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WATERSHED CLASSIFICATION FOR THE CANADIAN PRAIRIE

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ABSTRACT

Classification and clustering approaches provide a means to group watersheds according to similar attributes, functions, or behaviours, and can aid in managing natural resources within these regions. While widely used, approaches based on hydrological response parameters restrict analyses to regions where well-developed hydrological records exist, and overlook factors contributing to other management concerns, including biogeochemistry and ecology. In the Canadian Prairie, hydrometric gauging is sparse and often seasonal, large areas are endorheic and the landscape is highly modified by human activity, complicating classification based solely on hydrological parameters. We compiled climate, geological, topographical, and land cover data from the Prairie and conducted a classification of watersheds using a hierarchical clustering of principal components. Seven classes were identified based on the clustering of watersheds, including those distinguishing southern Manitoba, the pothole region, river valleys, and grasslands. Important defining variables were climate, elevation, surficial geology, wetland distribution, and land cover. In particular, three classes occur almost exclusively within regions that tend not to contribute to major river systems, and collectively encompass the majority of the study area. The gross difference in key characteristics across the classes suggests that future water management and climate change may carry with them heterogeneous sets of implications for water security across the Prairies. This emphasizes the importance of developing management strategies that target sub-regions expected to behave coherently as current human-induced changes to the landscape will affect how watersheds react to change. This study provides the first classification of watersheds within the Prairie based on climatic and biophysical attributes, and our findings provide a foundation for addressing questions related to hydrological, biogeochemical, and ecological behaviours at a regional level.

WATERSHED CLASSIFICATION FOR THE CANADIAN PRAIRIE

1. INTRODUCTION

Extrapolating catchment-scale field and modelling studies is challenging in hydrological science, partly because of the inherent difficulty in explaining and predicting different responses among basins. This has proven particularly challenging in Canada's Prairie landscape where vast environmental changes have occurred since the late nineteenth century. Most of the natural grassland in the region has been converted to agriculture, and as a result, much of the landscape is intensively managed. Predominant agricultural practices have changed over the decades, and each is known to influence water cycling and storage, including tillage practices, summer fallowing, and cropping type (Awada et al., 2014; van der Kamp et al., 2003; Shook et al., 2015). Some land management decisions are made explicitly to influence the distribution of water on the landscape, such as wetland drainage and consolidation (Van Meter and Basu, 2015). The artificial increase in drainage is critically important in the region, where mobilization of dissolved nutrients and contaminants in water draining the landscape is linked to degradation of downstream water bodies, such as Lake Winnipeg (Golden et al., 2017; Main et al., 2014; Ulrich et al., 2016).

Like many regions, the Canadian Prairie has experienced significant warming over the last 70 years, especially in winter (Coles et al., 2017; DeBeer et al., 2016). There is a trend towards more rain at the expense of snow (Vincent et al., 2015), and multiple-day rainfall events have been increasing in frequency relative to shorter events in some regions (Dumanski et al., 2015; Shook and Pomeroy, 2012). Shook and Pomeroy (2012) also found increased autumn and spring rainfalls, which increase the likelihood of saturated soil conditions and the development of ice layers at the snow-soil interface. This in turn can decrease infiltration rates during snowmelt and further increase runoff and flood risk. These observed changes in precipitation have reduced the predictability of runoff derived from snowmelt, and add uncertainty to water management and agricultural decision-making. Disentangling the relative impacts of climate and land-use changes on water quantity and quality is complex, particularly as their effects are heterogeneous across spatial extent and scale.

Classification provides a means of grouping watersheds according to similar attributes, or behaviours, and can identify sub-regions that are expected to exhibit coherent responses. This strategy can identify how catchment characteristics influence hydrologic response, and in turn, can inform how changes to key traits (e.g., climate and land management) may effect system function (McDonnell and Woods, 2004). Hydrological characteristics have been used widely as a tool for classification owing to their potential linkages between watershed features and hydrologic responses (Brown et al., 2014; MacCulloch and Whitfield, 2012; Sivakumar et al., 2013; Spence and Saso, 2005). Such approaches based on hydrologic indices as well as a wider number of characteristics, including biophysical attributes, have been applied to differentiate watershed classes (e.g. Sawicz et al. 2014, Burn 1990). Accordingly, the regionalization of hydrological response through watershed classifications has been used to inform natural resource management (Detenbeck et al., 2000; Jones et al., 2014).

In Canada, watershed classification has been applied in many regions (e.g. Cavadias et al. 2001; Ouarda et al. 2002; Spence and Saso 2005). However, since Durrant and Blackwell (1959) grouped watersheds based on flood regime, no Prairie-wide classification has been pursued. Some studies have limited their scope to provincial boundaries, such as Manitoba (Burn, 1990) and Alberta more recently (Jones et al., 2014). Classifications focused on stream hydrology in the region (e.g. MacCulloch and Whitfield 2012) have by necessity included watersheds from other regions (e.g. mountains to the west) owing to hydrometric data limitations within the Prairie.

One of the key opportunities in pursuing a watershed classification is to link biophysical structure, including hydroclimate, with watershed function (Wagener et al., 2007). Linkage of streamflow dynamics to local surface geology and land cover have been observed in the Prairies and the more northern Boreal Plans ecozone (Devito et al., 2005; Mwale et al., 2011). The argument could be made, however, that by emphasizing hydrologic response variables in the classification, as has been the case for other classification efforts in the Prairie region, there exists a prejudice to classify only those watersheds where a reasonably robust understanding of hydrology exists. Indeed, stable isotope-based investigations of runoff from small lake catchments in the Boreal Plain emphasize the need for local-scale characterization of watershed behaviour (Gibson et al., 2010, 2016). In such instances, where classification proceeds according to readily available hydrometric observations for larger and well-studied or monitored basins, we may risk overlooking other functions that may be equally important to the management of a watershed's natural resources, including ecology and biogeochemistry. Accordingly, there exists an opportunity to characterize sub-regional variability in watershed behaviour using landscape and land management factors for a comprehensive approach to classification.

The objective of the present work is to develop a watershed classification system for the Canadian Prairie. In developing such an approach, we seek to advance our understanding of watershed hydrology and broader watershed behaviour within the Prairie. This approach also de-emphasizes classification according to known hydrologic response, and increases the spatial resolution of watershed classification relative to many existing approaches. We compile climatic and geographic characteristics, including geology, wetland distribution, and land cover, of watersheds approximately 100 km^2 to achieve this. This framework will identify those areas that are climatically and physiographically similar, and thus might be expected to respond in a hydrologically coherent manner to climate and land management changes. Additionally, it provides a foundation on which to base prediction of watershed hydrologic, biogeochemical and ecological responses to these stressors.

2. METHODS

2.1. Region domain and description

The Canadian Prairie (Prairies ecozone) spans the provinces of Alberta, Saskatchewan, and Manitoba, and is part of the Nelson Drainage Basin (Fig. 1). Climate is semi-arid, with mean annual precipitation ranging between 350 and 650 mm (1970–2000) increasing from west to east (ECCC 2017). Mean annual temperature was 5.7–7.4˚C over the same period. Much of the region deglaciated during the Late Pleistocene approximately 10,000 years before present, resulting in an often hummocky landscape with numerous depressions. Combined with the dry climate, the relatively short post-glaciation history has prevented maturing of a ubiquitous drainage network, and many headwaters remain disconnected from higher order streams (Shook et al., 2015). These depressions, and the wetlands that form within them, are important features for Prairie hydrology (van der Kamp et al., 2016) and often facilitate groundwater recharge (i.e., depression-focused recharge) (van der Kamp and Hayashi, 2009). The location of wetlands and their size, relative to the watershed outlet controls hydrologic gate-keeping (e.g., Spence and

Woo 2003), and thus the potential to contribute streamflow to higher-order watersheds (Leibowitz et al., 2016; Shaw et al., 2012; Shook et al., 2013). The size distribution of wetlands within a watershed and spatial arrangement also dictate biogeochemical function and provide habitat and foraging for biota (Evenson et al., 2018).

2.2. Watershed boundaries

The focus of this study was on those watersheds that drain a distinctively prairie landscape. Thus, we constrained our study to the Canadian Prairie ecozone; watershed areas of larger exotic streams in the region originating in the Rocky Mountains to the west were not included. Delineations of candidate study watersheds were obtained from the HydroSHEDS global dataset (Lehner and Grill 2013). Watershed boundaries within this dataset were calculated at a 15 arc-second resolution, based on Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM). Watersheds completely within the Canadian Prairie ecozone (Fig. 1) were extracted (n=4729). Those watersheds that were very large (>4000 km^2) or small (<5 km^2) were removed from analysis as were those consisting largely of lakes or urban areas (see Table S1). After considering these criteria, 4175 watersheds remained for use in subsequent analyses. Mean watershed area for this subset was 99.8 ± 58.7 km^2.

2.3. Watershed data sources

Watershed variables were assembled from Canadian Provincial and Federal governments and non-governmental agency datasets (see Table S2 for a full list of variables and their sources). Variables were derived from climatic, hydrologic, geological, geographic, and land cover data, and details are described briefly below. Spatial processing and statistical analyses were conducted in ArcGIS version 10.5 and R version 3.4.3 (R Core Team, 2018), respectively.

2.3.1. Climate

Mean annual precipitation and temperature data were derived from the Canadian Gridded Temperature and Precipitation Anomalies (CANGRD) dataset spanning 1970 to 2000 (ECCC 2017). Mean values were constructed from 50 km resolution gridded cells (n=626) within and surrounding the Prairie ecozone, and interpolated to a raster by kriging using a spherical semivariogram. Values were clipped according to watershed boundaries, and averaged to obtain mean annual precipitation and temperature for each watershed. From the temperature values, mean annual potential evapotranspiration (PET) was calculated from the Thornthwaite equation (Thornthwaite 1948) using the *SPEI* package (Vicente-Serrano et al. 2010).

