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Abstract: We compared median runoff (R) and precipitation (P) relationships over 25 years from 20 meso-scale (50 to 5,000 km^2) catchments on the Boreal Plains (BP), Alberta, Canada, to understand controls on water sink and source dynamics in water-limited, low-relief northern environments. Long-term catchment R and runoff efficiency (RP^{-1}) were low and varied spatially by over an order of magnitude (3 to 119 mm yr^{-1}, 1 to 27%). Inter-catchment differences were not associated with small variations in climate. The partitioning of P into evapotranspiration (ET) and R instead reflected the interplay between underlying glacial deposit texture, overlying soil-vegetation land cover, and regional slope. Correlation and PCA results show that peatland-swamp wetlands were the major source areas of water. The lowest estimates of median annual catchment ET (321 to 395 mm) and greatest R (60 to 119 mm, 13 to 27% of P) were observed in low-relief, peatland-swamp dominated catchments, within both fine-textured clay-plain and coarse-textured glacial deposits. In contrast, open-water wetlands and deciduous-mixedwood forest land covers acted as water sinks, and less catchment R was observed with increases in proportional coverage of these land-covers. In catchments dominated by hummocky moraines, long-term runoff was restricted to 10 mm yr^{-1}, or 2% of P. This reflects the poor surface-drainage networks and slightly greater regional slope of the fine-textured glacial deposit, coupled with the large soil-water and depression storage and higher AET of associated shallow open-water marsh wetland and deciduous-forest land covers. This inter-catchment study enhances current conceptual frameworks for predicting water yield in the BP based on the sink and source functions of glacial landforms and soil-vegetation land covers. It offers the capability within this hydro-geoclimatic region to design reclaimed catchments with desired hydrological functionality and associated tolerances to climate or land-use changes, and inform land management decisions based on effective catchment-scale conceptual understanding.

Key Words: Boreal Plains, regional runoff, inter-catchment comparison, land cover, glacial landforms, catchment evapotranspiration

1. INTRODUCTION

Understanding the relative role and interaction of landscape attributes in generalizing catchment hydrological function and runoff patterns remains a key challenge in water resources research (Wagener *et al*., 2007). Quantifying these hydrological interactions is essential for understanding and predicting the effects of climate and land-use changes, as well as directing management and experimentation at both local and regional scales (Wolock *et al.*, 2004; Kennard *et al.*, 2010a; Tetzlaff *et al*., 2015). Within specific hydro-climatic settings, inter-catchment comparisons have increased our understanding of the potential roles and interactions of climate, landscape attributes (geology, soils, and land cover), and topography in developing local and regional hydrological pathways and spatial variations in storage that affect catchment runoff response to precipitation (P) and overall resilience to environmental change (Buttle 2006; van der Velde *et al*., 2013; Julian and Gardner, 2014). Most catchment comparison studies, however, have focused on humid regions with topographically-driven headwater catchments and geological settings that promote local-scale, lateral surface and subsurface flow with predictable slope to riparian and stream interactions (Jencso and McGlynn, 2011; McNamara *et al*., 2011; Nippgen *et al*., 2011). In regions with low relief or thick heterogeneous substrates, by contrast, upland to stream interactions are more diffuse. Vertical and subsurface exchanges may dominate, and heterogeneity in geology and soils strongly influence surface-groundwater interactions, catchment storage, antecedent moisture, and flow pathways (Devito *et al*., 2005a; Tetzlaff *et al.,* 2009; Ehsanzadeh *et al*., 2012; Klaus *et al*., 2015). Our understanding and ability to conceptualize and generalize the primary landscape attributes that control runoff (R) and catchment hydrological function will be enhanced by comparisons across much broader hydro-climatic and geologic regions (Tetzlaff *et al.,* 2015). Herein, we examine the relative role of landscape attributes on the partitioning of P into R and evapotranspiration (ET) in catchments located in a low-relief, sub-humid northern environment.

Sub-humid climate, low relief, and thick, heterogeneous glacial deposits characterize Canada's Boreal Plains (BP) ecozone. This ecozone is part of Canada's Boreal Forest, which makes up 55% of Canada's land area, and is instrumental in global water and carbon cycles (Ireson *et al.*, 2015). The BP is currently experiencing intensive and extensive cumulative effects from climate change, anthropogenic (*i.e.* oil and gas, forestry) and natural disturbances (*i.e.* wildfire). The result is a large and continually increasing demand for water resources with potentially significant impacts to water quantity and quality (Schneider *et al.*, 2015). Concerns over long-term water security are heightened by the close balance between potential ET (PET) and P in the region and low, but highly variable long-term runoff (Mwale *et al.*, 2011; Ireson *et al.*, 2015). Development of adaptive best management or reclamation practices to protect and address future water availability and cumulative impacts from a range of disturbances requires characterization of the dominant sinks and sources of water that control the magnitude and spatio-temporal variability of catchment runoff (Winter, 2001; Buttle, 2006).

Conceptual syntheses of research from across the BP (Johnson and Miyanishi, 2008; Devito *et al.*, 2012; Ireson *et al.*, 2015), and similar ecohydrological regions (Winter, 2001; Schoeneberger and Wysocki, 2005; van der Kamp and Hayashi, 2009), predict large spatial variability in catchment hydrological function due to complex interactions of a dynamic climate with subtle variations in topographic relief, moderate to poor regional drainage, and spatially variable glacial deposits and soil-vegetation land cover. Major differences in hydrologic function attributable to the surficial geology across the BP have been broadly categorized into three general glacial deposit textures: 1) coarse-textured glacio-fluvial and glacio-lacustrine deposits, 2) fine-textured clay-rich hummocky moraines, and 3) fine-textured clay-rich glacio-lacustrine plain deposits (Bridge and Johnson, 2000; Devito *et al.*, 2005a; Ireson *et al.*, 2015). These three glacial landforms encompass the spatial

variations in recharge, water table configurations, scale and magnitude of surface-groundwater interactions, and degree of surface and subsurface connectivity (Winter, 2001; Devito *et al.*, 2012).

The BP is also a mosaic of forestland, wetland, and aquatic soil-vegetation land covers that contrast in hydrological function (Devito *et al.*, 2005a; Ireson *et al.*, 2015). Such land-covers largely control spatial differences in soil storage and AET that, in turn, influence runoff regimes within individual BP catchments (Njissen and Lettermaier, 2002; Devito *et al.*, 2005b; Thompson *et al.*, 2015). However, the relative role of and interaction between land-cover types may depend on the texture of the larger glacial landform they are located upon (Winter, 2001; Devito *et al.*, 2012). Peatland land covers (*i.e.* bog or fen peatlands, swamps) that dominate in low-relief terrain on both coarse- and fine-textured glacial deposits typically have surface vegetation and peat structure that reduce AET, promote shallow water tables (Petrone *et al.*, 2007; Waddington et al., 2015), and have been shown to be the primary sources of lateral runoff in many hydro-climatic regions (Gibson *et al.*, 2002; Tetzlaff *et al.*, 2009; Gracz *et al.*, 2015). In contrast, aquatic or marsh wetlands typically have standing water, AET rates at or above P, and would be expected to reduce catchment runoff efficiency (Nijssen and Lettenmaier, 2002; Petrone *et al.*, 2007). The hydrological function of a forestland is largely dependent on the glacial-landform, where substrate texture interacts with long-term climate to influence vegetation type, soil moisture dynamics, and water transmission (Bridge and Johnson, 2000; van der Velde *et al.*, 2013). On coarse-textured glacial deposits, forestlands may act as long-term water sources, as deeper water tables and higher rates of recharge reduce vegetation access to water and thus reduce AET (Smerdon *et al.*, 2008; Ireson *et al.*, 2015). In contrast, on fine-textured landforms, forestlands are typically aspen-dominated with steeper slopes, thus soil-water storage is large relative to P and long-term R is typically low (Redding and Devito, 2008; Barr *et al.*, 2012).

The regulation of regional hydrological functions and runoff from large catchments of varying local-scale distributions of glacial deposit texture and soil-vegetation land covers has not been systematically tested across low-relief, geologically heterogeneous regions, such as the BP (Soulsby *et al*., 2009; Ali *et al*., 2012; Ireson *et al*., 2015). Studies of catchment runoff response to precipitation on the BP have largely been limited to smaller catchments, hillslope plots or individual catchments that lack sufficient breadth to assess the role of various landform attributes on overall catchment function (Njissen and Lettermaier, 2002; Devito *et al.*, 2005b; Redding and Devito, 2008). Herein, we analyze long-term R and P relationships and quantify the relative sink-source function of 20 meso-scale (50 to 5,000 km^2) catchments that represent the climatic variability and varying proportions of glacial depositional textures and soil-vegetation land covers typical of the Central Mixedwood Ecoregion in the Boreal Forest of Alberta. We hypothesize that the overall catchment sink or source function is related to the proportion of glacial deposit type and overlying soil-vegetation land covers that regulate the spatial partitioning of P to R and long-term AET loss. Based on local-scale studies, we predicted: 1) increased runoff magnitude (R) and efficiency (RP^{-1}) with greater proportions of coarse-textured glacial deposits because they limit forest AET, and increase groundwater recharge and discharge; 2) increased R and RP^{-1} with greater proportions of low-relief, fine-textured glacial deposits having reduced sub-surface water transmission and effective storage that promotes near-surface saturation and soil-vegetation structure (*i.e.* peatlands) with low AET; and 3) decreased R and RP^{-1} with greater proportions of fine-textured glacial deposit types with greater relief and large storage in surface depressions (*i.e.,* marshes) and the subsurface (*i.e.,* deciduous forests) that facilitate soil-vegetation structure with greater AET (Winter, 2001; Devito *et al*., 2005a; Petrone *et al*., 2007; Smerdon *et al*., 2008; Ehsanzadeh *et al*.,2012).

