

Flood-Drought Hazard Assessment for a Flat Clayey Deposit in the Canadian Prairies

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ABSTRACT. Dry climate, clayey soil, and flat topography govern water balance in the southern part of the Canadian Prairies. This paper aims at assessing flood-drought hazard using Regina as a typical urban centre in the region. The main achievements are the inclusion of long-term historical analyses of recent meteorological data, physiographic features (such as topography, land use, soil type) of watersheds, various types of drought (agricultural, meteorological, and hydrological), and management strategies for surface water. Results indicate that extreme weather patterns are frequent and meteorological parameters have significantly changed from 1970 to 2015: precipitation (+50 mm), air temperature (+0.9 °C), relative humidity (+6%), wind speed (-1.35 km/hr), and solar radiation (+0.9 MJ/m²). In the dry climate (*D/fb*), 77% of the total annual precipitation (386 mm/year) occurs from April to September. The runoff coefficient of 0.6 relates to 63% impervious areas (commercial, industrial and residential) and 35% near-impervious areas (open spaces with low hydraulic conductivity). The flat topography (570 m through 600 m asl over 124 km²) along with a low channel slope of up to 0.4% results in water ponding during short-term and high-intensity rainfalls. Water is managed through the Wascana Creek that holds 98% of the total water volume (84 × 10⁶ m³) in the city. From April to September, volume fluctuations depend on antecedent water levels and meteorological conditions. The city has recently received several events of flash floods (2010 and 2014) and long-term droughts (1984 and 2017). The negative average change in storage indicates drought-like conditions during spring-summer.

Keywords: flood-drought, hazard assessment, flat terrain, clayey deposit, dry climate

1. Introduction

Floods and droughts adversely affect civil infrastructure, agricultural production, and life quality. The southern part of the Canadian Prairies (Alberta, Saskatchewan, and Manitoba) provides an interesting combination of climate, topography, and soils that governs surface water fluctuations. Over the last decade or so, several cities (Regina, Calgary, Winnipeg) and wide spread farmlands in the area have received record flash-floods and long-term droughts thereby resulting in acute public distress. Clearly, there is a need to understand the response of watersheds to ensure a sustainable (cost effective, environmentally friendly, and socially viable) management of surface water for use in urban centers and rural communities.

The management of water resources in the Canadian Prairies is affected by the following (Wheater and Gober, 2013): (i) ensuring an uninterrupted drinking water supply for 3 × 10⁶ inhabitants; (ii) trade-off between industrial (mining and petroleum) and agricultural water usage; (iii) allocation between upstream (Alberta) and downstream (Saskatchewan and Manitoba) water use; and (iv) water quality for urban and rural communities. Generally, the region is characterized by a significant

moisture deficit, such that evaporation exceeds precipitation (Lemmen, 1998). This is attributed to the restricted inland movement of Pacific air masses beyond the Rockies. However, large precipitation events associated with continental air masses from the south are also not uncommon (Vickers et al., 2001). Furthermore, the area is vulnerable to climatic impacts and experience large variations in seasonal weather (Lundqvist, 1999). The tree ring records (indicative of moisture due to precipitation and evapotranspiration) suggest several multi-year spells of drought and sporadic flooding over the last 300 years (George et al., 2009; Bonsal et al., 2011). These studies give an indication of the driest decades (1720s and 1790s), longest droughts (1840 ~ 1880 and 1920 ~ 1940), and major floods (1747, 1762, 1826, 1852, 1862, 1950, and 1997).

Floods and droughts are becoming more frequent and widespread in the region due to climatic changes causing extensive variability of precipitation both spatially and temporally (Bonsal and Wheaton, 2005). These climatic hazards are compounded by the ever increasing impervious areas (especially in urban settings), which results in low infiltration and high runoff. Over the last three decades, summer fallow has changed into continuous annual cropping thereby increasing evapotranspiration from croplands and, in turn, causing increased drought spells and severity (Gameda et al., 2007). Such trends are quite observable in the Palliser Triangle that has experienced severe and/or multi-year droughts in the 1920s, 1930s, and 1980s with serious social, economic, and environmental

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consequences. Similarly, southern Saskatchewan (that occurs within the Triangle) experienced multi-year droughts in the 1890s, 1930s, late 1950s, and early 1960s, 1980s, and most recently from 1999 ~ 2005 (Bonsal et al., 2011). Despite a dry climate, the area received irregular flooding during the last few years, specifically in 2011, 2013, 2014, and as far back as 1927, 1948, 1955, and 1969 (Shook and Pomeroy, 2015).

Regina (Saskatchewan) is a typical example of a flood-drought affected area in the southern Canadian Prairies because of a flat terrain, clayey soil, and a dry climate. These geomorphic, geologic, and climatic features are quite representative of the region, especially in and around Winnipeg, Swift Current, Moose Jaw, and Edmonton. Generally, the Prairies exhibit a flatland with typical glacial landforms such as moraines (raised ground that covers unsorted till) and eskers (long winding ridge of sorted gravel) as well as lakes and low velocity rivers resulting from the meltwater of the retreating glaciers (Ito and Azam, 2009; Savage, 2011). Likewise, the surface soils are predominantly loamy to clayey with variable amounts of organic matter (Rostad et al., 1993) and possess low infiltration and high water holding capacity (Ito and Azam, 2013).

The city (50°26' N, 104°40' W) falls under a dry continental climate, as per the Köppen climate classification system, and experiences extensive seasonal variations in meteorological parameters. Extreme weather events include short duration and high intensity rainfalls and extended time periods with no rainfall. Likewise, the underlying soil comprises a fine grained clayey deposit that inhibits infiltration due to a low hydraulic conductivity of 5×10^{-9} m/sec (Ito, 2009). Additionally, the low ground relief (derived from high overburden load of glacial ice sheets (Ito and Azam, 2009)) facilitates water ponding. Due to these unique features, the city has experienced three major flood events in the last decade, including the one in June 2014 when storm sewers backed up in at least 276 homes (Shook and Pomeroy, 2016). Similarly, droughts (water deficit spanning over several months) have recently impacted crop yield thereby resulting in huge losses to the economy (Wittrock and Wheaton, 2007).

The main purpose of this study was to conduct flood-drought hazard assessment in a flat clayey deposit under a dry climate. Using Regina as a typical urban centre from the southern Canadian Prairies, the research was carried out by adopting the following step-wise approach: (i) analysis for climate trends and climate normals, (ii) determination of spatial distribution of land use and land form, (iii) statistical assessment of floods and droughts, and (iv) temporal water budget analyses.

2. Literature Review

Research related to flood hazard assessment in the Canadian Prairies include the following: (i) constructing intensity-duration-frequency (IDF) curves for Saskatoon using the observed daily precipitation from 1992 to 2009 (Alam et al., 2015); (ii) developing dimensionless flood frequency curves for five homogeneous regions in southwestern Alberta using regression analysis and flood index with the precipitation data

of 1912 to 1978 (Xu, 1999); (iii) investigating factors affecting 2013 southern Alberta flood using measured precipitation data (Teufel et al., 2017); (iv) identifying the areal extent of 1997 flood in the Red River Valley using satellite imagery from 27 April 1997 to 1 July 1997, (Wilson et al., 2005); and (v) estimating stream flow across Canada for historical (1961 ~ 2005) and future (2061 ~ 2100) time-periods by using Catchment-based Macro-scale (CaMa) method (Gaur et al., 2018). Likewise, studies related to drought hazard assessment in the Canadian Prairies focused on the following: (i) monitoring agricultural drought in 43 districts using 1920 ~ 1999 precipitation and temperature data (Quiring et al., 2003) (ii) investigating agricultural drought in 34 regions using multiple drought indices and 1976 ~ 2003 crop yield data (Sun et al., 2012); (iii) identifying healthy and stressed vegetation through satellite imagery in southern Alberta from 2000 ~ 2006 (Hanesiak et al., 2011); (iv) calculating daily moisture anomalies over 1950 ~ 2009 using variable soil infiltration capacity (Wen et al., 2011); and (v) classifying consecutive drought events using time series analysis from daily and monthly precipitation totals of 1959 ~ 2000 and 1909 ~ 2000 (Chipanshi et al., 2006).

