Shallow groundwater systems in sub-humid, low-relief Boreal Plain landscapes: Interactions between glacial landforms, climate, and topography

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ABSTRACT

We test the influence of the hierarchical controls of climate, glacial deposit types, and topography on recharge, storage, and shallow groundwater flow in the Boreal Plains, a low-relief, sub-humid, glaciated region experiencing unprecedented disturbances. Hydrogeological, geochemical, and isotopic data were collected from surface waters to 40m depth, along a 55km transect encompassing pond-wetland-forestland complexes across the major glacial depositional types typical of the Boreal Plains. High spatial variability of water table fluctuations and responses to climate signals illustrate the strong controls that surficial geology and topography exert over scales of groundwater flow within and between glacial landforms. Scale of flow varies from local to intermediate in the coarse outwash, and is predominately local in the fine-textured landforms. For management and monitoring applications, chemoscapes and isoscapes delineate areas with characteristic water storage and transmission properties, which control scales of flow and responses to climate.

RESUME

Nous testons l'influence des contrôles hiérarchiques - climat, types de dépôts glaciaires, topographie - sur le rechargement, stockage, et flux des eaux souterraines peu profondes des Plaines Boréales - région à faible relief, subhumide, glaciaire, subissant des perturbations inouïes. Des données hydrologiques, géochimiques et isotopiques ont été recueillies des eaux de surface à 40m de profondeur, sur un transect de 55km couvrant des complexes bassin-marais-forêt dans les dépôts glaciaires typiques des Plaines Boréales. La grande variabilité spatiale des fluctuations des nappes phréatiques et les réponses aux signaux climatiques illustrent les forts contrôles que géologie et topographie exercent sur le flux des eaux souterraines dans et entre les reliefs glaciaires. L'échelle du flux varie de local à intermédiaire dans les dépôts bruts, et se localise principalement dans les reliefs à fine texture. Les paysages chimiques et isotopiques délimitent les régions ayant des propriétés de stockage et de transmission des eaux caractéristiques.

1 INTRODUCTION

Reconciling complex spatial and temporal interactions between scales of hydrologic processes and integrating operational hierarchies at multiple scales remains a considerable challenge in hydrology and hydrogeology (Sophocleous, 2002). Although broad hierarchical frameworks for generalizing water balances of individual land units have been developed (*e.g.*, Winter, 2001), these frameworks do not adequately address the problem of cross-scale interactions to explain hydro(geo)logic variability over both time and space. Additionally, most work has emphasized runoff generation and topographically defined basin responses to precipitation (Gupta et al., 2012); there is a notable gap in research concerning coupling of variable-scale surface and subsurface hydrologic processes over time and space.

The Boreal Plains (BP), located in the Western Glaciated Plains, is characterized by pond-peatland-forestland complexes underlain by thick glacial deposits, which result in in highly complex surface water processes and groundwater (GW) flow systems with varying spatiotemporal controls (Winter, 2001). The BP exists in a sub-humid climate, where evapotranspiration (ET) often equals or exceeds precipitation (P), resulting in a delicate water balance, wet–dry climate cycles, and a propensity for vertical flow, larger than average ET demands, and large, highly variable unsaturated zone storage (Devito et al., 2005; Bothe and Abraham, 1993). In humid climates water predictably flows from topographic highs to topographic lows, and the water table (WT) mirrors surface topography (Freeze and Witherspoon; 1967). However, in the deep glaciated deposits of the BP, GW flow patterns are not solely determined by topography, but also their hydrogeological setting and climate (Meyboom, 1966; Winter, 2001). Consequently, at certain spatial scales, P, ET, and subsurface geology may have a greater control than topography over local hydrology.

Due to its wet-dry cycles, complex geology, and low relief, the BP offers an ideal setting for developing and testing hierarchical frameworks to explain surface-water/groundwater interactions at multiple scales. Additionally, the BP is experiencing unprecedented anthropogenic disturbances, in the forms of climate change, forestry, agriculture, and oil and gas operations. The spatial and temporal scales at which BP hydrological processes operate are not well understood, thus to successfully model, manage, and adapt to the ongoing disturbances, processes need to be explored at micro (*e.g.*, soil profile), small (*e.g.*, hillslope), meso (*e.g.*, glacial landform(s)), and regional (*e.g.,* groundwater divides) spatial scales, and short (*e.g.*, snowmelt, P), intermediate (*e.g.*, seasonal), and long (*e.g.*, multi-year) time scales.

Characterization of GW flow systems requires identification of the dominant spatial and temporal patterns of GW movement, and scale of GW flow (Tóth, 1963). Identifying the spatial variability of scale of GW flow yields insights regarding the source and fate of GW and the time scales governing WT behavior and GW chemical signatures, in addition to indicating the hydrologic connectivity of a given landform to its surroundings. Haitjema and Mitchell-Bruker (2005) identified the different hydrogeological conditions that would affect WT position, and thus scale of GW flow, finding that the primary controls on WT position are texture, recharge, and relief. Here, we explore the relationship between texture and relief in a generally low-recharge environment to determine the relative importance of recharge (climate) or topography at our sites.