2. STUDY AREA

This study was conducted on the BP Ecozone of Canada, where geologic transitions of the Montane Cordillera Ecozone and the outcrop of the Boreal Shield Ecozone define the western and eastern boundaries, respectively. The latitudinal boundaries are defined largely by climate, with a northern transition to boreal forest having sporadic and discontinuous permafrost and a southern transition to forest parkland and prairie vegetation. The physiography of the BP in Alberta is relatively diverse, and here the national scale BP Ecozone is further delineated into higher resolution provincial Natural Subregions within the Boreal Forest Natural Ecoregion of Alberta (NRC 2006; Figure 1). The study catchments are located within the Central Mixedwood (CMw) subregion, with the headwaters of six catchments extending into the Low Boreal Highlands (LBH) subregions (Figure 2a). The CMw and LBH are bounded by the Dry Mixedwood subregion (DMw) to the south and west, where agricultural land use dominates. The CMw-LBH is bounded to the southwest by the wetter and cooler Lower and Upper Foothills Natural Ecoregion, with much steeper terrain and transitional to Cordilleran Ecoregions (NRC, 2006).

The CMw and LBH subregions are sub-humid with similar mean annual air temperatures of 0.2°C and -1.0°C, and mean annual P of 478 and 495 mm, respectively (Table I). Long-term ecodistrict estimates of annual PET for the catchments across both subregions (PET_{eco}; derived using the Thornthwaite approach) range from 511 to 523 mm (Marshall *et al*., 1999). Growing season (April to August) P represents about 70% of the annual P and R is characterized by summer peak flows with minor peaks during spring melt (Devito *et al.*, 2005b; Mwale *et al.*, 2011).

The CMw has subtle relief; with flat to undulating plains and inclusions of hummocky uplands, while the portions of the study catchments located in the LBH are gently sloping with some undulating terrain and hummocky uplands (NRC, 2006). Elevation ranges from 200 to 1050 m and 400 to 1050 m above sea level in the CMw and LBH, respectively. The minimum and maximum

range in elevation is 71 to 689 m and an overall slope less than 1.4^o in the 20 study catchments (Figure 2; Table I). The sediment thickness over bedrock varies in depth from 20 to 200 m (MacCormack *et al.*, 2015) and bedrock aquifers do not play a large role in surface runoff. The surficial geology of the CMw is roughly equal portions of fine-textured glacio-lacustrine deposits, hummocky clay-rich glacial till moraines and coarse-textured glacio-fluvial and aeolian deposits (Fenton *et al.*, 2013; Figure 2). The LBH is largely comprised of till moraines, with till in both CMw and LBH becoming coarse (*e.g.,* sandy moraines) in the eastern part of Alberta (NRC, 2006).

Forest soils in better-drained fine-textured moraines and clay-plains are predominantly Orthic and Grey Luvisols, with Dystric and Orthis Brunisols in coarse-textured landforms (NRC, 2006). In poorly-drained sites, organic soils (predominantly peatlands) of 1 to over 4m depth represent significant cover (40%), but locally vary across the CMw. In poorly-drained, low-relief glacio-lacustrine areas, typical of large areas in the center of the subregion (Figure 2), organic soils can cover up to 80% of the area. In hummocky terrain, associated with stagnant ice moraines on regional highs at the periphery of the CMw, organic soils may represent only 20% of the land area (NRC, 2006).

Organic soils have aboveground canopy covers primarily comprised of black spruce (*Picea mariana*) and tamarack (Larix sp), while peatland mosses dominate ground cover. Forests on fine-textured moraine landforms are largely comprised of closed-canopy mixedwoods, with aspen (*Populus tremuloides*) and birch (*Betula papyrifera*) leading early successional stages, and white spruce (*Picea glauca*) and balsam fir (*Abies balsemea*) becoming ubiquitous with age. Pine (*Pinus banksiana*) is common in well-drained, coarse-textured landforms (NRC, 2006).

3. DATA and METHODS

3.1 Study Catchments, Climate and Runoff

Twenty study catchments (50 to 5,000 km^2) monitored by Water Survey of Canada (WSC, 2013) from 1986 to 2010 were selected. The catchments represent the variation in climate, land-cover, surficial geology, and topography across the CMw-LBH region of central Alberta (Figure 2; Table I). Four catchments are predominantly drained from the CMw (>80%), though their outflows are located on the DMw subregion (CID# 7,18,21,23). The study catchments are of sufficient area (meso-scale) to 1) reduce edge effects in cross-boundary movement of groundwater for catchment budgets (Winter, 2003; Devito *et al*., 2005a), and 2) reduce bias in areal estimates of catchment characteristics. Additionally, the 25-year hydro-climatic record captures the full range of wet, dry, and mesic climate patterns experienced in this region (Devito *et al.,* 2005b; Mwale *et al*., 2011) and is of sufficient length to reduce temporal and spatial uncertainties in estimates of long-term catchment P and R (Winter, 1981; Kennard *et al*.,2010b).

Monthly stream discharges (m^3 mo^{-1}) obtained from the WSC HYDAT database (WSC, 2013) (Table I) were normalized into unit-area runoff (mm mo^{-1}) using catchment drainage areas provided. For streams or years without winter flow records (November to March), monthly winter flow was estimated assuming exponential recession from October to April, as observed in previous years or adjacent rivers with winter flow records (Devito *et al.*, 2005b; Mwale *et al.*, 2011). Annual (water year) R was derived using monthly runoff sums from November to October. Annual P (mm) was determined by distance weighting between 3 to 5 of the closest Alberta Agriculture and Forestry Sacramento gauges (2014) (alter shielded; measured twice per year; April 1 and October 31) to produce a continuous 25-year P record (Figure 2). Runoff efficiency (RP^{-1}) was determined from the 25-year median annual ratios of median R and P. The median of the 25-year annual P minus R was used as an estimate of the long-term actual ET (AET$_{est}$) for each catchment. Estimates of long-term

ecodistrict precipitation (P_{eco}) and potential evapotranspiration (PET_{eco}) were determined by weighting individual ecodistrict coverage of each catchment (Marshall *et al*., 1999). To compare long-term water-energy balances of the various catchments, the Budyko framework was utilized, where the dryness index (PET_{eco}/P_{eco}) was compared with the evaporative index (AET_{est}/P_{eco}) and plotted on the theoretical Budyko (1974) curve.

3.2 Catchment Hydrological Response Areas (HRAs)

In this study we define three hydrologic response area (HRA) classifications to represent and categorize coarse- or fine-textured glacial deposits; the former as *Coarse* HRA, and the latter subdivided into hummocky moraine (*HM*) and clay-plain (*Clay-Plain*) HRAs. The HRAs were determined from Alberta Geological Survey surficial geology mapping (Fenton *et al.*, 2013). The texture of each mapped surficial geology unit was defined as being coarse or fine from the primary texture classification if available (coarse = gravel, sand, sandy-gravel, silty-sand, silty-gravel; fine = silt, clay, sand-silt-clay, sandy-silt, sandy-clay, silty-clay, clayey-silt). If no primary texture was provided, geomorphic class and landform genesis was used (Fenton *et al.,* 2013; Atkinson *et al.,* 2014); fluvial, glacial-fluvial, aeolian, and littoral glacio-lacustrine landforms were combined for coarse HRAs *(%Coarse)*. The fine-textured percentage cover *(%Fine)* was equal to 100-*%Coarse*. Within the fine-textured classified areas, non-sandy stagnant ice moraines, and moraines with hummocky geomorphic class were combined to derive the percentage coverage of hummocky moraine HRA (*%HM*). The percentage of clay-plain cover *(%Clay-Plain)* included lacustrine, distal glacio-lacustrine, and thrust moraine landforms, which represents the remainder of fines (100-*%Coarse-%HM*). Organic deposits (*i.e.* peatlands) were assumed underlain by fines, but classified as *%Coarse* if >75% of the perimeters of organic deposits were surrounded by coarse-textured landforms. Due to the limited number of catchments available for analyses, and to reduce the

potential for spurious correlations (Berges, 1997), only two of the three defined glacial landforms *(%Coarse, %HM)* were used in our analyses.

Average slope in degrees for each catchment was calculated using ArcGIS software, where the slope of each DEM cell (30 m resolution) was calculated using the maximum rate of elevation change between each cell and its 3x3 cell neighborhood, then averaged across the entire catchment.