It is clear that the above research studies are limited by their time duration (single floods and/or short-term analyses), spatial extent (generalized assessments of large areas), and meteorological focus (primarily based on precipitation), and scoping issues (lack of recent historical analyses and a focus on agricultural droughts). As such, these works have the following shortcomings: (i) inadequate capture of physiographic features (such as topography, land use, soil type) in urban watersheds; (ii) lack of long-term historical analyses of recent meteorological data; (iii) neglect of several other types of drought; and (iv) lack of water resource management strategies for urban centers.

Table 1 summarizes the various estimation, measurement, and statistical methods for flood and drought hazard assessment. For each method, the first reference pertains to the Canadian Prairies and the second reference is for a typical case elsewhere on the globe. The methods are briefly described and the main limitations highlighted.

The current study uses IDF curves to determine long-term flood estimates based on average intensities representing data from several storms. The peak flow could not be estimated because the discharge data at various locations in the watershed was not available. Similarly, the measurement techniques could not be used as these either focus on one station with extensive data scatter (due to biases, obstructions, procedures, locations, and instrumentation) or lack continuous long-term data even if spatially spread out. Likewise, the CaMa-floodplain method could not be used because of the absence of a river in the investigated watersheds and the inadequate treatment of evaporation and infiltration. Whereas the multivariate stochastic formulation may be applicable, it was not used because of the associated complexity and excessive data requirement.

Likewise, this study uses the SPI to determine a wide range (meteorological, agricultural, and hydrological) of long-term droughts using cumulative precipitations. The multi in-

Table 1. Summary of Methods for Flood-drought Hazard Assessment

Method and References*	Description	Limitations
Flood		
Estimation		
Precipitation based flood index (Alam et al., 2015), (Kuo et al., 2015)	Uses rainfall intensity-duration-frequency curve for estimating flood	Does not represent time histories of real storms
Peak flow based flood index (Benson, 1962), (Xu, 1999)	Determines magnitude and frequency of peak flow	Assumes natural flow with minimum flow level regulations
Measurement		
Rain gauges (Carbone et al., 2014), (Teufel et al., 2017)	Measures amount of precipitation for calculating flood	Data is captured at one station only
NOAA-AVHRR ¹ and Radarsat (Domenikiotis, et al., 2003), (Wilson et al., 2005)	Measures spatial extent of flood	Satellite may not receive signal through clouds
Statistical		
CaMa ² -floodplain (Ikeuchi et al., 2015), (Gaur et al., 2018)	Simulates hydrodynamic flow in rivers	Evaporation and infiltration are not considered
Multivariate stochastic rainfall (Efstratiadis et al., 2010), (Asong et al., 2016)	Captures spatio-temporal variations in rainfall for calculating flood	Requires long-term rainfall data
Drought		
Estimation		
Precipitation based drought index (SPI) (Quiring et al., 2003), (Bonsal et al., 2011)	Compares dryness degree based on a minimum 30-year record	Does not account for climatic parameters affecting evaporation
Multi-index drought (Sun et al., 2012), (Chen et al., 2018)	Combines NDI ³ , PDSI ⁴ , and SPI of drought	Applicable only for agricultural drought ranges
Measurement		
Satellite and Radar (Hanesiak et al., 2011), (De Jesús et al., 2016)	Measures drought from vegetation maps	Requires frequently captured vegetation maps
Variable infiltration capacity (Liang et al., 1994), (Wen et al., 2011)	Measures drought from soil moisture data	Cannot process physical objects on ground
Statistical		
Time series (Chipanshi et al., 2006), (Hao et al., 2018)	Uses historical data of precipitation to calculate drought	Does not capture soil moisture
Artificial intelligence (Sadri, 2010), (Hao et al., 2018)	Models nonlinear interactions in various drought indicators	Uses existing relationships between predictor and predicand only

¹ National Oceanic and Atmospheric Administration's (NOAA), Advanced Very High Resolution Radiometer (AVHRR)

² Catchment-based Macro-scale

³ NOAA Drought Index

⁴ Palmer Drought Severity Index

dex method was not used because it focuses on agricultural droughts only and uses several indices deemed unnecessary for the current study. Similarly, the measurement methods could not be used because of the unavailability of frequently acquired soil vegetation and soil moisture maps. Finally, the statistical methods could not be used because of inadequate capture of soil infiltration (time series) or the absence of strong relationships among various drought indicators (artificial intelligence) for the investigated watershed.

3. Research Methodology

The monthly total precipitation and average data for mean air temperature, wind speed, and relative humidity from 1970 ~ 2015 were acquired from Environment Canada: 1970 to 2007 from the Regina International Airport station and 2008 to 2015 from the Regina Christian School station. Likewise, the solar radiation data from 1993 to 2003 were acquired from the De-

partment of Geography at the University of Regina. The climate trends were analyzed using the least square method: annual total for precipitation and annual average for air temperature, wind speed, relative humidity, and solar radiation. Similarly, the climate normals were calculated from the average values for each month.

Land use was identified by the supervised classification method (Anderson et al., 1976) for quantitative analysis of remotely sensed images in ArcGIS 10 (developed by Environmental System Research Institute, USA). The Landsat (thematic mapper TM 4-5) satellite image, taken in August 2010, was acquired from the United States Geological Survey (USGS). The following three classes of land use were identified: water (blue, 0000FF), urban areas (magenta, FF00FF), and open spaces (green, 008000). Furthermore, the urban areas (distinct shades of magenta, as given in Figure 3) were further divided into commercial, industrial, and residential by using Google Earth 7.3. The 7, 4, and 2 spectral band combination preset was

used to capture the natural color of land reflection in the satellite image. A given pixel in the image was compared with the identified spectral profiles and an appropriate class was assigned to this pixel. An in-built maximum likelihood algorithm was used to ensure precision (agreement between the classified image) and accuracy (agreement between an assumed standard image and the classified image). Thereafter, the software calculated the area covered by each class of land use.

Flood discharge curves were developed from the IDF curves using the rational method (City of Regina, 2010). Using C for runoff coefficient, i for rainfall intensity (m/s), and A for watershed area (m²), peak discharge (Q_p , m³/s) was calculated for various return periods (T_r of 5, 25, and 100 years) over 24 hours using the following equation (Bedient et al., 2013):

$$Q_p = CiA \quad (1)$$

The Severity Duration Frequency (SDF) curves were developed using the standardized precipitation index method in SPI_SI_6.exe (Abramowitz and Stegun, 1965; Sabau, 2014). To determine a cumulative SPI, the monthly total precipitation data were used to obtain a normal cumulative probability distribution thereby obtaining a mean value at 0.0 and a standard deviation of ± 1.0 (Edwards and McKee, 1997). Several combinations of 3, 6, 9, and 12 month periods were simulated and the drought events were identified when the cumulative SPI ≤ -1.0 (McKee et al., 1993). The corresponding cumulative precipitation was plotted with respect to the above durations. Furthermore, the return period for cumulative precipitation (based on cumulative SPI) was calculated using r for rank of event (the severity of event ranked in ascending orders) and m for number of events (total number of events in each duration) according to the following equation (Juliani and Okawa, 2017):

$$T_r = \frac{2m}{100(2r-1)} \quad (2)$$

The watershed geometry included watershed areas, contours, water bodies and slopes. Watershed areas were acquired from the Agriculture and Agri-Food Canada whereas the digital elevation model (obtained from USGS and possessing a 30 m resolution) was used to create 10 m interval contours and water bodies in ArcGIS 10. Using Δh for difference in elevation between end points of a channel, L for the watershed length (straight line distance along the channel), the slope (s) was calculated using the following equation:

$$s = \frac{\Delta h}{L} \quad (3)$$

In Equation (3), L was calculated using x_1 , x_2 for X -coordinates and y_1 , y_2 for Y -coordinates, as follow:

$$L = [(x_2 - x_1)^2 + (y_2 - y_1)^2]^{\frac{1}{2}} \quad (4)$$

Depth of creeks (Wascana and Pilot Butte), retention ponds,

and storm channels was acquired from Wascana Authority, City of Regina, and field measurements in summer 2017; all of the depths were duly calibrated to the mean sea level (msl). Similarly, the top width of water bodies was measured from the Regina map. Using f for depth, b for bottom width (equaling $T - 2d/\tan 30^\circ$, with the slope angle assumed to be 30° with the horizontal line), and T for top width, the cross sectional area (A) of a water channel was calculated for a trapezoidal shape, as follows:

$$A = \frac{f(b+T)}{2} \quad (5)$$

The volume of a water channel was calculated by multiplying length with cross sectional area.