Although regional flow systems have been defined in the BP using regional-scale topographic divides (on the order of 10^4 km^2; Tóth, 1978), smaller local flow systems within the regional systems have not been explored, and are at a scale where climate (*i.e.,* recharge) and geology could have stronger influences over GW movement compared to topography alone. While Tóthian flow is valid in humid regions or at large spatial scales where the WT mirrors topography, it may be less relevant in sub-humid regions or at smaller spatial scales.

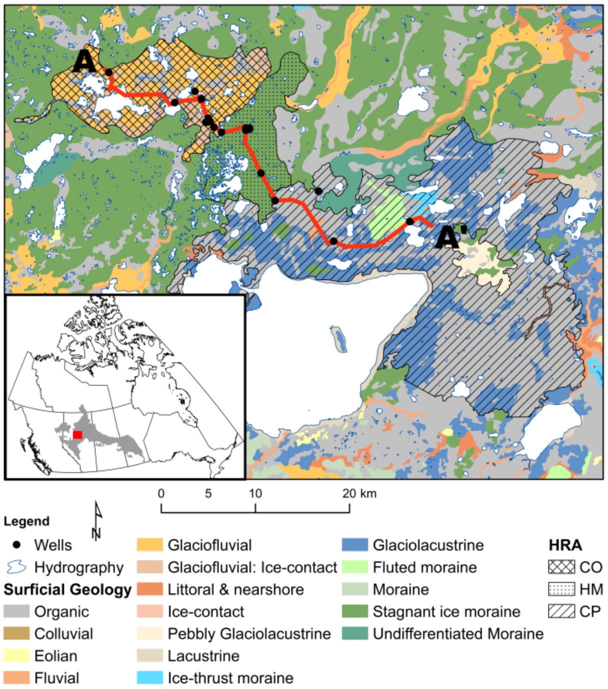


Figure 1. Utikuma Research Study Area (URSA) with surficial geology (Fenton et al., 2013), well locations, and delineated HRAs: Coarse (CO), hummocky moraine (HM), and clay plain (CP). Relative location within Canada and Boreal Plains ecozone (inset). Transect A-A' is referenced throughout the text.

Traditionally, hydrologic response units (HRU), derived from a combination of soil characteristics, land use, and topography, have been used primarily to predict runoff (*e.g.,* Arnold et al., 1998; Beven, 1979), of which there is little in the BP (Devito et al., 2017). Thus, we argue it is more suitable to use the hydrogeologic setting to delineate hydrologic response areas (HRA), which are areas with similar water transmission and storage properties, rather than solely basin topography. And while the disaggregation of the landscape into discrete sub-regions is not only helpful, but necessary in most modelling scenarios (Becker and Braun, 1999), doing so by only considering surficial characteristics and processes (*e.g.,* basin topography, soil type, vegetation, surface runoff) has limited applicability in regions with low-relief and deep substrates, such as the BP. In contrast, HRAs are areas delineated by first considering the depth and texture of the geologic substrate.

The concept of HRAs has been used to successfully explain the variation in annual runoff from large (50 to 5,000 km^2) BP catchments (Devito et al., 2017); however, they have not been fully physically characterized for shallow GW flow patterns. Specifically, there is a need to identify the dominant spatiotemporal scales of GW flow in HRAs, and the influence of topography and climate.

Here we delineate and characterize 3 HRAs that represent the main glacial depositional types typical of the BP and analyze 19 years of hydrogeological data at sites that span topographic positions to test the concept of HRAs in explaining the variability of shallow GW flow systems. We hypothesize that topography (elevation) alone cannot be used to predict WT position and that geology (texture) and climate (recharge) will have an overriding influence. To evaluate the spatial and temporal variability of shallow GW flow systems, we use four major measures: magnitude and frequency of WT fluctuation, vertical hydraulic gradients (*i.e.*, recharge vs. discharge), geochemical signatures, and water isotope ratios.

2 METHODS

2.1 Study site

The Utikuma Research Study Area (URSA; 56°N, 115°W) is located 370 km north of Edmonton, Alberta, in the BP ecozone of Canada (Figure 1, inset). The climate is sub-humid with annual potential ET (517 mm) often exceeding annual P (481 mm) (Bothe and Abraham, 1993). The region is characterized by low topographic relief, deep heterogeneous glacial substrates (45 to 240 m), that can be characterized by glaciofluvial, glaciolacustrine, and moraine deposits, all overlying the Smoky Group, a Cretaceous marine shale (Pawlowicz and Fenton, 2002). Previous research at URSA includes several multi-year ecohydrological and hydrogeological studies spanning 1998 to present (Devito et al., 2016).