3.3 Catchment Hydrological Units (HUs)

Statistical analyses using 20 catchments requires parsimonious selection of vegetation land-cover groups (HUs) to reduce spurious relationships (Berges, 1997; Pearl, 2000). HUs were estimated using 24 vegetation classes present in a remotely-sensed (Landsat TM) Ducks Unlimited Enhanced Wetland Classification (DUC, 2011): a) *%Open_Mr* merged aquatic wetlands with persistent standing water, including open-water, emergent wetlands and meadow marsh classifications, b) *%Peat_Sw* merged terrestrial wetlands with shallow water tables, including fen (graminoid, shrubby, treed rich and poor fens), bog (open shrub and treed) and swamp (conifer, tamarack, hardwood, and mixed) classes, and c) *%Decid_Mw* merged upland deciduous and mixedwood forest classes.

3.4 Statistics

MATLAB was used to compute descriptive statistics and conduct comparative analyses. Spearman's rank correlation coefficients were used to assess correlations between multiple catchment characteristics and calculated long-term 25-year median R and P or estimated P_{eco} and PET_{eco} (Table II). Correlations between variables that include products (or ratios) or sums of the original variable (*i.e.,* R or P vs. RP^{-1} or AET_{est}) were not conducted due to the potential for spurious correlation (Berges,1997). To avoid Type I errors associated with multiple comparisons, the appropriate

Bonferroni correction was used to assess statistical significance (Dunn, 1961; McDonald, 2008), which was ranked as weakly significant if $p<0.0125$, significant if $p<0.00625$, and strongly significant if $p<0.00125$. Only correlations that were at least weakly significant are reported in this study. The best single regression model for each catchment characteristic with median AET_{est}, R and RP^{-1} was determined by comparing and assessing studentized residuals for several linear and nonlinear models provided within MATLAB's Curve Fitting Toolbox® 3.5.1. Forward-selection stepwise linear regression was used to assess the most important climate and catchment characteristics (see Table II) in predicting 25-year median R and RP^{-1}. The *stepwise* function in MATLAB was used with an entry and exit *p*-value for predictor variables of 0.05 and 0.10, respectively. R and RP^{-1} values were square-root transformed to adjust for skewness in the data towards small R and RP^{-1} values, while simultaneously forcing predicted R and RP^{-1} to be positive (Helsel and Hirsch, 1992). Principal component analyses (PCA, Pearson-type) were conducted on standardized data (z-scores) using the *princomp* function in MATLAB to further examine interactions between catchment climate, HU and HRA groups and median R and RP^{-1}.

4. RESULTS and DISCUSSION

4.1 Inter-catchment Climate

All study catchments had dryness indices greater than 1 and were classified as water-limited on the Budyko curve (Figure 3a). Estimates of catchment moisture deficit (P_{eco}-PET_{eco}) ranged from -30 to -120 mm and were not related to R (Figure 3b). Comparatively, the climate of the White Gull catchment of the Boreal Ecosystems Research and Monitoring Sites (BERMS) in Saskatchewan (Nijssen and Lettenmaier, 2002; Barr *et al.*, 2012), which is characteristic of the eastern portion of the BP, falls within the climatic range of the study catchments. The study catchments are much drier

than the energy limiting conditions on the eastern Boreal shield of North America and Scandinavia (van der Velde *et al.*, 2013; Karlsen *et al.*, 2016).

4.2 Catchment Characteristics and Runoff

The spatial variation in median annual R (3 to 119 mm), RP^{-1} (0.01 to 0.27), and AET_{est} (321 to 473 mm) (Table I) were not significantly correlated with climatic variables (Table II; Figure 4). R and RP^{-1} were highly correlated (r=0.99, p<0.001), had similarly poor relationships with median annual P, and virtually identical relationships with catchment characteristics (Table II; Figure 4). This indicates that variation in R, rather than P, influences difference in runoff efficiency between catchments and, thus, the results focus on relationships with R. Median annual R was strongly and negatively correlated with *%HM* but, although hypothesized, no significant relationship was observed with *%Coarse*. Median annual R was strongly positively correlated with *%Peat_Sw*, and negatively correlated with *%Open_Mr* and *%Decid_Mw*. Stepwise linear-regression analyses identified *%HM* (*p*=0.001) and *%Peat_Sw* (*p*=0.002) as the two most significant predictor variables, explaining 81% (p<0.001) of the variation in median annual R among catchments (Table III).

The PCA results using R with catchment slope, climate, %HU, and %HRA data for the 20 catchments is presented in Figure 5. PCA using R or RP^{-1} with the other catchment characteristics provided similar strength of loadings (length of arrows) and interactions of indices. Therefore, only the PCA results for the interaction of R and catchment characteristics are presented here (Figure 5). Catchment *%Peat_Sw* and *%HM*, along with R, had the greatest loadings on PC1, which explained 49% of variance in catchment characteristics (Figure 5). PCA results show a negative association between *%Open_Mr* and R. Catchment slope, P and PET_{eco} had the greatest loadings on PC2, which explained 22% of the variance among the catchments. The slope of the loadings (arrows) relative to PC1 and PC2 axes indicate considerable interaction of HU and HRA indices with climate, catchment

slope and R. Catchments associated with greater *%HM* HRAs have lower R and also lower slope and greater PET. Catchments discriminated by %*Decid_Mw* are also associated with less runoff, but in contrast are associated with greater slope and P. Likewise, although catchments with large %*Peat_Sw* coverage are associated with greater R, they are characterized as areas with lower slope and slightly lower P. PCA results also indicate that catchments characterized with higher *%Coarse* HRAs are associated with less PET and greater R. Based on PCA scores, and visual inspection, four groups of catchments were identified: deciduous mixed-wood (CID# 21,23), peatland-swamp (CID# 11,12,14), hummocky moraine (CID# 7,8,20), and coarse-textured (CID# 2,4) catchments (Figure 5). These catchment groups serve as examples for further illustrating the interaction of HUs with HRAs in relation to climate and median R, and are discussed in the following section.

The correlation and PCA analyses support most of the predicted relationships between long-term water fluxes (AET$_{est}$, R, and RP^{-1}) and the proportion of HRAs and HUs in the study catchments. The relative functional role of different HUs and HRAs, acting as sinks or sources of water are broadly consistent with conceptual frameworks developed from local-scale studies on the BP (Devito *et al*., 2005b; Ireson *et al*., 2015). Further, without explicit consideration of the spatial configuration and hydrologic connectivity to the catchment outlet in this study, we still observed strong relationships and explanatory power between runoff and selected catchment characteristics. These results indicate not only the large control of HUs on catchment AET but also the large contrast in relative roles of landforms and land covers on regional runoff in this hydro-geoclimatic region. Therefore, best-fit models predicting median AET$_{est}$ and R from the trends in proportions of catchment land covers, and comparative differences of catchment groups selected from the PCA (Figure 5), can be used to quantify the hydrological role of landforms and land covers.

4.3 Quantifying Controls on Long-term Runoff and Efficiency

4.3.1 Influence of Hydrological Units

The relative influence of AET_{est} on the spatial variability in catchment R is indicated by significant relationships between median AET_{est} and the proportion of each HU, and the lack of relationship between R or AET_{est} and regional PET_{eco} or P (Figure 3 and 6). Direct comparisons of median R (or RP^{-1}) with AET_{est} are not possible in this study because of the spurious correlation (Berges, 1997) as catchment-scale AET was estimated using the catchment water balance. Studies at the stand level within individual catchments on the BP have illustrated similar control of land cover and the dominant influence of AET relative to PET and P on catchment hydrology (Baker *et al*., 2009; Barr *et al*., 2012). Comparison of HU coverage and AET_{est} (as calculated in this study) from the White Gull catchment, containing the BERMS sites (Nijssen and Lettenmaier, 2002), fit well with the relationships developed in this inter-catchment study (Figure 6), indicating the potential for further regional generalization of HU control on long-term median R.

4.3.1.1 Wetland HUs: Terrestrial vs Aquatic

As predicted, terrestrial peatland-swamp wetland HUs, which experience shallow water tables, functioned as long-term water sources (Figure 4; Table III). Estimates from the regression relationships (extrapolating to 100% HU coverage) indicate that *Peat_Sw* dominated HUs had the lowest median annual AET_{est} (301 ± 70 mm (95% CI)) resulting in the greatest R (137 ± 57 mm; 35 ± 13% of P) compared to all other HUs (Table IV; Figure 6). These values are comparable to long-term estimates of annual AET (383 ± 26 mm) and R (108 mm; 22% of P) determined from the residuals of tower-based water balances for the Old Black Spruce BERMS site. This land-cover has shallow water tables and organic soils (Barr *et al*., 2012), similar to *Peat_Sw* land covers in our study. Furthermore, similar ET rates and AET/PET ratios were also observed in riparian poor fens

located on hummocky moraine landforms (Petrone *et al*., 2007; Brown *et al*., 2010) and an expansive

plateau bog (Thompson *et al*., 2014) on the CMw of Alberta.

Catchments dominated by peatland-swamp wetlands, visually delineated from the PCA

(CID# 11,12,14), had the lowest median annual AET_{est} (321 to 395 mm) and highest R (60 to 119

mm, 13 to 27% of P), even though they experienced some of the lowest median annual P and

relatively high PET_{eco} (Table II; Figure 5). Some of the unexplained variance in long-term R by

%Peat_Sw likely reflects differences in their configuration and connectivity within each catchment.

