynamics of water movement, distribution and quality from a global to hillslope scale. Through this pursuit, hydrology contributes to inform water management practices and prediction of potential flood events. Central to Hydrology is the analysis of hydrographs (graphs depicting the change of discharge with time) and hyetographs (graphs depicting the change of precipitation with time). These analyses consist of computing several hydrograph parameters, including initial abstraction, time to peak, response lag, lag to peak, centroid lag, rising time, time of concentration and storm hydrograph duration. Precipitation characteristics (*e.g.*, duration, intensity and timing) as well as antecedent moisture conditions (*e.g.*, time elapsed since the preceding precipitation event) cause these hydrograph characteristics to vary (Bracken & Croke, 2007; Singh, 1997). Fundamental to accurate forecasting is an understanding of the precipitation-runoff relationship encapsulated in the hydro-hyetograph, *i.e.*, an understanding of the processes that transform rainfall inputs into runoff outputs on annual, seasonal and event bases. Currently, hydrologists are confronted with many questions regarding the processes that govern the precipitation-runoff transformation, including questions of the relative importance of temporal and spatial runoff control factors, nonlinearity of runoff response, and data scarcity.

1.1.1 Challenges in predicting the precipitation-runoff relation

Hydrograph shape is influenced by the spatial characteristics of the watershed and precipitation event. Numerous studies have built lists of such factors that include watershed size (drainage area), watershed shape, topography, slope aspect, geology, soil properties, land use and land cover (Jencso & McGlynn, 2011), as well as the spatial pattern of precipitation amount, intensity and duration (Singh, 1997). However how these spatial watershed characteristics function in concert to determine the shape of the hydrograph is uncertain due to their diverse and continuous nature (Jencso & McGlynn, 2011). Similarly, it remains unclear how temporal precipitation characteristics, such as duration, intensity and timing, rank in importance or interact to influence the conversion of precipitation into runoff (Singh, 1997).

The watershed precipitation-runoff relationship is also difficult to predict as it is nonlinear (*e.g.*, Ali *et al.*, 2011, 2013; Detty & McGuire, 2010; Dunne & Black, 1970; Lehmann *et al.*, 2007; Mosley, 1979; Tromp-van Meerveld & McDonnell, 2006; Spence, 2010; Tsukamoto & Ohta, 1988; McDonnell, 1990; Tani, 1997; Hutchinson & Moore, 2000; Weiler *et al.*, 2005; Woods & Rowe, 1996; Zehe et al, 2005). Similar to the wetting of a sponge, water inputs into a watershed are not proportional to runoff outputs across time: precipitation is not immediately transformed into runoff but a certain critical point exists that, when exceeded, leads to the initiation of runoff (Phillips, 2006).

Thresholds for initiation of flow have been identified within watersheds at the soil matrix, macropore, pipeflow, hillslope and catchment scales (Spence, 2010), and this threshold behavior has been observed in various landscapes around the world (*e.g.*, mountain foothills in Portugal (Doerr & Thomas, 2000); steep mountainous in western Canada (Hutchinson & Moore, 2000); gently sloping loess in Germany (Zehe *et al.*, 2001); shield in subarctic Canada (Spence & Woo, 2003); steep hilly in the United Sates (Tromp-van Meerveld, 2004); steep mountainous in New Zealand (Graham & McDonnell, 2010); Prairie pothole region of south-central Canada (Shaw *et al.*, 2012)). Overall, previous work has revealed thresholds for initiation of runoff that ranged from 0.84 mm to 55 mm of rainfall (Hood *et al.*, 2007; Tromp-van Meerveld & McDonnell, 2006). The nonlinear precipitation-runoff relationship is often hockey stick-shaped, although a variety of other nonlinear shapes describing threshold-governed runoff generation is possible (Ali *et al.*, 2013). It remains unclear which type of variables (temporal, spatial or both) determine the shape of nonlinear precipitation-runoff relationships and whether hydrologic thresholds are a universal watershed feature (Lehmann *et al.*, 2007; McDonnell, 2003; McGrath *et al.*, 2007)**.** To present, outside of the pothole region (Shaw *et al.*, 2012), the potential existence of hydrologic thresholds in Prairie watersheds has received very little consideration in the literature.

1.1.2 Data scarcity and runoff modeling in data-poor watersheds

In addition to the multiple unknowns described above relating to temporal factors, spatial factors, and threshold behavior in watershed runoff generation, hydrologists are also faced with data scarcity. Models developed to predict runoff from precipitation inputs are typically heavily parameterized, requiring large amounts of data to function while the vast majority of watersheds across the globe are ungauged and data-poor – thus making hydrologic forecasting difficult (Candela *et al.*, 2012). As an alternative to these data-intensive physical models, empirical models and methodologies have been developed to predict the watershed precipitation-runoff relationship. These models remain popular and heavily used despite the availability of more sophisticated process-based models because of their relative ease-of-use and minimal data requirements. One of the most well-known and widely-utilized of these empirical models is the United States Soil Conservation Service (now the United States Department of Agriculture Natural Resources Conservation Service) curve number method.

What is commonly referred to as the US SCS-CN methodology is a runoff volume estimation technique for ungauged watersheds that requires only rainfall, watershed characteristics (hydrologic soil type, land use, land cover) and generalized antecedent moisture conditions as input data (United States Soil Conservation Service, 1989). The SCS-CN method consists of determining the average “curve number” for a watershed to allow for the prediction of the depth of the direct runoff for an event of a given depth of rainfall (Natural Resources Conservation Service, 2004). The SCS-CN method is used around the world (*e.g.* Aronica & Candela, 2007); however, as it was originally developed by a government agency, little academic research of its effectiveness and applicability has been undertaken, and few details of its origins and development are known (Ponce & Hawkins, 1996). Thus it remains unclear whether this global use is appropriate given the SCS-CN's empirical origins and weak physical basis, and development with consideration for the United States only.

1.1.3 Special challenges in the Prairie region

Prairie hydrology presents an additional layer of unknowns to the issues described above. While the challenges detailed above are equally true in a Prairie setting, little study considering these topics has taken place in such a peculiar landscape setting. Namely, a landscape for which snowmelt dominates annual precipitation inputs and the hydrologic regime, frozen ground seasonally limits infiltration of precipitation, near-zero relief diminishes topography's role in runoff generation, and intensive human modification of the landscape (including engineered stormwater control infrastructure) impact runoff generation in a way that has yet to be quantified.

1.2 Objectives and significance of research

The planned contribution of this M.Sc. thesis is to address some of the aforementioned questions and knowledge gaps by examining the spatio-temporal variability of the precipitation-runoff relationship across a system of nested Prairie sub-watersheds described below. Flooding is a seasonal concern on the Prairies; hence, information on how runoff thresholds are expressed could orient further Prairie hydrologic threshold studies, which could ultimately change water management and forecasting in near-level Prairie landscapes. Near-level Prairie landscape systems and artificial drainage networks have received little attention thus far in existing watershed runoff threshold behavior literature. As these thresholds are progressively being accepted as a basin signature (Spence, 2007), understanding them across all landscape types is of fundamental importance. Likewise, relatively little academic study concerning SCS-CN methodology has been conducted although this model is widely used by design engineers in the United States and around the world, and has been incorporated into modern runoff prediction models (Ponce & Hawkins, 1996; Arnold *et al.*, 1998). Validation of aspects of the SCS-CN model performance in a near-level Prairie landscape with experimental data would substantiate, or possibly refute, this extensive use in hydrologic engineering design.

The objective of the proposed research is to further understand the precipitation-runoff transformation using a combined field data and empirical modeling approach. Specifically, this MSc project aims to address the following questions:

(i) Do the same precipitation-runoff patterns identified on pristine, higher relief watersheds around the world exist in this engineered, near-level Prairie landscape? Specifically, the gaps in hydrological knowledge of low relief, heavily human-impacted landscapes such as those of the Prairies in south-central Canada are addressed by considering the following questions: How do watershed (1) land use and land cover and (2) topographic characteristics affect runoff? And (3) do hydrologic thresholds, as described in other landscape types, exist in the Prairies?

(ii) Does the empirical SCS-CN methodology adequately predict initial hydrological abstractions on Prairie landscapes?

1.3 Structure of thesis

The two chapters of this thesis which document original research (Chapters 2 and 4) are written as stand-alone manuscripts to be submitted for publication in the near future. Collectively, they encompass the results of hydro-meteorological data collection and analysis in the Catfish Creek Watershed, a near-level, agro-forested Prairie watershed in southern Manitoba. Chapter 2 details analysis pertaining to the search for physical runoff controls and threshold behaviour in the aforementioned watershed. Chapter 3 presents a preliminary synthesis and transition into Chapter 4. Chapter 4 combines a literature review and field data analysis to determine if the United States Soil Conservation Service Curve Number Method is representative of the physical processes taking place in the study watershed. Finally, Chapter 6 summarizes the overarching conclusions of this work and opportunities for future research.

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CHAPTER 2.

HYDROLOGIC DYNAMICS OF A LARGE PRAIRIE WATERSHED: LOOKING FOR RUNOFF CONTROLS IN AN ENGINEERED, MIXED USE LANDSCAPE

2.1 Abstract

Low relief, heavily human-impacted landscapes like those of the Prairies in south-central Canada have received little attention in previous hydrological research. Here, knowledge gaps are addressed by considering the following questions: How do watershed (1) land use and land cover and (2) topographic characteristics affect runoff? And (3) do hydrologic thresholds, as described in other landscape types, exist in the Prairies? Rainfall-runoff hydrographs at 12 gauging stations located in a 642 km^2, near-level, mixed land use and engineered Prairie watershed were analyzed for runoff controls and threshold behaviour. Rainfall-runoff parameters were calculated for each event. Average parameters were compared with topographic and land cover characteristics for the subwatershed upstream each gauging station. Surrogate measures of antecedent moisture conditions were calculated and examined in conjunction with event parameters via correlation analysis. Generally, lag times were short, initial abstraction correlated moderately with total event rainfall, and rainfall intensity correlated moderately with runoff magnitude. Subwatershed landscape characteristics did not influence average hydrograph characteristics. Results suggest that the predominant runoff generation mechanism is Hortonian overland flow; although a shift in the dominant runoff process was observed under certain conditions, as indicated by a marked increase in time of concentration of certain rainfall-runoff events. Watershed storage satisfaction and associated threshold behaviour were observed in only two of the subwatersheds during the study period. Prairie runoff generation processes were concluded to differ significantly from those of humid, pristine catchments of higher relief and a conceptual model is proposed with that regards.

2.2 Introduction

One of the main goals of hydrology is accurate runoff prediction to ensure the protection of people, infrastructure, and the water resource itself (Blöschl, 2013). Towards achieving that goal, many process hydrologists have been trying to answer the questions of how, and how much, precipitation becomes runoff (McDonnell, 2003), not only through the suggestion of different runoff generation mechanisms (*e.g.*, Horton, 1933; Betson, 1964; Hewlett and Hibbert, 1967; Dunne and Black, 1970; Mosley, 1979; Sklash and Farvolden, 1979) but also through the examination of potential control factors (*e.g.*, Ambroise, 2004; Bracken and Croke, 2007). Despite all those efforts, a complete understanding of the precipitation-runoff relationship remains elusive (McDonnell, 2003). Reasons often put forward to explain that incomplete understanding include the complex feedbacks and interactions between all involved processes (McDonnell *et al.*, 2007) as well as the lack of data from different parts of the World that are required to develop generalized theories and resolve the idiosyncrasies of single site or single watershed studies (McDonnell and Woods, 2004). Both recent and older studies have relied on spatially intensive measurements of surface and subsurface flow to advance process understanding (*e.g.*, Grayson *et al.*, 1997; Tromp-van Meerveld and McDonnell, 2006b; Jencso *et al.*, 2009); however, such measurements are impossible to replicate over large spatial scales.

In contrast to spatially intensive surface and subsurface flow measurements, hydrograph analysis is a more readily available method to assess the precipitation-runoff relationship. Hydrograph parameters, as the result of the integration of precipitation and runoff processes, are useful for inferring watershed behaviour and runoff generation controls. For example, the lag time is indicative of watershed flashiness, while the initial abstraction represents the watershed storage deficit to be satisfied before the initiation of runoff (Carey and DeBeer, 2008). Many spatial and temporal factors are known to influence hydrograph shape (Buttle, 2006). Precipitation characteristics (*e.g.*, duration, intensity and timing) as well as antecedent moisture conditions (*e.g.*, time elapsed since the preceding precipitation event) have been shown to significantly impact hydrograph parameters (Bracken and Croke, 2007; Singh, 1997). Numerous studies have also built lists of physical factors which impact hydrograph parameters, including watershed size (drainage area), watershed shape, topography, slope, geology, soil properties, land use and land cover (Jencso and McGlynn, 2011). Vegetative cover type is known to influence infiltration (Seyfried and Wilcox, 1995), and thus initial abstraction. Deforestation has been linked to greater discharges (Jones and Grant, 1996), while agriculture has been linked to increased and flashier responses to rainfall relative to otherwise similar non-agricultural catchments (Lana-Renault *et al.*, 2011; Pilgrim *et al.*, 1982). In high-relief watersheds, runoff generation has been strongly linked to topography (Anderson and Burt, 1978; Jencso and McGlynn, 2011). As for the hydrographs of engineered landscapes; *i.e.*, landscapes that have been physically altered by humans via increased drainage through ditching, diking of streams, road construction, etc.; they are typically marked by higher peak flows and shorter lag times relative to pristine landscapes (White *et al.*, 2003).

While all the aforementioned spatial and temporal factors determine the shape of the hydrograph, identifying which watershed characteristics exert the greatest influence on runoff generation remains challenging because the exact nature of how watershed structure influences watershed runoff is poorly understood (Jencso and McGlynn, 2011). Questions of scale and watershed heterogeneity make it unclear if previous findings regarding watershed behaviour apply equally well, if at all, to watersheds of different size, shape or location (Troch *et al.*, 2009). The existence of threshold hydrological behaviour further complicates process inference: indeed, the non-linearity of the precipitation-runoff relationship has been described by many over the past decades (*e.g.*, Dunne and Black, 1970; Mosley, 1979; Tsukamoto and Ohta, 1988; McDonnell, 1990; Woods and Rowe, 1996; Tani, 1997; Hutchinson and Moore, 2000; Weiler *et al.*, 2005; Zehe *et al.*, 2001; Tromp-van Meerveld and McDonnell, 2006a; Lehmann *et al.*, 2007; Spence, 2010; Detty and McGuire, 2010; Ali *et al.*, 2011; Ali *et al.*, 2013). Thresholds for initiation of flow have been identified within watersheds at the soil matrix, macropore, pipeflow, hillslope and catchment scales (Spence, 2010), and this threshold behavior has been observed in various landscapes around the world, among which are mountain foothills in Portugal (Doerr and Thomas, 2000); steep mountainous in western Canada (Hutchinson and Moore, 2000); gently sloping loess in Germany (Zehe *et al*., 2001); shield in subarctic Canada (Spence and Woo, 2003); steep hilly in the United States (Tromp-van Meerveld, 2004); steep mountainous in New Zealand (Graham and McDonnell, 2010); and the Prairie pothole region of south-central Canada (Shaw *et al*., 2012). These thresholds have been observed to range from 0.84 mm to 55 mm of rainfall for the initiation of runoff (Tromp-van Meerveld and McDonnell, 2006a), and they can result from a critical surface storage deficit (*e.g.*, Spence, 2007), bedrock topography storage deficit (*e.g.*, Freer *et al*., 2002; Tromp-van Meerveld and McDonnell, 2006b), or soil moisture storage deficit (*e.g.*, Zehe *et al*., 2005) that needs to be satisfied, or from the exceedance of rainfall intensity relative to infiltration capacity (Ali *et al*., 2013).

While the previously cited studies have contributed great, novel hydrologic knowledge, the direct transferability of this knowledge to less typical watersheds remains uncertain. Studies of runoff generation controls have traditionally taken place in pristine, forested, humid temperate catchments of at least moderate relief. However, the Prairie environments characterizing the southern portions of Alberta, Saskatchewan, and Manitoba (Canada), for example, present a sharp contrast to these pristine, forested, humid temperate environments: they can be described as engineered, agricultural, semi-arid landscapes of near-zero relief. Dominant Prairie runoff processes likely change seasonally in response to the seasonality of precipitation (snowfall versus rainfall), soil conditions (frozen in winter, saturated during spring runoff, dry during the summer months), and vegetative cover (seeded versus harvested agricultural land). Hence, while topography has historically been considered a dominant control on runoff generation (Anderson and Burt, 1978), and although recent research has challenged this status quo (*e.g.*, Grayson and Western, 2001; McDonnell, 2003; Devito *et al*., 2005), Prairie hydrologists are left wondering what the most important controls on Prairie runoff are in the absence of significant topographic relief and in the presence of significant human landscape modifications (*e.g.*, roads and drainage ditches). Similarly, the existence of threshold behaviours in the Prairies has only been documented in association with surface water storage in Prairie potholes (Shaw *et al*., 2012), while other hydrologic thresholds possibly unrelated to surface storage have received little consideration in the literature. Therefore, the goal of this study was to investigate precipitation-runoff relationships in an exhaustive manner in a typical, engineered Prairie watershed and to quantify how hydrologically similar or dissimilar these relationships are in comparison to those observed in other landscapes. Three questions were used to guide this investigation, namely:

(1) What is the influence of land use and land cover on Prairie runoff generation?
(2) What is the influence of topographical characteristics on Prairie runoff generation?
(3) Do rainfall thresholds exist for runoff generation in the Prairies, as they do in other landscape types?

2.3 Study area description

The 642 km^2 Catfish Creek watershed (CCW, also referred to as Designated Watershed 14 by the Provincial Government of Manitoba; Millar, 1974) is located in the southeast of the Province of Manitoba, Canada, and its outlet is located on Traverse Bay of Lake Winnipeg (Figure 2.1). The CCW is characterized as a low-relief, engineered, agro-forested watershed (~48% forest, ~37% cropland, ~13% wetland, ~2% other). Surface runoff is managed by a network of artificial drains in both the forested and cultivated portions of the watershed; these drain are maintained by landowners (first-order drains on private property), local municipal governments (first- and second-order drains on public land) and the Provincial government (all drains of third order and greater on public land). Without regular maintenance drains become choked by vegetation; thus periodically an excavator is used to clear the drains. Culverts are abundant in the watershed as they are used to connect drains beneath roads and access ways. Flow in most drains of the CCW is ephemeral.