Water budget was determined over spring-summer (April to September) assuming constant precipitation throughout the city (because of a concentrated watershed with no mountains to facilitate localized orographic rainfall) as well as no base flow (because of the absence of shallow groundwater in the watershed), and negligible inflow and outflow (because of the flat terrain of the entire area in and around the watershed); the spring runoff from melting snow is controlled upstream of Regina. Furthermore, snow melt was not considered because of the modeling limitations albeit being 23% of the total annual precipitation. Using P for precipitation, R for runoff, I for infiltration, E for lake evaporation and ET for evapotranspiration, the change in storage (ΔS) was calculated as follow:

$$P - R - I - E - ET = \Delta S \quad (6)$$

The precipitation data were acquired, as mentioned before. Runoff and infiltration were simultaneously calculated in HEC-HMS (4.2) for the various sub-watersheds (Bedient, 2013). The Soil Conservation System (SCS) curve number method was used to calculate infiltration. An average soil water content was assumed because of the low hydraulic conductivity and the high water holding capacity of the clay (Ito, 2009). The Muskingum method along with the SCS unit hydrograph was used to calculate channel flow. Likewise, evaporation was obtained using the Meyer's equation developed for the Canadian Prairies, as given below (Martin, 2002):

$$E = C_a(V_w - V_a)(1 + \alpha W)(1 + \beta A_e) \quad (7)$$

The above equation denotes monthly evaporation by E , calibration coefficient by C_a (10.1 for this study corresponding to vapour pressure based on 24 observations of air temperature per day), monthly mean saturated vapour pressure by V_w , actual monthly mean vapour pressure by V_a , monthly mean wind speed by W , elevation above mean sea level by A_e , and coefficients by α (6.21×10^{-2}) and β (3.28×10^{-5}). Finally, evapotranspiration (evaporation from soil surfaces including vegetation (Tran et al., 2015) was calculated by multiplying evaporation with a pan coefficient of 0.76 (similar to the semiarid climates of central Tunisia (Alazard et al., 2015).

4. Results and Discussion

Figure 1 shows the climate trends of metrological parameters from 1970 through 2015. The data were analyzed in terms of annual means and standard deviations from the means. The best fits (linear equations along with the coefficients of regression, R^2) as well as the maximum and minimum values are given. Generally, the annual mean values are close to the best-fit climate trends (albeit low statistical significance, as indicated by $R^2 \leq 0.34$) with the exception of solar radiation for which the range of available data were limited, that is, 1993 to 2003. Over the investigated time, the meteorological parameters changed as follows: precipitation (+50 mm), air temperature (+0.9 °C), relative humidity (+6%), wind speed (-1.35 km/hr), and solar radiation (+0.9 MJ/m²). Furthermore, the large data scatter indicates the frequency of extreme weather patterns on an annual basis.

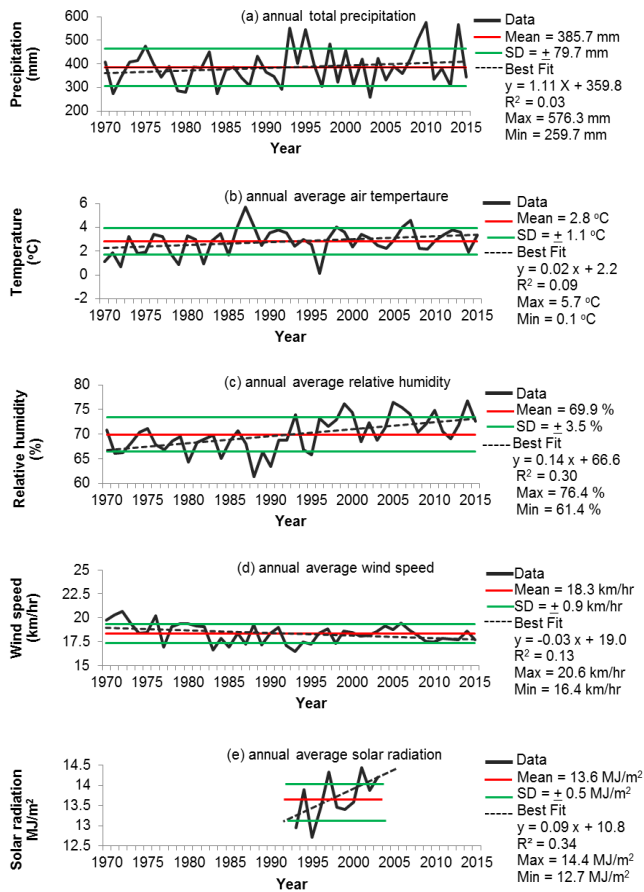


Figure 1. Trends of metrological parameters: (a) annual total precipitation; (b) annual average air temperature; (c) annual average relative humidity; (d) annual average wind speed; (e) annual average solar radiation. (Data obtained from Environment Canada and Department of Geography, University of Regina).

Figure 2 shows the climate normals of metrological parameters from 1970 through 2015. The data were analyzed in

terms of annual means and standard deviation from the means with the maximum and minimum values also given. The figure shows a monthly mean precipitation (Figure 2(a)) of 32 mm. The total annual precipitation was found to be 386 mm/year, of which 77% occurs from April to September. This is the time of the year when the air temperature is mostly positive (that is, H₂O is in liquid form) although the annual mean air temperature (Figure 2(b)) is 2.8 °C. During this season, relative humidity is lower than the mean value whereas solar radiation is higher than the mean value and wind speed is not correlated. The last four meteorological parameters are used to calculate evaporation, as presented later in this paper. Based on climate normals, Regina is classified as *Dfb*: where, *D* is for average air temperatures of above 10 °C in five months and below -3 °C in the coldest month, *f* is for precipitation in all months (minimum of 11 mm in February), and *b* is for average air temperatures of below 22 °C in the warmest month (July).

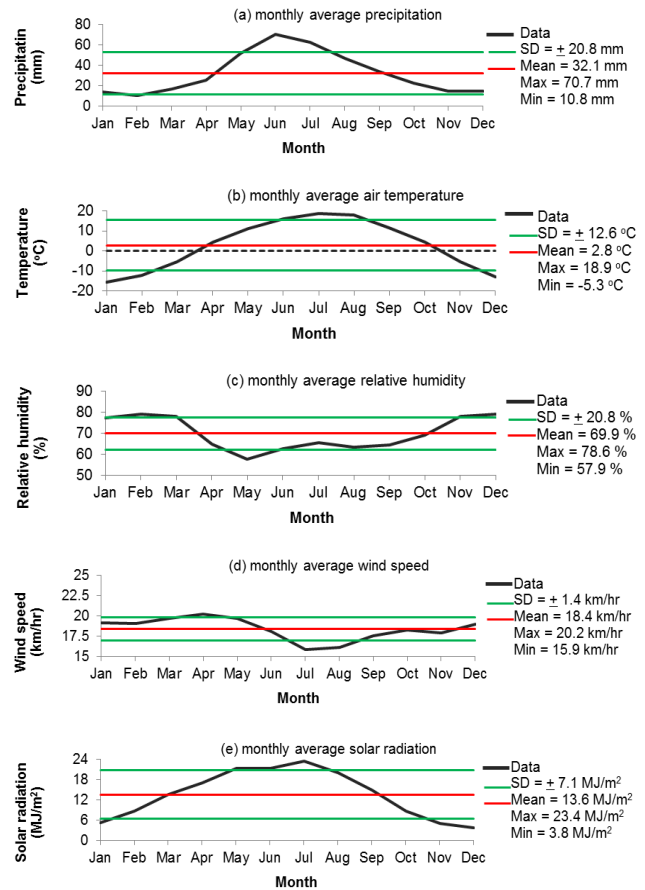


Figure 2. Climate normals of metrological parameters: (a) monthly average precipitation; (b) monthly average air temperature; (c) monthly average relative humidity; (d) monthly average wind speed; (e) monthly average solar radiation. (Data obtained from Environment Canada and Department of Geography, University of Regina).