2.3.2. Wetland traits

Large regions within the Canadian Prairie have been designated as being "non-effective", where they do not contribute flow to the stream network, at least one year in two (Godwin and Martin, 1975). The location of these regions are shown in Figure 1. The "non-effective" regions are caused by the intermittent connectivity of the landscape depressions, which trap runoff, and prevent it from contributing to downstream flow when the depressions are not connected. Trapped surface water can form wetlands (hereafter, inclusively referring to water area ponded in these depressions). Thus the non-effective portion of a basin is an index of its lack of contribution. These depressions can store water, and are indicative of water storage of the basin.

The Global Surface Water dataset (Pekel et al., 2016) provides a geographically comprehensive layer of any ~30 m pixel that was inundated at least once between 1984 and 2015, as identified from the Landsat constellation of satellites. It was assumed that the dataset was indicative of potential maximum wetland coverage, as this period spanned several wet cycles. As such, "wetland" in this context can include some seasonal prairie potholes as well as larger or more permanent water bodies, like lakes (but see Section 2.2 and Table S1). Using the R *raster* package (Hijmans, 2017), wetland variables were calculated for each study watershed (wetland density), including fractional wetland area, and the number of wetlands within the watershed. The ratio of the largest wetland to total wetland area (i.e., W_L) was also used as a metric. Further, we used the ratio of the linear distance of the largest wetland's centroid to the watershed outlet (L_W), to the maximum watershed boundary distance to the outlet (L_O) to represent a centroid fraction (L_W/L_O; i.e., the relative location of the largest wetland to watershed outlet). The basin outlet was defined as the point of lowest elevation on the watershed boundary.

To estimate wetland size distribution, it was assumed that they followed a Generalized Pareto Distribution (GPD) defined according to (Seekell and Pace, 2011; Shook et al., 2013):

$$F(z) = GDP(\mu, \beta, \xi) = 1 - \left[1 + \xi\left(\frac{z-\mu}{\beta}\right)^{-1/\xi}\right]$$

Where z is wetland area, μ is the location parameter, and scale (β) and shape (ξ) parameters are determined for each watershed. The latter two parameters provided information on the wetland frequency distribution in ensuing cluster analyses, and allowed a way of predicting the size distribution of wetlands within each class. Note that because the sizes of water bodies were taken from monthly remote-sensing measurements, they are biased against short-lived wetlands. Fitted size distributions were constrained at its minimum and maximum by the Global Surface Water dataset spatial resolution (i.e., 30 m pixel size) and the median area of the largest wetland observed in each watershed class, respectively

2.2.3. Topographical parameters

Geographical parameters of surficial geology, local surface landforms, soil particle size classes (sand, silt, clay), and soil zone were included in the analysis. Surficial geology polygons were derived by compiling provincial government data sources for Alberta (Atkinson, 2017), Saskatchewan (Simpson, 2008), and Manitoba (Matile, 2006). Each of these sources defined coarse categories in a consistent way that allowed for comparison across provincial boundaries. Local surface form (i.e., areas categorized by slope, relief, and morphology) and soil zone data were obtained from the Soil Landscape dataset (AAFC, 2013). The soil zones identified were by colour: black, dark brown, brown, gray, and dark gray. Clay, silt, and sand content were collected from the Detailed Soil Survey of Canada (AAFC, 2015). Catchment values for each particle size class were determined by areal weighting of soil polygons within the watershed boundary.

Topographic variables including the mean elevation, mean and coefficient of variation of slope, and stream density were also calculated for each watershed. Because of the hummocky nature of many regions in the domain, it is possible for a basin to have some fraction of its area located at an elevation below that of the outlet. As such, the fraction of area below the basin outlet (A_{BO}) was calculate for each basin. The elevation and slope variables were based on a DEM generated from the SRTM dataset. Stream vectors were obtained from the Hydrographic features CanVec (1:50000) series available from Natural Resources Canada (https://open.canada.ca/data/en/dataset?q=canvec&sort=&collection=fgp). The total length of streams within a watershed was summed, and then divided by the watershed area to calculate the stream density. The dimension shape factor (DSF) describes watershed shape and has been found important for hydrologic response in previous Canadian catchment classification exercises (Spence and Saso, 2005). The DSF was calculated as follows:

$$DSF = \frac{(0.28 \cdot P)}{A}$$

Where P and A are the watershed perimeter and area, respectively, derived from the HydroSHEDS global dataset (Lehner and Grill 2013).

2.3.4. Land cover and cropland practice

Fractional area of land-use type were derived from the Agriculture and Agri-Food Canada 2016 Annual Crop Inventory (AAFC, 2016). These raster data defines land-use and land cover. Variables used in our analysis were standardized to watershed area and included unmanaged grasslands, forests (i.e., the sum of coniferous, deciduous, and mixed forests), pasture, and cropland (sum of cropped land). Predominant cropland practice was defined according to fractional area of till activity by agricultural region sub-division (e.g., normalized to the amount of area prepared for seed within that division by year). Multi-year averages (2011 and 2016) of area for each practice, including zero-till, conservation till (leaving crop residue on soil surface), and conventional till (incorporating residues into soil) (Statistics Canada, 2016), were used to describe these activities, and normalized as a fraction of the watershed.

2.3.5. Hydrologic variable calculation

The relatively sparse hydrometric stream gauging in the domain, and the resulting paucity of data, presents two notable challenges to hydrologic response-based watershed classification. The first is that the basin network is biased to stations on higher-order (and often exotic) streams traversing the region (i.e. larger basins), and thus there is a limited number of hydrometric gauges on streams draining solely Prairie watersheds, particularly at the spatial resolution of our study watersheds (~100 km^2). Further, only a subset of these are considered reference stations (i.e., gauging unmanaged flows). Second, in the more arid and/or cold regions of the Prairie, some of these hydrometric stations are operated only seasonally, presenting additional challenges in using these records for classification exercises (e.g. MacCullough and Whitfield 2012).

As a result, mean annual runoff (Q2) and 1:100 year flood (Q100) magnitude was estimated for the 4175 watersheds using relationships defined from canonical correlation analysis (CCA) to correlate gauged data to multivariate climatic and physio-geographic data according to procedures in Spence and Saso (2005). Prairie stations (n = 11) were identified in MacCulloch and Whitfield (2012) and data were obtained from archived databases of the Water Survey of Canada (https://wateroffice.ec.gc.ca/search/historical_e.html) between 1990-2014. Due to the fact that many watersheds within the HydroSHEDS dataset are likely to drain internally and do not consistently connect to a higher-order stream network, these streamflow data were interpreted as "runoff", meaning the amount of water accumulated within the watershed polygon that drains to its lowest point annually.

Briefly, CCA correlates the streamflow record of gauged basins to physio-climatic characteristics of watersheds by representing the original variables as a reduced set of canonical variables. The analysis results in two canonical variable sets: one for the physio-climatic variables (i.e., V1 and V2) and another for the hydrological variables (i.e., W1 and W2). These canonical variables are constructed from linear combinations of the original variables such that the correlation of the canonical variables are maximized. Canonical variables plotting similarly on X-Y plots (W1-W2 and V1-V2), indicate good correlation (Spence and Saso, 2005). If canonical correlations ($\lambda 1$, $\lambda 2$) were above 0.75 (Cavadias et al., 2001), that set of variables was deemed useful for estimating hydrological variables from physio-climatic ones. Those physio-climatic variables passing this threshold were included as variables in a multiple regression to develop a predictive equation for Q2. Analyses were performed using the R *vegan* package (Oksanen et al. 2018).

2.4. Cluster analysis and watershed classification

2.4.1. Pre-processing compositional datasets

Principal components analysis (PCA) was used as a pre-processing step to reduce the dimensionality associated with compositional datasets (e.g., topographical and land cover parameters). Using this approach, the principal components (PC) that could explain 80% of the variation in a subset of compositional data were included in the subsequent cluster analysis. This procedure identified the major data patterns and aided in reducing the number of zero-weighted variables. Where necessary, variables that were not transformed into PCs were log-transformed to reduce data skewness.

2.4.2. Cluster analysis

Clustering analysis was performed on the complete suite of variables, which included PC variables derived from pre-processing. Agglomerative hierarchical clustering of principal components (HCPC) was used to define clusters of watersheds using the *HCPC* function in the R *FactoMineR* package (Lê et al. 2008, Husson et al. 2009). This function applies a PCA on the standardized multivariate dataset of watershed attributes and was the basis for clustering. The PCs that could explain in total 50% of the variation in the dataset (n = 6) were retained for agglomerative clustering. Retaining these PCs made it easier to focus on main trends in the data and reduced the impact of noise on subsequent analyses.

The agglomerative hierarchical clustering was performed using the Euclidean distances (from the PCA) and Ward's criterion for merging clusters. Consequently, watersheds located close to each other in PC-space were deemed as being similar in watershed attributes. This approach decomposes the total variability, or inertia, into within- and between-group inertia. Watersheds are grouped according to pairs that minimize within-group inertia (Begou et al., 2015), and are differentiated based on between-group inertia gained by adding clusters. Variables contributing to cluster characteristics were determined by v-test (Husson et al. 2009). This test assessed whether the cluster mean for a given variable was significantly ($\alpha = 0.05$) higher or lower than the overall mean. Watershed area, DSF, latitude, and longitude were used only as supplementary variables, and thus did not explicitly affect the clustering analysis. These variables did, however, aid in watershed class characterization and interpretation.