2.2 Precipitation

P data were collected throughout the study period (1999 – 2017) using two to three tipping bucket rain gauges, (adapted for snowfall using reservoirs of antifreeze). Due

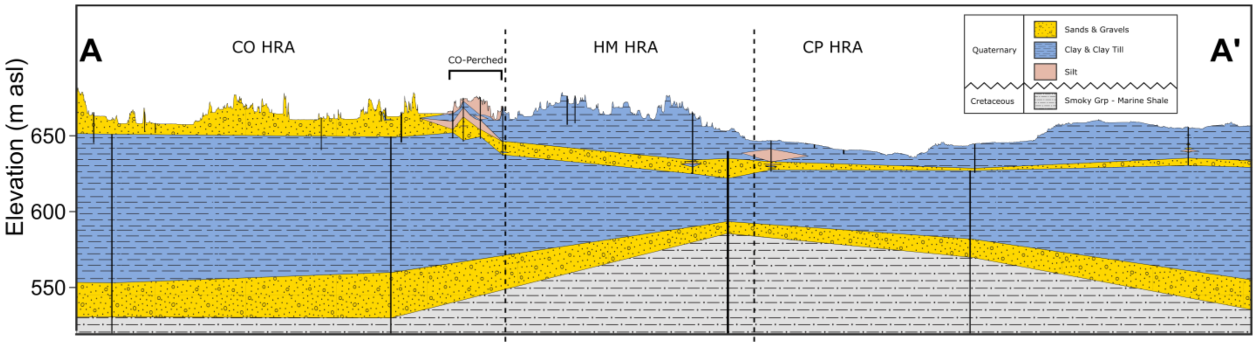


Figure 2. A generalized geologic cross section along transect A – A', showing the HRA boundaries (dashed lines) and well locations (numbers). Vertical black lines represent boreholes. Boreholes that intersect the bedrock were collected by the Alberta Research Council, who did not differentiate beyond the sand aquifers.

to the strong effect of antecedent moisture conditions on hydrologic response in the BP (Devito et al., 2005), the two year cumulative departure from the mean was calculated using the long-term mean (444 mm; 1987 to 2015) to identify wet and dry periods.

2.3 Hydrological response area (HRA) delineation

Three main HRAs were delineated at URSA based on the surficial geology and local topographic relief present: coarse (CO), clay plain (CP), and hummocky moraine (HM). The HRAs were determined from Alberta Geological Survey surficial geology mapping (Fenton et al., 2013), following Devito et al. (2017), to represent the broad spatial differences in local relief, storage, and transmission (Winter, 2001; Devito et al., 2017). Meso-scale topography was used to constrain an HRA to the study area. Isolated pockets (*i.e.,* less than 1 km wide) of different geology were incorporated into larger HRAs.

2.4 Hydrogeology

At 24 sites, a total of 24 wells (0.051 m diameter PVC) and 15 piezometers (0.025 to 0.051 m diameter PVC) were installed in mineral uplands to depths ranging from 2 m to 38 m in all three HRAs at various local and regional topographic positions. Wells were screened for the entirety of the well, and piezometers were screened only below the WT, at 0.2 to 2 m lengths. The borehole annulus was filled with a sandpack to 0.25 to 0.5 m above the screen, sealed with bentonite chips, and backfilled with cuttings. Where the substrate would collapse into the borehole, typically in saturated coarse material, wells and piezometers were driven into the native substrate. Water levels were measured at least once a year, in late July, from 1999 to 2017; most wells were monitored several times yearly.

Stratigraphy of the unconsolidated substrate was logged at each borehole, where the texture was assessed by hand. Supplementary information, including depths to bedrock and aquifers, was provided by the Alberta Geological Survey (Pawlowicz and Fenton, 2002). Vertical hydraulic gradients were calculated between the piezometer and the WT measured at 14 primary monitoring sites along the main transect (Figure 1). Horizontal saturated hydraulic conductivity (K) was estimated at 184 monitoring sites (290 total measurements). At wells and piezometers, the Hvorslev (1951) method was used; for shallow depths (<1 m below ground surface) above the WT, a Guelph Permeameter was used. Elevations and topography were obtained from LiDAR datasets.

2.5 Chemical and isotopic compositions:

Surface water and GW were sampled and analyzed for a suite of anion and cation concentrations, including: Mg+, Ca^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, CO_3^{2-}, and HCO_3^{-}. Electrical conductivity of water was measured in both the field and lab using a conductivity probe.