Figure 3 shows the land use classification for Regina. Most of the city is classified as residential and open spaces with

areas of about 46 km² (37%) and 43 km² (36%), respectively. These results were double checked using Google Earth 7.3 as well as field surveys within the study area. Some of the water bodies appearing in the figure (such as in the north and in the south) were found to be temporary and, as such, not included in subsequent analysis. The various types of areas are distributed as follows: industrial in the north-east; residential spread out over most of the city; commercial mainly in downtown, east, north, and south; open spaces (parks and fields) in and around the city; and water bodies mainly in the south-east and scattered elsewhere. Using the corresponding runoff coefficients, *R/P* (Bedient et al., 2013), a weighted average value of 0.6 was obtained.

Runoff is primarily attributed to impervious areas (commercial, industrial and residential), which account for about

63% of the entire city. In contrast, open spaces (35%) mainly contribute to infiltration and evapotranspiration, and water bodies (2%) to evaporation with the remainder reporting as runoff. Given the low saturated hydraulic conductivity of the clay (5×10^{-9} m/s that decreases by several orders of magnitude under unsaturated antecedent conditions (Ito, 2009)), infiltration through open spaces is expected to be low albeit the presence of surficial soil cracks that may consume some water for self-healing.

Figure 4 gives flood-drought hazard assessment methods. The discharge volume (Figure 4(a)) was calculated for different return periods: 5 years for sewers, inlets, and gutters, 25 years for flow routes, roadways, watercourses, and 100 years for detention facilities (City of Regina, 2010). As expected, these trends followed the IDF curves for all of the return periods, that

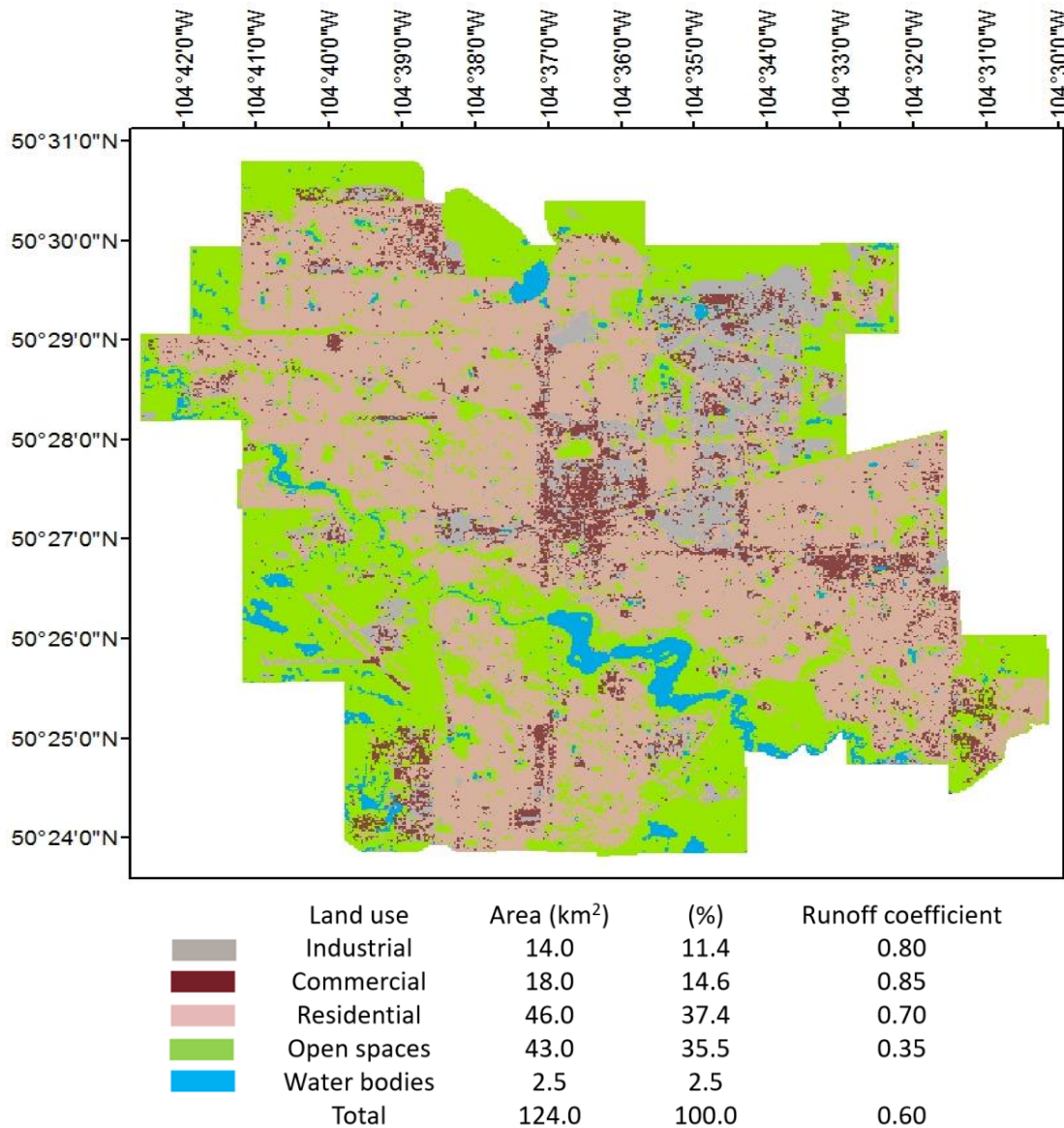


Figure 3. Spatial distribution of land use.

is, discharge increased with an increase in return period. Furthermore, each curve is characterized by two slopes: a steep slope up to 2 hours and a flat slope thereafter. The actual floods of 06 September 2010 and 28 June 2014 resulted in $9.6 \times 10^6 \text{ m}^3$ (Environment and Climate Change Canada, 2018) and $9.9 \times 10^6 \text{ m}^3$ of water over 24 hours, respectively. Although, IDF curves do not represent actual rainfall histories (Mcpherson, 1978), these events were found to be close to the 100 year return period.

The severity duration frequency curve (Figure 4(b)) for the above-mentioned return periods were developed for the following selected durations of significance (Edwards and McKee, 1997): 3 months (*meteorological drought*, onset of a dry weather pattern), 6 months (*agricultural drought*, insufficient soil moisture for crops), and 9 ~ 12 months (*hydrological drought*, water level decrease in streams and reservoirs). The actual 12-month drought events in 1984 and 2017 resulted in 225 mm and 125 mm of precipitation, respectively (Lizée, 2018). Once again, these events were found to exceed the 25-year and the 100-year return periods, respectively.

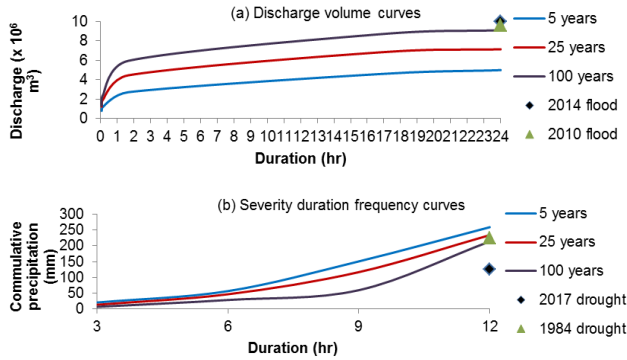


Figure 4. Flood-drought hazard assessment methods: (a) discharge volume curves and (b) severity duration frequency curves.