3. RESULTS

3.1. Canonical correlation analysis

The canonical coefficients from the CCA were λ_1 0.97 and λ_2 0.77, respectively. Hydrological variables were strongly associated with W2 (Table 1), and therefore the physio-climatic variables strongly associated to V2 were used in the multiple regressions. These variables were watershed area, DSF, areal fraction of rock, and areal fraction of natural area. Plots of observed and predicted runoff Q2 (R^2=0.45) and Q100 (R^2=0.48) show moderate agreement at lower flow values (Fig. 2). However, the regressions tend to underestimate higher flow rates. As Q2 and Q100 exhibited high collinearity, only Q2 was included in subsequent cluster analyses. Q2 was predicted using the following equation:

$$\log(Q2) = 0.130*\log(A) - 0.077*\log(N) + 0.117*\log(R) - 0.141*\log(DSF) - 0.620$$

Where *A* was the watershed area, natural area fraction (*N*) was the sum of grasslands and forest, *R* was the rock fraction area, and *DSF* was the dimensional shape factor of the watershed.

3.2. Dimension reduction: Variable principal components

Variation in geology and soil was best explained by two or three principal components (Table 2; Fig. S1). Two PCs captured over 80% of the variation in surficial geology, with PC1 (proportion explained: 73%) positively relating to glacial till deposits and negatively with glaciolacustrine deposits, and PC2 (14%) positively related to riverine or erosive deposits, such as glaciofluvial, alluvial, and eolian deposits. Particle size class data were explained by the first two PCs, where PC1 (75%) was positively associated with sand and negatively associated with silt and clay, while PC2 (14%) was related negatively to silt. For soil zone, positive PC1 (55%) scores defined the dominance of black soils, and PC2 (43%) described dominance of brown or dark brown soils on positive or negative scores, respectively. Finally, three PCs described the local surface form dataset. PC1 (55%) captured the shift from greater portion of hummocky forms to undulating forms, and PC2 (24%) was negatively associated with higher river-incised landscape fraction. The portion of level surface form was negatively related to PC3 (12%).

Three PCs were needed to explain over 80% of the variation in land cover (Table 2; Fig. S1). Land cover PC1 (37%) was positively associated with higher cropland and negatively with unmanaged grassland; whereas PC2 (25%) was negatively associated with higher pasture and forest cover. PC3 was associated with greater fallow and pasture areal proportion (21%). Cropland practice was described by PC1 (90%) and showed a negative association with zero-till practices. Although it only explained 9%, PC2 was also retained to described the shift between conventional and conservation till practices, with the practices exhibiting a positive and negative relationship, respectively.

3.3. Classification: Principal component analysis

A total of 29 watershed attributes, including the PCs from compositional datasets, were used in the clustering analysis as active variables, and four were included as supplementary (Table 3). In the classifying PCA, the first six PCs explained 54.3% of data variation, and eleven PCs were needed to explain >80% (Fig. 3).

PC1 was positively associated with elevation, mean slope, land cover PC2, and surface form PC3, and negatively with, total annual precipitation, soil zone PC1, wetland density, land practice PC1, land cover PC1, and longitude (Table 3; Fig. 3). PC2 was associated with non-effective area fraction, wetland density, β, and surface form PC2, and negatively related to land practice PC1, total water in the largest wetland, and river density. The PC3 was positively related to wetland fraction, W_L, ξ, soil texture PC2, and DSF. Negatively associated with PC3 were watershed area, and runoff.

Variable correlations were less strong for the remaining three PCs (Table 3). PC4 was mainly associated with soil texture PC1, surficial geology PC1 and surface landform PC1, characteristic of sandier soil areas featuring glacial till deposits and higher hummocky surface forms, as well as higher mean slope. PC4 was negatively related to land cover PC2. The cluster analysis PC5 was related positively to PET, fraction below outlet, and soil zone PC2, and negatively to land cover PC1, river density, and slope CV. Finally, PC6 was mainly associated with soil texture PC2 and land cover PC3, and negatively with surface landform PC2.

3.4. Classification: Hierarchical cluster analysis

Seven clusters were identified from the hierarchical cluster analysis based on the amount of between-group inertia gained by increasing cluster number (k). The HCPC analysis suggested three clusters resulted in the greatest reduction of within-group inertia while minimally increasing k (Fig. 4). Further increasing k improved definition of clusters up to seven (k=7). Minimal additional separation was observed up to k=9, and increasing $k > 9$ resulted in little inertia gained between clusters. Thus, seven clusters, or classes, were manually selected based on this analysis (Fig. 4).

3.5. Class characteristics

Our analysis provides a process for clustering watersheds into sub-regions according to climatic, physiographic, wetland, and land cover variables. The seven clusters, or classes (Fig. 5), are described by multivariate sets of attributes (Table 4). Influential classifying variables across all classes were mean elevation, total annual precipitation, land practice, surface forms, and wetland density. Other variables influential to class differentiation included fraction of non-effective area, land cover, and soil variables. In particular, climate and elevation are likely responsible for the west to east watershed clustering pattern. Moreover, we observe strong spatial concordance among some classes (Fig. 5), which is likely due to the hierarchical nature of the analysis. For simplicity, we interpret classes based on the variables where large, significant differences in cluster mean versus the overall mean of the dataset were observed. The clusters can be interpreted as follows: Southern Manitoba (C1); a prairie pothole region (C2, C3); major river valleys (C4); and grasslands (C5, C6, and C7).

3.5.1. Southern Manitoba (C1)

The majority of Class 1 (C1; n = 365) watersheds occurred in the eastern prairie south of Lake Winnipeg (Fig. 5) and thus "Southern Manitoba" is used as the class name. Distinguishing characteristics associated with this class included soil zone PC1 (predominantly black soils) and cropland practice PC1 (predominantly conventional till) (Table 4). Southern Manitoba had a high incidence of glaciolacustrine and alluvial deposits, as indicated by moderately negative and positive relationships with surficial geology PC1 and PC2, respectively, and the class also had lower mean elevation. Topology tended to be level, as shown by mild slopes and strong association with land surface form PC3 (Table 4). Notably, these watersheds exhibited both greater annual precipitation and PET, and this class was the only one to have no mean moisture deficit (i.e., precipitation – PET > 0) (Fig. 6). Southern Manitoba watersheds also exhibited small fractions of non-effective areas and grasslands than other classes (Fig. 7).

3.5.2. Prairie Potholes (C2 and C3)

The Prairie Pothole group, consisting of Class 2 (C2; n = 879), or Pothole Till, and Class 3 (C3; n = 681), Pothole Glaciolacustrine, collectively represents the largest cluster of watersheds spatially, spanning the northern part of the Alberta prairie to the southeastern part of Saskatchewan (Fig. 5). Mean annual precipitation was relatively high, leading to a slightly negative moisture deficit (Fig. 6). These watersheds contained large fractions of non-effective area (~75%) (Fig. 7a), and they exhibited positive scores on land cover PC1 (Table 4) indicating high cropland cover (~70%), whereas unmanaged grassland cover was typically very low (<20%) (Fig. 7b-c). On average, Pothole watersheds had a greater density of wetlands, with C2 exhibiting the highest wetland density (wetlands km^{-2}) of all classes (Fig. 8a).

Surficial geology differentiated these two classes. Overall, glacial till and hummocky landforms dominated the pothole region; however, C2 was more associated with these characteristics, scoring greater mean values on PC1 of local surface form and surficial geology. In contrast, glaciolacustrine deposits were more common in C3, and soils had a higher incidence of clay and silt, whereas C2 watersheds were sandier (Table 4). Although both classes contain many wetlands, C2 watersheds had the smallest values of W_L, indicating the smallest fraction of areal water extent was contained in the largest wetland (Fig. 8b).

3.5.3. Major River Valleys (C4)

Class 4 (C4; n = 536) watersheds were associated with river valleys, and as such, extend across the prairie region (Fig. 5) and often coincide with major rivers (e.g., North and South Saskatchewan, Qu'Appelle) and large water bodies (e.g., Quill Lakes, Manitou Lake). These watersheds had the greatest proportion of water area in the largest depression (W_L) (Fig. 8b), as well as greater slope CV, wetland fraction, and fractions of black soil (i.e., higher soil zone PC1 scores) (Table 4). These watersheds were also associated with soil texture PC1 and surficial geology PC2, suggestive of higher incidence of sandy riverine deposits (e.g., alluvial and glaciofluvial deposits). The major river valleys tended to have high wetland area. The watersheds tended to be small, narrow as indicated by higher DSF, and consequently had lower Q2.

Taken together, these watersheds were related to parameters typical of fluvial environments, including glaciofluvial or alluvial deposits, and sandier soils. High mean slope values and large variation in the parameter were also typical of river valley watersheds. About half the basin area tends to be non-effective in these watersheds, compared to the much greater fractions in the pothole regions (Fig. 7a) that surround many of the Major River Valley watersheds. Bering river valleys, C4 watersheds were generally narrow and small in area. Higher

DSF (i.e., narrower watersheds) and smaller areas were generally associated with lower Q2 values (Table 1). Thus, although these watersheds have a high likelihood of contributing to streamflow of major rivers, the watershed Q2 contributions were predicted to be small (Table 4).

3.5.4. Grasslands (C5, C6, and C7)

The southwestern Canadian Prairie, which includes the majority of southern Alberta and western Saskatchewan from the South Saskatchewan River to the Cypress Hills, was occupied by classes C5, C6, and C7. These watersheds tended to have a higher faction of unmanaged grasslands (negative land cover PC1) and mean elevation (Table 4). Compared to the rest of the Prairie, this sub-region tended to be arid, with a strong moisture deficit (Fig. 6). As a result, these classes exhibited relatively low values of wetland density (Fig. 8a).