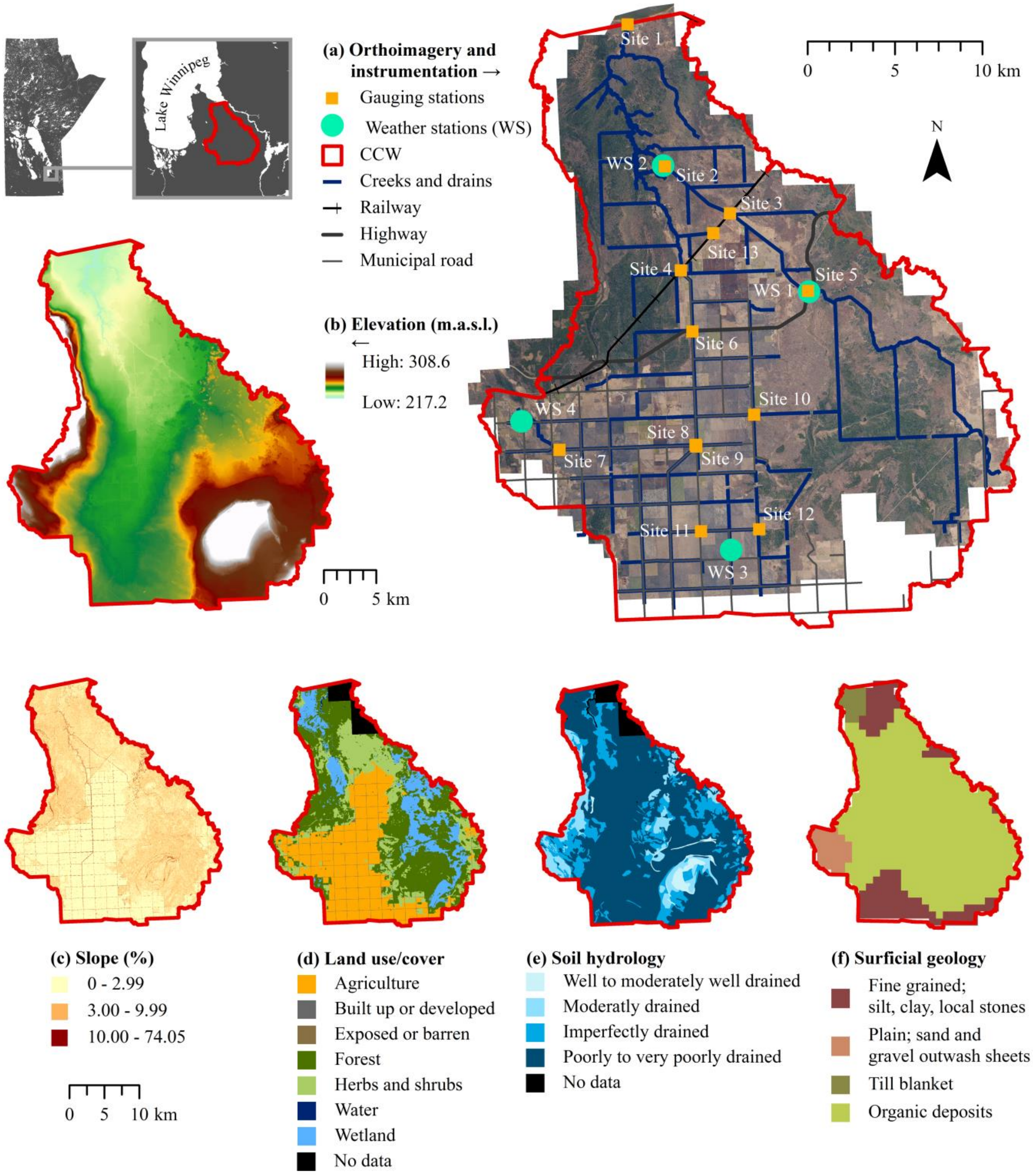

Figure 2.1: Location of the Catfish Creek Watershed in Manitoba; (a) instrumentation sites (orthoimagery from Manitoba Infrastructure and Transportation – Water Management and Structures (MIT-WMS, 2012), (b) digital elevation model (from MIT-WMS, 2012), (c) land slope, (d) land use and land cover (Agriculture and Agri-Food Canada, 2014), (e) soil hydrological descriptions (Western Land Resource Group - Agriculture and Agri-Food Canada (2002a-d), (f) surficial geology (GIS Map Gallery, 2006).

Natural mixed-forest and wetlands are present throughout the lower CCW, as well as on the higher-relief eastern portion of the upper watershed. To the west, the landscape is dominated by intensive, large scale agricultural operations on a near-level landscape. Soybeans and wheat are the most common crop types of the region (occupying ~ 32% and ~ 27% of the watershed's agricultural land in 2013, respectively; Agriculture and Agri-Food Canada, 2014). The region also stands out as producing the majority of the Province of Manitoba's sod (sod occupied ~ 7% of the watershed's agricultural land in 2013; Agriculture and Agri-Food Canada, 2014).

Data from the Manitoba Conservation Fire Program, the only agency collecting weather data in the CCW prior to 2013, indicates the average annual rainfall is 459 mm (for 1999 through 2013), the largest portion of which (~25%) falls in June. Inter-annual rainfall was highly variable, ranging from a low of 271 mm to a high of 669 mm during the 15 year record. The same dataset yields an average January temperature of -13.7°C, and an average July temperature of 24.3°C (temperature measured daily at 1300 hrs local time; Manitoba Conservation Fire Program, 2014). No historic snowfall record exists for the area. Annual potential evapotranspiration (PET), calculated using the Thornthwaite equation and average temperatures recorded in the CCW, is 1345 mm for 2013 and 1129 mm for the first eight months of 2014.

The CCW consists of generally low relief (less than 10 m) lacustrine clay plains between the Winnipeg River and the Kanipatenak, Murray, and Brightstone Sand Hills, which rise up to 50 m above the plain (Matile and Groom, 1987; Ecological Stratification Working Group, 1996). Overall, the watershed ranges in elevation from 220 m.a.s.l. at the outlet to 305 m.a.s.l. at the peak of the Brightstone Sand Hills (Canada Centre for Mapping, 1995; 1996). The most extensive soil type in the watershed is deep peat formed by paludification. Underlying these organic soils is typically calcareous lacustrine clay. In the area of the Catfish Creek itself in the northern CCW, peat is largely fibrous fenic and derived mainly from sedges. Immediately adjacent to the creek in the northern portion of the watershed is gleyed dark grey clay of the Framnes Series. In the southernmost portion of the watershed, clay-textured carbonated rego-humic gleysols of the Glenmoor Series predominate (Smith *et al*., 1967).

The majority (69% by area) of the soils of the CCW are described as “poorly” or “very poorly” drained by the Canadian Soil Information Service (Western Land Resource Group - Agriculture and Agri-Food Canada, 2002a-d). The eastern portion of the watershed is underlain by massive granitic and gneissic Archean bedrock of the Precambrian Shield. To the west, the bedrock is formed of interbedded shale and quartzite sand layers of the Ordovician Winnipeg Formation (Manitoba Geological Survey, 2012).

2.4 Methods

2.4.1 Field data

In early 2013, instruments for hydrometric and meteorological monitoring were deployed throughout the CCW. In-stream water levels were monitored using laboratory-calibrated Odyssey^{TM} capacitive water level loggers, logging data at 15 minute intervals from initial spring thaw to winter freeze-up. All loggers were placed in stilling wells constructed from ABS pipes and screened along their entire length. In total, in-stream water level loggers were installed at 13 gauging sites, monitoring nested subwatersheds of a variety of sizes and land uses (summarized in Figure 2.2). The extent of each subwatershed was defined topographically using a filled, 1 m resolution LiDAR dataset acquired in 2012. Topographic characteristics (slope and elevation statistics) of the subwatersheds were calculated from the LiDAR digital elevation model (DEM). Land use and land cover, pedological, surficial geology, and drainage density statistics were also calculated for each subwatershed using a GIS and existing data from the Manitoba Land Initiative (Western Land Resource Group - Agriculture and Agri-Food Canada, 2002a-d) and Manitoba Geological Survey (Manitoba Geological Survey, 2012) databases. Water level loggers were removed in late October 2013 (at freeze-up) and re-deployed six months later for the 2014 open water period.

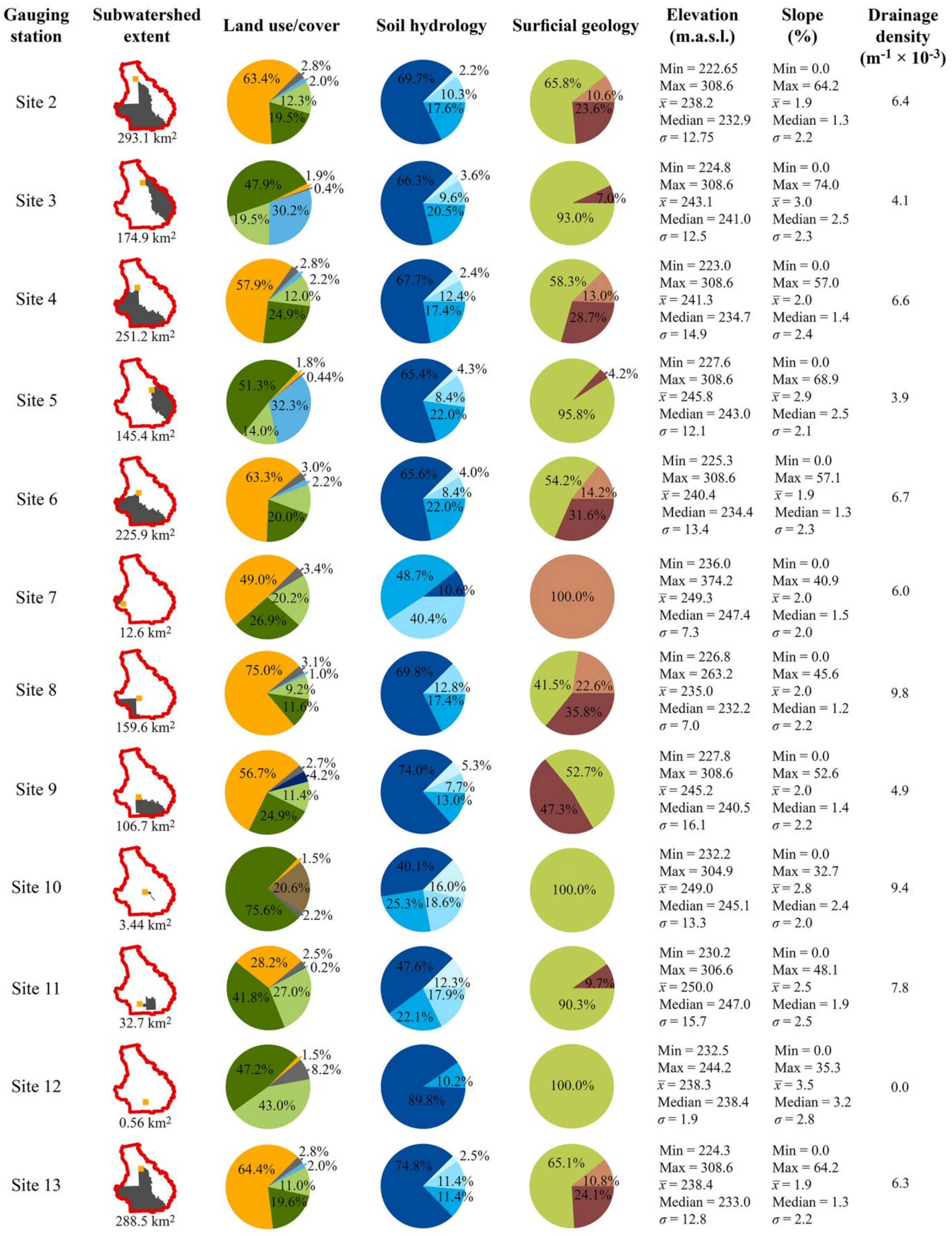

Figure 2.2: Characteristics of the topographically defined study subwatersheds of the Catfish Creek Watershed. For the land use/cover, soil hydrology and surficial geology pie charts, the colors follow the same legends used in Figure 2.1. All government-recognized streams and drains were included in the computation of the drainage density.

Since spring 2013, weather conditions in the CCW have been monitored year-round by a network of 4 HOBO^{TM} U30-GSM data logging weather stations with sensors recording rainfall (0.2 mm resolution), wind speed, wind direction, temperature, relative humidity and atmospheric pressure. Data were logged at 1 minute intervals. Rain gauge calibration was confirmed at the beginning of the 2013 and 2014 open water seasons.

2.4.2 Hydrograph analysis

Rainfall events were delineated manually for the period of March 2013 through August 2014. Any measured amount of rainfall was designated a rainfall event. Runoff events were also delineated at 12 of the 13 gauging stations; data from the gauging station at the outlet of the CCW was not analyzed due to frequent backflow into the mouth of the Creek from Traverse Bay. Runoff events at each retained gauging station were associated with rainfall events recorded at the nearest weather stations. Certain rainfall and runoff events were excluded from analysis, including rain-on-snow events, rainfall events during the spring freshet period, and hydrograph fluctuations that occurred independent of any rainfall event recorded at the nearest weather station. The remaining events occurred during the months of May through August in 2013 and 2014 (hereafter referred to as the “study period”). Three gauging sites experienced an interruption in data collection during the 2014 study period: reasons for such interruptions were human interference, animal interference, and a stilling well partially dislodged following a rainstorm. Thus, 2014 results specific to these sites are treated more cautiously as they are based on fewer events than the remaining 9 sites.

For every event hydrograph, 10 rainfall and runoff event parameters were calculated. These parameters are defined as illustrated in Figure 2.3. Rainfall begins at time t_{RFi}, and continues to t_{RFf}. Duration of the rainfall event (T_{RFd}) is given by $T_{RFd} = t_{RFf} - t_{RFi}$. Total event rainfall ($RF$) is divided by T_{RFd} to get the average event rainfall intensity (RF_I). Initial abstraction (RF_{abst}) is the portion of event rainfall which fell prior to the initial runoff hydrograph response (t_{WLi}). The end of the storm hydrograph (t_{WLf}) is defined at the inflection point of the recession limb, and the duration of the runoff event given by $T_{WLd} = t_{WLf} - t_{WLi}$. Two runoff response lag time parameters were calculated, specifically the response lag time (T_r) equal to the time elapsed between the initial rainfall pulse and the initial hydrograph response ($T_r = t_{WLi} - t_{RFi}$), and the time to peak (T_p) equal to the time elapsed between the initial rainfall pulse and the time of peak runoff (t_{WLp}) ($T_p = t_{WLp} - t_{RFi}$). The magnitude of each runoff event was inferred using two parameters, namely (i) the difference between the peak event water level and the water level immediately preceding the event (ΔWL), and (ii) the area under the event hydrograph curve. While ΔWL only provides information about pre-event and peak event conditions, the area under the event hydrograph curve corresponds to the integral of the hydrograph function and is assumed to indicate the total volume of event flow (Dingman, 2002). Finally, the time of concentration (T_c), specifically the time required for runoff to arrive at the outlet (gauging station) from the most hydraulically distant point of the subwatershed, was obtained by computing the difference $t_{WLf} - t_{RFf}$. When short, computed T_c values were considered meaningless; as weather stations were not co-located with each study site gauging station, it was possible for the end of event rainfall measured at the nearest rain gauge to occur either before or after the end of event rainfall at the water level gauging station. The spatial variability of rainfall (especially the spatial differences in the duration of rain bursts) were therefore thought to lead to a significant number of low T_c values.

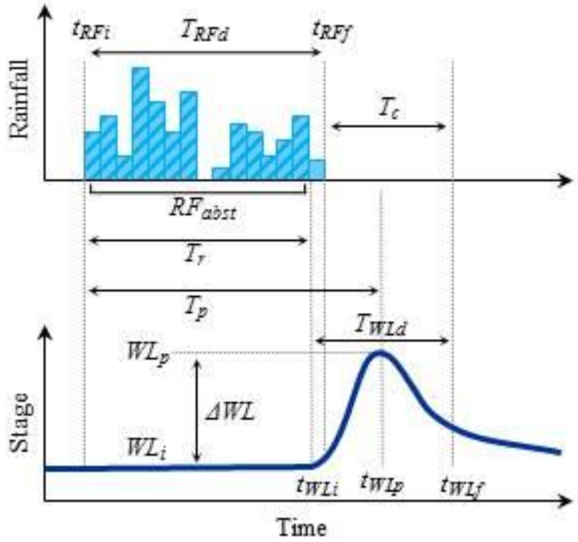

Figure 2.3: Rainfall and hydrograph parameters considered for analysis. TRFd = duration of rainfall event, tRFi = start time of rainfall event, tRFf = end time of rainfall event, Tc = time of concentration, RFabst = initial abstraction, TWLd = duration of runoff event, tWLi = start time of runoff event, tWLf = end time of runoff event, tWLp = time of peak event water level, WLi = initial water level, WLp = peak water level, ΔWL = maximum event water level fluctuation.

In addition to the aforementioned event parameters, surrogate antecedent moisture variables were calculated for each runoff event to infer the impact of antecedent rainfall conditions (ARFs) on watershed behaviour. Total rainfall in the 1 hr, 3 hrs, 6 hrs, 12 hrs, 24 hrs, 2 days (48 hrs), 3 days (72 hrs), 6 days (144 hrs), 12 days (288 hrs), and 24 days (576 hrs) preceding the beginning of event rainfall was estimated ($ARF_{xhrs/days}$). For each event, the sum of $ARF_{xhrs/days}$ and event rainfall RF (*i.e.*, $ARF_{xhrs/days}+RF$) and the time elapsed since the last rainfall event were also computed, for the purpose of threshold identification.

All runoff event parameters were correlated with all rainfall event parameters and ARF variables. The non-parametric Spearman rank correlation coefficient (r_s) was used to measure the statistical dependence of the variables. Figures generated for each variable pairing (*i.e.*, bivariate scatter plots) were assessed visually. Correlations between the mean, median, and standard deviation of hydrograph parameters and summary watershed characteristics (mean, minimum, maximum and standard deviation of slope and elevation, percent watershed area occupied by 7 land use/cover categories, percent watershed area occupied by 4 soil drainage classifications, and percent watershed area occupied by the 4 surficial geology types that make up the CCW) were also calculated.

Certain limitations presented themselves throughout this study; oftentimes as a result of the unique qualities of the Prairie landscape. Automated hydrograph separation using various algorithms proved impossible; the strong diurnal fluctuations of water levels measured in the drains of the CCW were regularly identified as runoff events by the algorithms in question. Further to this, the graphical separation of the hydrograph into eventflow and baseflow components using the fixed-interval, sliding-interval, or local-minimum methods produced unrealistic results; specifically, eventflow depths greater than event rainfall depths. This was attributed to the lentic nature of the drains: post spring runoff, water was typically observed as stagnant (especially in 2013, when most sites dried completely by the end of August). Event runoff coefficients (defined as total event flow divided by total event precipitation) were therefore not computed; the two measures of event runoff magnitude retained for this study, *i.e.* ΔWL and the area under the event hydrograph curve, were chosen because they did not rely on specific assumptions about dominant runoff generation processes. Spring runoff was not included in the current analysis as the complexities of snowmelt, rain-on-snow events and runoff over frozen soils were beyond the scope of this study.