Figure 5 shows the characteristics of all of the watersheds (numbered in flow direction) in Regina. Most of the city comprises of watersheds V (39.9 km² in the center and south to south-west) and VI (49.3 km² in the north). Smaller watersheds I (8.2 km²), II (1.8 km²), III (8.8 km²), and IV (15.8 km²) are located in the center and south to south-east. The small areas around the city limits were considered to be insignificant. The elevation changes from 600 m asl in the north-east through 570 m asl in the south-west. This uni-directional elevation change is attributed to alternate glacial advances and retreats during the Wisconsin (Christiansen and Sauer, 2002). Furthermore, the Wascana Creek (from point E in the south-east to point L in the north-west) is the main flow channel in the city that receives discharge from the Pilot Butte Creek (from point A in the north-east to point D in the south-east) at point D. The corresponding creek slopes gradually decrease from 0.28% to 0.17% and from 0.41% to 0.30%, respectively. The storm channels, located in watershed V (points I ~ J with 0.29% slope and points H ~ J with 0.36%) and watershed VI (points M ~ L with 0.21%

slope), are used for snow dumping in winter. Finally, the retention ponds are located in the north-west (Lakewood, Lakeridge, and Rochdale in watershed VI) and in the south-east (Windsor in watershed III). The near-flat topography along with a low slope in the main channels results in water ponding during short-term and high-intensity rainfalls.

Figure 6 presents the theoretical volume of all surface water in Regina. The total volume of water bodies is $84 \times 10^6 \text{ m}^3$, of which 98.3% is in the Wascana Creek (E ~ L), 1.3% is in the retention ponds, and 0.4% in the storm channels and the Pilot Butte Creek. The volume of water at 0.4 m lower depth is $10 \times 10^6 \text{ m}^3$ lower than the total capacity and could have accommodated the 2010 and 2014 floods. However, this did not happen because of the possible high water level in the water bodies. Clearly, the water volume is highly dependent on antecedent condition of water level. Furthermore, the volume of water from snow melt was found to be $10 \times 10^6 \text{ m}^3$ as a product of annual total snow (93 mm), watershed area (124 km²), and volume correction for phase change (0.9). This usually does not result in flood in an average spring because it takes 2 ~ 4 weeks for snow melt thereby allowing enough time for water to discharge.

The total monthly (April through September) values for precipitation, runoff, infiltration, evaporation, evapotranspiration, and change in storage were analyzed using meteorological data of 1970 ~ 2015. The data were analyzed (plots not provided in this paper) in terms of means and standard deviations from the means. Identical trends were observed for precipitation, runoff and infiltration. Likewise, evaporation and evapotranspiration were identical to one another but did not exhibit discernible trends with the aforementioned water budget components due to various influencing factor (Figure 1): air temperature, relative humidity, wind speed, and solar radiation. These plots are summarized in Figure 7 in terms of average monthly volumes (1970 ~ 2015) along with their standard deviations. This was achieved by multiplying each of the water budget component with the corresponding area, as derived from Figure 3.

Figure 7(a) (precipitation in m³ using the watershed area of 124 km²) shows that the mean values increase from April (25.7 mm = $3.1 \times 10^6 \text{ m}^3$) to June (73.6 mm = $8.9 \times 10^6 \text{ m}^3$) and then decrease up to September (34.7 mm = $4.2 \times 10^6 \text{ m}^3$). The precipitation in April requires that the antecedent height should be decreased by an additional 0.1 m to accommodate both snowmelt and the April rainfall volume. The resulting 0.5 m total depth lowering is enough for the remainder of the months in an average year because the highest total mean (occurring in June) is lower than the sum of snow melt and April water volume. However, high-intensity and short-term precipitation events may not be accommodated because rapid dissipation is prevented in the flat topography, as was the case in 2010 and 2014 floods.

Figure 7(b) (runoff volume in m³ using the watershed area of 124 km²) show that the mean values increase from April (7.4 mm = $0.9 \times 10^6 \text{ m}^3$) to June (37.6 mm = $4.6 \times 10^6 \text{ m}^3$) and then decrease up to September (12.8 mm = $1.6 \times 10^6 \text{ m}^3$). Again,

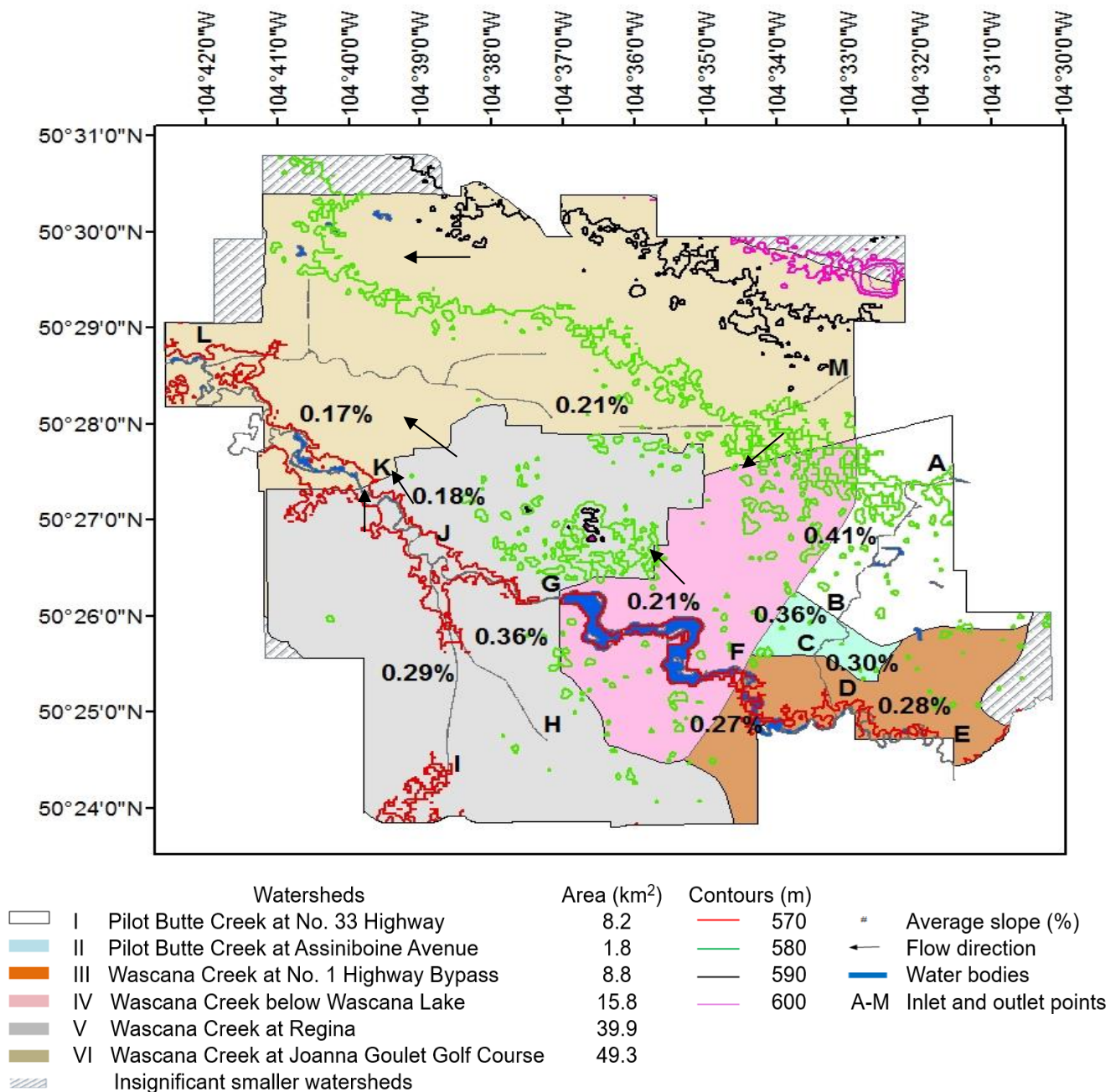


Figure 5. Characteristics of watersheds.

discharge is governed by the flat topography such that even the maximum discharge in June amounts to 5.5% of the total volume capacity ($84 \times 10^6 \text{ m}^3$). To ensure that an adequate water volume is available across the city, discharge is controlled at selected locations by using stop logs (0.385 m high steel panels).