Nevertheless, *%Peat_Sw* alone explained 63% of the spatial variance in median annual R (Figure 4;

Table IV). This inter-catchment comparison illustrates the potentially large influence of water

conservation feedbacks that reduce AET (Barr *et al*., 2012; Kettridge and Waddington, 2014;

Waddington *et al*., 2015) and promote surface saturation and lateral flow (Ferone and Devito, 2004;

Thompson *et al*., 2015) such that peatland-swamp ecosystems function as the primary contributing

areas to runoff on the BP. This reconfirms studies in other boreal regions showing that increased

water availability and runoff is associated with increased coverage of peatlands at the regional scale

(Tetzlaf *et al*., 2009; van der Velde *et al*., 2013; Gracz *et al*., 2015; Karlsen *et al*., 2016).

Shallow open-water and marsh wetlands, with persistent standing water, functioned as

hydrologic sinks within their catchments. The best-fit model of *%Open_Mr* vs median AET_{est}

(Figure 6) provides an estimated median annual AET of 530 $\pm$ 91 mm if extrapolated to 100% open-

water wetlands , with median R from a catchment approaching zero with *%Open_Mr* coverage of 12

to 33%. This study indicates a low limit to the coverage of open-water systems to maintain

catchment water yield, and that 3 to 8 times catchment to aquatic wetland areal ratio is required to

provide water to maintain such wetland ecosystems on the BP. High AET in open-water wetlands

can be expected in both coarse-textured (Smerdon *et al*., 2005) and fine-textured (Ferone and Devito,

2004; Petrone *et al*., 2007) landscapes. Large estimates of annual AET from aquatic wetlands (500 to

600 mm), and their opposing role relative to the hydrologic function of terrestrial peatland-swamp wetlands, has been documented in catchments located across different boreal and temperate hydro-geoclimatic landscapes (Nijssen and Lettenmaier, 2002; Petrone *et al.*, 2007; van der Velde *et al.*, 2013).

4.3.1.2 Forestland HUs

We show that *Decid_Mw*, which dominate forestlands in the CMw, function largely as water sinks. Extrapolation of the regression model estimates 493 ± 87 mm yr^{-1} of AET$_{est}$ in pure (100%) *Decid_Mw* catchments (Figure 6) that slightly exceeded median annual P (459 mm). These results are similar to studies in other water-limited regions, where growing season ET of forests converge to within $\pm$ 10% of annual P, and indicate the importance of soil-water storage during the non-growing season on AET and water yield on the BP (Sun et al., 2011). Further, estimated catchment R approaches zero with 75% or greater *Decid_Mw* cover (Figure 4; Table IV). Interestingly, *%Decid_Mw*, or even total percentage forest cover, rarely exceeded 50% coverage in the study catchments (Table I). This may indicate a maximum forestland proportion that balances large production and AET demand with catchment water yield (RP^{-1} < 10%) (Farley et al., 2005). Given that summer precipitation dominates annual inputs and is often less than PET, our results show that aspen and mixed-wood stands remove most of the precipitation over the long-term in the BP (Devito *et al.*, 2005b; Barr *et al.*, 2012).

Catchment comparisons further illustrate the hydrologic function of aspen and mixed-wood stands on regional water yield. Catchments that were dominated by *%Decid_Mw* (CID# 21, 23), and not influenced by fine-textured hummocky terrain, had high long-term median annual AET$_{est}$ (459 to 470 mm) and AET$_{est}$ /P ratios (0.91 to 0.96) and low R (20 to 43 mm; 4 to 9% of P) (Table I). Post hoc analyses showed no correlation between the percentage of non-*Decid_Mw* forest (*%Forest -*

%Decid_Mw) and R (r=0.163, *p*=0.488), further linking the water sink function to deciduous forests. AET_{est}/P ratios and R for *%Decid_Mw* dominated catchments in this study are similar to annual runoff estimates from experimental plots (URSA: Redding and Devito, 2008), long-term eddy flux tower (30 $\pm$ 35 mm; Barr *et al.*, 2012), aspen hummock (Thompson *et al.*, 2015) and catchment water balance (Devito *et al.*, 2005b) studies across the BP (Figure 1). These results illustrate the strong contrast in hydrologic function between upland forests and peatland-swamps as observed across a range of climatic and geomorphic regions in the boreal (Gibson *et al.*, 2002; Barker *et al.*, 2009; van der Velde *et al.*, 2013; Karlsen *et al.*, 2016).

4.3.2 Influence of HRAs

Our study indicates that relationships of the proportion of HUs with different AET rates on catchment R must be considered in the context of other landscape-scale flow-generation or storage mechanisms influencing the partitioning of P into ET and R (Winter, 2001; Devito *et al.*, 2012; Ireson *et al.*, 2015). In the BP, climate and topography appear to interact with heterogeneous glacial landforms and differences in substrate texture and permeability that subsequently influence soil-water and depression storage, hydrological flow paths and connectivity, as well as soil and plant development and water use (Bridge and Johnson, 2000; Winter, 2001).

4.3.2.1 Fine-Textured HRAs

As predicted, fine-textured hummocky moraine HRAs functioned as long-term water sinks (Table III; Figure 5). The best-fit models predict a decline in median R to <10mm (2% of P) with >55% cover of *%HM* (Table IV). Hummocky terrain and poor regional-scale drainage of fine-textured *HM* HRAs influence the net hydrologic function of all three HUs. Although the *HM* HRAs are often dominated by *Decid_Mw* and have considerable *Peat_Sw* cover (NRC 2006), median

annual R in *HM* dominated catchments (3 to 17 mm) was lower than in deciduous mixedwood, and certainly peatland-swamp dominated catchments (Table I). Field and modeling studies show that local-scale runoff from *Peat_Sw* and *Decid_Mw* HUs located on *HM* HRAs are focused towards depressions (Ferone and Devito, 2004; Thompson *et al*., 2015). These depressions are largely isolated and contain *Open_Mr* HUs with high water demand, which results in negligible outflow and low regional-scale runoff (Ehsanzadeh et al., 2012). The lowest annual R (3 to 5 mm; 1% of P) of the study was observed in the catchments (CID 18, 19) with the largest percentage cover of *HM* HRA and *Open_Mr* and *Decid_Mw* HUs (Table I). This inter-catchment comparison highlights the need to constrain current conceptualizations in scaling local processes and regional runoff analyses by placing HUs in the context of larger HRAs (Devito *et al*., 2012; Ireson *et al*., 2015).

Counter to other inter-catchment studies on the boreal (Tetzlaff *et al.*, 2009; Karlsen *et al.*, 2016)*, post hoc* analyses in this study indicate no relationship between median R and *%Clay-Plain* (*%Clay-Plain = %Fine-%HM,* r=0.250, p >0.2)*. At the scale of surficial geology maps and larger catchments, areas prone to high runoff generation on the *Clay-Plain* HRAs are likely areas that have developed into peatland and mineral swamp wetlands (Ferone and Devito, 2004; Olefeldt *et al*., 2013). Locally, slightly elevated deciduous mixedwood "islands" with large soil storage and water demand (Hokanson *et al*., 2016; Lukenbach *et al*., 2016) and open-water wetlands with high AET (Petrone *et al.*, 2007) presumably act to counter high runoff potential from peatland-swamp HUs across clay-till plain HRAs at larger scales. This can explain the lack of correlation between median R and *%Clay-Plain*, while a strong relationship with peatland-swamp HUs remains.

4.3.2.2 Coarse-Textured HRAs

The hypothesized relationship of increased catchment R with proportion of *%Coarse* was not supported by the correlation analyses. PCA results indicate, however, that greater *%Coarse* provides

some enhancement of runoff responses (Figure 5). In this study, coarse-textured catchments have relatively low median annual AET_{est} (381 to 388 mm), and thus higher median R (76 to 96 mm) compared to fine-textured HRAs. However, the influence of *%Coarse* on R is confounded by the strong negative relationship with *%HM* (r=-0.71, Table II) and interactions with %*Peat_Sw*. Micrometeorological studies at the Old Jack Pine BERMS sites located on coarse-textured soils estimate considerably lower point annual AET (306±21 mm) and a higher net surplus for runoff (187±55 mm) (Barr *et al*., 2012) than observed in our study. These estimates may represent more localized rates of recharge. Forestland HUs on coarse-textured HRAs have been shown to develop local flow systems that discharge at low-lying areas creating peatlands with integrated surface connections that can potentially enhance catchment runoff (Smerdon *et al*., 2005; van der Velde *et al.*, 2013; Plach *et al*., 2016). However, conifer and deciduous stands associated with loamy sand are abundant on coarse HRAs (CNR, 2006), and previous studies on the CMw indicate lower long-term annual recharge rates of 40 to 80 mm, compared to the BERMS site (Smerdon *et al*., 2008; Carrera-Hernandez *et al*., 2011). Further, the relative distance and spatial integration of recharge locations on coarse HRAs relative to the catchment outlet, and the interaction of flow systems that discharge into or through aquatic wetlands or riparian areas with high evapotranspiration, can have the cumulative effect of reducing meso-scale catchment runoff relative to the localized land-cover water balances.