2.5 Results

The 2013 and 2014 field seasons illustrated the inter-annual variability of hydrologic conditions generally observed in the Prairies, with short, alternating cycles of drought and deluge (Bonsal *et al.*, 2013). Average rainfall measured in the CCW during the months of May through August 2013 was 176.6 mm while the same period received an average of 356.8 mm of rainfall in 2014. Extensive summer rainfall-triggered flooding occurred throughout Manitoba in 2014, dramatically reinforcing this contrast. Because of this, statistical analysis was conducted on the years 2013 and 2014 separately and then in combination, producing at times contrasting results.

2.5.1 Temporal variability of rainfall and hydrological conditions

In both 2013 and 2014, the degree of spatial variability of rainfall was high. Standard deviation from the mean of total seasonal rainfall was 23.1 mm in 2013 and 46.0 mm in 2014 (for a relative standard deviation of 13% for both years). In total, 161 rainfall events were recorded for analysis during the study period. Not all 161 rainfall events were observed at each weather station, and not all rainfall events produced a runoff event. Figure 2.4 depicts the frequency of rainfall event totals by weather station and year, while Figures 2.5a and 2.5b show the rainfall hyetographs and runoff hydrographs associated with the 2014 event #48 (a typical event) in the lower and upper CCW, respectively. Note that while Weather Station 2 and Weather Station 3, the two weather stations of the lower CCW, are located only 11 km apart, they exhibit different patterns in rainfall timing and very different total event rainfall amounts (17.2 mm versus 0.4 mm).

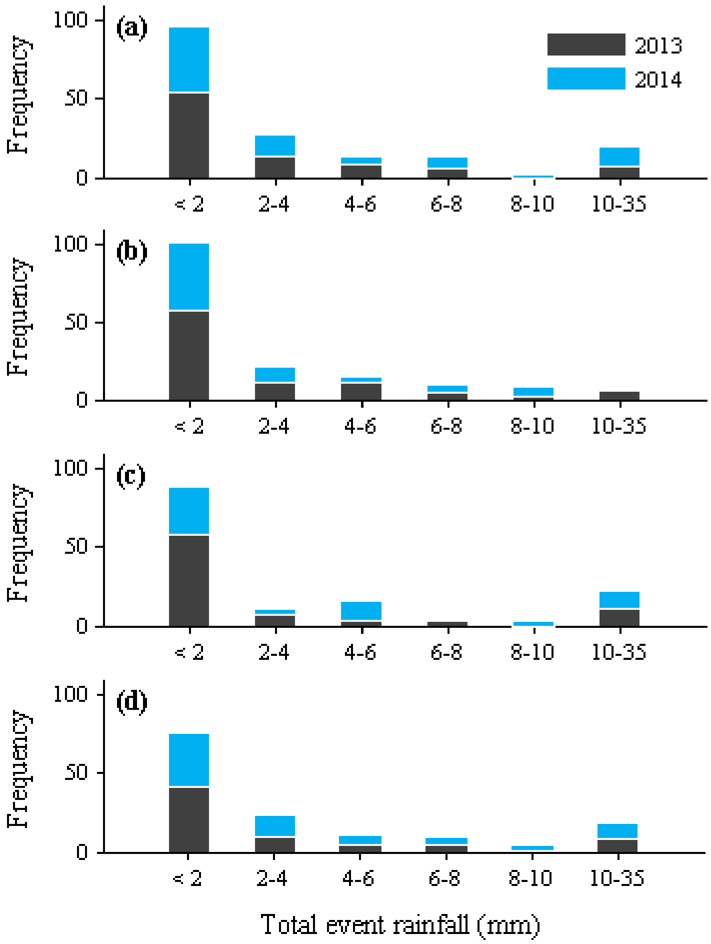

Figure 2.4: Frequency of total event rainfall sums recorded by each of the 4 weather stations located in the CCW; (a) weather station 1, (b) weather station 2, (c) weather station 3, (d) weather station 4.

Event hydrographs presented several qualitative commonalities noted during the event delineation process: the studied subwatersheds are flashy, with water level responses to rainfall typically being near-immediate (low T_r values). Runoff events are also generally short-lived, with water levels quickly receding to pre-event levels soon after peak time t_P (low T_c values). Event-specific hydrograph behaviour also varied by site: in Figure 2.5, for example, the water level at Site 5 responds almost immediately to rainfall, while the other sites exhibit no response. Also, although Site 3 is located 7 km directly downstream from Site 5, event water from Site 5 does not appear to travel to Site 3. This lack of longitudinal connection between upstream and downstream sites was typical through the study period.

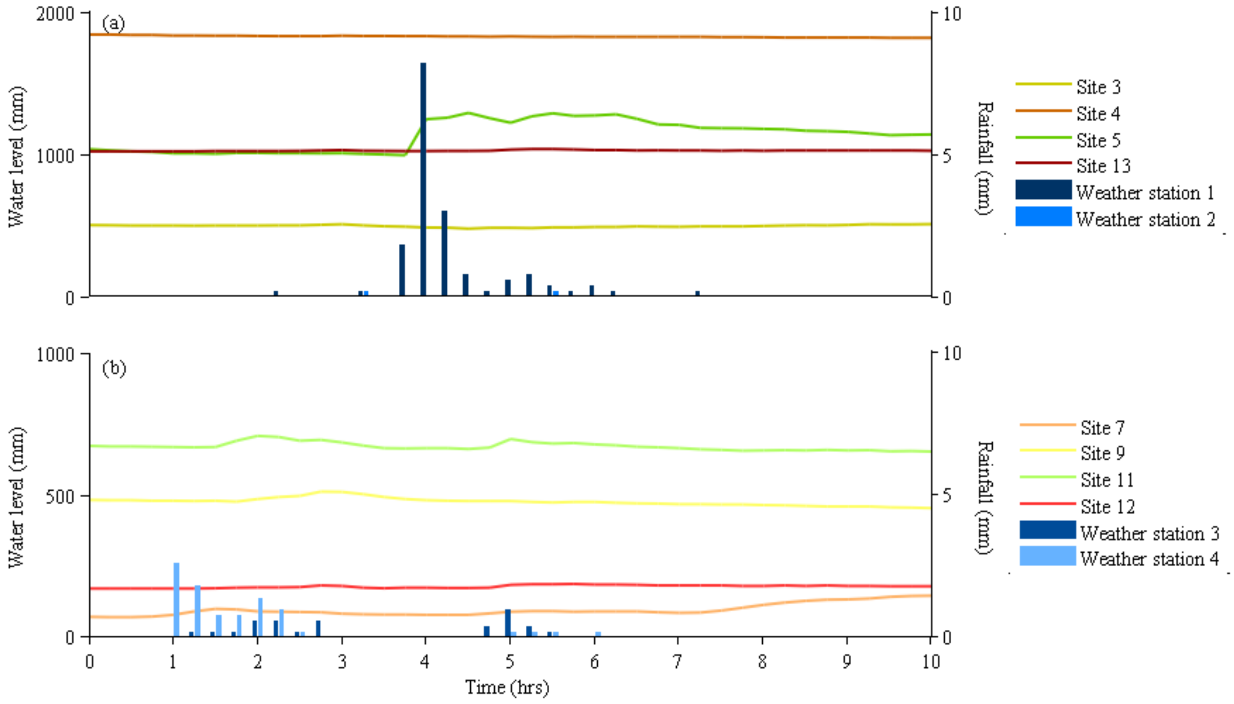

Figure 2.5: Rainfall hyetographs and runoff hydrograph for the 2014 event #48, occurring in the morning of 24 June. Comparison is made between sites located in the (a) lower and (b) upper CCW.

2.5.2 *Correlations between average runoff characteristics and watershed characteristics*

Correlation analysis between mean, median and standard deviation of hydrograph parameters and subwatershed characteristics yielded no clear connection between watershed structure and hydrograph characteristics. Both in individual study years and the entirety of the study period, no significant ($p < 0.05$) relationship was found between the extent of soils of various drainage classifications, subwatershed area or drainage density, and any hydrograph characteristic. The spatial extent of some surficial geology types and land use/land cover types seemed somewhat influential on runoff generation, but inconsistently among hydrograph parameters and the time period being considered. Topographic characteristics correlated somewhat consistently to hydrograph characteristics. In 2013, a significant negative correlation was found between the standard deviation of slope and certain hydrograph characteristics (median runoff event duration, median lag to peak, median time of concentration; r_s = -0.65, -0.78, -0.58, respectively). These correlations were not found in the 2014 dataset, or in the combined 2013-2014 dataset. In 2014, subwatershed maximum elevation and range of elevation negatively correlated to median ΔWL fluctuation (r_s = -0.62, -0.66, respectively). A significant relationship was not found in 2013, or with the 2013-2014 combined dataset. The 2013-2014 combined dataset did however show significant negative correlation between both median T_{WLd} and median T_c and the standard deviation of subwatershed slope (r_s = -0.60, and r_s = -0.69, respectively).

2.5.3 Characterization of event-specific rainfall-runoff relationships

Correlation analysis between event runoff and rainfall parameters by gauging station produced results generalizable for the CCW: typically, when a significant correlation was found between two event parameters at one site, a significant correlation between the same two parameters was also found at other sites for all the considered time periods (*i.e.*, 2013 only, 2014 only, or 2013-2014). Results of rainfall and runoff correlation analysis are summarized in Tables 1 (2013 data), 2 (2014 data) and 3 (combined 2013-2014 data). In general, correlations were slightly higher for 2013 alone and slightly lower for 2014 alone, with correlations for the 2013-2014 combined dataset falling in between the two. Results are discussed more specifically below, with strong Spearman rank correlation coefficients correlations defined as $|r_s| \geq 0.7$, moderate correlations as $|r_s|$ = 0.45-0.7, and weak correlations as $|r_s| \leq 0.45$; with a 95% significance level.

Table 2.1: Significant ($p < 0.05$) results of rainfall and runoff correlation analysis for 2013. Dashed cells correspond to non-significant correlations.

Significant rs values (p < 0.05)

Site no.	T_{WLd}				T_r				T_p			
	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	0.42	0.41	-	-	-	-	-	0.74	0.51	0.63	-	-
3	-	-	-	-	-	-	-	0.53	-	-	-	-
4	0.61	0.61	-	-	-	-	-	0.49	-	0.77	-	-
5	0.52	0.38	-	-	-	-	-0.40	-	-	0.53	-0.43	-
6	0.43	0.63	-	-	0.50	0.40	-	0.75	0.49	0.69	-	-
7	0.48	0.34	-	-	-	-	-	0.52	0.34	0.50	-	-
8	0.61	0.55	0.35	0.34	-	-	-	0.78	0.46	0.46	-	0.49
9	0.61	0.53	-	-	-	-	-	0.64	0.44	0.63	-	-
10	-	0.59	-	-	-	-	-	0.62	0.41	0.46	-	0.45
11	0.56	0.66	-	-	-	-	-	0.75	0.48	0.56	-	-
12	0.48	0.51	-	-	0.39	0.40	-	0.64	0.44	0.61	-	-
13	0.71	-	0.68	-	-	-	-	-	-0.48	-	-	-

Site no.	T_C				ΔWL				Area under curve			
	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	-	-	-	-	0.63	0.40	0.34	0.42	0.61	0.44	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	0.62	0.45	0.40	0.59	0.81	0.57	-	0.46
5	-	-	0.47	-	0.92	0.61	0.54	0.51	0.76	-	0.50	0.44
6	-	-	-	-	0.68	0.49	0.38	-	0.67	0.66	-	-
7	-	-	-	-	0.65	0.46	0.47	0.46	0.58	-	0.46	0.47
8	-	-	-	-	0.87	0.64	0.66	0.36	0.78	0.55	0.60	0.42
9	-	-	-	-	0.63	0.51	0.44	-	0.63	0.38	0.52	-
10	-	-	-	-	0.60	0.53	-	0.51	0.50	0.39	-	0.42
11	-	-	-	-	0.78	0.54	0.60	-	0.67	0.56	0.44	-
12	-	-	-	-	0.76	0.59	0.55	0.48	0.80	0.74	0.42	0.47
13	0.62	-	0.75	-	0.62	0.39	0.33	-	0.61	-	0.63	-

Table 2.2: Significant ($p < 0.05$) results of rainfall and runoff correlation analysis for 2014. Dashed cells correspond to non-significant correlations.

Significant rs values ($p < 0.05$)

Site no.	T_{WLd}				T_r				T_p			
	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	-	0.92	-	-	-	-	-	0.80	-	0.73	-	-
3	0.69	0.70	-	-	-	0.46	-	0.81	0.76	0.77	-	-
4	0.65	0.75	-	-	-	-	-	0.83	0.70	0.80	-	-
5	0.64	0.62	-	-	0.31	0.33	-	0.64	0.66	0.77	-	-
6	0.50	0.43	-	-	-	0.45	-	0.82	0.61	0.58	-	0.46
7	0.53	0.65	-	0.42	0.50	0.56	-	0.92	0.60	0.71	-	0.59
8	0.52	0.62	-	-	-	-	0.51	0.86	0.53	0.57	-	-
9	0.41	0.66	-	-	0.49	0.42	-	0.77	0.39	0.55	-	0.39
10	0.96	0.93	-	-	-	-	-	0.83	0.92	0.92	-	-
11	0.63	0.65	-	-	-	-	-	0.81	0.72	0.58	-	0.39
12	0.63	0.52	-	-	0.56	-	0.36	0.83	0.65	0.64	-	0.34
13	0.58	0.71	-	-	-	-	-	0.78	0.61	0.75	-	-

Site no.	T_C				ΔWL				Area under curve			
	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	-	-	-	-	0.47	-	0.58	-	0.82	0.83	-	-
3	0.64	0.58	-	-	0.76	0.64	0.33	-	0.71	0.67	-	-
4	-	-	-	-	0.45	0.42	-	-	-	0.73	-	-
5	-	-	-	-	0.92	0.69	0.56	-	0.84	0.58	0.35	-
6	-	-	-	-	0.47	0.28	0.34	-	0.56	-	-	-
7	0.36	0.37	-	0.54	0.53	0.31	0.33	-	0.60	0.47	-	-
8	-	-	-	-	0.37	0.34	-	-	0.59	0.56	-	-
9	-	-	-	-	0.47	0.41	-	-	0.56	0.55	-	-
10	-	-	-	-	0.59	0.46	-	-	0.89	0.82	-	-
11	-	-	-	-	0.49	0.34	0.26	-	0.69	0.58	-	-
12	0.40	-	0.56	-	0.53	0.38	0.25	-	0.59	0.53	-	-
13	-	-	-	-	0.63	0.57	0.28	-	0.61	0.66	-	-

Table 2.3: Significant ($p < 0.05$) results of rainfall and runoff correlation analysis for the entire 2013-2014 study period. Dashed cells correspond to non-significant correlations.

Significant r_s values ($p < 0.05$)

	T_{WLd}				T_r				T_p			
Site no.	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	0.28	0.48	-	-	-	-	-	0.81	-	0.63	-	0.29
3	0.51	0.61	-	-	-	-	-	0.83	0.49	0.62	-	-
4	0.58	0.68	-	-	-	0.40	-	0.67	0.51	0.77	-	-
5	0.60	0.54	-	-	0.21	0.29	-	0.86	0.51	0.70	-	-
6	0.45	0.55	-	-	0.29	0.33	-	0.91	0.56	0.66	-	0.38
7	0.48	0.55	-	0.40	0.30	0.45	-	0.85	0.44	0.63	-	0.50
8	0.53	0.57	-	-	-	-	-	0.85	0.44	0.50	-	0.30
9	0.45	0.54	-	0.27	-	-	-	0.78	0.36	0.51	-	0.34
10	-	0.55	-	-	-	-	-	0.77	0.42	0.57	-	0.46
11	0.57	0.63	-	-	-	-	-	0.86	0.53	0.51	-	0.32
12	0.56	0.51	-	0.32	0.41	0.34	-	0.90	0.55	0.61	-	0.40
13	0.48	0.39	-	0.40	-	-	-	0.82	0.32	0.60	-	-

	T_C				ΔWL				Area under curve			
Site no.	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}	RF	TRF_d	RF_I	RF_{abst}
2	-	-	-	0.34	0.33	0.29	-	0.56	0.40	0.48	-	0.41
3	0.36	0.45	-	-	0.52	0.35	0.30	-	0.57	0.56	-	-
4	-	-	-	0.34	0.46	0.38	0.21	0.41	0.62	0.65	-	0.35
5	0.21	-	-	0.32	0.93	0.66	0.56	-	0.82	0.50	0.40	-
6	-	-	-	0.35	0.48	0.31	0.33	-	0.61	0.57	-	-
7	0.33	0.34	-	0.48	0.51	0.34	0.33	0.41	0.55	0.44	0.25	0.45
8	-	-	-	-	0.51	0.40	0.29	-	0.57	0.47	0.28	-
9	-	-	-	-	0.50	0.41	0.24	-	0.57	0.45	-	-
10	-	-	-	-	0.55	0.48	-	-	0.49	0.45	-	-
11	-	-	-	-	0.53	0.34	0.36	-	0.64	0.54	0.28	-
12	0.34	-	0.42	0.31	0.59	0.41	0.35	0.51	0.68	0.61	0.25	0.43
13	-	-	-	0.39	0.62	0.52	0.30	-	0.50	0.40	-	-

The parameter which most strongly correlated with the runoff event magnitude measures (*i.e.*, ΔWL and the area under the storm hydrograph curve) was *RF*. The strength of this relationship varied from site to site from a low of r_s = 0.33 (Site 2) to a high of r_s = 0.93 (Site 5) for *RF* and ΔWL, and from a low of r_s = 0.40 (Site 2) to a high of r_s = 0.82 (Site 5) for *RF* and the area under the storm hydrograph in 2013. ΔWL also demonstrated weak to moderate correlation to RF_I, particularly in 2013, when r_s values ranged from 0.33 to 0.66 (average: 0.47) for 10 of the 12 examined sites. However, the area under the hydrograph curve correlated more weakly with RF_I, and at fewer sites. Significant correlations between the same parameters were also found in the 2014 and 2013-2014 datasets, though they tended to be only weak to moderate in strength.

The highest correlations coefficients were found when RF_{abst} was correlated with T_r, with nearly all sites characterized as having a strong relationship; r_s ranged from 0.67 to 0.90 in the 2013-2014 study period as a whole (these correlation coefficients were slightly higher in 2014 and slightly lower in 2013). However, no other statistically significant correlations involving what were typically very low T_r values (median values by study site ranged from 30 to 75 minutes) were found. RF_{abst} was found to correlate moderately and positively with *RF* at all gauging sites (r_s = 0.38-0.75) in 2013. In 2014, this changed to 5 of 12 sites (r_s = 0.40-0.77). Overall in the combined 2013-2014 study period, correlation of RF_{abst} and *RF* were weak.