Figure 7(c) (infiltration in m^3) shows that the mean values increase from April ($4.0 \text{ mm} = 0.6 \times 10^6 \text{ m}^3$) to June ($26.5 \text{ mm} = 1.1 \times 10^6 \text{ m}^3$) and then decrease up to September ($0.7 \text{ mm} =$

$0.7 \times 10^6 \text{ m}^3$). Figure 7(c) was obtained by using 43 km^2 of open spaces excluding residential lawns and soil under water bodies. As mentioned before, infiltration is low (a maximum of 1.3% of the total volume capacity) due to a low hydraulic conductivity of the clay (Ito, 2009).

Figure 7(d) (lake evaporation in m^3) shows that the mean values increase from April ($68.3 \text{ mm} = 0.1 \times 10^6 \text{ m}^3$) to July ($184.6 \text{ mm} = 0.3 \times 10^6 \text{ m}^3$) and then decrease up to September ($126.4 \text{ mm} = 0.2 \times 10^6 \text{ m}^3$). Figure 7(d) was obtained by using

2.5 km² of area of water bodies. It is noteworthy to mention that the highest mean evaporation occurs in July (and not, June) when precipitation is low. Overall, these plots indicate low evaporation volumes (a maximum of 0.4% of the total volume capacity) owing to the low total area of water bodies.

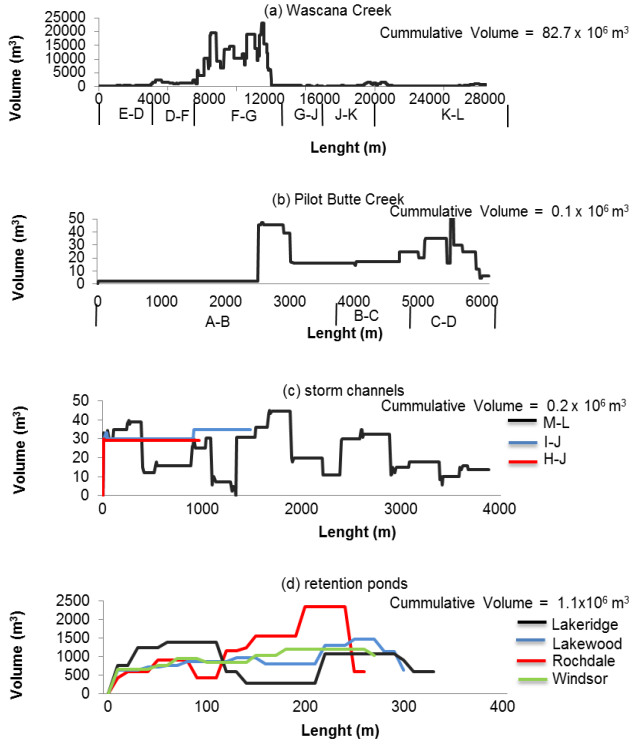


Figure 6. Theoretical volume capacity of water bodies: (a) Wascana Creek, (b) Pilot Butte Creek, (c) storm channels, and (d) retention ponds.

Figure 7(e) (evapotranspiration in m³) is similar to the corresponding evaporation plots discussed above. The mean values increase from April (51.9 mm = 2.2×10^6 m³) to July (140.3 mm = 6.0×10^6 m³) and then decrease up to September (96.0 mm = 4.1×10^6 m³). Figure 7(e) was obtained by multiplying the data by 43 km² of open spaces covered with grass. These plots indicate low evapotranspiration volume (a maximum of 7% of the total volume capacity).

The change in storage is given in (Figure 7(f)). The mean values were found to be always negative highlighting a net water deficit (representing droughtlike conditions) during spring-summer. The trends largely follow those of evaporation and evapotranspiration with a decrease in storage from April (-0.7×10^6 m³) to August (-3.8×10^6 m³) and back to September (-2.5×10^6 m³). The April height value of 0.01 m (based on areas of water bodies) means that the calculated height lowering of 0.5 m (Figure 7(a)) is required to accommodate the sum of April rainfall and snow melt. For the remainder of the season, the maximum height is 0.12 m in August and 0.07 m in September.

To manage flashfloods, it is suggested to construct detention ponds at different low elevation locations in the city such

as in the north and south (Figure 3 and Figure 5) and improve current retention ponds through channelization and increase in volume capacity (Fitri et al., 2010). Likewise, it is recommended to increase pervious areas through porous pavements particularly in new residential/commercial areas around the city (Hu et al., 2018) as well as through plant beds in parking lots and medians in existing roads throughout the city (Bedient et al., 2013). In contrast, the primary measures to combat long-term droughts include rainwater harvesting in residential and commercial areas for reuse through on site tanks, which collect rainwater/snowmelt from roofs (Van der Sterren et al., 2012) and snow dumping in the storm channels in the north and southwest of the city (Figure 3 and Figure 5) and then recycling the meltwater for agricultural and domestic purposes (Exall, 2004).

It is recommended to extend this research further beyond the following limitations: (i) use of climate data spanning over 45 years (1970 to 2015) only; (ii) unavailability of recent high resolution satellite imagery; (iii) neglecting snowfall and snowmelt in water budget estimation; and (iv) use of precipitation-based methods only for flood-drought hazard assessment.

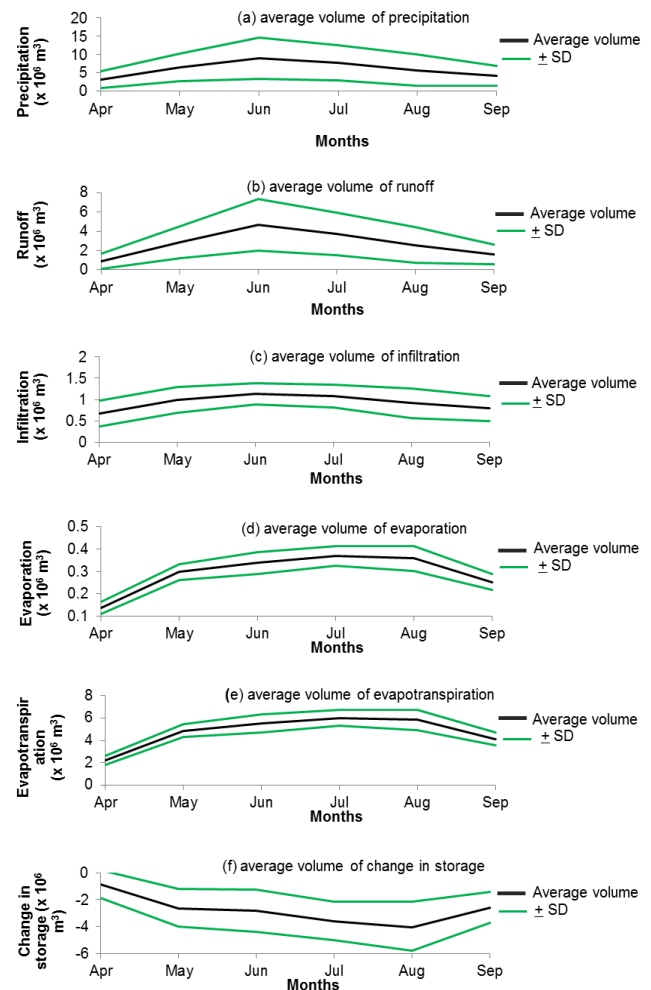


Figure 7. Estimated average total volumes of water budget components.

