University of Birmingham
Research at Birmingham

Diverse response of shallow lake water levels to decadal weather patterns in a heterogeneous glacial Boreal Plains landscape

Leader, Sam; Kettridge, Nicholas; Hannah, David; Mendoza, C.; Devito, K. J.

DOI:
10.1002/hyp.15125

License:
Creative Commons: Attribution (CC BY)

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Leader, S, Kettridge, N, Hannah, D, Mendoza, C & Devito, KJ 2024, 'Diverse response of shallow lake water levels to decadal weather patterns in a heterogeneous glacial Boreal Plains landscape', *Hydrological Processes*, vol. 38, no. 4, e15125. https://doi.org/10.1002/hyp.15125

Link to publication on Research at Birmingham portal

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of ‘fair dealing’ under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 07. May. 2024

Received: 18 October 2023 | Revised: 1 March 2024 | Accepted: 5 March 2024

DOI: 10.1002/hyp.15125

RESEARCH ARTICLE

WILEY

Diverse response of shallow lake water levels to decadal weather patterns in a heterogeneous glacial Boreal Plains landscape

S. Leader[1] | **N. Kettridge**[1,2] | **D. Hannah**[1] | **C. Mendoza**[3] | **K. J. Devito**[2,4]

[1]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

[2]Department of Biological Sciences, University of Alberta, Edmonton, Alberta, Canada

[3]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

[4]Canadian Rivers Institute, University of New Brunswick, Fredericton, New Brunswick, Canada

Correspondence

S. Leader, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
Email: samantha.n.leader@gmail.com

K. J. Devito, Department of Biological Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada.
Email: kdevito@ualberta.ca

Funding information

Natural Sciences and Engineering Research Council of Canada, Grant/Award Numbers: CRD238050-00, CRDPJ337273-06, CRDPJ477235-14; Natural Environment Research Council

Abstract

To examine the relative controls of landscape and climate on spatial variability, we measured water level dynamics of shallow lakes over two decades that represent both the heterogeneity of surficial geology classifications, and thus the potential range in surface and groundwater connectivity, and the long-term weather patterns of the Boreal Plain hydrogeoclimatic setting. Large ranges in shallow lakes water levels (between 0.25 and 2 m) were observed corresponding to extremes in precipitation relative to the long-term mean precipitation over the study period. We found low concurrence in water level dynamics among four detailed study lakes that received the same meteorological weather signal, but were located in different surficial geology texture classifications that incorporated important landscape parameters associated with lake water balance and storage. Surficial geology classification alone did not, however, distinguish between different ranges in lake water level measured in a broader synoptic survey of 26 lakes across the region. Thus, simple surficial geology classifications cannot alone be applied to classify Boreal Plain lake water level dynamics and other controls, notably landscape position, must also be considered. We further show that inter-annual variability in lake water levels was significantly greater than seasonal variability in this hydrogeoclimatic setting. This emphasizes the need for studies of sufficient length to capture weather extremes that include periods of wetting and drying, and demonstrates how observed magnitudes of water level variability, and lake function, can be an artefact of study length and initiation date. These findings provide a foundation to test and calibrate conceptual understanding of the wider controls of lake water levels to form holistic frameworks to mitigate ecological and societal impacts due to hydrological changes under climate and anthropogenic disturbance within and between hydrogeoclimatic settings.

KEYWORDS

glacial lakes, inter-annual variability, lake–landscape interaction, sampling bias, surficial geology, water-level dynamics

1 | INTRODUCTION

The timing and amplitude of lake water level fluctuations (WLFs) affect the physical, chemical, and biological processes that are integral to lake structure, function, and ecosystem services (Bayley & Prather, 2003; Fergus et al., 2022). Lakes occur abundantly in belts across mid-latitudes and the boreal, largely associated with recent glacial activity (Hutchinson, 1957). The hydro-geoclimatic setting varies tremendously across these latitudes, which also coincide with regions experiencing greater non-stationary climatic forcings (Stralberg et al., 2020; Tetzlaff et al., 2013). Natural spatiotemporal patterns in lake hydrology and WLF, and thus lake function, vary among lake types and hydro-geoclimatic settings, and are influenced by multiple anthropogenic factors (Fergus et al., 2022; Kraemer et al., 2020). Lake hydrology studies that capture regional differences in climate, geology, and topography across spatial and temporal scales are needed for developing conceptual frameworks (Buttle, 2006; Devito, Creed, & Fraser, 2005; Devito, Creed, Gan, et al., 2005; Fergus et al., 2021; Winter, 2001) to improve our understanding and prediction of natural ranges in lake hydrology and WLF and disentangle the relative influence of land-use and climate change on ecosystem function.