2.5.4 Impact of ARFs on event-specific rainfall-runoff relationships

Correlation analyses of $ARF_{xhrs/days}$ with various hydrograph parameters throughout the study period identified significant relationships inconsistently among sites and were less generalizable throughout the CCW than rainfall-runoff parameter analysis. Generally, the strongest relationships between ARFs and rainfall-runoff parameters were found when 2013 alone was considered, with relationships found to be substantially weaker or absent in the 2014 dataset and the combined 2013-2014 dataset. In 2013, most sites demonstrated some relationship (positive or negative) between ARFs and runoff magnitude; ARF_{1hr} and ARF_{3hrs} correlated weakly to moderately with ΔWL (r_s = 0.35-0.58 at 9 of 12 sites) while half the study sites showed weak to moderate correlation with the area under the event hydrograph. The relationship between ARFs and measures of runoff magnitude was weak to absent in the 2014 dataset or the combined 2013-2014 dataset. Site 12 behaved uniquely, with hydrograph parameters that were influenced by ARFs computed over longer temporal windows (*i.e.*, temporal windows of 1 day and more): ΔWL showed moderate negative correlation with ARF_{24hrs}, ARF_{48hrs}, and ARF_{3days} (r_s = -0.32, r_s = -0.40, and r_s = -0.34, respectively).

RF_{abst} also presented a counterintuitive relationship with ARFs; correlations with ARF_{3hrs} were weakly to moderately positive at most sites in 2013 (r_s = 0.36-0.75 at 10 of 12 sites). However, correlations were found at fewer sites as the temporal window widened. The expected negative correlations between RF_{abst} and ARFs were only found at Site 4, notably when ARF_{3hrs} and ARF_{24hrs} were considered (r_s = -0.48 in both cases). In 2014 and 2013-2014, significant correlations were fewer and weaker. ARFs were generally found to be unrelated to the other rainfall-runoff parameters considered here (T_{WLd}, T_r, T_p, T_c). While individual sites demonstrated weak to moderate correlation with some of these parameters at specific temporal windows in 2013, significant correlations were virtually absent in 2014 and for the combined 2013-2014 dataset. Time elapsed since the last rainfall event was found to be generally unrelated to hydrograph parameters.

Upon visual analysis of all hydrograph parameters plotted against all hyetograph parameters for all sites for the entirety of the study period (*i.e.*, 2013-2014), threshold behaviour was found to be almost entirely absent. Indeed, basic rainfall-runoff scatter plots make it clear that similar amounts of rainfall can generate very different runoff responses from one event to another. Although variable ARFs are generally assumed to be responsible for variable runoff responses to rainfall events of similar magnitude, the scatter in the data here is not clearly relatable to ARFs. This is evident in the scatter plots of Figures 2.6 and 2.7 depicting total event rainfall plotted against runoff event magnitude with symbols colour-coded according to ARF_{3days}. Threshold behaviour was observed at two study sites, and in both instances the threshold was of the "hockey stick" shape (Ali *et al.*, 2013): the event rainfall-runoff magnitude (*i.e.*, area under the storm hydrograph curve) relationship at Site 3 had a ~ 20 mm threshold with two outliers; while upstream Site 5 had an ~ 18 mm double-trajectory threshold (see Figure 2.7). Also at Site 5, runoff behavior is near-linear when total event rainfall is plotted against ΔWL (see Figure 2.6). However, like at all other sites, these relationships are unaffected by the antecedent moisture conditions portrayed by ARF variables. When hydrograph timing parameters are considered in place of ARFs, a clearer relationship emerges in the scatter plots. Figure 2.8 depicts the same rainfall-runoff relationship as Figure 2.7, but symbols are colour coded based on T_c rather than ARFs and a logarithmic y-axis is used for better clarity. Figure 2.8 not only shows that the largest magnitude runoff events are generally those with longer T_c, but also that events of longer T_c are often those of high runoff but low rainfall which appear as outliers in rainfall-runoff plots.

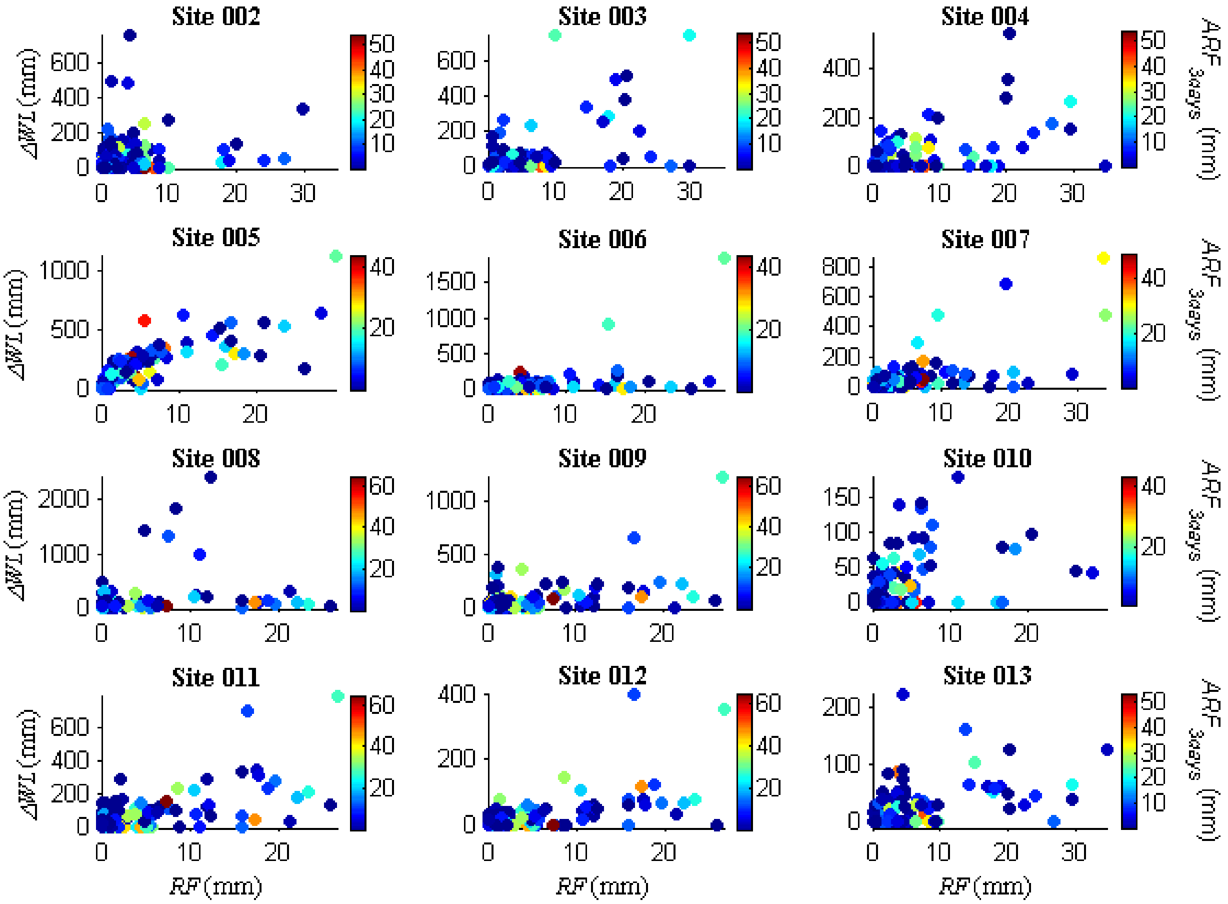

Figure 2.6: Event rainfall-runoff relationship by study site for the entire study period (2013-2014), with runoff magnitude inferred by the difference between peak event stage and pre-event stage. Colour coding is proportional to the cumulative rainfall measured in the 3 days preceding the rainfall event. x-axis and y-axis limits are different in each scatter plot.

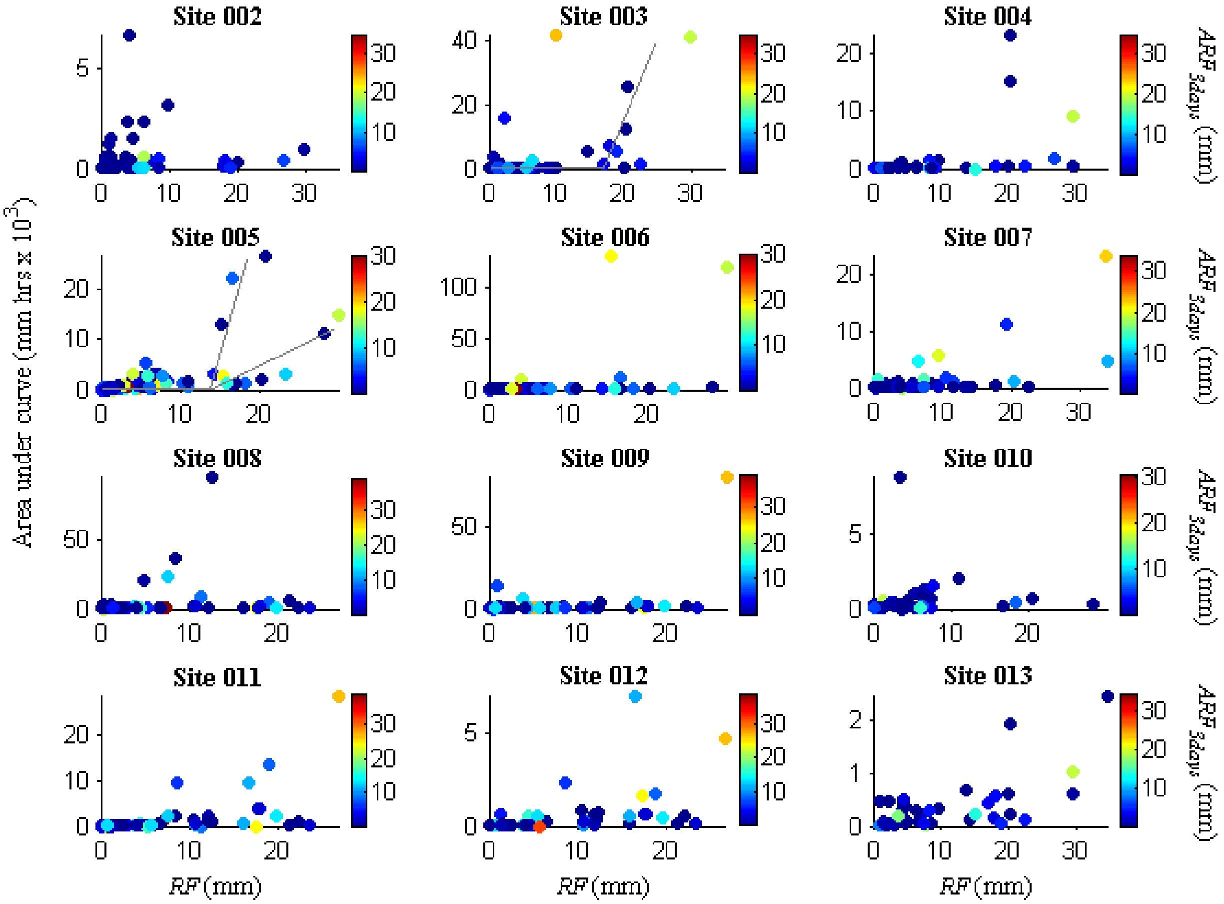

Figure 2.7: Event rainfall-runoff relationship by study site for the entire study period (2013-2014), with runoff magnitude inferred by the area under the event hydrograph. Colour coding is proportional to the cumulative rainfall measured in the 3 days preceding the rainfall event. x-axis and y-axis limits are different for each scatter plot. Where present, threshold behaviours are highlighted with gray lines.

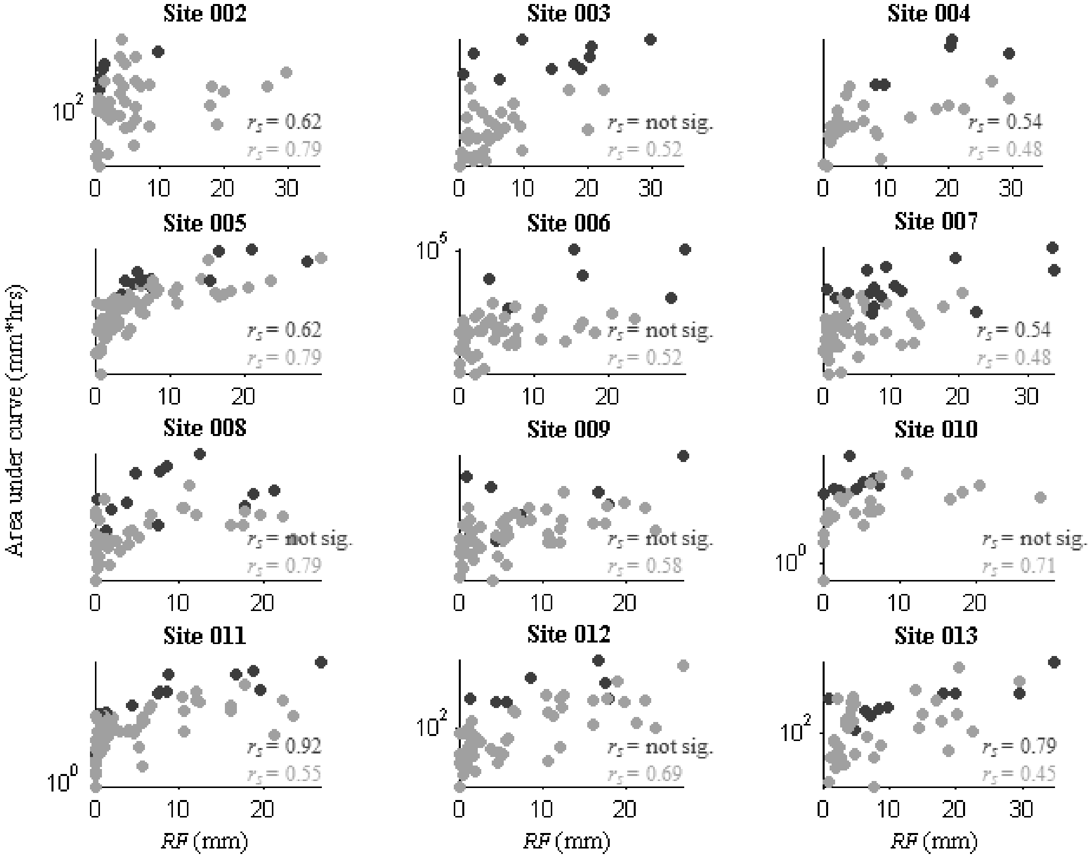

Figure 2.8: Event rainfall-runoff relationship by study site for the whole study period (2013-2014), with runoff magnitude inferred by the area under the event hydrograph. Colour coding indicates Tc by event, with Spearman correlation coefficients rs given for events with Tc > 10 hrs (darker points) and events with Tc ≤ 10 hrs (lighter points). x-axis and y-axis limits are different for each scatter plot; y-axis is logarithmically scaled.

2.6 Discussion

2.6.1 What is the influence of land use and land cover on Prairie runoff generation?

Results of hydrograph analysis suggest that landscape characteristics do not play a significant role in runoff dynamics in the CCW. Strong correlations between pedologic, geologic and land use/cover indices and summary statistics of hydrograph parameters are mostly non-existent. It was expected that forested subwatersheds, where greater interception slows the arrival of rainfall to the ground and likely also to the stream itself, would exhibit larger T_r than agricultural catchments (*e.g.*, Lana-Renault *et al*., 2011). However, this was not the case in the CCW where T_r was uniformly short. Median T_r values for the studied subwatersheds range from only 30 to 75 minutes, without strong differentiation with dominant subwatershed land cover. Most field studies on the land use/cover control of runoff generation have been conducted on watersheds several orders of magnitude smaller than the larger subwatersheds considered here (*e.g.*, Burch *et al*., 1986, Lana-Renault *et al*., 2011); hence, it is difficult to assess whether these results are comparable to those of non-Prairie watersheds, or if the absence of a relationship between land use/cover and hydrograph parameters is the result of scale effects (*i.e.*, larger watersheds are typically more heterogeneous and thus the effect of a given land use/cover type is lost in the integration of many different landscape processes (Pilgrim *et al*., 1982)).

2.6.2 What is the influence of topographical characteristics on Prairie runoff generation?

The relationship between subwatershed topographic characteristics and summary statistics of hydrograph parameters is weak. The only topographic characteristic which showed significant correlation with any hydrograph parameters was the standard deviation of subwatershed slope with various median hydrograph parameters; elevation statistics and subwatershed area showed no correlation with hydrograph parameters. Due to the generally low relief of the CCW, subwatershed slope statistics are heavily influenced by the engineered drains and drainage density rather than natural topography, *i.e.* local slopes are mostly high in the vicinity of the man-made drains due to the sloping design of those drains. In Figure 2.1(c), it can be seen that the only portion of the CCW where natural topographic variation is widespread is to the southeast; therefore, only 2 of the 12 study subwatersheds (subwatersheds 3 and 5) include extensive natural slopes. Thus, in the CCW, standard deviation of slope does not indicate the spatial heterogeneity of slope but rather the extent of engineered drainage; and correlation of hydrograph parameters to standard deviation of slope represents the relationship of these parameters to channel morphology and density rather than the natural landscape.

2.6.3 Do rainfall thresholds exist for runoff generation in the Prairies, as they do in other landscape types?

Threshold behaviour in watersheds results from watershed inputs exceeding a critical point of either intensity or storage capacity. Therefore, it was expected that if threshold behaviour existed in the CCW it would manifest itself in scatter plots of rainfall versus runoff parameters. It should be noted that the two measures of runoff magnitude used in this study at times yielded different results in correlation and graphical analysis, attesting to the contrasting qualities of individual event hydrographs (flashy versus longer, less peaked runoff events).

Storage threshold behaviour in the event rainfall-runoff magnitude relationship was identified in scatter plots for Site 3, as well as just upstream of that location at Site 5 (see Figure 2.7). Subwatersheds 3 and 5 are different from the other examined subwatersheds in that they showcase the greatest natural relief and slope – in Figure 2.1(c) the southeastern portion of the CCW is clearly of higher relief, while to the west slopes > 3% are associated only with the human-altered portions of the landscape (drains and roads). This natural relief may lead to saturated conditions due to concentration of moisture by topography into lower-lying areas, potentially triggering saturated overland flow (SOF) or subsurface storm flow (SSSF) sooner, giving rise to the thresholds observed at Sites 3 and 5. Subwatersheds 3 and 5 also contain fewer roads than the other subwatersheds under study, meaning that they contain less human infrastructure (*e.g.*, culverts, gates) that can impede or block runoff from the upstream contributing area as has been shown in other studies of Prairie watersheds (*e.g.,* Shaw *et al.,* 2012).