5. Summary and Conclusions

Knowledge of region-specific issues is critical for efficient watershed management. Dry climate, clayey soil, and flat topography govern water balance in the southern part of the Candaina Prairies. This research assessed flood-drought hazards in a typical urban centre of the area (Regina, Saskatchewan) by adopting the following step-wise approach: analysis for climate trends and climate normals, determination of spatial distribution of land use and land form, statistical assessment of floods and droughts, and temporal water budget analyses. The main conclusions of the study are given below:

- Over the investigated time (1970 through 2015), meteorological parameters have changed as follows: precipitation (+50 mm), air temperature (+0.9 °C), relative humidity (+6%), wind speed (-1.35 km/hr), and solar radiation (+0.9 MJ/m²). Likewise, extreme weather patterns are frequently observed in the area. Under the prevalent dry climate (Dfb), 77% of the total annual precipitation (386 mm/year) occurs from April to September. This study provided long-term historical analyses of recent meteorological data for the Regina area. Further research is required to include snowmelt (causing partial flooding) in early spring, evaporation in late fall (causing drought-like conditions), and the effect of snow cover in winter.
- The runoff coefficient of 0.6 highlights the significance of impervious areas (commercial, industrial, and residential) and near-impervious areas (open spaces with low hydraulic conductivity), accounting for 63% and 35% of total area, respectively. The near-flat topography (570 m through 600 m asl over 124 km²) along with a low channel slope of up to 0.4% results in water ponding during short-term and high-intensity rainfalls. As such, this study adequately captured physiographic features (such as topography, land use, soil type) and included various types of drought (agricultural, meteorological, and hydrological) in the watershed analyses. Any new development (causing land use changes in the area) must incorporate the watershed features and long-term trends to ensure minimal disruption to the innate balance of physical, chemical, and biological ecosystems within the area.
- Water is managed through the Wascana Creek that holds 98% of the total water volume (84×10^6 m³) in the city. From April to September, volume fluctuations depend on antecedent water levels and meteorological conditions. The city has recently received several events of flash floods (2010 and 2014) and long-term droughts (1984 and 2017). The negative average change in storage indicates drought-like conditions during spring-summer. Such flood and drought hazards affect both water quantity for irrigation of parks and trees and water quality for aquatic life in the lakes. Excessive storm water during flashfloods can contaminate the drinking water system thereby causing health issues as well as erode soils thereby damaging creeks, shorelines, and houses. This study provided water resource management strategies for a typical urban watershed in the Canadian Prairies.

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References

- Abramowitz, M. and Stegun, I.A. (1965). *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*. Dover Publications, Inc., New York, USA.
- Alam, M.S. and Elshorbagy, A. (2015). Quantification of the climate change-induced variations in Intensity–Duration–Frequency curves in the Canadian Prairies. *Journal of Hydrology*, 527:990-1005. <https://doi.org/10.1016/j.jhydrol.2015.05.059>
- Alazard, M., Leduc, C., Travi, Y., Boulet, G., and Salem, A.B. (2015). Estimating evaporation in semi-arid areas facing data scarcity: example of the El Haouareb dam (Merguellil catchment, Central Tunisia). *Journal of Hydrology: Regional Studies*, 3:265-284.
- Asong, Z.E., Khaliq, M.N., and Wheeler, H.S. (2016). Multisite multivariate modeling of daily precipitation and temperature in the Canadian Prairie Provinces using generalized linear models. *Climate Dynamics*, 47:2901-2921. <https://doi.org/10.1007/s00382-016-3004-z>
- Anderson, J.R. (1976). *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*. US Government Printing Office, Publication Series No. 964.
- Bedient, P.B., Huber, W.C., and Vieux, B.E. (2013). *Hydrology and Floodplain Analysis*. 5th ed., Pearson Education, Inc., New jersey, USA.
- Benson, M.A. (1962). Uniform flood-frequency estimating methods for federal agencies. *Water Resources Research*, 4(5):891-908. <https://doi.org/10.1029/WR004i005p00891>
- Bonsal, B.R., Aider, R., Gachon, P., and Lapp, S. (2011). An assessment of Canadian prairie drought: past, present, and future. *Climate Dynamics*, 41(2): 501-516. <https://doi.org/10.1007/s00382-012-1422-0>
- Bonsal, B.R. and Wheaton, E.E. (2005). Atmospheric circulation comparisons between the 2001 and 2002 and the 1961 and 1988 Canadian Prairie droughts. *Atmosphere-Ocean*, 42(2):163-172. <https://doi.org/10.3137/ao.430204>
- Bonsal, B.R., Wheaton, E.E., Chipanshi, A. C., Lin, C., Sauchyn, D.J., and Wen, L. (2011). Drought research in Canada: a review. *Atmosphere-Ocean*, 49(4):303-319. <https://doi.org/10.1080/07055900.2011.555103>
- Carbone, M., Garofalo, G., Tomei, G., and Piro, P. (2014). Storm tracking based on rain gauges for flooding control in urban areas. *Procedia Engineering*, 70:256-265. <https://doi.org/10.1016/j.proeng.2014.02.029>
- Chen, S., Muhammad, W., Lee, J.H., and Kim, T.W. (2018). Assessment of Probabilistic Multi-Index Drought Using a Dynamic Naive Bayesian Classifier. *Water Resources Management*, 32(13): 4359-4374. <https://doi.org/10.1007/s11269-018-2062-x>
- Chipanshi, A.C., Findlater, K.M., Hadwen, T., and O'Brien, E.G. (2006). Analysis of consecutive droughts on the Canadian Prairies. *Climate Research*, 30(3):175-187. <https://doi.org/10.3354/cr030175>
- City of Regina, 2010, *Development Standard Manual*. City of Regina, Saskatchewan, Canada.
- Christiansen, E.A. and Sauer, E.K. (2002). Stratigraphy and structure of Pleistocene collapse in the Regina Low, Saskatchewan, Canada. *Canadian Journal of Earth Science*, 39:1411-1423. <https://doi.org/10.1139/e02-038>
- Domenikiotis, C., Loukas, A., and Dalezios, N.R. (2003). The use of NOAA/AVHRR satellite data for monitoring and assessment of forest fires and floods. *Natural Hazards and Earth System Science*, 3(1/2):115-128. <https://doi.org/10.5194/nhess-3-115-2003>
- De Jesús, A., Bre-a-Naranjo, J.A., Pedrozo-Acu-a, A., and Alcocer