4.3.3 Regional Relief

This inter-catchment study illustrates the influence of low regional relief on catchment-scale storage, AET and runoff. Subtle differences in catchment slope are correlated with *%Decid_Mw* (Table II; Figure 5). Increasing catchment slope is associated with deeper water tables and large soil-water storage that promotes forest growth, increased AET and reduced runoff. The association of increasing slopes with storage and reduced runoff has been documented in small, relatively steep

aspen catchments on the BP (Devito *et al.*, 2005b), other glaciated landscapes (Tetzleff *et al.*, 2009; Karlsen *et al.*, 2016), and may be common to catchments in general (Sayama *et al.*, 2011; Klaus et al., 2015). This is important in the CMw subregion where *HM* HRAs, particularly stagnant ice moraines (Eyles *et al*., 1999), make up much of the regional topographic highs and catchment headwaters with characteristics that exert a large control on runoff.

Conversely, *%Peat_Sw*, which is positively correlated with runoff, is also associated with low catchment slope (Table II; Figure 5). This relationship has been observed in inter-catchment studies in Scotland (Tetzlaff *et al*., 2009), boreal Sweden (Karlsen *et al*., 2016) and Alaska (Gracz *et al*., 2015). In this study, extensive peatland-swamp formations occur in either poorly-drained, low-relief fine-textured clay-plain HRAs, regardless of landscape position, or in groundwater discharge zones found in low-lying topographic positions of permeable substrates in coarse-textured HRAs (Winter, 2001; van der Velde *et al*., 2013). Saturated areas promote the accumulation of organic soils that effectively fill local-scale surface depression storage over time with hydrologically responsive soils associated with peatland-swamp HUs. In low-relief regions, the expansion of peatland-swamp complexes that coalesce into better-integrated surface and shallow sub-surface flow networks increase the catchment runoff (Gracz *et al*., 2015). These factors and the extensive distribution of peatlands across both coarse and fine-textured plains may explain the lack of correlation between *%Peat_Sw* and *%Coarse* (Table II) or *%Clay-Plain* (r=0.338, p>0.2), and the lack of relationship between *%Clay-Plain* and catchment R.

4.4. Interactions at the ecoregion scale

The interplay of regional relief, glacial HRA and soil-vegetation HU on catchment storage appears to influence runoff distribution at the ecoregion scale, as illustrated in catchment groupings in the PCA analyses (Figure 5). Seven catchments represent topographically high regions,

predominantly of fine-textured (carbonate bedrock source) hummocky moraines, that fringe the south and western portions of the CMw. These catchments have greater cover of *%Decid_Mw* (40 $\pm$ 11%), lower *%Peat_Sw* (28 $\pm$ 11%) (NRC, 2006) and low median annual R (15 $\pm$ 10 mm; 3 $\pm$ 2% of P). Proximal to these higher lands, regional glacial flooding resulted in low-relief and fine-textured landforms that are associated with expansive regions of peatlands (Atkinson *et al.*, 2014; NRC, 2006) across much of the interior of the CMw (Figures 2 and 5). The interior catchments indicate the type of flow expected from this portion of the CMw with expansive *%Peat_Sw* (57 $\pm$ 11%), little but varying *%HM* (16 $\pm$1 0%) and *%Decid_Mw* (28 $\pm$ 11%) and higher observed median annual R (64 $\pm$ 12 mm; 14 $\pm$ 3% of P). The LBH and moraines of the north-eastern portion of the CMw in Alberta have much coarser texture due to the proximal location of the Precambrian shield and granite bedrock source (NRC, 2006). The largest median R (97 $\pm$ 16 mm; 21 $\pm$ 4% of P) was observed, on average, from six catchments representing the northeast margin of the CMw with large *%Coarse* (47 $\pm$ 17%) and *%Peat_Sw* (61 $\pm$ 12%) (Figure 5). As such, this regional analysis supports interaction of enhanced runoff with *%Coarse* and *%Peat_Sw*. Notably, the White Gull catchment of the BERMS study is in a similar regional setting and has similar catchment characteristics and runoff regimes as this group of catchments.

In addition, the interaction of relief, glacial HRAs, and HUs appear to differ with other ecological subregions adjacent to the CMw-LBH. The lower runoff regimes observed in the adjacent Dry Mixedwood (DMw) compared to the CMw in this study (Mwale *et al.*, 2011) may reflect the slightly drier climate, but may also reflect subtle interactions of increased relief of the Peace River valley with fine-textured landforms and the development of land-cover with greater AET (NRC, 2006). Higher runoff responses in the adjacent Foothills subregions compared with the CMw are associated with a wetter climate, steeper relief, and the much coarser texture of fluvial and moraine landforms influencing catchment storage and AET (Peters *et al.*, 2013). Compared to the CMw,

higher runoff magnitudes and differences in flow regimes are observed in northern, sub-arctic catchments, as continuous and discontinuous permafrost influence catchment characteristics (McEachern *et al*., 2006). This study reconfirms the need to consider hydro-geoclimatic frameworks in understanding and quantifying landscape controls on catchments within and across regions, and in defining cross-scale interactions (Tetzlaff *et al*., 2009; Kennard *et al.*, 2010a).

5. IMPLICATIONS

The concepts of catchment water sink and source function presented in this study fill a knowledge gap needed for developing adaptive best management or reclamation practices in water-limiting and low-relief environments (Winter 2001; Schoeneberger and Wysocki, 2005). Peatland-swamp wetlands function as much more than simple receivers of flow from adjacent upland forests (*e.g.,* Prepas *et al.*, 2006; Price *et al*., 2010; Ireson *et al*., 2015). They are integral to overall catchment hydrologic function and potentially productivity. Catchment water yield is drastically reduced, and macro-ecosystem productivity may become restricted in landscapes where the ratio of forestland and aquatic-wetland area to peatland-swamp area approaches 2:1 (Farley *et al.,* 2005; Sun *et al.,* 2011). The conceptualization of potential runoff generation within peatland-swamp wetlands and loss of water in forestland complexes should be considered when scaling up runoff generation processes (*e.g.* Faramarzi *et al*., 2015) for regional-scale assessments. Furthermore, the configuration and proportion of forest and wetland HUs can be designed to optimize downstream water yield in watershed construction (Johnson and Miyanishi, 2008; Wytrykush *et al*., 2012).

Given the relatively low regional runoff, concerns regarding water security, and the scale of cumulative land-use impacts in the BP, our results highlight that regional-scale analyses and best management practices should focus on protecting or securing the functional behavior of peatland-swamp wetland land covers. They are primary water sources for lakes, streams and rivers on the BP.

This study further underlines the need to consider the contrasting hydrological function of different wetland types (*i.e.,* terrestrial vs. aquatic) in delineating and assessing their value, particularly in the Boreal Forest of Alberta where wetland types vary tremendously and coverage can range from 20-80% of the landscape (NRC, 2006).

The impact of land use, climate change and associated climate-mediated disturbance on catchment hydrologic function and water yield will vary in magnitude and timing across catchments with different configurations of HUs and HRA. Due to the small difference between P and PET, and contrasts in hydrological function and storage, land use or climate disturbance that shifts peatland-swamp systems to open-water (*e.g.,* flooding, beaver activity) or forestland (*e.g.,* drainage) systems will have a larger impact on water yields than shifts in land cover between forestland and open-water on the BP (Farely *et al.*, 2005; van der Velde *et al.*, 2013; Caners *et al.*, 2014). Moreover, differences between sink and source roles suggest that forestlands or aquatic ecosystems, with high water demand, may be more susceptible to climate change than peatland-swamp ecosystems that are characterized by negative feedbacks that tend to conserve water (Schneider *et al.*, 2015; Waddington *et al.*, 2015).

6. CONCLUSION

On the Boreal Plain, low-relief ($\leq 2°$) and a water-limiting climate combine to accentuate the influence and relative role of heterogeneities in glacial deposit type (hydrologic response area, HRA) and overlying soil-vegetation land cover (hydrologic unit, HU) on catchment storage and the long-term partitioning of P to AET or R. Catchment runoff was predominantly generated from peatland-swamp HUs in low-relief areas in both coarse- and fine-textured HRAs. This reflects the reduced AET, low soil-water storage of accumulated sediments and the integrated surface-flow networks of this HU in both coarse and fine-textured HRAs. In contrast, less catchment runoff was associated

with greater proportions of open-water wetland and deciduous-mixedwood forest HUs, reflecting the importance of storage and increased AET. Runoff was significantly limited in fine-textured hummocky moraine HRAs. This reflects the poor surface-drainage networks, negligible subsurface flow, and greater regional slope resulting in large potential storage in these fine-textured glacial deposits, coupled with higher AET of associated shallow open-water wetlands and deciduous forest land covers. Due to the broad distribution of stagnant ice moraines across the BP, the primary source of fine-textured hummocky moraine landforms, low runoff can be expected in many catchments across this ecoregion (Eyles *et al.*, 1999; Ehsanzadeh *et al.*, 2012). Regional differences in runoff were observed across the Boreal Forest natural ecoregion of Alberta, reflecting regional variations in relief, configurations of HRAs and the distribution of peatland and forestland HUs.