At the remaining 10 subwatersheds considered in this study, thresholds, if they exist, were very difficult to discern. Throughout the study period, RF_I correlated weakly to moderately with ΔWL, similarly to the relationship between RF and ΔWL. Those correlations highlight the influence of rainfall intensity on runoff generation, thus hinting towards Hortonian overland flow (HOF) as the dominant runoff generation process for most runoff events. A rainfall intensity threshold could however not be identified: this suggests that across the majority of the events examined, the rainfall rate did not exceed the infiltration capacity of the soils; hence vertical percolation losses occurred, surface runoff was not generated and land was disconnected from waterways. This interpretation is also supported by the statistically significant, although counter-intuitive, positive correlations between RF_{abst} and RF and between RF_{abst} and *ARFs*: those correlations illustrate the fact that soils in CCW can absorb ever larger amounts of water (*i.e.*, increasing RF_{abst}) in response to increasing rainfall RF and despite the presence of wet antecedent conditions (*i.e.*, high $ARF_{xhrs/days}$ values). Those correlations were however generally high in 2013 and low to moderate in 2014, indicating that intensity-driven processes might not have had been equally important throughout the study period.

The lack of persistence of some correlations from 2013 (generally drier year) to 2014 (generally wetter year) points towards a shift in dominant runoff generation processes. In general, strong relationships between various rainfall and runoff parameters were difficult to discern throughout the study entire period (combined 2013-2014 dataset). Quantitative results obtained from the correlation analysis support the more qualitative conclusions inferred from the visual graphical analysis (Tables 1 and 2). Also, while total event rainfall and measures of runoff magnitude were at times moderately correlated, the fact that at the majority of study sites rainfall events with similar total rainfall amounts can generate very different runoff responses unrelated to antecedent moisture conditions suggests that further complexities exist in the rainfall-runoff relationship of the CCW. The lack of any connection between subwatershed characteristics and hydrograph parameters, the near instantaneous response of water level to rainfall (low T_r values), and the seeming lack of connection between the upstream and downstream hydrograph suggests that hydrograph fluctuations for most events are likely the result of direct rainfall at the gauging station, rather than upstream and upland runoff. However, a minority of events have a much longer T_c than the median event T_c by site (ranging from 2.25-4.50 hrs), indicating the possible contribution of runoff sources from areas further away from the drains. It is these events that are also typically of largest runoff magnitude (*i.e.*, greatest area under the storm hydrograph curve). Some of those long T_c values were also associated with events of high runoff but low rainfall (outliers in rainfall-runoff plots in Figure 2.8), and that low rainfall character negates the presence of HOF and rather favors the existence of SOF (or SSSF). The conditions which trigger SOF could not be strongly related to surrogate moisture variables alone ($ARF_{xhrs/days}$, $ARF_{xhrs/days}+RF$, or time elapsed since last rainfall event), and thus may be heavily affected by inter-event conditions, such as PET. While temporal storm hydrograph parameters (*e.g.*, timing characteristics such as T_r and T_c) are rarely used for runoff process conceptualization, here the event-specific time of concentration was the most helpful variable in distinguishing extreme events from median or normal conditions. Temporal storm hydrograph parameters have previously been used to indicate a shift in the dominant runoff generation mechanism: in a case study by Kirnbauer *et al.*, hydrographs were classified as flashy with short recession time, or bimodal (an initial flashy peak followed by a less sudden peak) with significantly longer recession time, and a switch in the dominant runoff generation process was hypothesized to explain this contrast in the Austrian mountain study catchments (2005). In our study of the CCW, T_c values were so contrasted between normal (mostly 2013) and extreme conditions (*e.g.*, 2014 flood) that we could reasonably interpret long times of concentration as being attributable to larger upstream contributing or source areas, while shorter T_c values could be rather associated with measurement artefacts due to rainfall variability, direct rainfall effects, or a general lack of connectivity between land and drains due to infiltration losses.

2.6.4 Implications of the results: a proposed conceptual model for the CCW

The observations made over the course of this study indicate that engineered, near-level landscapes such as the CCW behave fundamentally differently in response to rainfall than their pristine, higher relief counterparts. These differences are illustrated using a hypothetical conceptual model shown in Figure 2.9. In Figure 2.9(a), a drain typical of the very low relief, southwestern portion of the CCW is pictured. The inset (Figure 2.9(b)) shows the culverts at the drain outlet. Likely due to a mix of imperfect engineering and drain maintenance, culverts in the CCW sit above the drain bottom preventing downstream flow (Figure 2.9(c)). During the majority of rainfall events (Figure 2.9(d)), water level rapidly increases due to direct rainfall onto the stagnant water. This water is prevented from flowing downstream due to the elevation of the outlet culverts and drain morphology which concentrates rainfall into the lowest point in the “U” to “V” shaped drains. However, this fluctuation is not great enough to initiate downstream flow through the culverts. Adjacent to the drains, deep soils provide ample infiltration for rainfall. The absence of relief results in more or less uniform landscape wetting across the watershed, with few hillslopes or valleys where soil water could concentrate, possibly leading to SOF or SSSF. Thus, runoff from land does not contribute to runoff measured in the drain, runoff events begin and end with rainfall events, and T_c is very short and does not actually reflect travel time of water in the watershed. Between rainfall events, the high PET of the Prairies results in rapid evaporation of event water in the drain and soil moisture, quickly returning the watershed to pre-event moisture conditions (Figure 2.9(c)). However, if a rainfall event is large enough or antecedent moisture conditions high enough, the water table can reach the ground surface, small local depressions fill, the watershed storage threshold is satisfied, and runoff generation processes shift suddenly to SOF and SSSF (Figure 2.9(e)). Because runoff from land is now contributing to runoff measured in the drain and it must travel from more hydrologically distant points of the watershed, T_c is much greater than those for events generated in the aforementioned scenario. Contribution of runoff from land to the drain ultimately results in high peak water level WL_p, exceeding the difference in drain-to-culvert elevation, and flow downstream is achieved. However, surface and possibly subsurface transit of event water from land to the drain can be obstructed by human infrastructure, including roads and dikes.

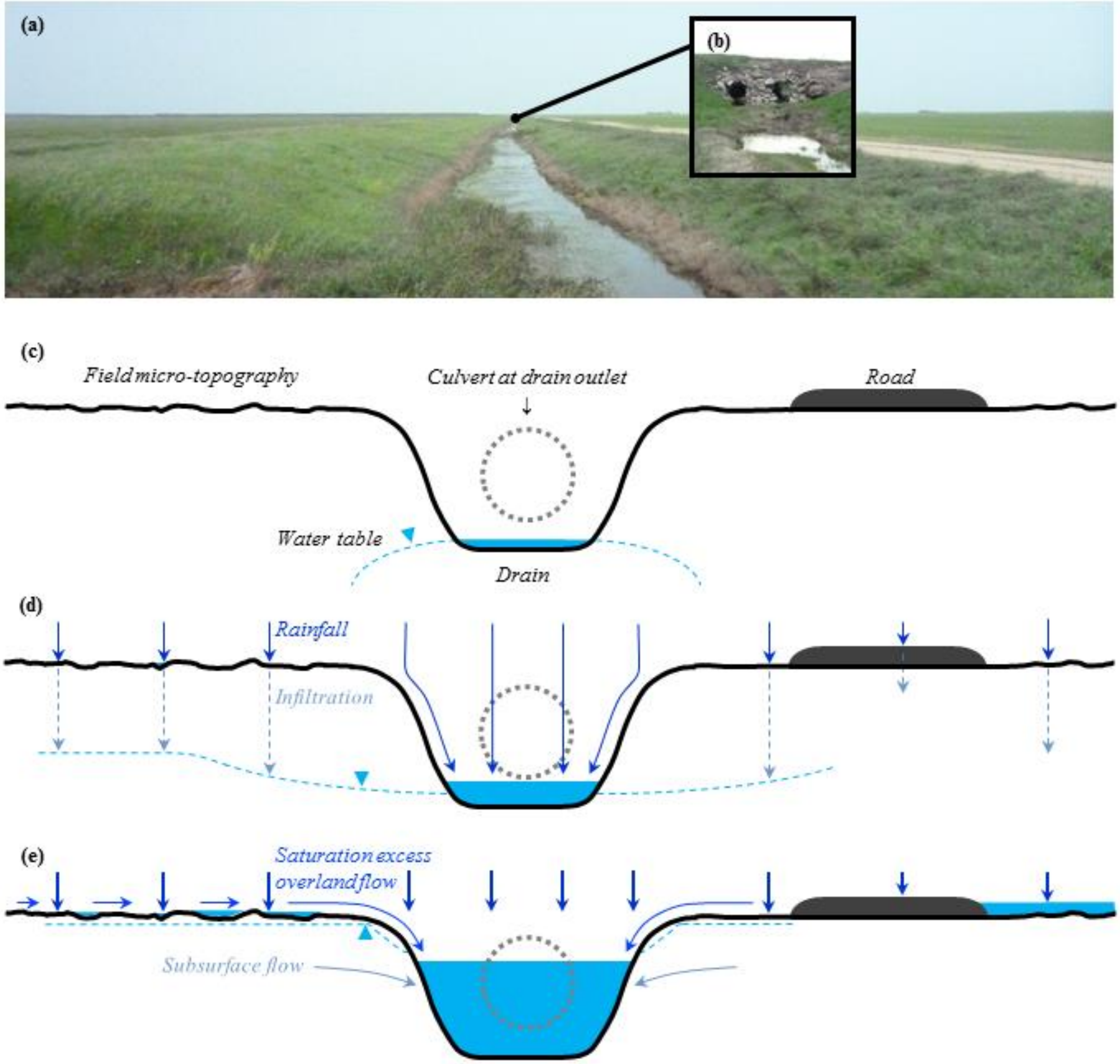

Figure 2.9: Conceptual model of runoff generation from rainfall event; (a) photograph looking downstream from Site 7, a view typical in the CCW; (b) the culverts at the drain outlet, near Site 8 – note the culvert elevation is above that of the drain bottom; (c) the drain between rainfall events; (d) the drain during a typical rainfall event; (e) the drain during an extreme rainfall event or rainfall event occurring while AMCs are extremely high. See text for full description.

2.7 Conclusions

In this study we sought to determine runoff controls in a near-level, engineered Prairie watershed. Using data collected at 12 gauging stations during the 2013 and 2014 open water seasons, correlation analysis of storm hydrograph parameters with rainfall event parameters and landscape characteristics was undertaken to determine the influence of watershed characteristics on runoff and establish the presence or absence of threshold behaviour in Prairie watersheds. Event hydrograph parameters were found to relate moderately to rainfall characteristics, but failed to display any statistically significant correlation with subwatershed characteristics. The specific rainfall and runoff parameter pairs that yielded the greatest Spearman correlation coefficient values, as well as those pairs that do not, indicate a vertically dominated system: under most conditions during the study period, the landscape and waterways of the Catfish Creek watershed are disconnected. Storm hydrographs for most events are likely the result of direct rainfall, while rainfall onto land infiltrates into the deep Prairie soils of large infiltration capacity and does not flow laterally towards the drains. Longitudinally, drains are disconnected by the near level landscape where even very slight topographic variation in the channel can impede downstream flow, and by the many culverts of this heavily-engineered watershed. In the event that watershed storage is satisfied, upstream and upland areas begin to contribute runoff and hydrograph timing parameters, specifically time of concentration, increase markedly, reflecting this switch in runoff generation processes. The ability to predict when saturation excess upstream and upland runoff will be activated would prove a valuable to tool for prediction of rainfall-triggered flooding in the Prairies. Further research into the extent of subsurface flow in Prairie watersheds is therefore necessary to better understand the processes controlling this presumed shift in dominant runoff processes.

2.8 Acknowledgements

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CHAPTER 3.

PRELIMINARY SYNTHESIS AND TRANSITION

3. Hydrological processes and modeling in an unstudied landscape

The conclusions reached at the end of Chapter 2 highlight the complexity and variability of hydrological processes in a typical agro-forested Prairie watershed. Inter-annual conditions contrasted, with total study period rainfalls of 202.0 mm in 2013 and 335.4 mm in 2014. Vertical processes generally dominated in 2013, and events driven by saturated overland flow and subsurface storm flow were more frequent in 2014 as inferred by a shift in in the duration of time of concentration. Thus, while infiltration-excess and fill-and-spill are typically the focus of the Prairie hydrology literature, under certain conditions other processes are dominant. Rainfall thresholds for initiation of runoff were only observed in two of the twelve sub-watersheds considered. It is hypothesized that every sub-watershed does have a storage threshold; however, for most sub-watersheds it is large enough that it is only satisfied by high return period rainfall events.

The high complexity and spatiotemporal variability of Prairie watershed behaviour becomes of particular concern in hydrological forecasting and modelling. Process modelling will become increasingly important in all watersheds as never-before-seen climatological conditions are experienced (*e.g.*, the 2014 midsummer, rainfall-triggered flooding in southern Saskatchewan and Manitoba), making forecasting based on historical events and probability increasingly irrelevant. However, Prairie hydrologists have little option other than to rely on models developed in watersheds physiographically and climatically very different from those found on the Prairies, with little idea of how these physiographic and climatic differences may result in fundamental differences in runoff generation processes.

Currently, the United States Soil Conservation Service curve number model (often referred to in the literature as the US-SCS CN method, the NRCS CN method, or simply the CN method) continues to be used to estimate flows in ungauged watersheds in Manitoba (Water Management and Structures Division, Manitoba Infrastructure and Transportation, personal communication). The CN method is an empirical model developed in the United States in the 1950s and requires few landscape input parameters. Hydrologic abstractions are lumped into a single initial abstraction ratio, rather than broken down into components, or measured as the sum of event rainfall occurring before event hydrograph response (as it was calculated in Chapter 2). Like more contemporary process models, it is uncertain to what degree this empirical model is representative of the hydrologic processes of the Prairie landscape. Additionally, despite its widespread use in the United States and around the world, the details of the CN method development have been lost.

There is a need to explore the applicability of hydrologic models to Prairie landscapes. In the case of the CN method, the applicability of the model structure needs to be examined. Among the specific questions the model raises is the hydrologic representativeness of the single initial abstraction ratio in a near-level Canadian Prairie landscape. In the rest of this thesis, the goal is therefore to build upon Chapter 2 by comparing the field-derived initial abstraction values presented earlier to those obtained using the empirical CN method.

CHAPTER 4.

THE RUNOFF CURVE NUMBER (CN) METHOD: TESTING THE ASSUMPTIONS OF THE INITIAL ABSTRACTION RATIO IN NEAR-LEVEL PRAIRIE WATERSHEDS

4.1 Abstract

The Curve Number (CN) method has long been valued as a simple means to estimate runoff in ungauged basins. Since its development in the United States, it has been used around the world as it requires few, generally readily available, input parameters and models hydrologic abstractions using a simple initial abstraction ratio. In recent years, the originally published initial abstraction ratio (I_a/S) of 0.20 has been challenged as too high, and the use of a fixed value for this ratio has also been questioned. It is not known to what degree inter-event variation exists for I_a/S, either in general or under certain watershed conditions. Here, the stability of the I_a/S relationship is examined in a near-level Canadian Prairie region. Rainfall-runoff events were observed over two subsequent field seasons at four gauging stations (located ~ 90 km NE of Winnipeg, Manitoba). Hydrograph-derived I_a was compared among sites, event characteristics (*e.g.*, antecedent rainfall conditions, hydrograph response lag time, rainfall intensity during lag time) and antecedent moisture conditions. The analyses show that hydrograph-derived I_a values ranged widely, and that rainfall intensity during the abstraction period correlated most strongly with I_a. This is potentially due to dominant runoff pathways differing among events, whereas the structure of the CN method implies saturation-excess overland flow as the primary runoff mechanism for all events.

4.2 Introduction

The United States Soil Conservation Service curve number method (referred to hereafter as the CN method) is a well-established method for estimating direct runoff from event rainfall.

The CN method runoff equation is:

$$Q = [(P - I_a)^2] / [(P - I_a) + S] \qquad P > I_a \qquad [1]$$

$$Q = 0 \qquad P < I_a$$

where $I_a = 0.2S$ [2]

and where Q is the runoff depth (in.), P is the rainfall depth (in.), I_a is the initial abstraction (in.), and S is the maximum potential retention (in.) (Natural Resources Conservation Service (NRCS, 2004). Traditionally, CN values are to be selected from a table based on land use and land cover and hydrologic soil group (HSG) (Figure 4.1); and thus S is related to CN by the following equation:

$$S = [1000/CN] - 10 \quad [3]$$

Land use and land cover categories include various types of forest, urban infrastructure, agriculture (*e.g.*, small grain, broadcast legumes, fallow), and cultivation (*e.g.*, strait row, contoured, terraced). HSGs are classed A though D and provide an indication of the potential that a given soil will generate surface runoff based on their minimum infiltration rate (United States Department of Agriculture (USDA), 1986). Victor Mockus is credited with the development of the method, and he indicated that the equations were designed with an intended goal of estimating runoff from single rainfall events (Mockus, 1996; Mockus 1964 cited in Woodward *et al.,* 2002). The storm should be without breaks in rainfall – if significant temporal breaks do occur, a higher CN should be selected to take the change in watershed antecedent moisture value into account. It was originally intended for use with daily rainfall data, thus only storms with a duration of up to 24 hours are to be considered under traditional use (United States Soil Conservation Service, 1989). The US SCS-CN method was first officially published in the National Engineering Handbook, Section 4: Hydrology, chapter 10 (NEH-4, later renamed NEH-630; here, both names are used interchangeably where appropriate) in 1954. The method was then revised and re-published in the 1956, 1964, 1965, 1971, 1972, 1985, 1993 (Ponce & Hawkins, 1996) and 2004 (NRCS, 2004) versions of the handbook. In 1994, the SCS became the NRCS (NRCS) (Woodward, Hawkins, Hjelmfelt, van Mullem, & Quan, 2002); therefore, the CN method may also be referred to as the US NRCS-CN method.