Class 5 (C5; n = 635), Interior Grasslands, and 6 (C6; n = 702), High-Elevation Grasslands, were characteristic of the grasslands in southeastern Alberta. These watersheds had the greatest values of mean fractional grassland area, with cropland and grassland fractions being comparable (35–40%) (Fig. 7). Distinguishing features of Interior Grasslands were higher A_{BO}, and a notably large non-effective area fraction (Fig. 7a). High scores on land cover PC2 and PC3 indicate greater fractions of fallow and pasture. These watersheds also scored higher on soil zone PC2, suggesting more common occurrence of brown soils. Small magnitudes of mean slope and stream densities were observed, suggesting that the wetlands within the Interior Grasslands are relatively disconnected from the drainage network. Taken together, this characteristic might contribute to why these watersheds have more large wetlands (Fig. 8c). In contrast, High Elevation Grasslands were characterized as having greater mean elevation and slope values, and smaller non-effective fractions (Table 4). These watersheds also had greater stream densities and smaller wetland densities. Finally, High Elevation Grasslands occupied upstream areas of the Bow and Red Deer valleys.

Class 7 (C7; n = 377), Sloped Incised, watersheds are characterized by dissected, river-incised landscapes, as indicated by positive associations with local surface form PC3 (Table 4). Like High Elevation Grasslands (C6), Sloped Incised watersheds followed the Bow, Red Deer, as well as the Milk River valleys. In this way, these watersheds suggest a similar function as those of the Major River Valleys class. The magnitude of the wetland density is among the smallest in Sloped Incised watersheds, owing to their steepness, which results in surface water reaching stream networks rather than collecting on the landscape (Fig. 8).

3.6. Predicting wetland size distributions from class parameters

We simulated wetland size distributions for each cluster based on the generalized Pareto distribution and the median shape (ξ) and scale (β) from individual clusters. Simulated distributions were compared to observed size distributions from study watersheds. To be consistent among datasets, simulated data were constrained to the pixel size (30 m, 900 m^2) of the Global Surface Water data. As such, the simulated dataset presented here does not capture wetlands below this threshold.

The median wetland density was greatest in C2, followed by C3, C1, and C5 (Fig. 8a). Median wetland density in C6 and C7 was less than 1. C4 had the highest fraction of water in the largest wetland by area (W_L), which was over 40% (Fig. 8b), while C2 had the lowest value at ~10%. For the rest of the classes, this value was constrained to between 28% and 34%. The simulated wetland distributions slightly overestimated that of observed values, especially at the 25th percentile. However, the pattern of wetland area in different quartiles was generally conserved across classes (Fig. 8c). The size for the smallest 25% of the wetlands appears to be quite consistent across the classes, with more variation occurring at higher percentiles. The largest difference among classes in wetland size was in the 75th percentile, with the greatest range in C5 and the smallest in C1.

4. DISCUSSION

4.1. Classifying Prairie watersheds

Few studies have classified watersheds specifically within the Canadian Prairie. Most previous studies spanned larger areas, and this often results in the Prairie being identified as a homogenous region due to relatively low streamflow and atypical geology and surface topography (MacCulloch and Whitfield, 2012; Mwale et al., 2011). The only example that was found in the literature was by Durrant and Blackwell (1959), whose findings parallel those described herein. Durrant and Blackwell (1959) described regions of Saskatchewan and Manitoba based on mean annual flood, distinguishing five sub-regions including southwestern

Saskatchewan, north and central Saskatchewan, and southern Manitoba near the Red River and Assiniboine River confluence. This suggests that our approach, with a comprehensive consideration of factors important to watershed behaviour, can yield classification with relevance to hydrologic function, despite the use of few hydrologic indices in our analysis (Fig. 5). In Alberta, Mwale et al. (2011) found that annual hydrologic regimes based on data from 200 stations and physical attributes linked closely with provincial ecoregions. In the current study, surficial geology and land surface form strongly influenced how grasslands were separated among the three clusters, which reinforces the role of local topography. Likewise, surficial geology were particularly distinguishing for the pothole (Till and Glaciolacustrine) classes.

The classification grouped Prairie watersheds using geological, biophysical, hydrological, and climate attributes. In their review of classification approaches, Sivakumar et al. (2013) indicate that solely using physiographic data is advantageous when there are limited hydrological data; however, the relationship between physical attributes and hydrologic behaviour is not necessarily definitive in all regions. For these reasons, it was important to include traits indicative of structural hydrologic connectivity, such as Q2 estimates and wetland parameters. In particular, the immature drainage network and relative importance of water storage in depressions as wetlands make prairie hydrology relatively distinct (Jones et al., 2014; Shook et al., 2013). Notably, three classes (i.e., Pothole Till, Pothole Glaciolacustrine, and Interior Grasslands) occur almost exclusively within regions that tend not to contribute to major river systems, and collectively encompass the majority of the study area (Table 4; Fig. 5). It is therefore expected that hydrological response will be very different in classes that exhibit higher hydrological connectivity (i.e., potentially lower wetland to stream densities and non-effective area fractions), such as the Major River Valley or Sloped Incised watersheds, than those that do not, such as Pothole classes.

Furthermore, the highly managed Prairie landscape reinforces the importance of considering anthropogenic alteration in understanding the hydrology. Crop rotation and how fields are managed for winter affect the accumulation and redistribution of snow (Fang et al., 2010; Harder et al., 2018; van der Kamp et al., 2003). Spring melting of the snowpack and consequent runoff are imperative to summer surface water availability (Dumanski et al., 2015; Shook et al., 2015), and depression-focused recharge of snowmelt into groundwater facilitates storage and mitigates flood impacts (Hayashi et al., 2016). Thus, classifying procedures in the Prairie must consider the human influence on the water cycle.

An example of the complexities introduced by human land management activities can be shown with C1 (Southern Manitoba) watersheds, where the land practice variable was a strong class descriptor. Agricultural activity is high in the Prairie; however, only C1 was associated with low zero-till practice, and instead favouring conventional till (Table 4). Manitoba has seen less coherent adoption of zero-till practices since the early 1990s in comparison to trends observed in Alberta or Saskatchewan, with conventional or other conservation till practices remaining common in Manitoba (reviewed in Awada et al., 2014). This is reflected within the cluster analysis, as zero-till practices are not as common for C1 watersheds as for other classes. Agricultural land modification is prevalent and artificial drainage networks have been created throughout southern Manitoba to facilitate rapid drainage of excess water and reduction of cropland flooding (Weber et al., 2017).

Sustained use of conventional tillage practice within this region may increase the a risk of soil erosion, which can negatively affect downstream water bodies (Cade-Menun et al., 2013). This, combined with landscape modifications, such as artificial drainage networks, serve to facilitate removal of water off land and may contribute to concurrent nutrient export from agricultural lands (Weber et al., 2017). These practices can be viewed as a trade-off, where high numbers of wetlands and level topography can pose flood risk during wet periods as wetlands fill and merge (Leibowitz et al., 2016), inundating tracts of adjacent land. Conversely, where landscape modification to enhance water export occurs, local, field-scale flood risk may be reduced, while heightening the risk of downstream flooding. Land-use and land management are important factors in understanding the connectivity and chemical transport in Prairie landscapes (Leibowitz et al., 2018). In southern Manitoba, where artificial drainage networks have been used to increase the area of arable land, beneficial management practices in the form of agricultural reservoirs have been implemented as a means of reducing nutrient export and improving downstream water quality while also mitigating the risk of downstream flooding (Gooding and Baluch, 2017). These factors illustrate the complexities when classifying and understanding hydrological response of watershed embedded in highly managed landscapes, and underscore that necessity of considering the human influence on the water cycle in such approaches.

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4.2. HCPC as a clustering framework

The HCPC method provides a procedure for integrating multiple physiogeographic attributes and describes resulting clusters by sets of significant variables (Husson et al., 2009). An advantage of the method is that one may select variables or sets of variables of interest to inform the clustering of watersheds, such as those based only on topographic parameters or those dictating local hydrology. As an example, climate variables may be excluded if the goal of the classification is informing application of a hydrological model, as these variables would likely also be a part of model parameterization. The relative ease with which different sets of variables can be added to or excluded from the analysis to consider different permutations of the classification is a real strength of the approach. Although this may result in differing cluster results, assessment of how these classes change with addition or removal of certain datasets can identify the variables that control class definition as well as elucidate spatial patterning of clusters.

There are a few considerations when using this method. First, the linear restrictions of this method are challenging when working with environmental data, which often do not conform to assumptions of normality. Non-linear PCA methods and self-organizing maps have been applied successfully to classify watersheds in Ontario and to regionalize streamflow metrics (Razavi and Coulibaly, 2013, 2017). Although these methods might be logical next steps for the current study, we chose to focus on conventional PCA due to its smaller computational cost when classifying the large number of watersheds in our study.

Second, the current analysis weighs all variables with equally. This can bias the analysis towards attributes that have greater variabilities, as these can overshadow other more constrained variables. For example, the location of the largest pond relative to the watershed outlet (coded as L_W/L_B) is important to controlling local prairie hydrology and gate-keeping potential (i.e., the likelihood of contributing hydrologically to the next order watershed) (Shook et al., 2013, 2015) and water quality (Hansen et al., 2018). Despite its hydrological importance, this variable had little influence on the clustering procedure overall, and was only a minor descriptor in certain classes, such as C5 and C6 (Table 4).

The clusters resulting from the HCPC are ultimately dependent on the types of data included. The availability of data and its geographic coverage determined the environmental parameters included in our analyses. Ideally, a more detailed estimate of runoff for each watershed, as well as a soil moisture dataset would have been include. A comprehensive wetland inventory or an index of wetland drainage activity that is comparable across the three Provinces does not currently exist. These would be valuable additions to future efforts to classify Prairie watersheds given the important role of land modification on watershed functions.