This study illustrates the need to consider hydro-geoclimatic frameworks in understanding and quantifying landscape controls on catchment hydrological function within and across regions (Wagener *et al*., 2007; Tetzlaff *et al*., 2015). Effective grouping of landforms into HRAs, with similar water storage and transmission characteristics, and land covers into HUs, with similar relative storage and AET, can provide a framework for articulating concepts of potential sink and source dynamics among landscape features common to the BP (Winter 2001; Devito *et al*., 2012; Ireson *et al*., 2015). The conceptualizations of 1) potential runoff generation within peatland-swamp wetlands and 2) drastic reductions in water yield on glacial landforms predominantly covered with deciduous forest and aquatic wetland types should be considered when implementing regional-scale cumulative effects management programs, designing constructed watersheds for reclamation, and evaluating the impacts of changing land use and climate. Accurate conceptualization of processes and representation in quantitative models will help ensure that downstream flow needs are met in the BP.

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Table I: Characteristics and indices of the study catchments

CID	Region	WSC	Area (km^2)	P (mm)	R (mm)	RP^{-1}	AET$_{est}$ (mm)	P$_{eco}$ (mm)	PET$_{eco}$ (mm)	HRA %Coarse	%HM	Slope (°)	HU %Peat_Sw	%Open_Mr	%Decid_Mw	%Forest	%Ag
4	NE	07CE003	279	464	76	0.16	388	463	513	64	0	0.8	54	0	30	44	0
2	NE	07CA012	425	477	96	0.20	381	463	514	62	3	1.3	44	3	34	46	0
11	NE	07DA006	1320	440	119	0.27	321	464	523	48	0	0.8	73	1	21	25	0
10	NE	07CA013	3078	502	43	0.09	459	451	516	47	2	1.1	36	7	36	50	0
12	NE	07DA008	1457	427	88	0.21	339	440	517	40	0	0.7	69	1	19	28	0
3	NE	07CB002	781	468	105	0.23	362	473	512	38	10	0.9	63	2	20	33	0
14	In	07DB001	5569	423	70	0.17	353	459	518	4	12	0.7	69	1	11	31	0
16	In	07JC002	619	455	60	0.13	395	413	518	14	17	0.7	66	1	25	28	0
9	In	07CA006	1120	473	65	0.14	408	470	518	14	10	0.8	61	2	21	29	0
15	In	07JC001	492	442	47	0.11	395	402	515	5	29	0.9	53	3	34	44	0
17	In	07JD003	582	484	56	0.12	428	403	516	23	2	1.3	53	3	35	43	1
13	In	07DA018	165	429	83	0.19	346	459	518	0	25	1.0	38	0	39	56	0
6	S&W	06AB001	4911	462	51	0.11	412	453	519	29	27	1.1	40	6	23	51	0
23	S&W	07HA003	1968	489	28	0.06	461	465	516	6	13	0.8	20	2	39	53	24
21	S&W	07BF009	427	491	20	0.04	470	469	517	9	31	1.2	30	2	57	57	0
7	S&W	06AB002	726	462	17	0.04	446	455	520	8	48	0.8	43	9	24	43	0
8	S&W	07BE003	57	424	26	0.06	398	481	518	2	51	1.1	41	1	43	44	0
20	S&W	06AC001	492	454	9	0.02	445	455	522	18	54	1.0	24	6	32	49	15
18	S&W	06AA001	4700	444	3	0.01	441	469	522	1	45	1.3	17	9	42	44	3
19	S&W	06AA002	2496	448	5	0.01	444	467	521	1	63	1.3	21	9	47	48	4
Median			753	459	53	0	403	461	518	14	15	0.9	44	2	33	44	0
Min			57	423	3	0.01	321	402	512	0	0	0.7	17	0	11	25	0
Max			5569	502	119	0.27	470	481	523	64	63	1.3	73	9	57	57	24

Median annual catchment precipitation (P), runoff (R), runoff efficiency (RP^{-1}) and AET$_{est}$ (P-R) calculated using years 1986-2010 from Alberta Agriculture and Forestry (2015), Sacramento Rain Gauge Station and Water Survey of Canada (WSC 2015).

Regions (see Figure 2 and 5) of central Alberta: Northeast Margin (NE), Interior (In), South and Western Margins (S&W).

See Figure 2 for river gauging locations (WSC), Sacromento Rain Gauge Stations, catchment boundaries and sub-regions. Peco and PETeco are catchment long-term precipitation and potential evapotranspiration derived from national eco-district database (Marshall et al., 1999).

Hydrologic Response Areas (HRAs) are from percent coverage of coarse-textured glacial (*%Coarse*) and hummocky moraine (*%HM*) landforms. Hydrologic Units (HUs) are from % land cover characteristics of the study catchments, where wetlands are divided into peatlands and swamps (*%Peat_Sw*) and open water and marsh (*%Open_Mr*); deciduous and mixedwood forests (*%Decid_Mw*); and total forest (*%Forest*); and land in agriculture (*%Ag*).

Table II: Spearman Rank correlation matrix of long-term median annual R and RP^{-1}, climate measures and catchment characteristics.

Parameter	R	P	RP^{-1}	AET_{est}	P_{eco}	PET_{eco}	Slope	%Coarse	%HM	%Peat_Sw	%Decid_Mw	%Open_Mr
P	--	•										
P_{eco}	--	--	--	--	•							
PET_{eco}	--	--	--	--	--	•						
Slope	--	--	--	--	--	--	•					
%Coarse	--	--	--	--	--	--	--	•				
%HM	-0.79^c	--	-0.79^c	--	--	--	--	-0.73^c	•			
%Peat_Sw	0.78^c	--	0.77^c	-0.77^c	--	--	-0.64^b	--	-0.64^b	•		
%Decid_Mw	-0.61^b	--	-0.58^a	0.56^a	--	--	0.68^c	--	--	-0.79^c	•	
%Open_Mr	-0.64^b	--	-0.62^b	0.64^b	--	--	0.61^b	--	--	-0.55^a	--	•

After Bonferroni correction, [a] $p<0.0125$ weakly significant; [b] $p<0.00625$ significant; [c] $p<0.00125$ strongly significant.

See Table I and text for definitions of acronyms.

Table III: Stepwise multiple linear regression of catchment climate, HRAs and HUs parameters on long-term median annual R

Parameter	$\sqrt{R}$
[a]$P \bullet x_1$	-0.020 (0.205)
$PET_{eco} \bullet x_2$	0.098 (0.407)
%Coarse $\bullet x_3$	0.015 (0.402)
%HM $\bullet x_4$	**-0.069 (0.001)**
%Peat_Sw $\bullet x_5$	**0.072 (0.002)**
%Decid_Mw $\bullet x_6$	0.010 (0.796)
%Open_Mr $\bullet x_7$	-0.167 (0.158)
c (Intercept)	5.053
R^2	0.83
Adjusted R^2	0.81
F-stat	40.3
p-value	<0.0001
rmse	16.84

R was transformed using square root prior to taking the 25-year median.

Bolded parameter coefficient estimates have been identified by the stepwise regression as associated with significant predictor variables

Probability values are in brackets.

The rsme was evaluated using untransformed values.

Table IV: Best model fits for significant correlations in the pairwise comparison for median annual R with median annual P, PET_{eco} and HRAs and HUs

	Equation	R^2
R =	$83.41e^{(-0.16(\%Open\_Mr))}$	0.39
R =	$-1.78\ (\%Decid\_Mw) + 109.60$	0.34
R =	$1.54\ (\%Peat\_Sw) - 17.08$	0.62
R =	$-1.32\ (\%HM) + 82.64$	0.61

Shown are best model fits regressing R with the 3 HUs and HM, based on significant spearman rank correlation (see Table II)
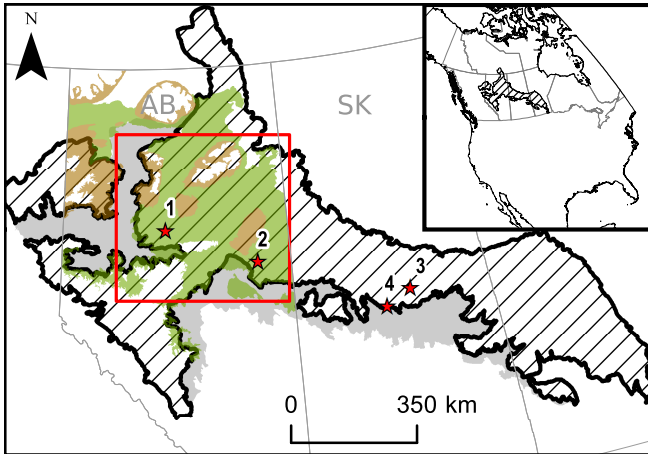
Legend

▭ (red)	Study Area
▮ (green)	Central Mixedwood (CMw)
▮ (brown)	Lower Boreal Highlands (LBH)
▨	Boreal Plain
▮ (grey)	Boreal Transitions