Additionally, surface water and GW were sampled for stable $^{18}O/^{16}O$ and D/H ratios, while P (rain and snow) was sampled throughout the study period to establish a local meteoric water line (LMWL). Results are expressed as per mil difference (‰), relative to Vienna Standard Mean Oceanic Water, or as the line-conditioned excess (lc-excess) which describes the deviation from the LMWL, a locally relevant metric (Landwehr and Coplen, 2006). Isotopic and hydrochemical analyses were performed at BASL laboratory, U. of Alberta, Edmonton.

3 RESULTS

3.1 Precipitation

Mean annual P for the 2002-2015 period was 453 mm, with the highest and lowest annual P occurring in 2007 (530 mm) and 2010 (282 mm), respectively. However, using the two year cumulative departure (2CDM) from the long term mean, 2013 was chosen as a representative 'wet' year, with a 2CDM of +22 mm, and 2003 chosen as a representative 'dry' year, with a CDM of -246 mm.

3.2 HRAs and HRA physical properties

The three main HRAs delineated at URSA (CO, HM, and CP) are shown in Figure 1. The entire elevation range at URSA is 87 m (630 to 719 m asl). The CO HRA has the largest range in elevation, while the HM and CP has slightly more limited ranges (Table 1). The average slope of both the CO and HM HRAs (0.82° and 0.74°, respectively) are significantly higher than the CP (0.32°), which is similar to the average slope of URSA (0.45°). Additionally, through

WT configurations and sediment layering, a transition zone has been identified within the CO HRA, near the border of the HM HRA, where a clay layer overlying sand perches several lakes and peatlands. This HRA is labeled 'CO-Perched' and is further explained below. The CP HRA is considerably larger than both the CO and HM HRAs, primarily due to the expansive nature of glaciolacustrine clays and their associated peatlands. Large-scale topography was used to constrain the CP HRA.

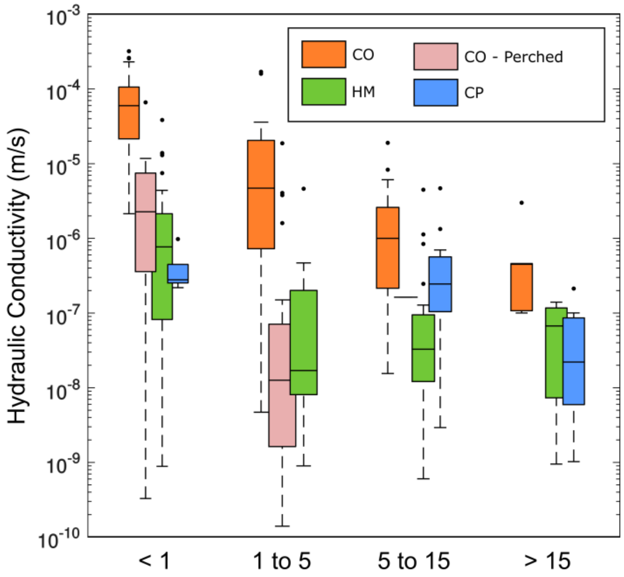
Table 1. Topographic characteristics at URSA.

		Slope (º)	Elevation (m)			Area (km^2)
		Mean	Min	Max	Range	Total
HRA	CO	0.82	656	719	63	160
	HM	0.74	642	690	48	95
	CP	0.32	630	669	39	610
All	URSA	0.45	630	719	87	865

3.3 Hydrogeology

The depth to the shale bedrock in the Northwest of URSA in the CO HRA ranges from 80 to 120 m, from 90 to 100 in the HM, and from 90 to 150 m in the CP HRA (Figure 2). The CO HRA in the NW is the start of a sand/gravel aquifer that extends below the CO-Perched and HM HRAs and tapers off under the CP. The CO HRA is predominantly sands and gravels, interbedded with small spatially discontinuous silt lenses. The CO-Perched transition lies on the eastern boundary of the CO HRA, and has a laterally unconfined WT, but is confined vertically by layers of low permeability clay overlying unsaturated coarse-textured sediments approximately 12 m above a WT in the underlying sand aquifer. Ponds and peatlands in lower topographic regions exist in the sand and gravel as discharge or flow-through systems, while the ponds and peatlands in higher topographic regions tend to be underlain with finer textured silts and clayey-silts. The HM HRA is predominantly silty hummocks underlain by clay and clay till, with small peatlands and ponds underlain with gyttja and clay. The CP consists of large expansive peatlands and ponds underlain by clay with small silty hummocks.

Field measurements show that the mineral K varies by 7 orders of magnitude across URSA, but is more tightly distributed within each HRA (Figure 3). The CO HRA has a mean K of 4.6x10^{-5} m/s, and the HM and CP HRAs have mean K values of 1.4 x10^{-6} and 4.2x10^{-7} m/s, respectively. Overall, the CO HRA has higher K, but the difference is most notable at shallow and intermediate (<5 m) depths. The CO, HM, and CO-perched HRAs all exhibit higher K values at very shallow depths (<1 m). The CP has the least variability in K, where most boreholes were exclusively lacustrine clay. At sites deeper than 1 m, K values in the HM are similar, ranging from 6.0x10^{-9} to 2.5x10^{-7} m/s (IQR), while the CO and CP K values decrease with depth. Conductivity data are sparse for deep sites (*i.e.,* in the sand aquifer below the clay confining beds) in the perched region of the CO HRA. The increase in K values in the 1 to 5 m range to the 5 to 15 m range show that K values at depth should be similar to those found in the CO HRA.