The Global Surface Water dataset used here provided spatial coverage of the Prairie. One consideration is that the pixel size (30 m) is quite coarse and will miss the numerous smaller wetlands in addition to their spatial arrangement, underestimating the number of wetlands observed. By nature of the period over which these data were collected, the dataset also integrates areas that are more regularly inundated with those that may have experienced only partial ponding during the record. Consequently, it is likely that the analysis neglected ephemeral wetlands for which whose persistence is short and size is small. Despite their known important ecological functions (Calhoun et al., 2017; Van Meter and Basu, 2015), the lack of permanent water and small size can exclude these wetlands from the databases that were used here. This may inadvertently result in being perceived as less significant as a result.

Use of the ξ and β parameters as indices of wetland size distribution were shown to estimate cluster distributions reasonably well (Fig. 8c). Although for consistency, we restricted our simulated dataset to the spatial resolution of the surface water raster, one could use these parameters to estimate the frequencies of smaller wetlands missed by satellite measurements, assuming conformity to a Generalized Pareto Distribution (Shook et al., 2013). Our analysis supports this application as simulated wetland areas generally approximated those seen across the observed data (Fig. 8c). Nonetheless, in regions where wetland drainage has been undertaken, it is expected that wetland size distribution has been altered via preferential loss of smaller water bodies (Evenson et al., 2018; Van Meter and Basu, 2015). Conversely, the number of wetlands may actually be smaller than indicated by the Global Surface Water dataset used in our classification, owing to wetland drainage which also alters spatial arrangement of these features. A more robust characterization of the size and permanence of wetlands in our study watersheds would be expected to improve the current dataset and to enhance the clustering analyses.

Finally, cluster membership is determinate. In reality, there can be large variability in some attributes within a cluster (e.g., Fig. 7). This is partially because membership is multivariate, and as such, not all defining variables must be higher or lower than the overall mean. Rather, membership is determined by the collective similarity of watershed attributes. Because the extent of the input data also may not match the boundaries of the clusters, one should be cautious of confidence of membership within a particular class near the cluster borders. Previous studies have used fuzzy c-means and Bayesian approaches that can assign a likelihood of membership to the classes (Jones et al., 2014; Rao and Srinivas, 2006; Sawicz et al., 2011). Such approaches are also un-supervised, which are probabilistic in nature and will eliminate the subjectivity due to the researcher pre-defining the number of classes. Our future work will include applying a fuzzy-cluster Bayesian framework to assess the current classification framework.

4.3. Management implications

Clustering and classification frameworks help to define sub-regions with potentially similar characteristics or behaviours. For example, climatic zones can be delineated, specifically the dry Grassland watersheds in the southwest and wet Potholes in the northeast and in Manitoba (Fig. 5). In some cases, this may be related to local wetland densities, with higher densities observed at lower moisture deficits (Fig. 6) (Liu and Schwartz, 2012). In contrast, climate variation may divide watersheds with seemingly similar geography into differing classes, as is the case with Major River Valleys and Sloped Incised watersheds. Both sets of watersheds tended to follow river valleys, but the former exhibit greater precipitation and lower PET while the reverse was true for the latter (Table 4). These divisions can be used to give context to regions we might expect to behave similarly, whether hydrologically, or ecologically, based solely on physical attributes, and echoes other methods, such as ecodistricts (Ecological Stratification Working Group, 1995) to classify landscapes. For example, areas that are geologically similar may differ in terrestrial or aquatic community assemblages, which should influence how each area might be managed (Jones et al., 2014; Wagner et al., 2007). If classifications are used to inform management, the resulting decisions for a given location will depend on the strength of the delineation, the scale at which management is applied, relationships among management practices and the attributes used to define that area, and the relationship of those attributes to the response variable of concern (Wagener et al., 2007).

This set of analyses was unique among watershed classification exercises in Canada in that it considered a suite of wetland variables. The arrangement of wetlands or landscape depressions and their size distribution define the hydrological behavior of Prairie watersheds (Shook et al., 2015; Shook and Pomeroy, 2011). The fill capacity and subsequent spill or merge moderates wetland connectivity, and thus the quantity of water available to move from one watershed to another (Leibowitz et al., 2016; Shaw et al., 2012; Shook et al., 2015). In turn, a wetland or depression's hydrological gate-keeping potential, or its likelihood to prevent connectivity to the downstream watershed, is a function of both its storage capacity and landscape position. Larger wetlands near an outlet have a great gate-keeping potential, as they effectively prevent much of the watershed from connecting, and it takes a great deal of water to fill them before contributing flow to the next order watershed (Shook and Pomeroy, 2011). Simulated distribution of wetland sizes indicate that the depressional storage of each cluster are very different (Fig. 8). For example, it may be that wetland management practices will have different influences between in each pothole classes, and possibly among all the clusters. This has implications for salinizing soils (Goldhaber et al., 2014), biodiversity (Balas et al., 2012), and floods (Evenson et al., 2018; Golden et al., 2017)

Wetland drainage and wetland consolidation changes hydrological connectivity as well as nutrient transport and loading into receiving water bodies (Brown et al., 2017; Vanderhoof et al., 2017). More positive values of the moisture deficit were associated with greater wetland density (Fig. 6) (Liu and Schwartz, 2012), and these areas were generally associated with greater fractions of cropland, such as Pothole Till, Pothole Glaciolacustrine, and Southern Manitoba watersheds. In these regions wetland drainage is widely practiced, historically or at present, and conflict over available arable land and wetland conservation is high (Breen et al., 2018).

Extensive drainage in combination with agricultural activity is known to increase the risk of mobility of agricultural nutrients and minerals (Kerr, 2017) from the landscape to receiving water bodies. Increased connectivity also reduces water residence time and thus tends to decrease wetland nutrient retention (Marton et al., 2015). Over time, zero-till practices can promote nutrient stratification in soils, where concentrations (especially phosphorus) accumulate at the surface, which can increase nutrient loading when surface runoff is generated (Cade-Menun et al., 2013). This cropland-wetland interface might also have important implications for pesticide mobility in Pothole Till and northern Pothole Glaciolacustrine watersheds. These areas coincide with extensive use of canola, which has been linked to high application rates of neonicotinoid pesticides which are known to have high persistence in small, temporary wetlands (Main et al., 2014). Watersheds in the Pothole Till class appear to have more hummocky landscapes than the Pothole Glaciolacustrine classification and smaller, more numerous wetlands (Fig. 8). Moreover, water area fraction occupied by the largest wetland is quite different between the classes. The landscape biogeochemical functionality of pothole wetlands is known to vary considerably according to pothole character (Evenson et al., 2018; Van Meter and Basu, 2015). As such, our classification may highlight contrasting biogeochemical functioning, including nutrient retention, between these classes. Thus, although water quality risks are common within the region, the clusters may respond very differently to environmental stresses.

5. CONCLUSION

This study provides a classification of Canadian Prairie watersheds that identifies areas of similar climatic and physiogeographic features and, potentially, of hydrological response (Fig. 5). The HCPC procedure offers a flexible analysis to elucidate the spatial arrangement of clusters given a large number of units to classify and a diverse set of attributes. In contrast to classifications based solely on hydrological function, using physiographic data allows for classifying smaller spatial scales, which are unlikely to be gauged. The classification divides Prairie watersheds into groupings that consider not only drainage patterns, but also land cover and land use and underlying geology. Wetland variables incorporate the hydrologic gate-keeping potential of wetlands as well as parameters indicative of wetland size distributions. With the classification based on a large and diverse set of attributes, a diversity of behaviours is captured. As such, we believe this watershed classification provides a useful framework on which to base future efforts to evaluate the efficacy of land and watershed management practices in the context of a changing climate.

Author contributions

JDW, CJW, and CS conceived the study, and JDW collected data and performed analyses. KRS wrote code to analyze wetland data. JDW wrote the manuscript with input from all co-authors.

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Tables and Figures

Table 1 – Canonical correlation coefficients for watershed attribute and hydrological variables of hydrological research stations from the canonical correlation analysis. Those variables used in multiple regression equations are denoted with a ‘*’.

	Correlation	
Watershed attributes	**V1**	**V2**
Area*	0.36	–0.83
DSF*	–0.26	0.90
Fraction rock*	–0.64	0.61
Fraction natural area*	–0.26	0.71
Stream density	–0.27	0.37
Mean annual precipitation	–0.14	–0.30
Fraction water area	0.53	–0.19
Hydrological variables	**W1**	**W2**
Q2	–0.82	–0.58
Q100	–0.22	–0.98
Canonical λ	0.97	0.77

Table 2 – Pre-processing of compositional data PCA results. Shown are the respective subsets, the number of initial fractional area variables before dimensional reduction, the number of principal components retains to reach over 80% of subset variation (except for tillage practice), and the proportion of variation explained by each component.

Variable subset	Number of initial variables	Number of principal components	Total variation explained by component
Surficial geology	6	2	1: 72.8% 2: 14.4%
Particle size class	3	2	1: 74.8% 2: 15.6%
Soil zone	5	2	1: 54.6% 2: 42.7%
Local surface form	5	3	1: 54.5% 2: 24.2% 3: 11.9%
Land cover	5	3	1: 36.8% 2: 25.2% 3: 20.6%
Tillage practice	3	2	1: 90.9% 2: 8.5%

Table 3 – Correlation of study watershed attributes to principal components (PC). The values for the six PCs used in the cluster analysis are shown.