- Yamanaka, V.H. (2016). The use of TRMM 3B42 product for drought monitoring in Mexico. *Water*, 8(8):325. <https://doi.org/10.3390/w8080325>
- Edwards, D.C. and McKee, T.B. (1997). *Characteristics of 20th Century Drought in the United States at Multiple Time Scales*. Climatology Report, Department of Atmospheric Science, Colorado State University, Colorado, USA.
- Efstratiadis, A., Vasiliades, L., and Loukas, A. (2010). Review of existing statistical methods for flood frequency estimation in Greece. In *EU COST Action ES0901: European Procedures for Flood Frequency Estimation (FloodFreq)-3rd Management Committee Meeting*, Prague, Czech Republic.
- Environment and Climate Change Canada (2018). Saskatchewan's Summer of Storms. <https://ec.gc.ca/meteo-weather/default.asp?lang=En&n=9CA5E424-1>
- Exall, K. (2004). A review of water reuse and recycling, with reference to Canadian practice and potential: 2. Applications. *Water Quality Research Journal*, 39(1):13-28. <https://doi.org/10.2166/wqrj.2004.004>
- Fitri, A., Hasan, Z.A., and Ghani, A.A. (2010). Effectiveness of Aman Lake as flood retention ponds in flood mitigation effort: study case at USM Main Campus, Malaysia. *3rd International Conference on Managing Rivers in the 21st Century: Sustainable Solution for Global Crises of Flooding, Pollution and Water Scarcity*, 277-283.
- Gameda S, Qian B, Campbell C.A., and Desjardins R.L. (2007). Climatic trends associated with summer fallow in the Canadian Prairies. *Agricultural and Forest Meteorology*, 142:170-185. <https://doi.org/10.1016/j.agrformet.2006.03.026>
- Gaur, A., Gaur, A., and Simonovic, S. (2018). Future Changes in Flood Hazards across Canada under a Changing Climate. *Water*, 10(10):1441. <https://doi.org/10.3390/w10101441>.
- George, S., Meko, D.M., Girardin, M.P., MacDonald, G.M., Nielsen, E., Pederson, G.T., and Sauchyn D.J. (2009). The tree-ring record of drought on the Canadian Prairies. *Journal of Climate*, 22(3): 689-710. <https://doi.org/10.1175/2008JCLI2441.1>
- Hanesiak, J.M., Stewart, R.E., Bonsal, B.R., Harder, P., Lawford, R., Aider, R., and Bullock, P. (2011). Characterization and summary of the 1999-2005 Canadian Prairie drought. *Atmosphere-Ocean*, 49(4): 421-452. <https://doi.org/10.1080/07055900.2011.626757>
- Hao, Z., Singh, V.P., and Xia, Y. (2018). Seasonal drought prediction: advances, challenges, and future prospects. *Reviews of Geophysics*, 56(1):108-141. <https://doi.org/10.1002/2016RG000549>
- Hu, M., Zhang, X., Siu, Y.L., Li, Y., Tanaka, K., Yang, H., and Xu, Y. (2018). Flood mitigation by permeable pavements in Chinese sponge city construction. *Water*, 10(2):172. <https://doi.org/10.3390/w10020172>
- Ikeuchi, H., Hirabayashi, Y., Yamazaki, D., Kiguchi, M., Koirala, S., Nagano, T., Kotera, A., and Kanae, S. (2015). Modeling complex flow dynamics of fluvial floods exacerbated by sea level rise in the Ganges-Brahmaputra-Meghna delta. *Environmental Research*, 10:124011.
- Ito, M. (2009). *Effect of Seasonal Climate on Volume Change Behavior of Regina Clay*. Master's Dissertation, University of Regina, Saskatchewan, Canada.
- Ito, M. and Azam S. (2009). Engineering characteristics of a glacio-lacustrine clay deposit in a semi-arid climate. *Bulletin of Engineering Geology and the Environment*, 68(4):551-557. <https://doi.org/10.1007/s10064-009-0229-7>
- Ito, M. and Azam, S. (2013). Engineering properties of a vertisolic expansive soil deposit. *Engineering Geology*, 152(1):10-16. <https://doi.org/10.1016/j.enggeo.2012.10.004>
- Juliani, B.H. and Okawa, C.M. (2017). Application of a standardized precipitation index for meteorological drought analysis of the semi-arid climate Influence in Minas Gerais, Brazil. *Hydrology*, 4(2):26. <https://doi.org/10.3390/hydrology4020026>
- Kuo, C.C., Gan, T.Y., and Gizaw, M. (2015). Potential impact of climate change on intensity duration frequency curves of central Alberta. *Climatic Change*, 130(2):115-129. <https://doi.org/10.1007/s10584-015-1347-9>
- Lemmen, D.S., Vance, R.E., Campbell, I. A., David, P.P., Pennock, D.J., Sauchyn, D.J., and Wolfe, S.A. (1998). *Geomorphic Systems of the Palliser Triangle, southern Canadian Prairies: Description and Response to Changing Climate*. Geological Survey of Canada, Ottawa, Ontario, Canada. <https://doi.org/10.4095/210076>
- Liang, X., Lettenmater, D.P., Wood E.F., and Burges. S.J. (1994). A simple hydrologically based model of land-surface water and energy fluxes for general circulation models. *Journal of Geophysics Research*, 99:14,415-14,428. <https://doi.org/10.1029/94JD00483>
- Lizée, T. (2017). Southern Saskatchewan in Drought for Almost a Year. <https://globalnews.ca/news/3797606/southern-saskatchewan-in-drought-since-november>.
- Lundqvist, O. (1999). *Climate*. Atlas of Saskatchewan. University of Saskatchewan, Saskatoon, Saskatchewan.
- McPherson, M.B. (1978). *Urban Runoff Control Planning*. Environmental Protection Agency, Washington, USA.
- Martin, F.R.J. (2002). *Gross Evaporation for the 30 Year Period: 1971-2000 in the Canadian Prairies*. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Technical Service, Saskatchewan, Canada.
- McKee, T.B., Doesken, N. J., and Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *8th Conference on Applied Climatology*. American Meteorological Society, California, USA.
- Quiring, S.M. and Papakryiakou, T.N. (2003). An evaluation of agricultural drought indices for the Canadian prairies. *Agricultural and Forest Meteorology*, 118(1-2):49-62. [https://doi.org/10.1016/S0168-1923\(03\)00072-8](https://doi.org/10.1016/S0168-1923(03)00072-8)
- Rostad, H.P.W., Bock, M.D., Krug, P.M., and Stushnoff, C.T. (1993). *Organic Matter Contents of Saskatchewan Soils*. Saskatchewan Institute of Pedology, Publication No, 114.
- Sabău, N.C. (2014). *Comparative study regarding performance of some free software for the calculation of the standardized precipitation index (SPI)*. Analele Universității din Oradea, Fascicula: Protecția Mediului, 23:779-788.
- Sadri, S. (2010). *Frequency Analysis of Droughts Using Stochastic and Soft Computing Techniques*. Ph.D. Dissertation, University of Waterloo, Ontario, Canada.
- Savage, C. (2011). *Prairie: A Natural History*. Greystone Books Ltd.
- Shook, K. and Pomeroy, J. W. (2016). The effects of the management of Lake Diefenbaker on downstream flooding. *Canadian Water Resources Journal*, 41(1-2):261-272. <https://doi.org/10.1080/07011784.2015.1092887>
- Sun, L., Mitchell, S.W., and Davidson, A. (2012). Multiple drought indices for agricultural drought risk assessment on the Canadian prairies. *International Journal of Climatology*, 32(11):1628-1639. <https://doi.org/10.1002/joc.2385>
- Teufel, B., Diro, G.T., Whan, K., Milrad, S.M., Jeong, D.I., Ganji, A., and Zwiers, F.W. (2017). Investigation of the 2013 Alberta flood from weather and climate perspectives. *Climate Dynamics*, 48(9-10):2881-2899. <https://doi.org/10.1007/s00382-016-3239-8>
- Tran, D.T., Fredlund, D.G., and Chan, D.H. (2015). Improvements to the calculation of actual evaporation from bare soil surfaces. *Canadian Geotechnical Journal*, 53(1):118-133. <https://doi.org/10.1139/cgj-2014-0512>
- Van der Sterren, M., Rahman, A., and Dennis, G.R. (2012). Rainwater harvesting systems in Australia. *InTech*, 471-496. <https://doi.org/10.5772/35382>
- Vickers, G., Buzza, S., Schmidt, D., and Mullock, J. (2001). *The weather of the Canadian prairies*. Graphic Area Forecast, 32.
- Wen, L., Lin, C.A., Wu, Z., Lu, G., Pomeroy, J., and Zhu, Y. (2011). Reconstructing sixty year (1950-2009) daily soil moisture over the

- Canadian Prairies using the Variable Infiltration Capacity model. *Canadian Water Resources Journal*, 36(1):83-102. <https://doi.org/10.4296/cwrj3601083>
- Wheater, H. and Gober, P. (2013). Water security in the Canadian Prairies: science and management challenges. *Philosophical Transactions of the Royal Society*, 371(2002):1-21. <https://doi.org/10.1098/rsta.2012.0409>
- Wilson, B.A. and Rashid, H. (2005). Monitoring the 1997 flood in the Red River Valley using hydrologic regimes and RADARSAT imagery. *Canadian Geographer*, 49(1):100-109. <https://doi.org/10.1111/j.0008-3658.2005.00082.x>
- Wittrock, V. and Wheaton, E. (2007). *Towards Understanding the Adaptation Process for Drought in the Canadian Prairie Provinces: The Case of the 2001 to 2002 Drought and Agriculture*. Prepared for the Government of Canada, Climate Change Impacts and Adaptations Program. Saskatchewan Research Council Publication No. 11927-2E07, Saskatchewan, Canada.
- Xu, B.X. (1999). *Regional Flood Frequency Analysis for Southwestern Alberta*. Master's Dissertation, University of Calgary, Alberta, Canada.