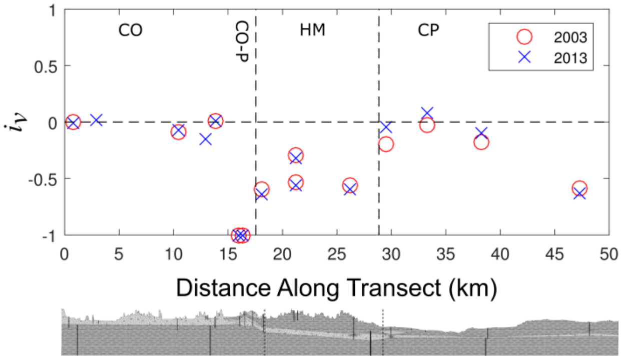


Figure 4. Vertical hydraulic gradients (i_V) along the transect A-A' (Figure 1) for the driest (2003) and wettest (2013) years during the study period, where positive values indicate an upward or discharge gradient.

Along the transect there were near negligible vertical hydraulic gradients in the CO HRA and strong recharge gradients in the HM HRA (Figure 4). In the CP HRA, near negligible to slight positive (discharge) vertical gradients were present in the 'valley' of the transect (~3500 m) trending to strongly negative (recharge) gradients on the plateau of the CP (Figure 2). The vertical gradients trended with overall regional topography and vertical distance to the upper sand aquifer. Considering both the wettest and driest years, within the CO and HM HRAs, vertical gradients did not follow the absolute elevation of the wells (R^2 = 0.55 and R^2 = 0.10, respectively), however in the CP HRA this was not the case (R^2 = 0.87). Vertical gradients in the HM and CO HRAs were not particularly sensitive to climate and did not vary between the wettest and driest years (2013 and 2003, respectively). Gradients in the CP were generally less negative in the wettest year, than in the driest year.

3.4 Long-term Water Levels

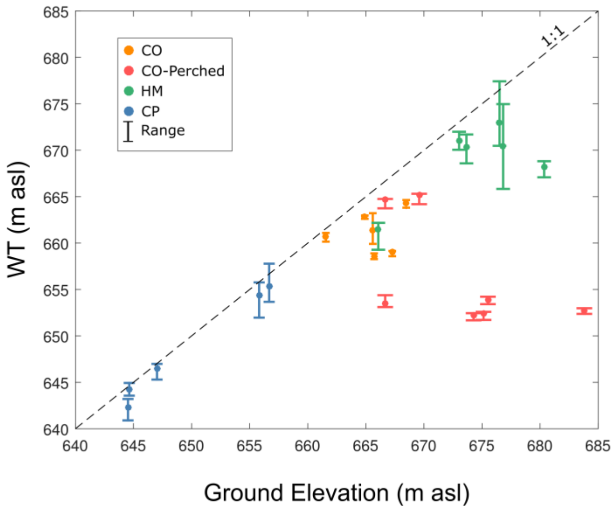


Figure 5. Long-term water table elevations measured at wells throughout the study period. Circles and bars denote median and historic range of WT elevation, respectively, at each site.

In the CO HRA, WT fluctuations varied greatly in both magnitude and frequency between sites, with some sites exhibiting highly stable water levels and others reacting strongly to inter-annual climate variability over the study period. Within the CO-Perched region, WT elevations were stable and not influenced by long-term or short-term climate. Both the HM and CP well sites showed high seasonality (*i.e.*, annual peaks) at most sites. The magnitudes of WT fluctuations over the study period showed differing patterns within each HRA (Figure 5). Within the CP HRA, the site with the largest WT fluctuation was located at the highest topographic position and sites at lower elevations had smaller fluctuations and the WT position generally followed ground surface topography (as denoted by the 1:1 line in Figure 5). This pattern was not evident at the HM or CO HRAs, where there was a strong departure from the 1:1 line and fluctuation magnitude was not related to topographic position. Two distinct WTs were evident at the CO-Perched sites. The relationships, in the case of the CP HRA, or lack thereof, in the case of CO and HM HRAs, between topographic position and WT fluctuation magnitude closely mirror trends regarding topography and vertical hydraulic gradients (Figure 4).