Variable	Abbreviation	PC1	PC2	PC3	PC4	PC5	PC6
Mean elevation	elevation	0.81	0.34	–0.14	0.09	–0.16	–0.17
Mean slope	slope.mean	0.61	–0.23	0.06	0.37	–0.10	0.11
Slope CV	slope.CV	0.30	–0.38	0.22	0.14	–0.41	–0.09
Total precipitation	precip	–0.85	–0.12	0.13	0.16	–0.07	0.30
Potential evapotranspiration	PET	0.31	–0.33	–0.33	–0.06	0.47	0.13
Non-effective area	NE.area	0.02	0.70	0.31	0.10	0.01	–0.15
Areal fraction below outlet (A_{BO})	A_BO	0.14	0.25	0.27	–0.17	0.42	–0.01
Stream density	stream.density	0.08	–0.42	–0.39	0.03	–0.41	0.08
Wetland density	wetland.density	–0.63	0.46	0.11	–0.04	0.12	0.24
Wetland fraction	wetland.frac	–0.30	0.19	0.66	–0.36	0.02	0.11
Water area in largest wetland to total in watershed (W_L)	W_L	0.31	–0.44	0.51	–0.32	–0.06	–0.12
Location of largest wetland to outlet (L_W/L_O)	L_W/L_O	–0.01	–0.06	–0.22	0.09	–0.07	–0.07
Beta (β)	beta	0.17	0.49	–0.02	0.01	0.09	0.05
Xi (ξ)	xi	0.21	–0.23	0.57	–0.31	–0.10	–0.17
Runoff (Q2)	Q2	–0.13	0.35	–0.47	0.00	–0.33	0.10
Soil texture PC1	Text.PC1	–0.07	–0.04	0.28	0.55	0.19	–0.32
Soil texture PC2	Text.PC2	0.02	–0.32	0.43	0.03	–0.31	0.54
Soil zone PC1	Soil.PC1	–0.65	–0.29	–0.07	0.19	–0.10	–0.24
Soil zone PC2	Soil.PC2	0.27	–0.12	–0.06	–0.11	0.40	0.25
Land cover PC1	LC.PC1	–0.44	0.38	–0.21	–0.26	–0.43	0.12
Land cover PC2	LC.PC2	0.42	0.22	–0.17	–0.53	0.15	0.03
Land cover PC3	LC.PC3	0.21	0.30	0.15	0.25	0.11	0.46
Surficial geology PC1	SF.PC1	0.06	0.21	–0.19	0.50	0.17	–0.09
Surficial geology PC2	SF.PC2	0.06	–0.38	0.24	0.47	0.11	–0.03
Surface form PC1	LL.PC1	–0.16	0.20	0.17	0.47	0.26	0.26
Surface form PC2	LL.PC2	–0.20	0.44	0.12	–0.03	0.04	–0.55
Surface form PC3	LL.PC3	0.41	0.38	0.20	0.21	–0.27	0.27
Land practice PC1	LP.PC1	–0.54	–0.58	–0.13	–0.10	0.32	–0.09
Land practice PC2	LP.PC2	0.14	–0.16	–0.24	–0.22	0.29	0.30
Supplementary variables							
Latitude	Lat	–0.15	0.24	0.26	–0.01	–0.33	–0.41
Longitude	Long	–0.73	–0.24	0.06	0.10	0.16	0.39
Area	Area	–0.05	0.27	–0.44	0.09	–0.15	–0.03
DSF	DSF	–0.02	–0.25	0.42	–0.05	0.12	0.01

Table 4 – Classes and distinguishing variables of prairie watersheds. The v-test statistics, based on Ward's criterion, are shown. Variables with v-test values greater or less than 10 and –10, respectively, are bolded to emphasize defining features of each class. All variables are significant to p < 0.001. *Classes: Southern Manitoba (1), Pothole Till (2), Pothole Glaciolacustrine (3), Major River Valleys (4), Interior Grasslands (5), High Elevation Grasslands (6), Sloped Incised (7).*

Class 1 (n=365)		Class 2 (n=879)		Class 3 (n=681)		Class 4 (n=536)	
Variable	v-test	Variable	v-test	Variable	v-test	Variable	v-test
LP.PC1	**48.11**	**wetland.density**	**28.23**	**LC.PC1**	**22.60**	**SF.PC2**	**19.83**
precip	**30.33**	**LL.PC1**	**24.81**	**wetland.frac**	**12.74**	**slope.CV**	**19.35**
Soil.PC1	**23.60**	**precip**	**22.74**	**Q2**	**12.63**	**xi**	**16.05**
LP.PC2	**14.74**	**SF.PC1**	**21.74**	**NE.area**	**11.12**	**W_L**	**15.39**
PET	**13.10**	**LC.PC1**	**17.19**	LL.PC2	9.45	**Text.PC2**	**15.07**
wetland.density	7.39	**LL.PC2**	**16.42**	wetland.density	8.05	**Text.PC1**	**14.40**
DSF	6.81	**Q2**	**15.77**	LC.PC2	6.70	**Soil.PC1**	**14.01**
SF.PC2	6.53	**Soil.PC1**	**15.76**	LL.PC3	6.53	**DSF**	**11.76**
stream.density	4.61	**NE.area**	**15.72**	xi	5.89	**precip**	**10.97**
LC.PC1	–3.37	**area**	**13.15**	W_L	4.58	**wetland.frac**	**10.92**
A_BO	–4.22	**Text.PC1**	**12.00**	precip	3.47	slope.mean	7.29
area	–5.46	LC.PC3	6.76	A_BO	–3.79	LP.PC1	3.52
slope.CV	–6.49	beta	5.31	slope.CV	–4.97	A_BO	–3.83
Q2	–8.47	L_W/L_O	4.20	L_W/L_O	–5.17	wetland.density	–4.41
SF.PC1	–8.90	LL.PC3	3.93	LP.PC2	–7.11	SF.PC1	–4.56
LC.PC2	–9.21	SF.PC2	–3.97	LC.PC3	–9.71	LC.PC1	–5.13
LL.PC2	**–14.18**	LP.PC1	–4.87	**LP.PC1**	**–12.38**	soil.PC2	–6.93
slope.mean	**–16.17**	stream.density	–5.92	**Soil.PC2**	**–13.01**	beta	–7.60
beta	**–16.88**	elevation	–7.15	**Text.PC1**	**–14.58**	elevation	–8.03
LC.PC3	**–18.13**	A_BO	–7.86	**slope.mean**	**–15.92**	**area**	**–11.04**
NE.area	**–28.97**	Text.PC2	–9.15	**SF.PC2**	**–17.03**	**LP.PC2**	**–11.44**
LL.PC3	**–36.59**	DSF	–9.93	**LL.PC1**	**–17.83**	**Q2**	**–13.27**
elevation	**–47.42**	**LP.PC2**	**–10.88**	**SF.PC1**	**–18.83**	**PET**	**–13.98**
		Soil.PC2	**–12.00**	**PET**	**–23.29**	**LC.PC2**	**–20.86**
		PET	**–13.15**				
		slope.mean	**–13.50**				
		slope.CV	**–16.26**				
		LC.PC2	**–16.29**				
		xi	**–21.49**				
		W_L	**–32.96**				

Table 4 – *(cont'd)*

Class 5 (n=635)		Class 6 (n=702)		Class 7 (n=377)	
Variable	v-test	Variable	v-test	Variable	v-test
A_BO	**34.10**	**elevation**	**29.29**	**Text.PC2**	**27.65**
LC.PC2	**21.53**	**PET**	**20.16**	**LL.PC3**	**25.69**
Soil.PC2	**20.81**	**slope.CV**	**17.67**	**slope.mean**	**22.32**
LC.PC3	**17.44**	**slope.mean**	**16.12**	**LC.PC3**	**14.84**
NE.area	**16.22**	**stream.density**	**14.55**	**stream.density**	**13.82**
beta	**15.96**	**LC.PC2**	**14.09**	**Soil.PC2**	**13.09**
elevation	**13.31**	W_L	9.47	**elevation**	**12.42**
PET	**11.47**	L_W/L_O	6.80	**PET**	**11.47**
LL.PC2	8.11	LP.PC2	5.73	SF.PC2	6.80
LP.PC2	7.67	area	3.72	LP.PC2	6.39
LL.PC3	7.31	LL.PC2	3.62	slope.CV	5.87
wetland.frac	5.77	LP.PC1	–3.60	W_L	4.63
LL.PC1	5.50	Q2	–3.94	precip	–4.75
SF.PC2	–4.74	DSF	–4.91	A_BO	–5.65
area	–4.86	A_BO	–9.47	LC.PC1	–7.62
L_W/L_O	–7.11	**Soil.PC1**	**–10.17**	Text.PC1	–8.34
Q2	–9.34	**LL.PC3**	**–10.62**	**LP.PC1**	**–11.42**
LP.PC1	–9.96	**LC.PC3**	**–13.17**	**NE.area**	**–13.33**
Text.PC2	**–11.36**	**NE.area**	**–14.11**	**wetland.frac**	**–13.64**
LC.PC1	**–11.38**	**LL.PC1**	**–15.44**	**wetland.density**	**–16.27**
slope.CV	**–12.42**	**Text.PC2**	**–15.78**	**Soil.PC1**	**–16.43**
precip	**–20.86**	**LC.PC1**	**–17.15**	**LL.PC2**	**–39.41**
Soil.PC1	**–23.58**	**wetland.frac**	**–21.48**		
stream.density	**–26.34**	**wetland.density**	**–29.58**		
		precip	**–37.27**		