The CN method was born as the need for hydrometric data and simple runoff estimation techniques on which to inform soil conservation measures became apparent (Rallison & Miller, 1982; Woodward *et al.*, 2002). Following the passage of the 1936 Flood Control Act (Public Law 74-738), the USDA began investigating methods for reducing watershed runoff, which led to the study of the influence of landscape practices on runoff generation from rainfall (Mishra & Singh, 2003; Rallison & Miller, 1982). Reportedly, thousands of sprinkling-type infiltrometer tests were undertaken as part of this effort by the SCS and other agencies (Mishra & Singh, 2003; Rallison & Miller, 1982; Woodward *et al.*, 2002). A series of rainfall retention/excess curves that could be used to estimate runoff volume was developed using these data by three private consultants hired by the SCS: W. W. Horner, R. E Horton, and R. K. Sherman. However, these curves ultimately were of limited use as they required recording rain gauge data, which was not widely available at the time (Mishra & Singh, 2003; Rallison, 1980; Woodward *et al.*, 2002). Building on this work done by Sherman, Victor Mockus suggested surface runoff could be predicted from a number of landscape and storm characteristics – this is widely cited as first being documented in a 1949 internal SCS memo: 'Exhibit A of Appendix B of a USDA report on the Grand (Neosho) River Watershed' (*e.g.*, Hjelmfelt Jr, 1991; Mishra & Singh, 2003; Ponce & Hawkins, 1996; NRCS, 2004; Rallison, 1980; Woodward *et al.*, 2002).

The 1980's to early 1990's was a period of extensive review of the CN method, the majority of which took place in conference papers, with few journal articles – virtually all of which were published by the American Society of Civil Engineers (ASCE); *e.g.*, Bondelid, McCuen, & Jackson (1982); Bosznay (1989); Cazier & Hawkins (1984); Hawkins (1975); Hawkins *et al.* (1985); Hawkins (1993); Hjelmfelt Jr (1980); Hjelmfelt Jr (1991); Hoesein *et al.* (1989); Miller & Cronshey (1989); Nielson &

Hjelmfelt Jr (1998); Plummer & Woodward (1998); Rallison (1980); Rallison & Miller (1982); Springer *et al.* (1980); van Mullem (1991); and Wood & Blackburn (1984). This list is not exhaustive as papers from regional and national conferences for this time period are difficult to locate. From the late 1990's onwards, the focus of CN method research has been on (i) examining its applicability outside of the United States (*e.g.*, Baltas *et al.*, 2007; D'Asaro & Grillone, 2012; Johnson, 1998; Patil *et al.*, 2008; Xiao *et al.*, 2011), and (ii) debating whether it is appropriate to help infer dominant runoff pathways and runoff contributing areas at the watershed scale. Several studies have suggested the CN method could be used to predict the watershed fraction that is saturated and generating saturation-excess surface runoff from variable source areas (VSAs) (*e.g.*, Lyon *et al.*, 2004; Schneiderman *et al.*, 2007; Steenhuis *et al.*, 1995), and this is mathematically formalized by saying that the effective watershed contributing area is equal to the derivative of runoff Q with respect to effective precipitation P_e ($P_e = P - I_a$; Dahlke *et al.*, 2012). This however assumes that the CN method accurately models effective precipitation, which is highly dependent on assumed initial abstractions I_a, and this assumption has been subject to debate (Hjelmfelt Jr, 1980; NRCS, 2004). The initial abstraction (I_a) is the portion of event rainfall which falls prior to the initial event hydrograph response. Hydrologic abstractions consist of interception (vegetative or man-made, depending on the setting), surface depression storage, infiltration, evaporation (including from lentic and lotic water features, and moisture directly from soil), and evapotranspiration (NRCS, 2004; Ponce & Hawkins, 1996). Estimation of certain I_a components is possible if landscape data is available: depression storage can be estimated using a DEM, and interception from land use and land cover data. However, the infiltration portion of I_a varies depending on antecedent moisture conditions, soil crusting and rainfall intensity. In addition, the infiltration portion of I_a varies in importance in and of itself depending on whether Hortonian, saturation-excess or subsurface flow dominates as the basic runoff generation mechanism. In the short term, infiltration is the most important abstraction while in the long term, evaporation and evapotranspiration are the most important abstractions – storage in surface depressions and interception are typically less important (Ponce & Hawkins, 1996). I_a values can also be derived from stream hydrographs by delineating individual hydrologic events and summing up the rainfall depths that fell prior to the initial event hydrograph rise. However, as event hydrograph analysis is a manual and often time-consuming process, there have been several examples of both experimental and applied studies where hydrologists have rather resorted to the CN method and Equation 2 for the routine computation of initial abstraction values, with little or no consideration of whether Equation 2 is indeed valid throughout the United States as well as elsewhere. For example, the CN method-based L-THIA (Long Term Hydrologic Impact Analysis) system is used to predict hydrologic impacts of future land use change (Harbor, 1994). However, there are numerous examples in the literature where no consideration of the validity of Equation 2 or the CN method as a whole in the context of the study is made (*e.g.*, Ahiablame *et al*., 2012; Lim *et al*., 2006; Zhang *et al*., 2011). Even when the importance of modelling low return period events to assess hydrological change is explicitly recognized, a λ of 0.2 is used without considering that runoff events resulting from smaller rainfalls may be excluded from predictions by setting the initial abstraction value too high (Bhadhuri *et al*., 2000).

Presently, the SCS-CN method has been adopted and adapted around the world and has become a standard inclusion in hydrology text books (ASCE/EWRI Curve Number Hydrology Task Committee, 2009). The CN is now commonly used in engineering, runoff event analysis and environmental impact assessments (Woodward *et al*., 2003), and it is used in water quality models such as SWAT, GLEAMS, CREAMS, and RUSLE2 (Garen & Moore, 2005; ASCE/EWRI Curve Number Hydrology Task Committee, 2009). The CN method is a required – and supported – procedure by United States federal government agencies (Pilgrim & Cordery, 1993; Ponce & Hawkins, 1996), which not only perpetuates its use but also '[…] gives its users basic protection in case of litigation' (Smith, 1997). However, while low parameterization makes the CN method user-friendly, its extensive usage has been misconstrued, at times, as extensive acceptance. In the early 1980's, Helmfelt Jr. noted that: 'Because the procedure is easily applied to ungauged watersheds, the technique has been widely accepted. Tests verifying the procedure have not been widely published, however, which raises some questions concerning its validity' (Hjelmfelt Jr, 1980, p. 1474). Even though tests have been performed since Hjelmfelt Jr's old position statement (*e.g.*, Cazier & Hawkins, 1984; Hawkins & Khojeini, 2000; Jiang, 2001; Springer *et al.*, 1980; Woodward *et al.*, 2003), his concerns regarding verification of the procedure remain relevant today. For example, the comprehensive 2009 review of the CN method by the ASCE concluded further research is still needed to determine which kinds of watersheds and watershed conditions result in rainfall responses incompatible with the CN method, especially as the CN method has been applied in many manners and landscapes beyond those for which it was originally developed (ASCE, 2009). This is notably the case in the Canadian Prairie provinces where the CN is routinely used for flow estimation in ungauged watersheds (Water Management and Structures Division, Manitoba Infrastructure and Transportation, personal communication). Canadian Prairie landscapes – which span the southern portions of Alberta, Saskatchewan, and Manitoba – are unique in that they can be described as engineered, agricultural, semi-arid landscapes of near-zero relief. Dominant Prairie runoff processes likely change seasonally in response to the seasonality of precipitation (snowfall versus rainfall), soil conditions (frozen in winter, saturated during spring runoff, dry during the summer months), and vegetative cover (seeded versus harvested agricultural land). In this context, the appropriateness of the CN method for Prairie runoff modelling is unclear, especially as many factors such as high evapotranspiration rates and human landscape modifications (*e.g.*, roads and drainage ditches) are likely to affect the spatial and temporal variability of runoff initial abstractions. The overarching goal of this illustrated review paper is therefore to address the extent to which the assumptions behind the CN method make it suitable for application in Prairie landscapes. Specifically, three related objectives are pursued, namely: (i) Provide an overview of the development history of the

CN method; (ii) examine the known strength and weaknesses of the CN method, especially when it comes to the computation of initial abstractions (I_a) at the event scale; and (iii) compare observed and modelled I_a values in typical Prairie watersheds.

4.3. Historical development of the SCS-CN method

4.3.1 Initial formulas leading to the current CN method

It worth stating that the SCS-CN method as portrayed by Equations 1, 2 and 3 looks slightly different from the original formulations dating from the early 1950's. Indeed, in a 1949 internal SCS memo, Mockus was with credited with developing the following equation:

$$Q = P \{1-(10)^{-bP}\} \quad [4]$$

where Q is direct runoff (in.) and P is storm rainfall (in.). As for b, it is an index of landscape and storm characteristics computed as follows:

$$b = [0.0374(10)^{0.229M}C^{1.061}]/[T^{1.990}D^{1.333}(10)^{2.271(S/D)}] \quad [5]$$

where M is the 5-day antecedent rainfall (in.), C is the cover practice index, T is a seasonal index (that is a function of date and temperature (°F)), D is storm duration (hrs) and S is a soil index (in./hr) (as cited in Rallison, 1980; Rallison & Miller, 1982). As b is based mainly on watershed characteristics, it was therefore possible to estimate storm runoff if rainfall event depth and watershed characteristics were known. It is implied that some tests took place in an effort to determine regional b values but all documentation about them has been lost, including information on which specific watersheds were used (Woodward *et al.*, 2002).

Meanwhile, several others in the United States government were undertaking work which would eventually be incorporated into the CN method: What became known as the multiple-correlation diagram, *i.e.*, a figure with a choice of curves to consider for different conditions, was first used in 1951 in a paper by the United States Weather Bureau (NRCS, 2004). Here, 'excellent results' were claimed when antecedent precipitation, week of the year and event duration were considered in the estimation of runoff from rainfall amounts (Kohler & Linsley, 1951). However, as this method required unique diagrams for each considered watershed, it could not be applied in ungauged basins as was needed by the SCS. The term and idea of the 'soil-cover complex' (the combination of ground cover type and extent, soil texture, and conservation methods), as still used in relation to the CN method today (NRCS, 2004), was developed by R. G. Andrews in an unpublished 1954 SCS document (as cited in Rallison, 1980 and Rallison & Miller, 1982). Andrews had discovered that textural class was the only soil characteristic which was consistent among grouped infiltrometer data from Arkansas, Louisiana, Oklahoma and Texas; based on this data, he established a graphical method for approximating runoff using event rainfall and soil-cover complex.

Factors affecting soil infiltration had been a research focus of the SCS for some time (*e.g.*, Musgrave & Free, 1936), and the hydrologic soil groups (HSGs) A, B, C, and D – as we know them today – had been in development for years (Hawkins *et al.*, 2005) before first being published in 1955 (Musgrave). As it required no runoff data, the work of Mockus in 1949 (as cited in Rallison, 1980) and Andrews in 1954 (as cited in Rallison, 1980), incorporating the hydrological soil classification of Musgrave (1955), would form the foundation of the CN method (Rallison, 1980; Rallison & Miller, 1982; Miller & Cronshey, 1989): ultimately, the assumption that runoff begins after some rainfall accumulation and that the rainfall-runoff relationship is asymptotic to the 1:1 line after this rainfall accumulation has taken place underlies the CN method (Rallison, 1980; Rallison & Miller, 1982). Doing away with the many coefficients and parameters necessary in Equation 5, Mockus suggested the rainfall-runoff relationship could be simplified to:

$$F/S = Q/P \qquad [6]$$

where *F* is the rainfall storage during an event, *S* is the maximum potential storage at the beginning of an event, *Q* is direct runoff, and *P* is the total event rainfall (NRCS, 2004; Rallison, 1980; Woodward *et al.*, 2002). Later, *P* would be substituted for by effective precipitation (the difference between total event rainfall and initial abstraction) (Woodward *et al.*, 2002). If *F* can be assumed to be the difference between rainfall and runoff ($F = P - Q$), the equation, solved for *Q*, becomes:

$$Q = P^2/(P+S) \qquad [7]$$

(NRCS, 2004; Rallison, 1980; Woodward *et al.*, 2002). Accounting for initial abstraction (I_a), this becomes:

$$Q = (P-I_a)^2/(P-I_a)+S \qquad [8]$$

(Rallison, 1980; Woodward *et al.*, 2002; NRCS, 2004). Recognizing the problems associated with drawing a linear relationship between I_a and S, Mockus preferred the use of $P - I_a$ in the CN method equations (Mockus, 1996); he would, however, go on to document the I_a/S ratio of 0.2 to reduce the CN method to a one-parameter method (Woodward *et al.*, 2002), reportedly at the instance of his superiors (Mockus, 1996). According to Rallison (1980), this relationship was based on data from ‘large and small watersheds', although no reference for the source of this information is given, and none of the original documentation supporting the selection of this I_a/S ratio is known to exist. Substituting I_a for 0.2S in Equation 8, the CN method equation becomes:

$$Q = (P-0.2S)^2/(P+0.8S) \text{ when } P \geq 0.2S, \text{ otherwise } Q=0 \qquad [9]$$

To further simplify the method, potential storage S was converted to a 'curve number' (Mockus, 1996), and the curve number was related to S as follows:

$$CN = 1000/(S+10) \qquad [10]$$

The final component in the selection of the CN, in addition to the HSG and land cover, is the general characterization of the hydrologic condition as poor, fair or good; this was contributed by Mockus (Mockus, 1996). Antecedent moisture conditions (AMCs) were accounted for by modifying the CN to a lower value for dry conditions (CNI) or a higher value for wet conditions (CNIII) based on the total rainfall in the days leading up to the event (*e.g.*, Soil Conservation Service, 1972). However, this method is no longer condoned by the NRCS (NRCS, 2004). The CN method in its entirety is summarized in Figure 4.1.

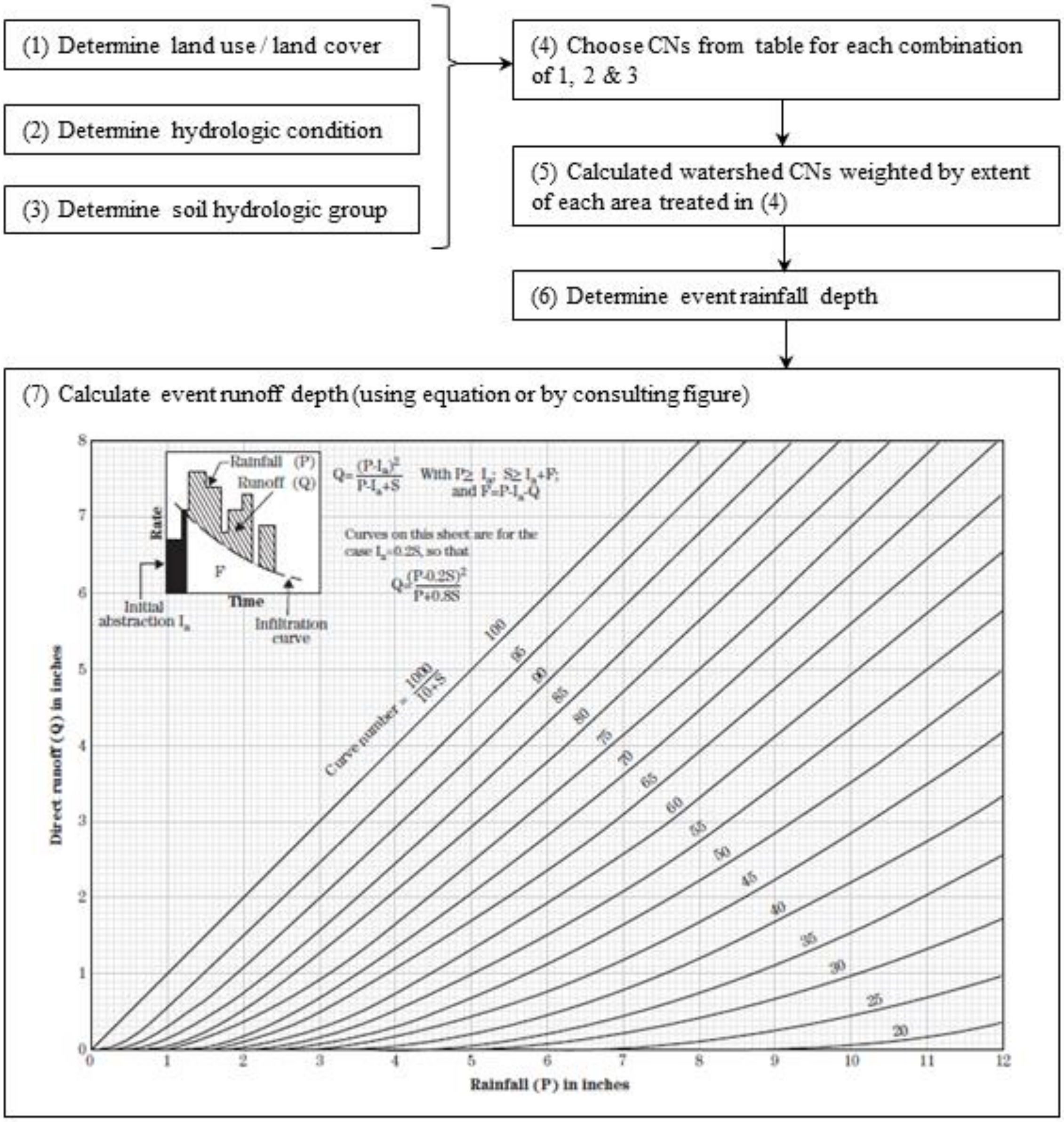

Figure 4.1: Steps of the CN method. Curve number diagram reproduced from Natural Resources Conservation Service (2004).

4.3.2 Physical basis and robustness of the CN method

It appears that most of the original documentation about how the curve number tables were developed has been lost (Hawkins *et al.*, 2005). According to Mockus in his 5 March 1964 letter to Orrin Ferris (as cited, described, and quoted in Miller & Cronshey, 1989; Rallison, 1980; Rallison & Miller, 1982; and Woodward *et al.*, 2002), the CN values were based on experimental data collected in research watersheds to determine the impact of land cover and soil conditions on runoff, and 'the research watersheds from which the data were used are located in various parts of the United States, so CN applies throughout the country' (Mockus, 1964, quoted in Rallison, 1980). Also in his 1964 latter to Orrin Ferris, Mockus describes the parameter *S* as limited by the lesser of infiltration rate or available soil profile storage (as cited in Rallison, 1980). *S* was determined using Equation 8 (Mockus, 1964, cited in Rallison & Miller, 1982). Apparently antecedent soil moisture was taken into consideration in the calculation of the CN values: 'The CN associated with the soil-cover complexes are median values, roughly representing the average conditions on a watershed. We took the average conditions to mean average soil moisture conditions when flood occurs because we had to ignore rainfall intensity' (Mockus 1964 quoted in Rallison, 1980; Miller & Cronshey, 1989; Woodward *et al.*, 2002). The scatter of the points was the basis for the wet and dry AMC curve numbers (based on 5-day antecedent rainfall), representing the upper and lower enveloping curves (Woodward *et al.*, 2002).