1. URSA
2. LLB20
3. White Gull
4. OA (BERMS)

Figure 1: The Boreal Plains ecozone of Canada (inset) and the catchment study area designated by the red square (see also Figure 2). Research locations of interest are indicated with red stars for: 1) Utikuma Region Study Area (URSA; Devito et al., 2005a), and 2) Lac La Biche (LLB20; Devito et al., 2005b) in Alberta (AB), and 3) White Gull Creek, and 4) the Old Aspen (OA) of the BERMS sites (Nijssen and Lattemaier, 2005; Barr et al., 2012) in Saskatchewan (SK). Shown is the distribution of Central Mixedwood (CMw) and Low Boreal Highlands (LBH) natural subregions for the Boreal Forest Alberta Natural Region (Natural Regions Committee, 2006) as compared to the national Boreal Plain (BP) ecozone delineation (Marshall et al. 1999). The Dry Mixedwood (DMw) natural subregion of Alberta corresponds to the Boreal Transitions and Peace Lowlands of the national delineation. The Upper and Lower Foothills Natural Regions correspond to the southwest portion of the BP
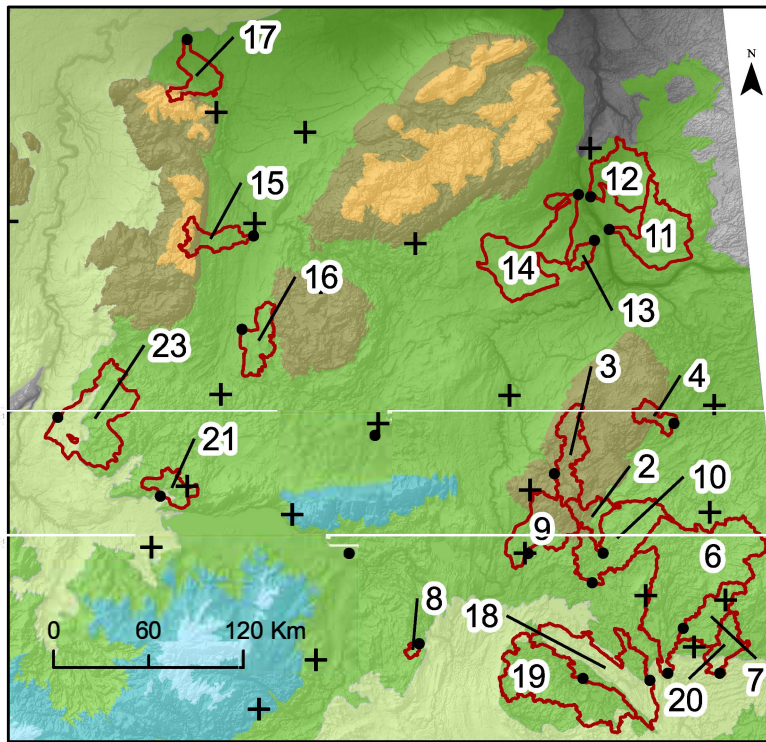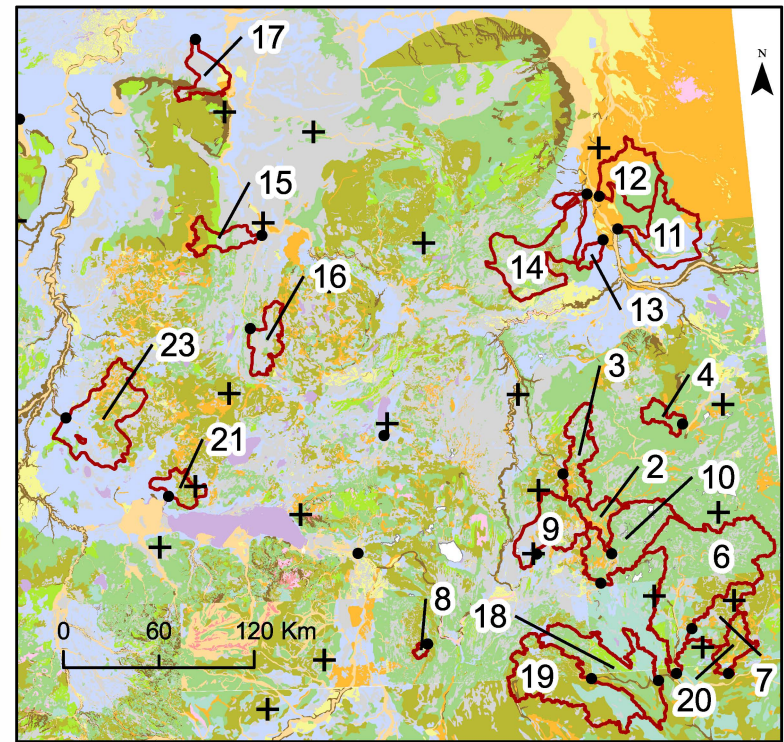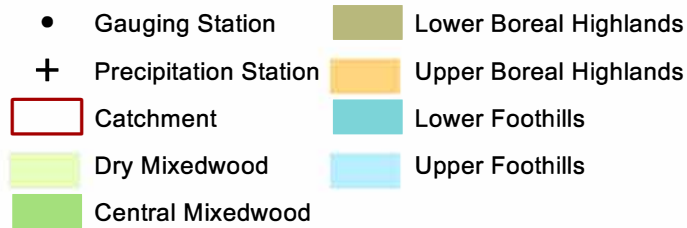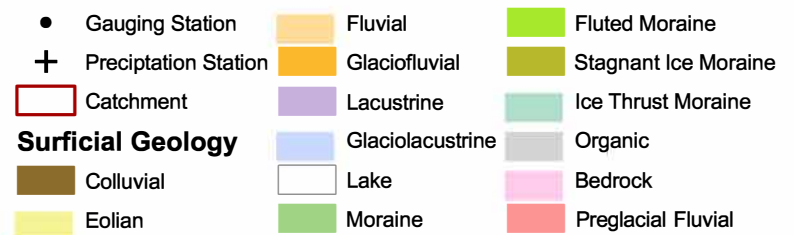
Figure 2: The distribution of the 20 study catchments showing river gaging sites, catchment boundaries and numbers (see Table I for CID#), and Sacramento precipitation gauge stations in relation to: a) the natural subregions of Alberta (NRC, 2006), and b) the surficial geology (Fenton et al., 2013) of the northern Alberta study area.
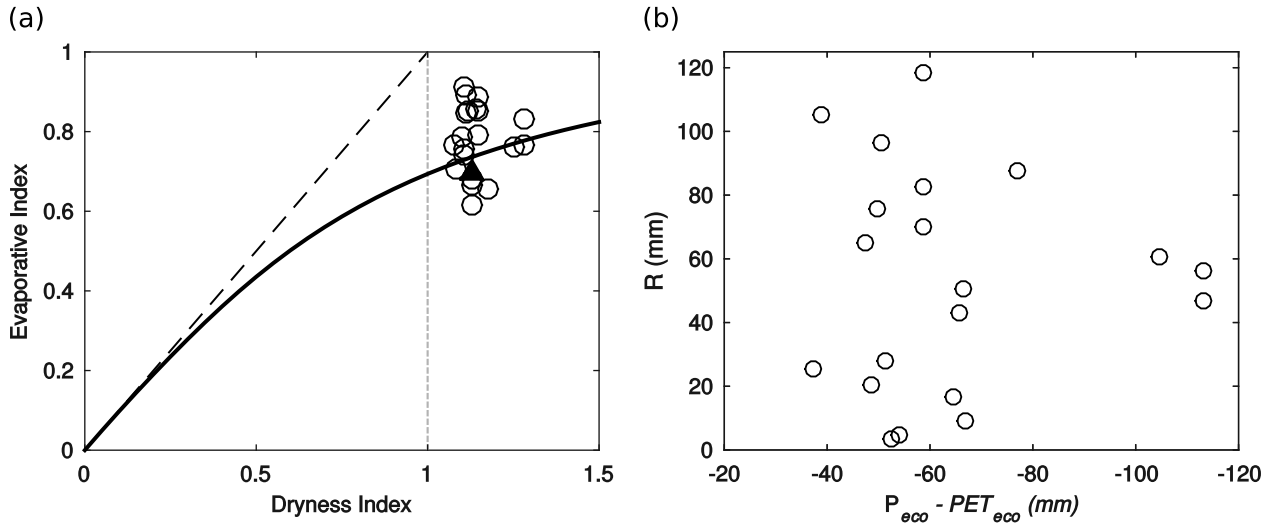
Figure 3: a) Evaporative index (AETest/Peco) vs. dryness index (PETeco/Peco) for the study catchments plotted against the Budyko curve (Budyko, 1974), and b) long-term median annual R vs. ecodistrict precipitation (Peco) minus ecodistrict potential evaporation (PETeco). See Table I for description of acronyms. White Gull catchment (see Figure 1) shown for comparison (solid triangle).