3.5 Chemoscapes and Isoscapes

Groundwater at all three HRAs showed the same hydrochemical facies: alkaline earths (Ca and Mg) exceed alkalis (Na and K). For the major cations (Mg+, Ca2+, Na+, K+) and anions (Cl-, SO42-,CO32- + HCO3-), there was a general pattern of concentrations: CO < CO-Perched < HM < CP. Electrical conductivity (EC) measured in the wells and ponds followed the same general trend, with CP and HM ponds and wells having generally higher EC than in the CO HRA. Across URSA ponds had lower EC values than GW. Ponds in the HM and CP ranged from 120 to 1200 µS, and from 15 to 360 µS in the CO HRA. There was no significant difference in EC between CO and CO-Perched ponds. GW EC in the HM and CP HRAs were similar and ranged from 530 to 5500 µS. GW in the CO and CO-Perched HRAs were significantly lower and ranged from 5 to 1000 and 140 to 1250 µS, respectively. Additional analysis is needed to explore the effects of climate variability on GW chemistry, and is a target for future work.

The lc-excess values at URSA (Figure 7) show that the individual evaporative signatures of both ponds and GW correlated very well with climate, with highly evaporative signatures corresponding with the driest year (2003) and vice versa.

The ponds generally showed a strong evaporative signature with a high degree of inter-annual variability. GW samples showed less inter-annual variability. In the HM and CP HRAs there was a strong separation of GW and pond signatures suggesting there is little to no hydraulic communication between the glacial substrate and neighboring ponds, and that GW primarily has an atmospheric origin with little opportunity for evaporation. This recharge signature corresponded well with vertical hydraulic gradients shown (Figure 4).

In contrast, the CO HRA had several sites that showed a mixing signature between the ponds and GW, specifically at km markers 2, 10, and 16 (Figure 7). The site at 16 km is in the CO-Perched area and warrants further investigation because it represents water in the sand aquifer overlain by low permeability clays; however the commonality at km 2 and 10 is their proximity to stagnant ice moraine geologic units. They were also the CO sites that experienced the greatest WT variability over time. The otherwise general separation of GW and pond lc-excess, and the very low hydraulic gradients in the CO, indicate that there is limited water movement between GW and surface water at URSA, or alternatively that any pond water that flows to mineral uplands is taken up by vegetation and does not affect the GW signature.

4 DISCUSSION AND CONCLUSION

4.1 The Concept of HRAs

This study illustrates the lack of correlation between topography and WT position. While there is a strong relationship between topography and WT behavior in regions of high recharge and relief, it is not a realistic assumption in low-relief, sub-humid regions like the BP. At a sedimentary basin scale, from the Rocky Mountains to the Canadian shield, there is a clear and dominant effect of topography on GW flow, where major topographic features (mountains and foothills) serve as GW recharge zones and major lowlands (Athabasca oil sands) are GW discharge zone (*c.f.*, Hitchon, 1969). URSA, and the BP as a whole, are in a generally low-relief region with thick (>100 m) unconsolidated substrates (Figure 8). While basin-scale gravity driven flow on a geologic time scale (Tóth, 1978) and hillslope scale fluxes (Smerdon et al.,2005; Thompson et al., 2015) have been simulated in the BP, no previous study has explored shallow GW systems at the meso-scale (*i.e.*, multiple pond-forestland complexes within a single regional basin). Here we show that at intermediate spatiotemporal scales, GW flow systems cannot be defined

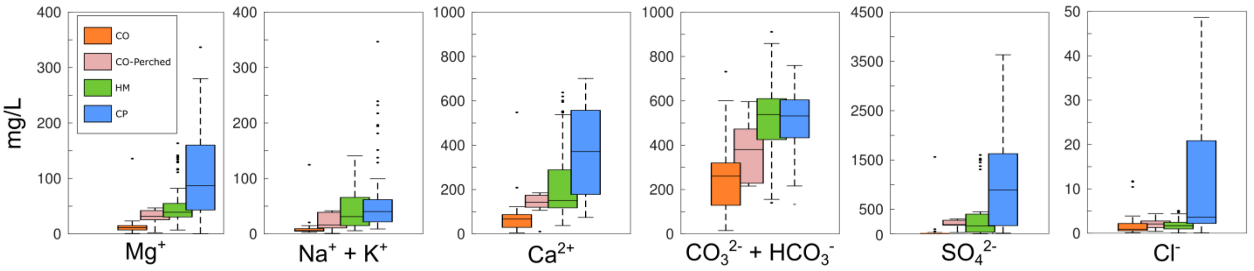


Figure 6. Boxplots of concentrations of major cations and anions in groundwater samples. Data represent samples from 2003, 2004, and 2012 - 2015.