The 2004 NEH, rather than explicitly accounting for antecedent moisture conditions, renamed AMCs 'antecedent rainfall conditions' (ARC). ARCs came to be considered error bands, as it has been found that ARC III corresponds to direct runoff at which ~ 90% of events at a given rainfall would be less, and ARC I at which ~ 10% would be less (Hjelmfelt Jr, 1991; NRCS, 2004). It was stated that 'no apparent relationship between antecedent precipitation and curve number exists', and that antecedent rainfall conditions (ARC) I (dryer-than-average conditions), II (normal conditions), and III (wetter-than-average conditions) depend on all of 'rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature', which together are the cause of CN variability (NRCS, 2004). It is however worth noting that no units of time are included in the CN method. Woody L. Cowan summarized the reasons no unit of time was included in the equations as (1) a lack of data regarding soil infiltration capacity with time and (2) insufficient detailed rainfall records (W. L. Cowan in a letter to H. O. Ogrosky, 1957, as cited in Rallison, 1980).

As a runoff estimation method, the CN method stands out for its low parameterization and simplicity. The underlying assumption of the method; *i.e.*, that ratios of actual runoff to potential runoff and actual retention to potential retention are equal; has been validated (Yu, 2012). The CN method has also been described as 'unique' in its conceptual basis because as effective precipitation (P - I_a) approaches infinity, retention ($P – I_a – Q$) approaches potential retention S. This is a departure from other models such as those described by Fogel and Duckstein (1970) and Hawkins (1992) where $Q = b(P – I_a)$, and as ($P – I_a$) approaches infinity, actual storage ($P – I_a – Q$) also approaches infinity, which does not reflect reality (Ponce & Hawkins, 1996). It has however been pointed out that construing this as a positive or advantageous aspect of the CN method is moot as 'storm depth is never unlimited' (Smith, 1997). A documented weakness of the CN method is that it is much more sensitive to changes in CN values than to event rainfall depths, especially for lower rainfall depths (Bondelid *et al.*, 1982; Hawkins, 1975). It can also be difficult to select CN values even when detailed soil and land cover data are available: indeed, no protocols exist for assigning the HSG to a soil not already listed in the HSG tables published by the USDA (Hawkins *et al.*, 2005), which directly impacts chosen CN values. It is also worth noting that definitions of the HSGs have changed considerably from their initial 1955 publication (by Musgrave), without adjustment of the curve numbers associated with the respective HSGs: for example, the minimum infiltration rate for Group B was originally expressed to be in the range of 0.15 to 0.30 in/hr (Musgrave, 1955), while now the minimum infiltration rate is 1.42 in/hr (NRCS, 2007) – which corresponds to a ~ 5-fold to ~ 10-fold increase.

4.4. From the CN to dominant watershed runoff pathways

4.4.1 Rationale behind the CN method I_a/S ratio

The source of the CN method I_a/S ratio of 0.2 is equally unclear as the source of the CN method itself. Both older versions of the NEH-4 (Figure 10.2 in Soil Conservation Service, 1972) and their modern counterpart (Figure 10-1 in NRCS, 2004) include a plot of I_a against S, for which the ratio of 0.2 is apparently drawn as the median value. There is considerable scatter among the points, and no indication of the source of the data is given beyond the remark that they 'are derived from experimental watershed data'. The selection of 0.2 as the I_a/S ratio has been questioned for some time, with Hjelmfelt Jr describing the I_a/S relationship as 'tenuous at best' (1980), and the latest NEH stating that 'establishing a relationship for estimating I_a is not easy' (NRCS, 2004).

Mockus states in NEH-4 that this ratio was based on natural rainfall data from watersheds less than 10 acres in size and attributes the scatter in the I_a/S relationship to errors in the estimation of I_a (Soil Conservation Service, 1972). Ten years after the initial publication of the CN method and the I_a/S ratio, he would state that further refinement of I_a was possible, but it was not undertaken as little was known of the degree of influence of surface storage and interception (Mockus 1964 in Woodward *et al.*, 2002). In current practice, it has become accepted that the initial abstraction ratio λ ($I_a=\lambda S$) varies widely from the suggested value of 0.2 and a different ratio can be used (*e.g.*, Bosznay, 1989; Jiang, 2001; NRCS, 2004; Ponce & Hawkins, 1996; Woodward *et al.*, 2003). A range of λ values from 0.0 to 0.3 have been used in studies through the decades and throughout the world (Ponce & Hawkins, 1996). λ has also been found to vary from watershed to watershed, and indeed storm to storm – but in all cases is typically found to be much smaller than 0.2 (Woodward *et al.*, 2003). Cazier & Hawkins (1984) found that setting the I_a/S ratio to 0.0 provided better results than 0.2 in an analysis of 109 American watersheds. Similarly, Springer *et al.* (1980) found 0.0 to be the most common I_a/S ratio in a study of three humid and three semi-arid American watersheds. Hawkins & Khojeini (2000) analyzed 5501 events (all > 1.0 in.) in 86 American watersheds, and found that an I_a/S ratio of 0.05 was much more appropriate than 0.2. Jiang (2001) rather found that in 307 watersheds located in 24 American states, no significant relationship existed between I_a and S for individual watersheds, and a weak negative correlation between I_a and S was found when all watershed data were considered together. The λ value calculated from existing datasets varies depending on whether natural or ordered datasets are used for their calculation; *e.g.*, Woodward *et al.* (2003) found median λ values of 0.0001 when natural data was used, but 0.0736 when the same data was ordered and the median value re-calculated.

If an I_a/S ratio of anything other than 0.2 is desired, new CN values must be calculated if one is using the method in the traditional sense, *i.e.*, referring to the NEH tables (ASCE/EWRI Curve Number Hydrology Task Committee, 2009). Jiang (2001) determined the following equation to convert NEH table CN values (λ=0.20) to CN values for which λ=0.05 by least-squares fitting using data from 307 American watersheds:

$$CN_{0.05}=100/\{1.879[(100/CN_{0.20})-1]^{1.15}+1\} \qquad [11]$$

Using a λ value of less than 0.2 (and the appropriately transformed CNs) results in lower calculated runoff for the largest rainfall events, and higher calculated runoff for the smallest rainfall events as I_a is satisfied more quickly (Woodward *et al.*, 2003). These differences are arguably less important in an engineering context, where over-engineering a structure may be financially more costly but generally better than under-engineering a structure in terms of public safety. However, in continuous modelling applications and in scientific investigation concerned with the hydrology of low or typical flow conditions, selecting the wrong λ value could be problematic.

4.4.2 Relation between the I_a/S ratio and dominant watershed runoff pathways

Questions as to which runoff pathways are implied by the CN method pose further difficulties in method application and evaluation. Indeed, runoff can be generated through several surface and subsurface pathways, including Hortonian (infiltration-excess) overland flow, saturation-excess overland flow, subsurface flow, and direct channel interception. Hortonian overland flow occurs when precipitation occurs at a rate greater than the rate at which the soil can absorb it (Horton, 1933), while saturation-excess overland flow occurs when rain falls on a soil profile which is already saturated, either by rainfall from the event in question, antecedent rainfall, or a combination of both (Dunne & Black, 1970). Subsurface flow occurs when infiltrated rainfall moves laterally below the ground surface (Sklash & Farvolden, 1979). Direct channel interception is the portion of rainfall which falls directly into a stream or channel, and it is generally considered to be negligible except in cases of large-area lentic systems.

The calculation of I_a as a function of S implies saturation-excess overland flow as the basis for the method. The previously included method of accounting for antecedent moisture conditions by varying the CN (and thus S), rather than the I_a/S ratio, makes the same implication. However, by defining the HSGs by maximum infiltration rates, it is implied that infiltration-excess overland flow is the dominant runoff generation mechanism under the CN method. A relationship between the CN method, notably I_a, and the partial area and variable source area concepts, has also been debated or applied (Dahlke *et al.*, 2012; Lyon *et al.*, 2004; Schneiderman *et al.*, 2007; Steenhuis *et al.*, 1995). It is reasonable to think that since the CN method was developed using watershed data, then it should represent the sum of all runoff processes that were simultaneously active in those watersheds. If the watersheds used to develop the method were geographically biased, this could also result in a runoff generation mechanism bias built into the method. Woodward *et al.* (2002) asserts the CN method is not appropriate for karst landscapes, as in these regions 'a large portion of the flow is subsurface rather than direct runoff', thus begging the question of how well it works in the many other regions and landscape types were subsurface flow dominates. It has been documented that the method performs inferiorly in forested regions with baseflow, where it is more common to find watersheds that do not conform to the CN method assumption; *i.e.*, where increasing P linearly does not lead to a proportional increase in the rainfall-runoff ratio (ASCE/EWRI Curve Number Hydrology Task Committee, 2009). Van Mullem (1991) found that the Green-Ampt infiltration model produced more accurate runoff predictions from rainfall than the CN method in nearly all cases, considering 99 rainfall events in 12 agricultural and rangeland watersheds in Montana and Wyoming. Implicit in this comparison is the assumption that the CN method models (poorly) events that are driven by infiltration-loss only. The implication that the CN method only accounts for surface runoff is also made through the manner by which CN is incorporated into continuous models; *e.g.*, Arnold *et al.* (1998) state that that the CN predicts 'surface runoff' in SWAT, while subsurface flow is accounted for separately within the model.

4.5. Evaluation of the CN-derived I_a in near-level Prairie watersheds

4.5.1 Study area

While the literature reviewed above demonstrates that multiple studies have tested the validity of the CN method, especially the λ (I_a/S) ratio, no tests have been run in Canadian Prairie watersheds where the CN method is still routinely used for flow calculation and modelling input. The last objective of the current paper is therefore to investigate the variability (or lack thereof) of the initial abstraction in a typical Prairie environment.

The Catfish Creek watershed (CCW, also referred to as Designated Watershed 14 by the Provincial Government of Manitoba; Millar, 1974) is located in the southeast of the Province of Manitoba, Canada, with its outlet located on Traverse Bay of Lake Winnipeg (Fig. 4.2). The 642 km^2 watershed is of low-relief and has a heterogeneous land cover (~48% forest, ~37% cropland, ~13% wetland, ~2% other). Surface runoff is managed by a network of artificial drains, in which flow is typically ephemeral. Natural mixed-forest and wetlands are present throughout the lower CCW, as well as on the higher-relief eastern portion of the upper watershed. To the west, the landscape is dominated by intensive, large scale agricultural operations on a near-level landscape. Soybeans and wheat are the most common crop types of the region (Agriculture and Agri-Food Canada, 2014).

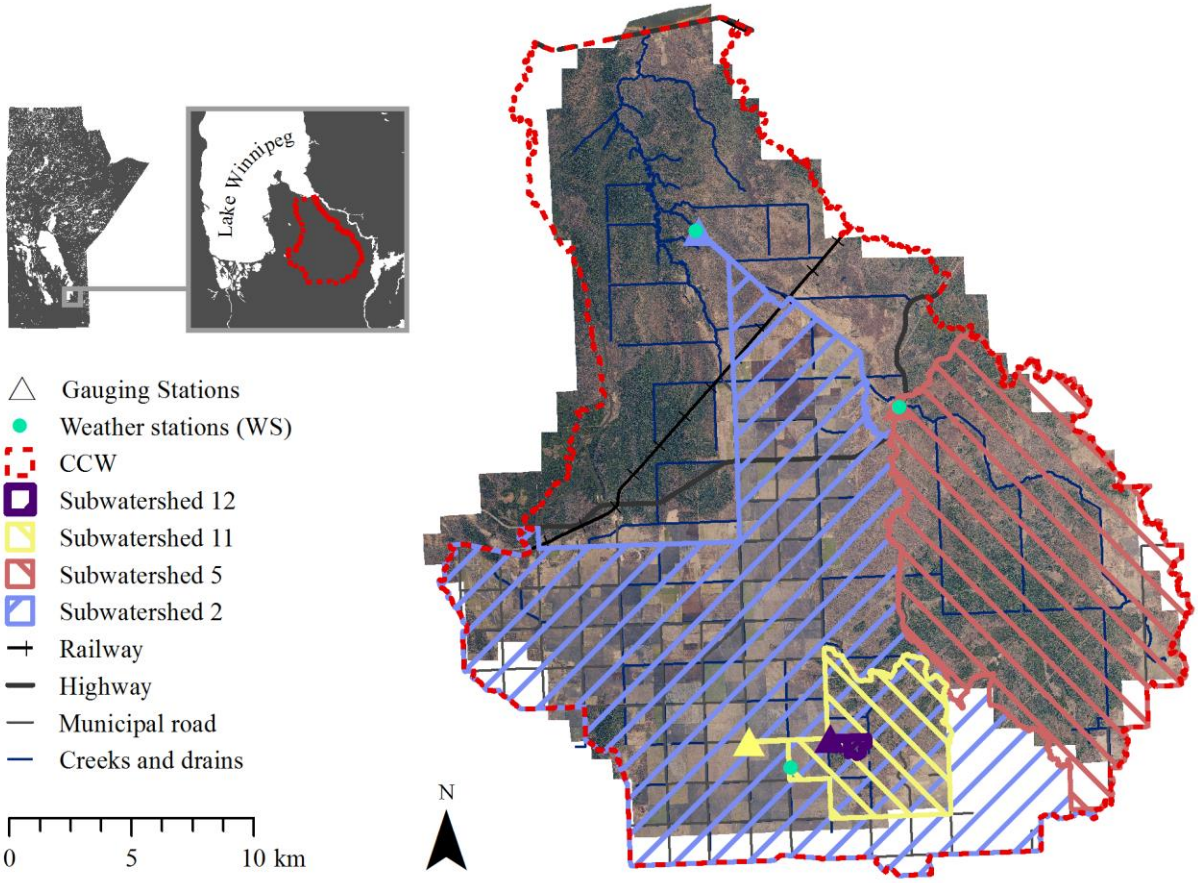

Figure 4.2: Orthoimagery of the Catfish Creek Watershed (Manitoba Infrastructure and Transportation - Water Management and Structures, 2012), with gauging locations and the extent of four selected sub-watersheds indicated.

The Manitoba Conservation Fire Program is the only agency which has consistently collected weather data in the CCW prior to 2013. This dataset indicates the average annual rainfall is 459 mm (for 1999 through 2013), the largest portion of which (~25%) falls in June. Inter-annual rainfall is variable, ranging from 271 mm to 669 mm during the 15 year record. Average temperature is -13.7°C in January and 24.3°C in July (temperature measured daily at 1300 hrs local time; Manitoba Conservation Fire Program, 2014).

The CCW generally consists of lacustrine clay plains between the Winnipeg River and the Kanipatenak, Murray, and Brightstone Sand Hills (Matile & Groom, 1987). Overall, the watershed ranges in elevation from 220 m.a.s.l. at the outlet to 305 m.a.s.l. at the peak of the Brightstone Sand Hills (Canada Centre for Mapping, 1995; 1996). In the area immediately adjacent to the Catfish Creek itself in the northern CCW, soils are dominated by fibrous fenic peat and the gleyed dark grey clay of the Framnes Series. In the southernmost portion of the watershed, clay-textured carbonated rego-humic gleysols of the Glenmoor Series predominate (Smith *et al.*, 1967). The majority of the CCW includes soils described as ‘poorly’ or ‘very poorly’ drained by the Canadian Soil Information Service (CanSIS; Western Land Resource Group - Agriculture and Agri-Food Canada, 2002a; b; c; d). The western portion watershed is underlain by interbedded shale and quartzite sand layers of the Ordovician Winnipeg Formation. To the east, bedrock comprises massive granitic and gneissic Archean bedrock of the Precambrian Shield (Manitoba Geological Survey, 2012).

For the present study, the focus was on four sub-watersheds within the CCW. These four sub-watersheds (Fig. 4.2) were delineated using a filled, 1 m resolution LiDAR dataset (Manitoba Infrastructure and Transportation - Water Management and Structures, 2012). Topograghic characteristics, land use and land cover proportions (Agriculture and Agri-Food Canada, 2014), as well as soil type extent (Western Land Resource Group - Agriculture and Agri-Food Canada, 2002a; b; c; d) were determined for each sub-watershed as reported in Table 4.1.

Table 4.1: Sub-watershed curve numbers and characteristics
(Agriculture and Agri-Food Canada, 2014; MIT-WMS, 2013)

	Sub-watershed			
	2	**5**	**11**	**12**
	Curve number			
	81	82	70	77
	Land use / land cover type (percent area)			
Brush	6.7	5.8	16.3	43.0
Exposed or barren land	0.0	0.1	0.3	0.0
Fallow with residue	0.1	0.0	0.0	0.0
Farmstead	0.5	0.0	0.1	0.0
Open space (good condition)	4.3	0.0	0.0	0.0
Pasture, grassland or range: meadow	10.4	9.0	12.7	0.2
Road (gravel)	2.2	0.3	1.0	0.0
Road (paved with ditch)	0.1	0.0	0.0	0.0
Row crops (strait row)	32.2	0.0	18.0	0.9
Small grain (strait row)	20.3	0.9	7.6	0.4
Urban / Developed: commercial and business	1.9	0.3	2.1	8.2
Water	0.0	0.0	0.0	0.0
Wetland	2.0	32.3	0.2	0.0
Woods (good condition)	19.3	51.3	41.7	47.3
	Hydrologic soil group (percent area)			
A	2.25	4.27	12.34	0
B	10.37	8.38	17.89	0
C	17.64	21.97	22.12	10.17
D	69.72	65.37	47.65	89.83
	Other sub-watershed characteristics			
Gross drainage area (ha)	29314.17	14535.86	3266.33	56.03
Drainage density (m/m^2 × 10^4)	6.38	3.90	7.83	0.00
Elevation range (m)	85.97	80.93	76.52	11.74
Median slope (%)	1.29	2.48	1.82	2.77

4.5.2 Field data, weighted curve numbers and data analysis

In early 2013, instruments for hydrometric and meteorological monitoring were deployed throughout the CCW. In-stream water levels were monitored using laboratory-calibrated Odyssey^{TM} capacitive water level loggers, logging data at 15 minute intervals. Loggers were placed in stilling wells constructed from ABS pipes and screened along their entire length. Rainfall was monitored by a network of HOBO^{TM} U30-GSM data logging weather stations (0.2 mm resolution); data was logged at 1 minute intervals. Two of the gauging stations are co-located with a weather station measuring rainfall; the remaining two are located 3.2 km (2 mi.) apart, and both are 2.0 km from a single weather station located at the longitudinal centre of the two gauging stations, and latitudinally 1.1 km south. All data loggers were re-calibrated and re-deployed for the 2014 field season.

Land cover was determined from an Agriculture and Agri-Food Canada remotely sensed dataset (2013). Soil type was determined from Canadian Soil Information Service (CanSIS) maps and then used to determine HSGs (Western Land Resource Group - Agriculture and Agri-Food Canada, 2002a; b; c; d). CanSIS does not provide detailed hydraulic conductivity data for all soil series, and the NRSC provides no standardized method for determining HSG for soils outside the United States; CanSIS's soil drainage classes were therefore used to assign each soil series present in the CCW to a relative HSG.