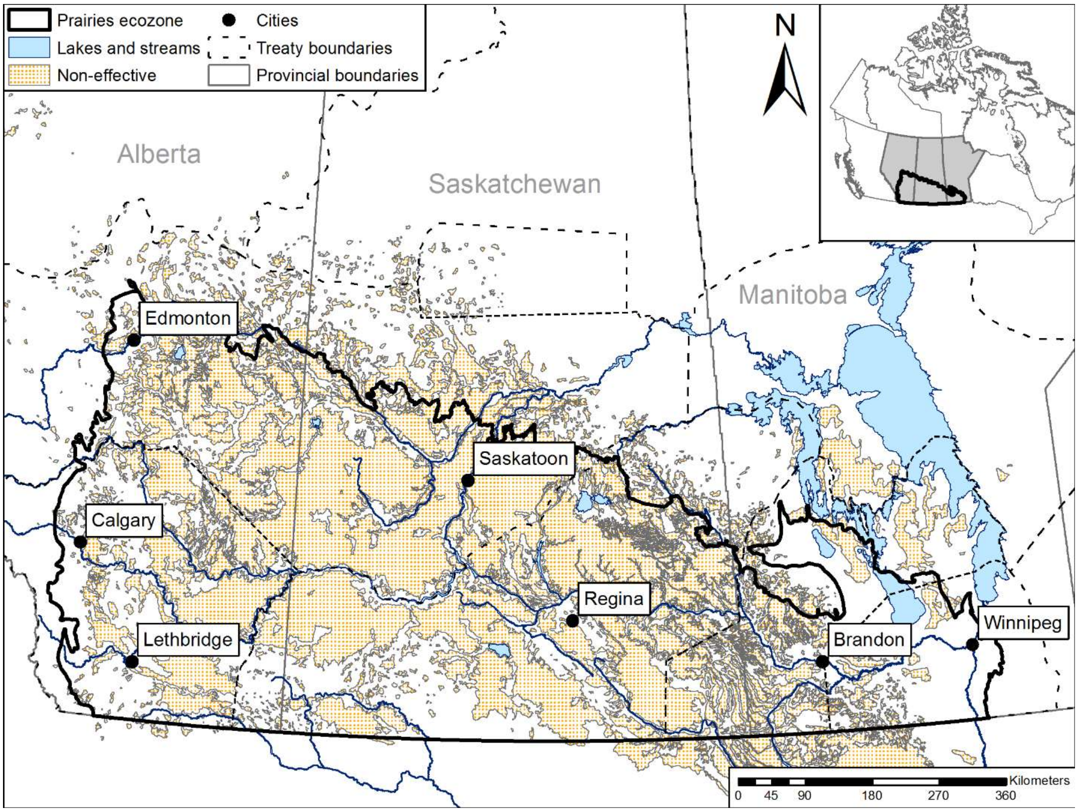

Figure 1 – Map of the study area spanning the Prairies ecozone in western Canada (inset). Large cities in each of the three provinces are shown for reference, while the land area characterized as not contributing runoff (2-year) is also shown.

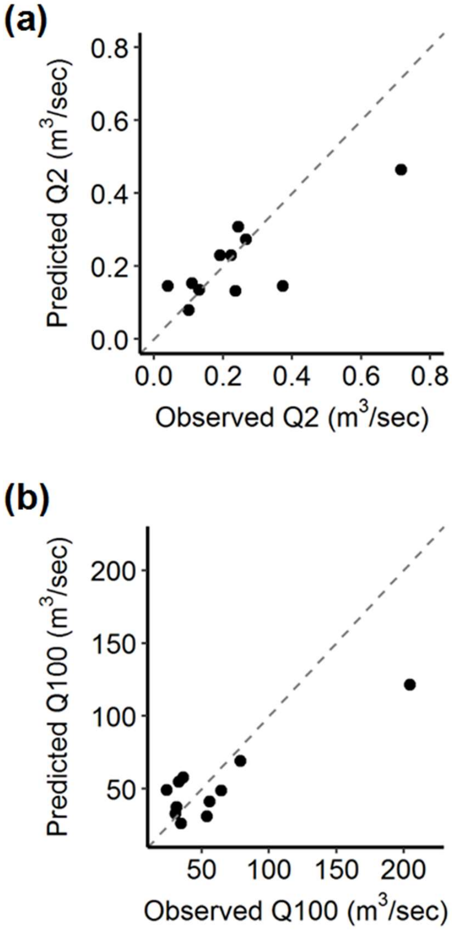

Figure 2 – Observed versus predicted estimates for (a) Q2, and (b) Q100.

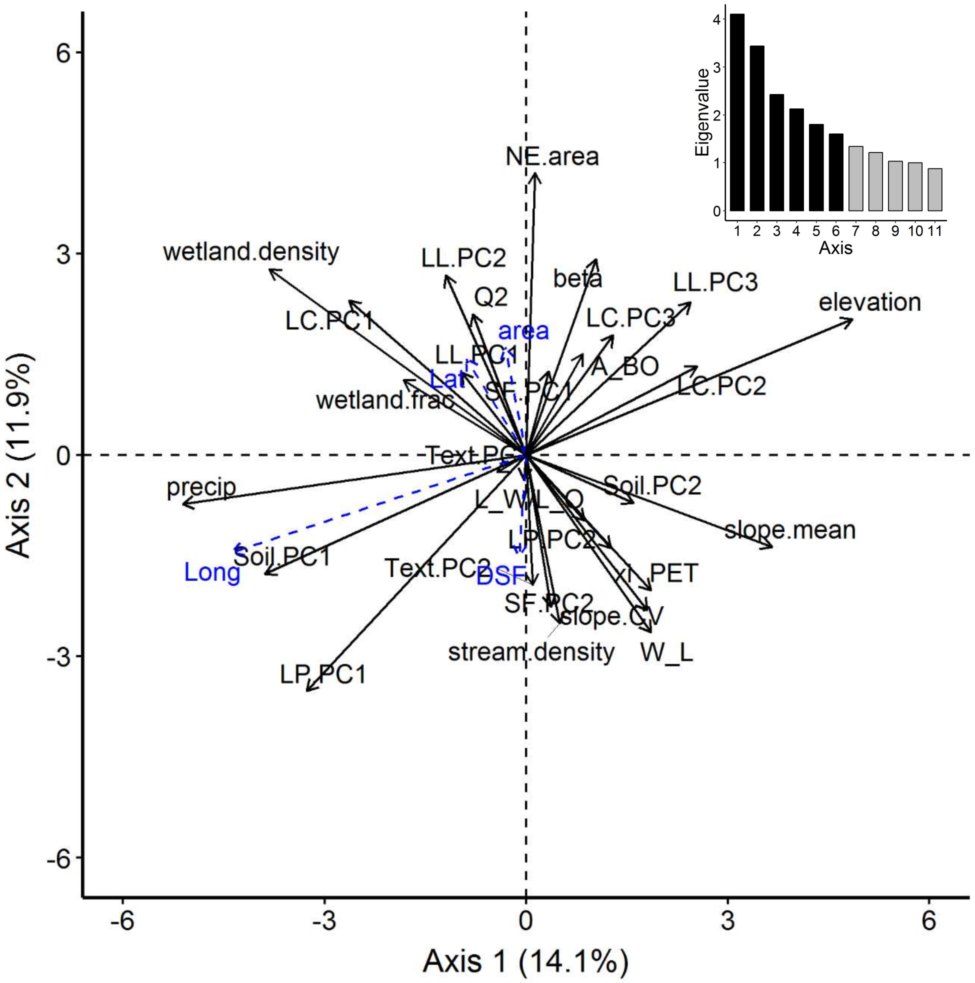

Figure 3 – Principal components analysis for candidate variables for classification. Active and supplementary variables are shown as solid black, and dashed blue arrows, respectfully. Eigenvalues for PC axes are provided (inset), with black bars denoting the six PCs used in the hierarchical clustering analysis.

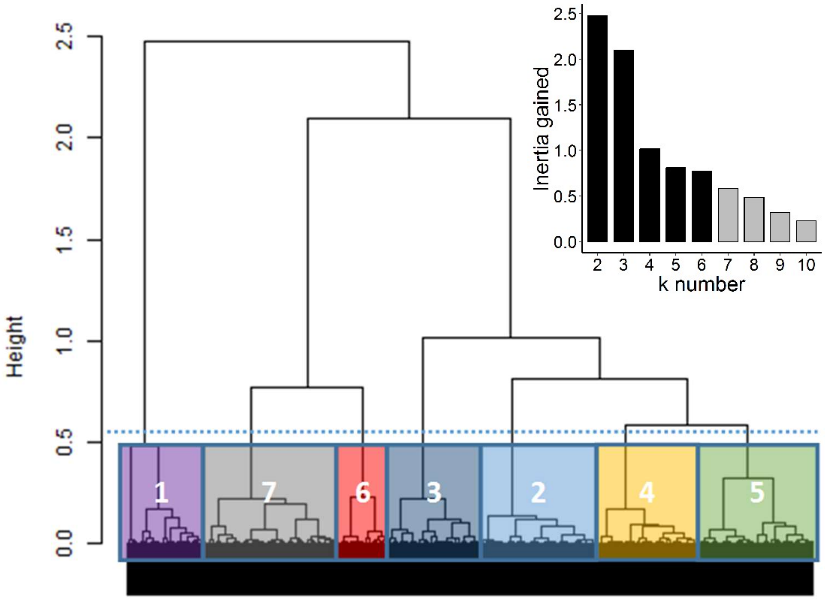

Figure 4 – Dendrogram resulting from the hierarchical cluster analysis of principal components. The blue, dashed line indicates the cut in the tree, resulting in seven clusters. The amount of inertia gained by increasing the number of clusters (*k*) is depicted in the inset panel.