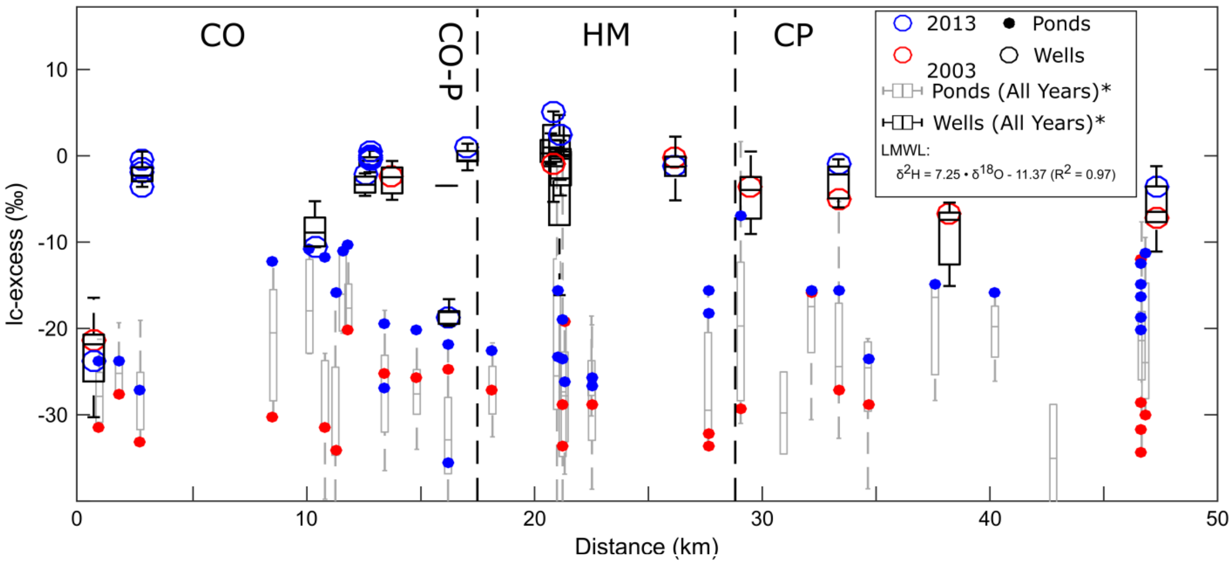


Figure 7. The line-conditioned (lc) excess of various surface and groundwater stable isotope samples taken at URSA over the study period, along the A-A' transect, with HRA boundaries shown as dashed lines. An lc-excess close to zero indicates little difference between samples and the LMWL, whereas more negative values indicate higher degrees of fractionation (evaporation). *****All-years here represent samples from 2003, 2004, and 2012 -2015. Not all sites were sampled during the wet (2013) and dry (2003) year.

by topography alone, but are defined by a hierarchy of climate, geology, and topography.

By delineating HRAs based on geologic substrate characteristics (*i.e.,* origin and texture) the physiographic characteristics within the HRA become dominant factors. When addressing URSA as a whole, the spatial variability of slope and relief was lost; however, after delineating the HRAs, distinctive patterns of topography were apparent (Table 1). HRAs do not account for regional topographical boundaries, but emphasize the importance of smaller scale relief (*e.g.*, hummocks and swales) within the HRA. The BP is an extremely low relief region, and as such, determining GW flow patterns becomes an almost impossible task (except for on a regional geologic scale) without intensive site-specific investigation. This study shows that HRAs are a useful way of discretizing the landscape into areas with predictable hydrogeologic characteristics and shallow GW flow patterns (or lack thereof) in a landscape that otherwise would be too flat and heterogeneous to use traditional methods like HRUs.

4.2 Topography vs. Recharge Controlled WTs

In the CP HRA, vertical hydraulic gradients and WT fluctuations showed that topography is the primary control over WT position and scale of GW flow, which followed surface topography very well. Sites in the higher elevations (*i.e.*, high WT fluctuations, strong recharge gradient) have more localized controls than sites at lower elevations with more stable WTs and more tempered hydrologic controls (*i.e.*, less localized controls). In the CP HRA the characteristic length of the relief is very large and therefore the effects of topography and substrate texture dominate over local scale controls like recharge, and ET (Haitjema and Mitchell-Bruker, 2005).