Rainfall-runoff events were delineated manually for the period of May through August, 2013 and 2014. Runoff events at each gauging station were paired with rainfall depths from the nearest weather station. Rainfall events during the spring freshet period in early May were not included in analysis, nor were rainfall events which began less than 24 hours following the end of the preceding rainfall event. For each rainfall event, initial abstraction (I_a) was determined in two ways, namely: (i) from the rainfall-runoff data set for each event, and (ii) via the CN method using both λ=0.20 and λ=0.05. For the case of λ=0.05, CN values were transformed using Equation 11 (Jiang, 2001).

Additional rainfall-runoff parameters were calculated, which were later compared to the measured and CN-estimated I_a. Specifically, these were total event rainfall, rainfall event duration, response lag time (*i.e.*, time elapsed between the initial rainfall pulse and the initial hydrograph response), average rainfall intensity during the response lag, and surrogate measures for antecedent moisture conditions. Antecedent moisture conditions were inferred using antecedent rainfall amounts (ARFs) in the 2 days (48 hrs), 3 days (72 hrs), 6 days (144 hrs), 12 days (288 hrs), and 24 days (576 hrs) preceding the beginning of each rainfall event (*ARFxhrs/days*).

4.5.3 Results and discussion

I_a values estimated by the CN method (hereafter referred to as CN-derived) are generally higher than I_a values measured at the four gauging stations (hereafter referred to as hydrograph-derived) (Table 4.2); runoff events are therefore predicted to happen less frequently via the CN method than they do in reality. Using $\lambda = 0.05$ alleviates this somewhat in comparison to using $\lambda = 0.20$, but still fewer runoff events are predicted to take place less than do in reality during the study period, as seen in Figure 3a. Hydrograph-derived I_a results exhibit large inter-event variation at all study sites. At all sites, mean and median hydrograph-derived I_a are much smaller than CN-derived I_a. Mean and median hydrograph-derived I_a values by site do not rank in the same order as the CN-derived I_a values by site. As the results using $\lambda = 0.05$ were closer to field observations, the following discussion and conclusions are based on these data only.

Table 4.2: Summary of CN-derived and hydrograph-derived I_a (mm) by sub-watershed

		Gauging Station			
		2	**5**	**11**	**12**
Number of events considered		*21*	*34*	*33*	*33*
Hydrograph-derived I_a	**Mean**	2.3	1.8	2.4	2.1
	Median	0.6	0.4	0.4	0.4
	Standard deviation	4.1	2.8	5.0	4.8
	Minimum	0.0	0.0	0.0	0.0
	Maximum	16.8	11.0	19.4	19.4
CN-derived I_a	**$\lambda = 0.05$**	4.5	4.6	8.8	5.9
	$\lambda = 0.20$	11.8	12.2	21.3	15.1

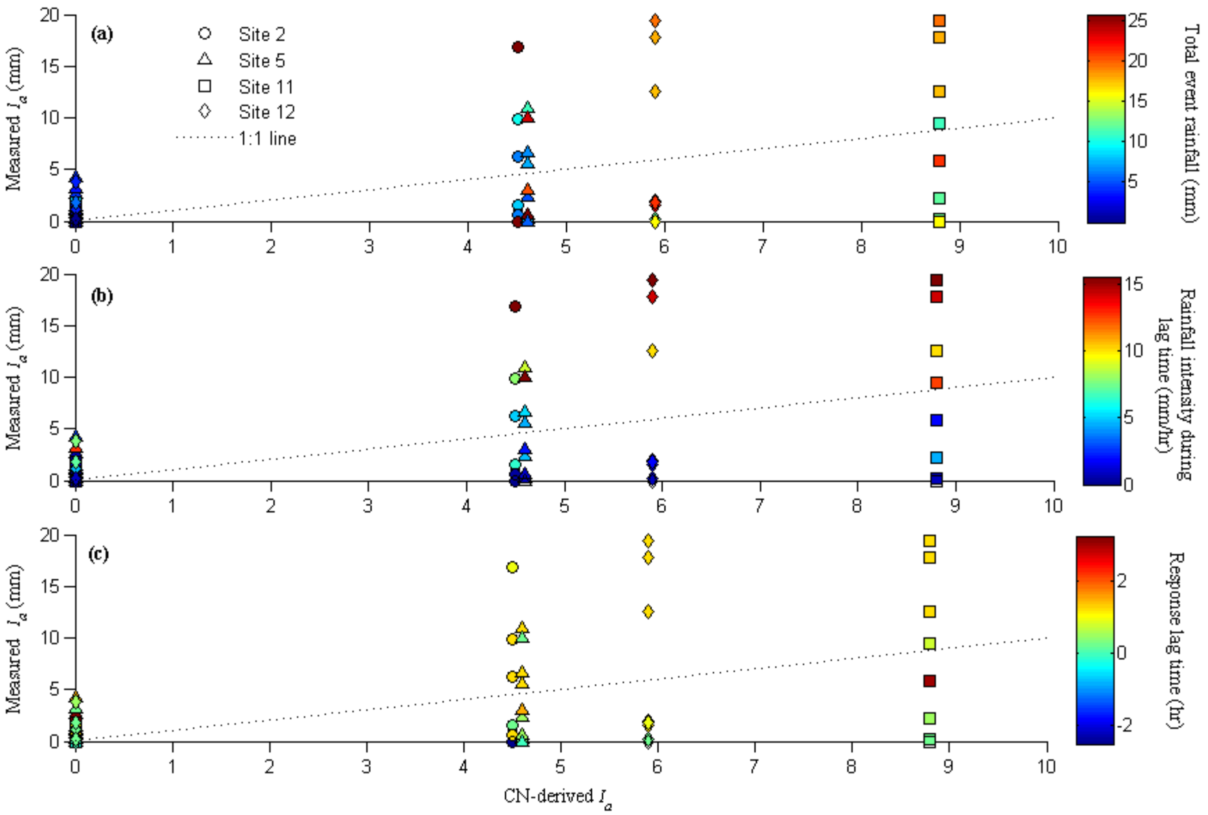

Figure 4.3: Comparison of CN-derived I_a and hydrograph-derived (measured) I_a for all four gauging stations; (a) colour-coded proportionally to total event rainfall; (b) colour-coded proportionally to the average rainfall intensity during the response lag time; (c) colour-coded proportionally to the response lag time.

The failure of CN-derived I_a values to follow the same rank-order as hydrograph-derived I_a values indicates that the CNs calculated for each sub-watershed may not be correct. The variability in hydrograph-derived I_a values is also much larger than the differences that would be expected in CN-derived I_a with a CN adjustment: thus, it is the assumption that λ is invariant between rainfall events that is the largest potential source of error in this study. Of all considered event characteristics, it is the rainfall intensity between the initiation of rainfall and the first rise of the hydrograph which correlates most strongly with the variability in hydrograph-derived I_a (Spearman's $r = 0.86$, $p < 0.001$; Fig. 4.3b). No clear relationship exists between hydrograph-derived I_a and the response lag time (Fig. 4.3c), although it should be noted that response lag times are usually very short. In addition, no relationship exists between hydrograph-derived I_a values and antecedent rainfall (Fig. 4.4), which is contrary to what has been indicated in past versions of NEH-4 (Soil Conservation Service, 1972).

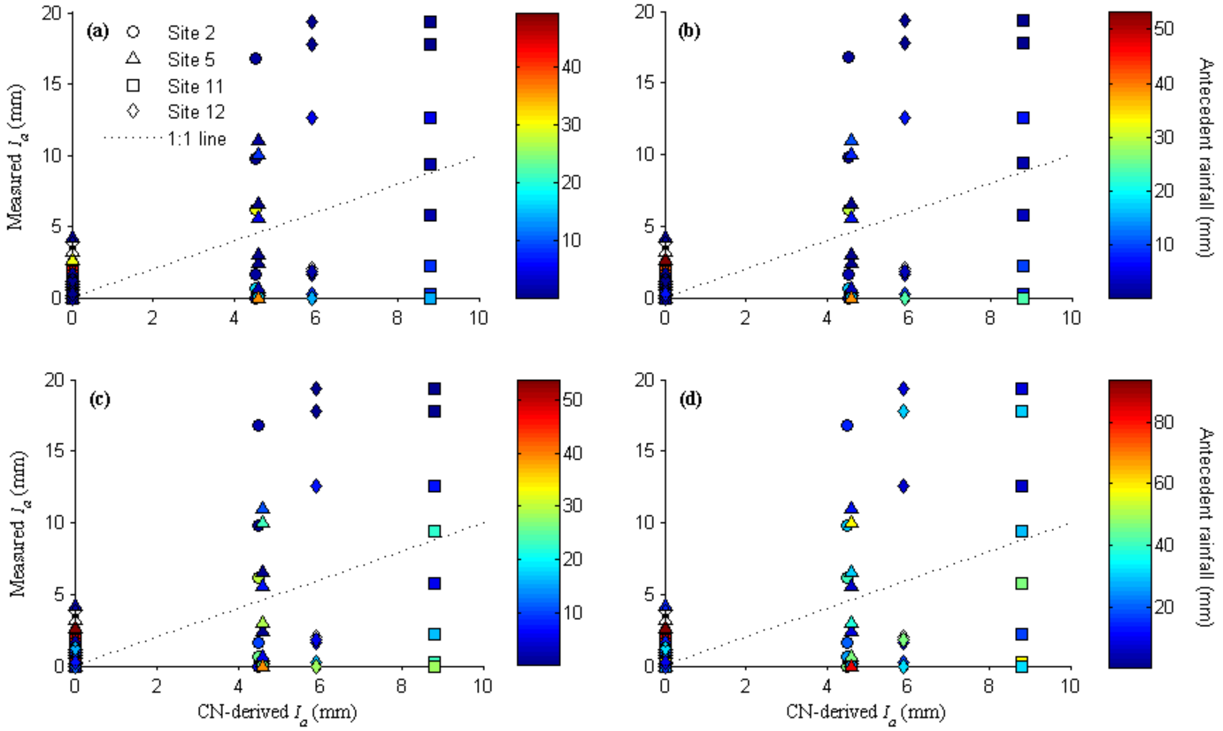

Figure 4.4: Comparison of CN-derived I_a and hydrograph-derived (measured) I_a for all four gauging stations, colour-coded proportionally to antecedent rainfall across a variety of temporal windows: (a) 2 days, (b) 4 days, (c) 6 days, (d) 12 days.

The correlation of rainfall intensity during the hydrograph response lag to hydrograph-derived I_a values suggests the variability of hydrograph-derived I_a (seen in Table 4.2) can be related to differences in the initial dominant runoff pathways among rainfall events. Indeed, sudden, intense rainfalls may produce rain faster than runoff can travel to the gauging station, resulting in large I_a values. However, it was also observed during the two-year study period that dominant runoff pathways are not consistent among events, and thus I_a may in certain cases be driven by process unrelated to rainfall intensity. The shifting dominant runoff processes of the region are clear even on the annual scale: In 2013 the average study period rainfall was 202.0 mm and, with the high PET of the Prairies, the system was dominated by vertical processes. In contrast, in 2014 average rainfall was 335.4 mm, saturated conditions were often observed, and events driven by saturation-excess more frequent (see Chapter 2 for a complete account of runoff processes in the CCW).

It is difficult to evaluate any aspect of the CN method. Without detailed information on its origins, it is always possible to argue that something about a given study design does not replicate the original experiments on which the CN method is presumably based. This examination of the method is not immune from these deficiencies: it is known that the method is most sensitive to changes in the CN value – any inaccuracy in the selection of the HSGs (for which there is no accepted standard method of doing so outside of the United States) would result in inaccurate CNs. If only the largest runoff events were used to design the CN method, as is suggested in the literature, a λ of 0.20 does become more plausible. Because it is unknown what instruments were used in the hydrometric monitoring undertaken in the development of the CN method, it is conceivable that many of the both the smallest rainfall and runoff events were missed entirely in the dataset, again resulting in a dataset for which an I_a/S ratio of 0.20, or indeed the concept of a linear λ at all, is plausible.

Although it is easy to highlight many flaws in the CN method, it must be noted that at the time of its development it was on the cutting edge of hydrology, as the ideas of partial contributing areas and saturated overland flow (Dunne & Black, 1970) had not yet been proposed. It is, however, at odds with the latest paradigm shift in hydrology. The CN method does treat the non-linearity of the rainfall-runoff relationship and it only includes one threshold effect (satisfaction of I_a), while contemporary hydrologic thought embraces many rainfall-runoff relationship shapes and threshold types (Ali *et al.*, 2013). Even though many modifications to the CN method have been published, none address the possibility of shifts in dominant runoff pathways. For example, Lyon *et al.* (2004), Schneiderman *et al.* (2007) and Steenhuis *et al.* (1995) only associate the CN method with variable source area hydrology and saturation-excess overland flow. Mishra *et al.* (2006) suggest a method for a non-linear I_a;

however, it is based on antecedent moisture conditions, which again relies on saturation-excess overland flow as the only runoff generation mechanism. Shaw & Walter (2009) propose incorporating the return period of soil moisture states as well as the return period of storms into the CN method, but they still use a linear λ and assume that runoff is generated via infiltration-excess overland flow only.

4.6. Conclusions

The wide-ranging use of the CN method can probably be explained by the fact that there are few alternative options when it comes to simple, low-parameter runoff estimation methods for engineering design. However here, after a comprehensive historical review of the CN method and field measurements of initial abstraction (I_a) on a near-level, heavily human-impacted Canadian Prairie landscape, it is concluded that the CN method should not be used in a deterministic context, *i.e.* it is not appropriate to use within continuous process models or when a runoff estimate is needed for a specific rainfall event. This finding is consistent with earlier studies and comments by Hoesein *et al.* (1989) and Woodward *et al.* (2002). Hydrograph-derived I_a is highly variable in the studied Prairie watersheds, and this variability best correlates with early event rainfall intensity, thus suggesting that changes in runoff generation processes among events may be the cause of variability in hydrograph-derived I_a values. Because CN values exist for a specific assumed I_a/S ratio, this assumption of a constant ratio is built-in to the CN values themselves, making them also unsuitable for use as a model parameter. Here it is suggested that research either explicitly recognize the limitations of the CN method or focus on developing a more flexible method inclusive of the variety of existing rainfall-runoff relationship shapes and possible runoff generation processes. In the context of the Canadian Prairies, this could be achieved through the incorporation of rainfall intensity in new methods for runoff prediction, which would be more valuable as a single parameter than antecedent moisture condition.

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CHAPTER 5.

FINAL SYNTHESIS AND CONCLUSIONS

5.1 Summary of conclusions and significance of research

Near-level, engineered Prairie landscape systems have received little attention thus far in hydrology literature. Similarly, no study concerning the SCS-CN methodology has been conducted in the Prairies, although this model is widely used by Provincial Government of Manitoba for runoff estimation and is included as an input parameter into modern runoff prediction models (Ponce & Hawkins, 1996; Arnold *et al.*, 1998). Therefore, the objective of this thesis was to address these knowledge gaps.Through the analysis of rainfall-runoff data of a meso-scale watershed in south eastern Manitoba, Canada, it is concluded that Prairies are hydrologically unique. This conclusion was reached based on a two-pronged research approach.

First, rainfall-runoff data were analysed in an effort to find runoff controls, and determine if runoff is controlled in the same way in near-level, engineered Prairie landscapes as in higher relief, pristine watersheds. As spatio-temporal watershed factors are known to influence hydrograph shape (Buttle, 2006), runoff controls were inferred using event hydrograph parameters. Specifically, land use and land cover and topographic characteristics of the study sub-watershed were considered for their effect on the hydrograph, and the rainfall-water level data was examined for threshold behaviour. Ultimately, storage thresholds were only observed in two of twelve of the study sub-watersheds, indicating that abundant storage is generally available in Prairie watersheds which combined with the high potential evapotranspiration of the region results in thresholds that can only be satisfied only by extreme rainfall events. Landscape characteristics did not influence the hydrograph, and correlation of total event rainfall with initial abstraction indicates that Prairie systems are typically dominated by vertical processes. Although, under certain conditions saturated overland flow and subsurface storm flow are activated, as inferred by an increase in the duration of event time of concentration. It is presumed that antecedent moisture conditions play a role in this shift, though generally surrogate antecedent moisture variables were not found to be strongly and consistently related to hydrograph parameters. A conceptual model for runoff in human-impacted Prairie landscapes was proposed to this regard. Understanding the dynamic runoff pathways in the Prairies has implications not only for water quantity, but quality as well: runoff pathway determines which areas of the watershed act as sources and sinks of contamination (Lyon *et al.*, 2006), contaminant travel within the watershed (Tomer *et al.*, 2010) , and connectivity to the outlet (Jackson & Pringle, 2010).

Second, initial abstraction specifically was examined to determine if the United States Soil Conservation Service curve number method (CN method) adequately predicts abstractions on Prairie landscapes. Generally, the CN-derived initial abstraction was larger than the hydrograph-derived initial abstraction, which results in an under-prediction of runoff event frequency by the CN method. Estimating total hydrologic abstractions based on a single, constant storage ratio was deemed unrepresentative of Prairie hydrology as inter-event abstractions varied widely. While initial abstractions were determined to be most strongly related to rainfall intensity during the hydrograph response lag, this was not always the case, due to the shifting nature of dominant runoff processes in the region. A wide range of inter-event initial abstractions were observed. This, along with the CN method's lack of explicit consideration for runoff generation pathways and its inability to account for shifts in dominant runoff generation mechanisms, led to the conclusion that the CN method should be used only probabilistically. A detailed summary of the history of the CN method, with special emphasis on the initial abstraction ratio, was also presented.

5.2 Opportunities for future research

This work raises many further questions regarding the hydrology of near-level, engineered Prairie landscapes. Research with the explicit goal of measuring the contributions of saturated overland flow and subsurface storm flow is needed to better understand the processes controlling the presumed shift in dominant runoff processes observed here. The conceptual model of Prairie runoff generation proposed here in Chapter 2, summarized in Figure 2.9, could be tested for applicability to other watersheds of analogous (near-level, engineered) regions of the Prairies. This could be undertaken through calculating hydrograph parameters from existing event rainfall-runoff datasets, or more expressly in a study designed with focus on culvert impact on Prairie runoff dynamics. If different runoff generation modes are indeed dominating at different times or under different conditions, knowledge of when and where runoff generation shifts from Hortonian overland flow to other mechanisms would improve prediction of rainfall-triggered flooding in the Prairies. Because of the dynamic nature of Prairie runoff processes, improvements to the CN method are also needed if it is to be used outside of a probabilistic engineering design context. A more flexible method which would allow for a diversity of rainfall-runoff relationship shapes would improve upon the status quo. Ultimately the Prairies, particularly of southern Manitoba, remain under-studied.

5.3 References

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