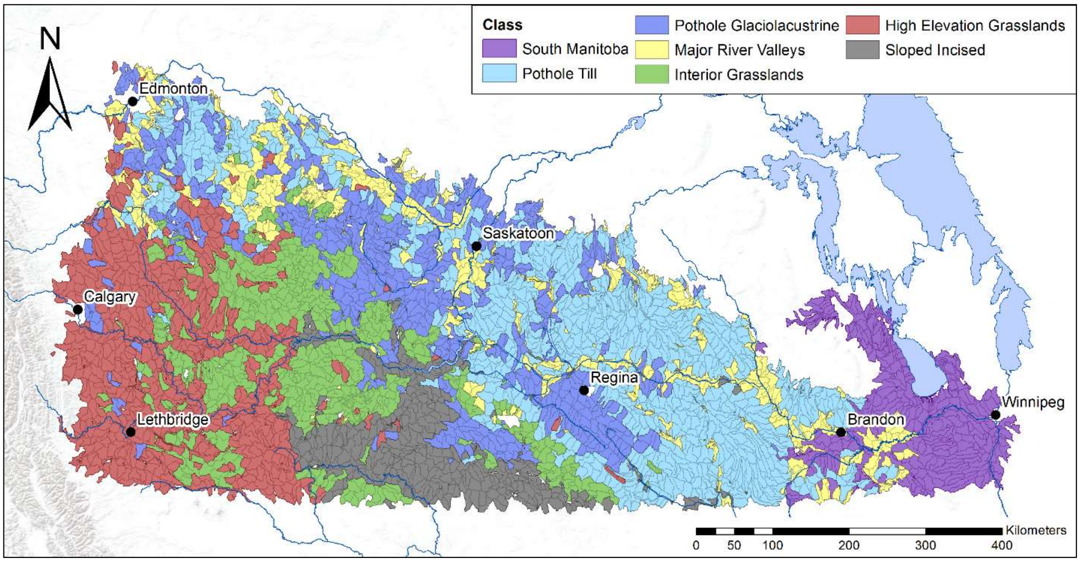

Figure 5 – Classification of Prairie ecozone watersheds. Watershed delineations are from Lehner and Grills (2013), available at www.hydrosheds.org. See text for detailed interpretation of the seven clusters.

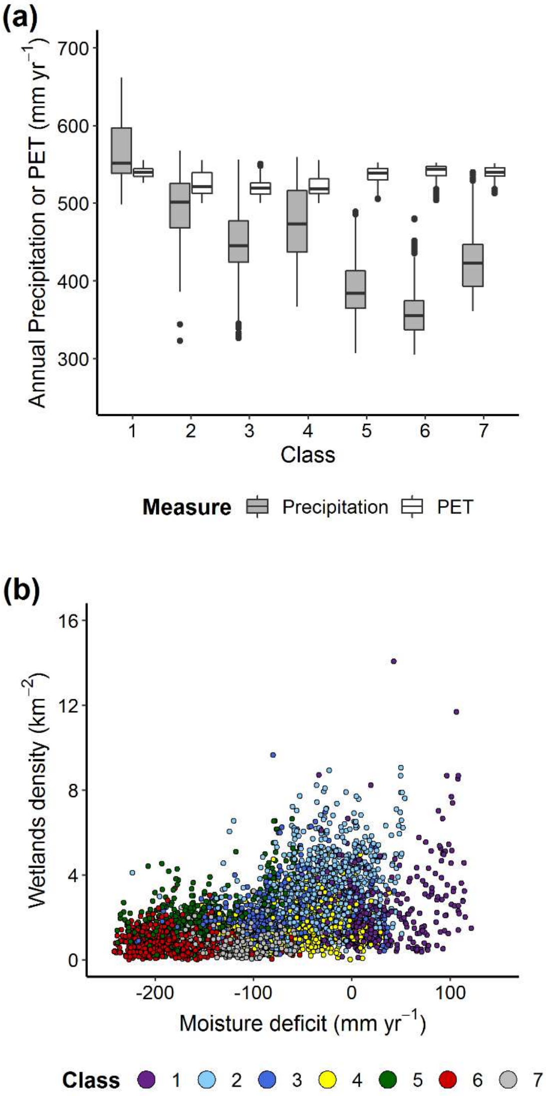

Figure 6 – Climatic variation among watershed classes. (a) Boxplots of total annual precipitation (grey) and potential evapotranspiration (PET) (white) for each watershed cluster. Lower, middle, and upper limits of boxes show the 25th, 50th, and 75th quantiles, respectively. (b) Wetland density to moisture deficit (Precipitation – PET). *Classes: Southern Manitoba (1), Pothole Till (2), Pothole Glaciolacustrine (3), Major River Valleys (4), Interior Grasslands (5), High Elevation Grasslands (6), Sloped Incised (7).*

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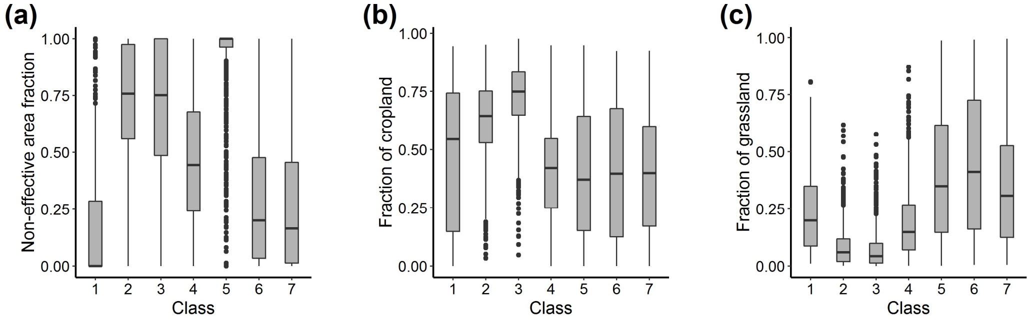

Figure 7 – Boxplots of select variables by watershed class: (a) fraction of non-effective area; (b) fraction of cropland; and (c) fraction of grassland. *Classes: Southern Manitoba (1), Pothole Till (2), Pothole Glaciolacustrine (3), Major River Valleys (4), Interior Grasslands (5), High Elevation Grasslands (6), Sloped Incised (7).*

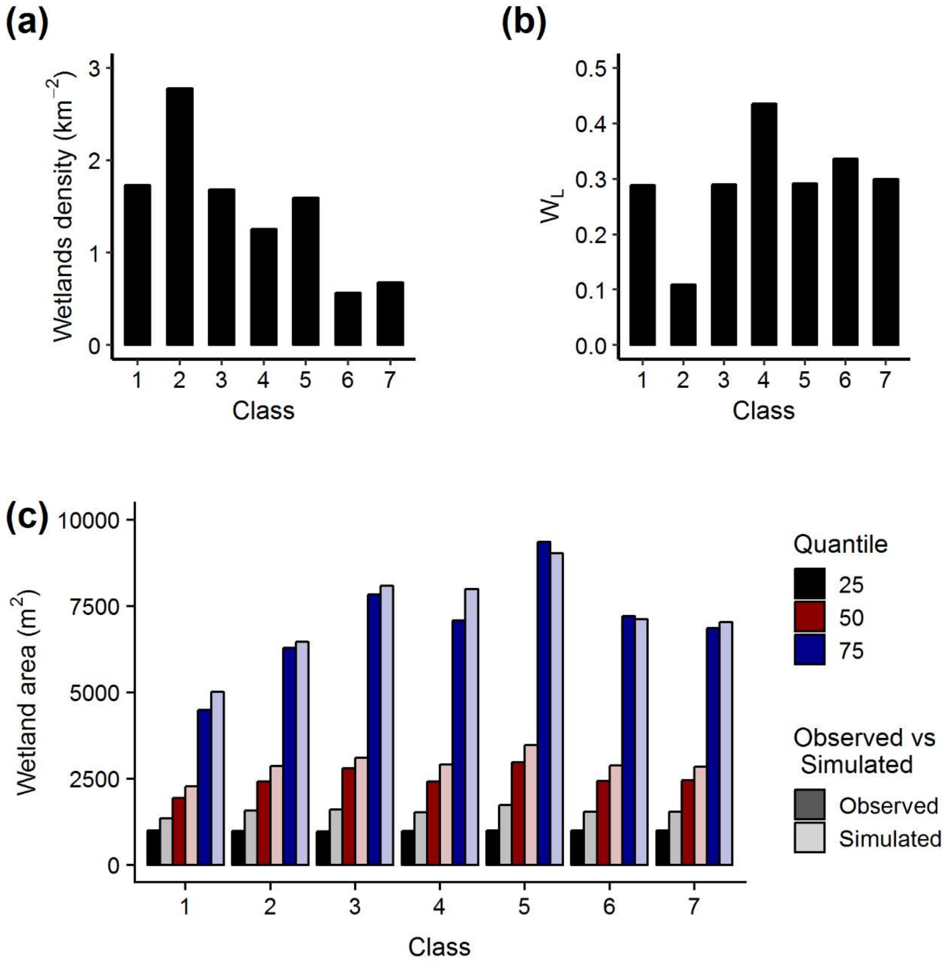

Figure 8 – Wetland variables and simulated size distributions. Median (a) number of wetlands and (b) fraction of total watershed water area in the largest wetland (W_L) are depicted by class. Panel (c) shows observed (solid) and simulated (transparent) quantiles of wetland areas. Predicted values are based on a generalized Pareto distribution and using median parameters of β and ζ for each cluster. Simulated data were restricted to the raster pixel resolution of observed data from the Global Surface Water dataset. *Classes: Southern Manitoba (1), Pothole Till (2), Pothole Glaciolacustrine (3), Major River Valleys (4), Interior Grasslands (5), High Elevation Grasslands (6), Sloped Incised (7).*

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