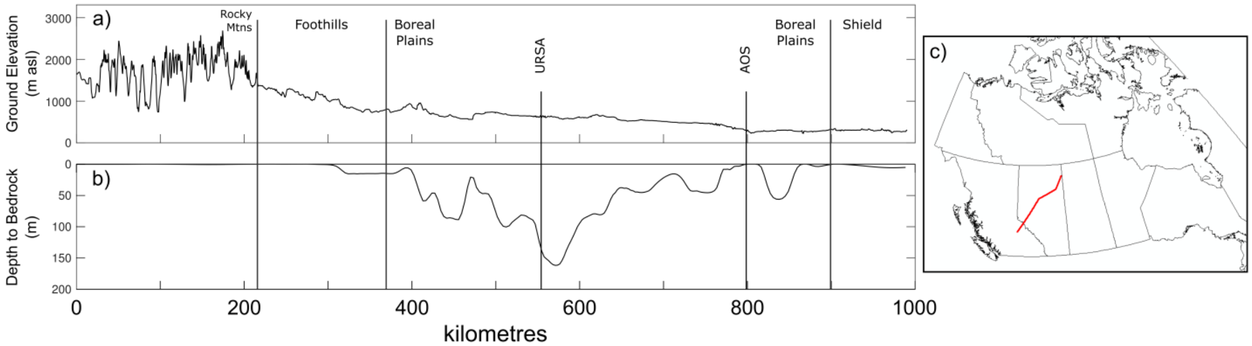


Figure 8. A regional profile showing (a) elevation and (b) depth to bedrock from the Rocky Mountains to the Canadian shield (c), where groundwater recharges in the mountains and foothills and discharges in the region of the Athabasca oil sands(AOS) (Hitchon, 1969). URSA is located in the middle of the basinal flow system in an area with deep substrates.

The HM HRA has substrates similar to those found in the CP, however they have a wider range in K and the local relief and slope were significantly higher (Table 1, Figure 2). WT position, WT fluctuation, and vertical hydraulic gradients did not follow topography (Figures 4 and 5). The site at the highest elevation in the HM HRA, had the deepest (relative to the ground surface) and most stable WT of all the HM sites. Because these sites showed WTs characteristic of locally controlled WTs, the effects of recharge and ET were the dominant controls, overwhelming the effects of local and meso-scale topography (Haitjema and Mitchell-Bruker, 2005).

The CO HRA substrates, in contrast to the CP and HM HRAs, are predominantly high K sands and gravels with little to no vertical gradient. In the CO-Perched sites, there were two clearly distinguishable WTs, in the sand aquifer and perched on the overlying silt and clay layers. Except at the lowest elevations in the CO HRA, the WT did not follow the topography and generally exhibited very small (relative to CP and HM HRAs) WT fluctuations over time (Figure 5). Because the relief in the CO is low relative to its hydraulic conductivity, the ground elevation of a hummock may belie its true topographic position in a lake dominated glacial outwash (Kratz et al., 1997). With generally flat WTs in a coarse grained setting with low recharge rates (Haitjema and Mitchell-Bruker, 2005), lake-to-lake flow, flowing through parts of the landscape, is the most probable GW flow path (Smerdon et al., 2005), and as such could be a better metric of landscape position than simply ground surface elevation alone. With this perspective in mind, a pattern becomes clear where sites located at intermediate lake elevation locations had the largest WT fluctuations and pond isotopic signatures, and sites at the lowest lake elevations had the most moderated or minimal WT fluctuations. However, isotopic data indicates that at most elevations, the flow is primarily vertical with little to no lateral hydraulic communication between landforms. The highest elevation (and therefore perched, at URSA) sites were also highly moderated due to the shallow confining layer, while the deep regional WT (under the confining layer) is regionally controlled.

4.3 Annual and Inter-annual Variability

In the sub-humid climate of the BP, the generally low recharge rates make the landscape especially sensitive to annual and inter-annual variability of climate and is a primary control over water table position and GW flow in the BP. Overall, the CO-Perched sites were least affected by multi-year climate signals, while the HM and CO were more sensitive. In the HM HRA, WT more closely followed topography during wet periods. Although CP sites showed high seasonality, they did not appear responsive to cumulative climatic wetting or drying.

4.4 Future Work and Conclusion

HRAs can be further refined by identifying hydrologic units (HU), which overlie the HRAs. HUs are defined based on their characteristic hydrologic fluxes at the surface, namely recharge and ET. The competing impacts of topography and recharge could be further complicated by highly variable ET rates from differing HUs. Future work should be directed at identifying and characterizing the various HUs (*e.g.,* open water, peatlands, forestlands). Examining whether particular HUs dampen or exacerbate the effects of HRAs as shown here, exploring seasonality of WTs and the hydrologic connectivity of various HU combinations on HRAs are valuable next steps.

It has been shown previously that the dominant fluid potential in any part of a regional basin is essentially the fluid potential at the topographic surface; in other words, flow and WT position are topographically driven. However, at the operational scale in the BP, smaller scale heterogeneity in geology and recharge can be a dominant factor over topography, notably in areas with high conductivity or hummocky terrain.

The use of HRAs to evaluate hydrogeological characteristics of the typical glacial landforms found in the BP lays the ground work for better understanding the effects of disturbance and the hydrologic function of both undisturbed and reclaimed landscapes. In the midst of unprecedented development there is an urgent need for hydrogeologically predictable and operable constructed landscapes, which will be composed of native glacial materials. The results presented here suggest that managers need to consider complex interactions of topography, recharge, and texture when planning these disturbed and constructed landscapes.

5 ACKNOWLEDGEMENTS

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