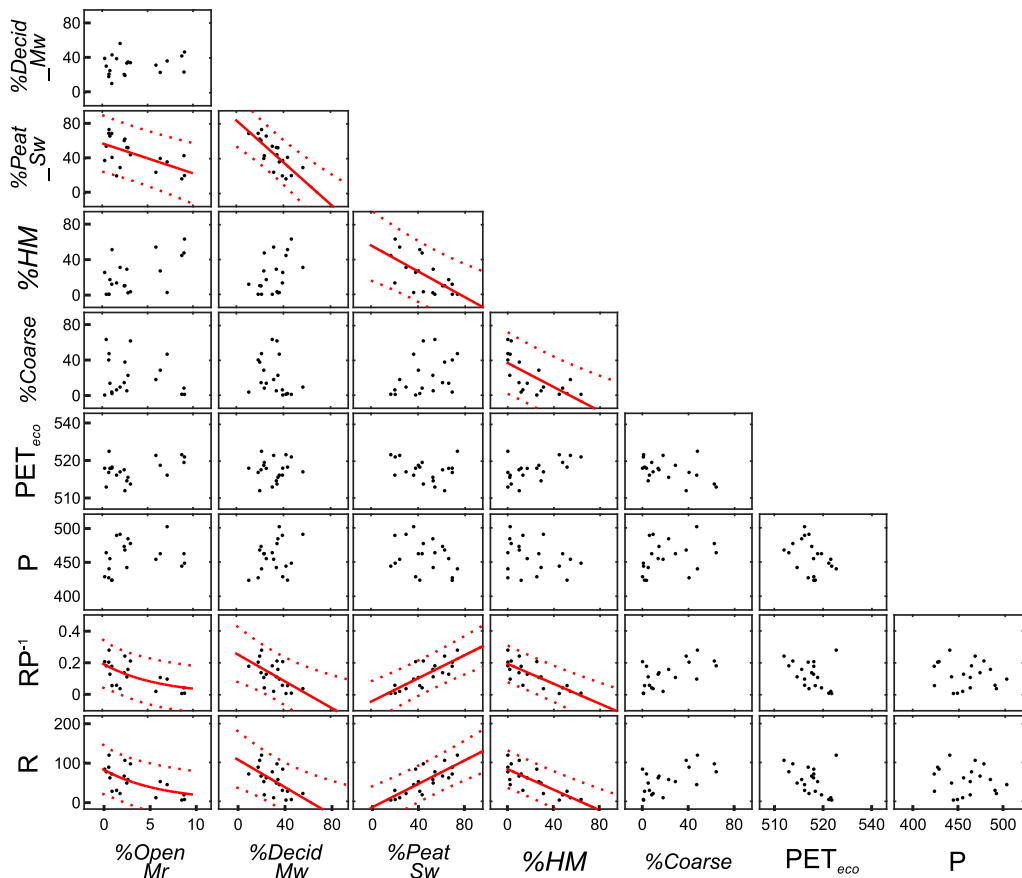
Figure 4: Pairwise comparison of median annual runoff (R mm) and efficiency (RP-1) with median annual P (mm), PETeco (mm) (Marshall et al., 1999) and selected landforms grouped into hydrologic response areas (HRA) and land-cover grouped into hydrologic units (HUs) in the study catchments. See Table I for description of acronyms. Shown are best-fits model for relationships with significant Spearman rank correlations (Table II), and with adjusted R2>0.30.
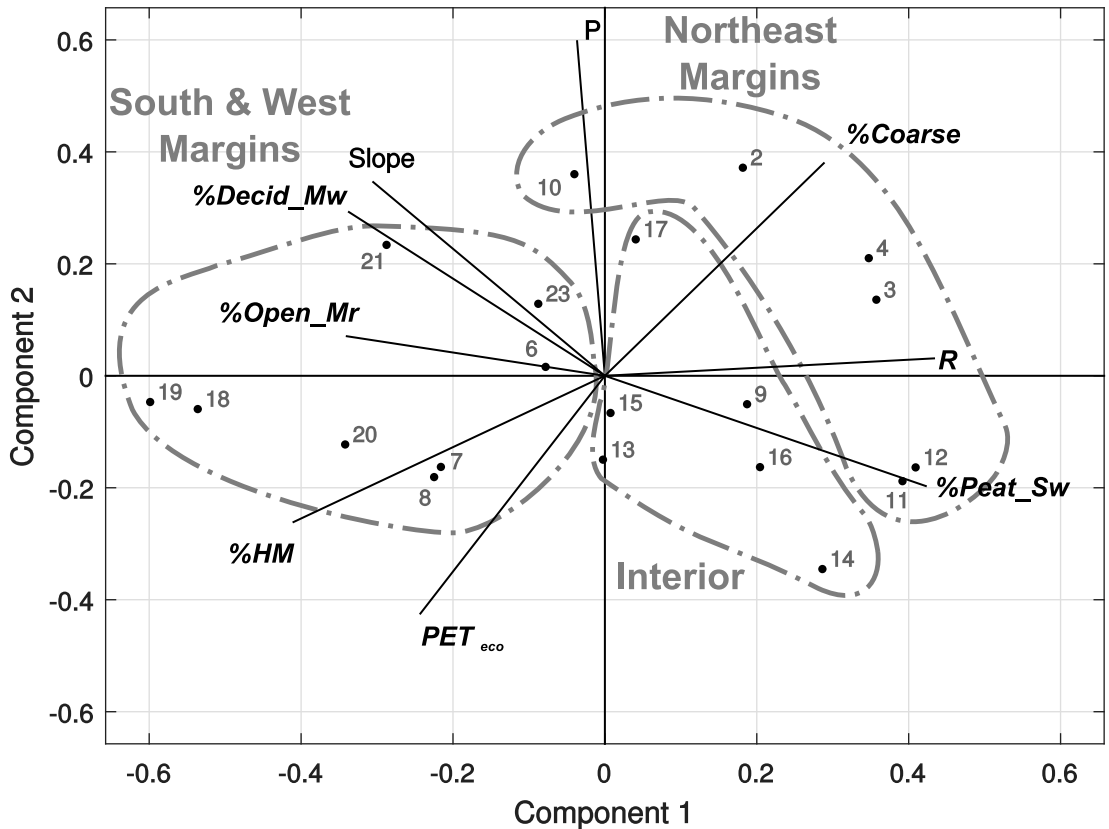
Figure 5: Plots of scaled catchment scores and arrows of loadings for the first two principal components (PC1 49% and PC2 22% of variance) for PCA of catchment R and 8 catchment indices: P, PETeco, catchment slope, %Coarse and %HM HRAs, and %Peat_Sw, %Decid_Mw, and %Open_Mr HUs. The length of their respective arrows illustrates the component loadings of the indices. Shaded areas represent groups of catchments characterized by hummocky moraine (%HM), % Decid_Mw, %Coarse, and %Peat_Sw. Dashed lines delineate regional differences in characteristics and climate for catchments located on: a) the south and western margin (deciduous mixed-wood uplands and HM), b) the interior (low-relief peatlands), and c) the northeastern margin (coarse-textured landscape and peatlands) of the CMw subregions of the Boreal Forest of Alberta. Numbers represent catchment identification numbers (CID; see Figure 2).
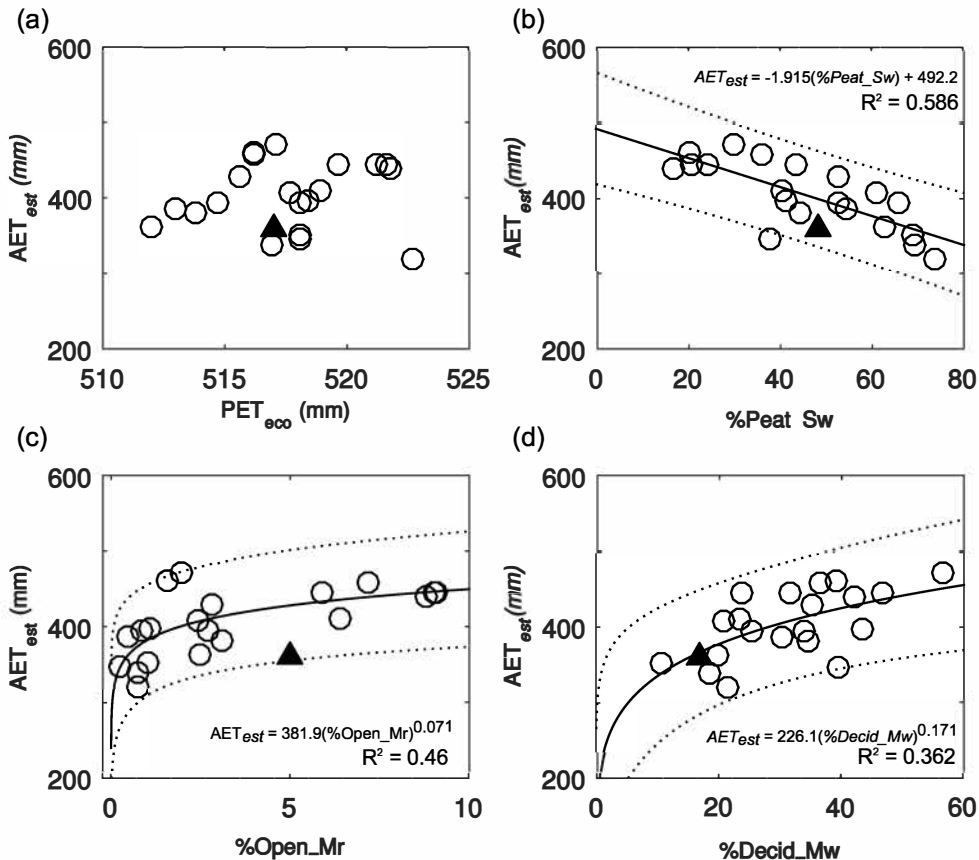
Figure 6: Pairwise comparison for long-term median annual catchment AETest (long-term catchment P − R) with catchment PETeco and proportion of land-cover HUs. See Table I for description of the acronyms. Shown are best-fits model (solid line) and 95% prediction interval (dashed lines). White Gull catchment (see Figure 1) shown for comparison (solid triangle) but was not used in the regression.