Development of lake hydrology frameworks requires hydrometric datasets that encompass natural WLF from seasonal, inter-annual, and interdecadal scales (Fergus et al., 2021; Molinos et al., 2015; Watras et al., 2022), and span diverse lake types and hydrogeologic settings to identify spatio-temporal variability in shallow lake WLF patterns (Winter, 2000). Studies with this breadth in both temporal and spatial observations are generally lacking (but see Fergus et al., 2022; Perales et al., 2020). High spatio-temporal resolution lake studies often concentrate on water quality metrics (Gibson et al., 2016), isotopes (Gibson et al., 2019), or remote-sensed data (Sass et al., 2007), rather than hydrometric field observations of WLF and lake function. Contrastingly, whilst some long-term, regional and global studies include diverse hydrogeologic settings (Ali et al., 2015; Carey et al., 2010; Tetzlaff et al., 2017), they are largely in disparate hydro-geographical regions and receive different weather patterns (Winter, 2000). Given the first-order importance of climate on hydrologic setting (Fergus et al., 2022), it is extremely challenging to unravel landscape controls from climatic controls within such data. Regionalization approaches and frameworks require characterization of spatial patterns in lake water dynamics concurrent with similar long-term weather patterns to most effectively predict and mitigate ecological and societal impacts of hydrological changes in lakes.

The Boreal Plains (BP) of Canada is characterized by sub-humid continental climate, low relief, glaciated hydro-geoclimatic setting, with abundant shallow lakes and lake-wetland complexes forming within irregularities in thick glacial deposits (Hokanson et al., 2021; Winter, 2000). Shallow lakes of the BP, as elsewhere, act as ecological, biodiversity, and biogeochemical hotspots (Bayley & Prather, 2003; Cheng & Basu, 2017; Pugh et al., 2021) and provide some of the world's richest bird communities (Morissette et al., 2018). The ecosystem function of shallow lakes is sensitive to WLF due to shallow depth and storage (Kolding & van Zwieten, 2012), which is compounded in the drier climate, where lakes exist in a fine balance between precipitation (P) and evaporation (PET), with large evaporative demands on lake water balances (Plach et al., 2016). The resilience of shallow lakes on the BP have been linked to stability of water levels (WLs), inferred from WLF amplitude (Cobbaert et al., 2014; Scheffer et al., 2001). Meanwhile, the threat of climatic warming to ecosystem health (Laudon et al., 2017; Price et al., 2013) is of importance in the BP, where industrial activities and resource extraction are heavily modifying the landscape at unprecedented scales (Webster et al., 2015).

The weather patterns in the BP are characterized by multi-year wet and dry cycles (Hokanson et al., 2019; Mwale et al., 2009). Additionally, BP lake basins overlay, and their catchments reside in, spatially heterogeneous thick glacial surficial deposits, with significant differences in transmission properties, which result in variable surface and groundwater processes and contributions from catchments to lake water balances (Devito et al., 2023; Hokanson et al., 2019; Winter, 2000) and, thus, spatial and temporal patterns in lake WLF, function, and resilience. Subsequently, during extended dry periods some isolated lakes dry out with exposed sediments, whereas other shallow lakes in relatively close proximity remain inundated (Smerdon et al., 2005; Thompson et al., 2015).

The potential for ecosystem-specific responses to the large inter-annual variability in precipitation and evaporation and subsequent variability in shallow lake water budgets observed on the BP (Devito et al., 2012; Ireson et al., 2015) pose challenges in predicting and disentangling the relative role of natural variation and impacts due to climate change or land-use. Moreover, the length of monitoring period may be important in assessing lake function, as patterns in lake WLF may differ when comparing short and long periods (Devito et al., 2023; Perales et al., 2020) as differences in climate forcings and lake basin and catchments characteristics interact and produce temporally variable lake water balances (Fergus et al., 2022; Hokanson et al., 2021). For example, in boreal shield hydrogeoclimatic settings, the humid climate and low upland soil storage of lake catchments results in predictable and large lake water inputs, and inter-annual variations in WLF amplitude that result from the sum of regular seasonal water balances superimposed on long-term climate signals (Soulsby et al., 2016). In contrast, due to the close balance of P and PET in the sub-humid boreal, small changes in inter-annual differences in P can shift regional moisture conditions to surplus or deficit, influencing the magnitude and threshold responses of lake inputs from the catchment, which result in large inter-annual variations in lake stage (Ferone & Devito, 2004; Smerdon et al., 2005; Winter, 2000). Thus, short- and long-term patterns in P and surface or groundwater inputs become critical fluxes in maintaining lake WLs and permanence during drought periods (Thompson et al., 2017; Winter, 2000). Further, weather patterns of P inputs interacting with lake catchments that have different glacial landform coverage can result in differences in long-term magnitude and threshold response of catchment runoff, such that the timing and amplitude of lake WLFs may differ both temporal and spatially (Devito et al., 2023; Figure 1). Although spatially contrasting amplitudes in WLF have been observed in BP lake in

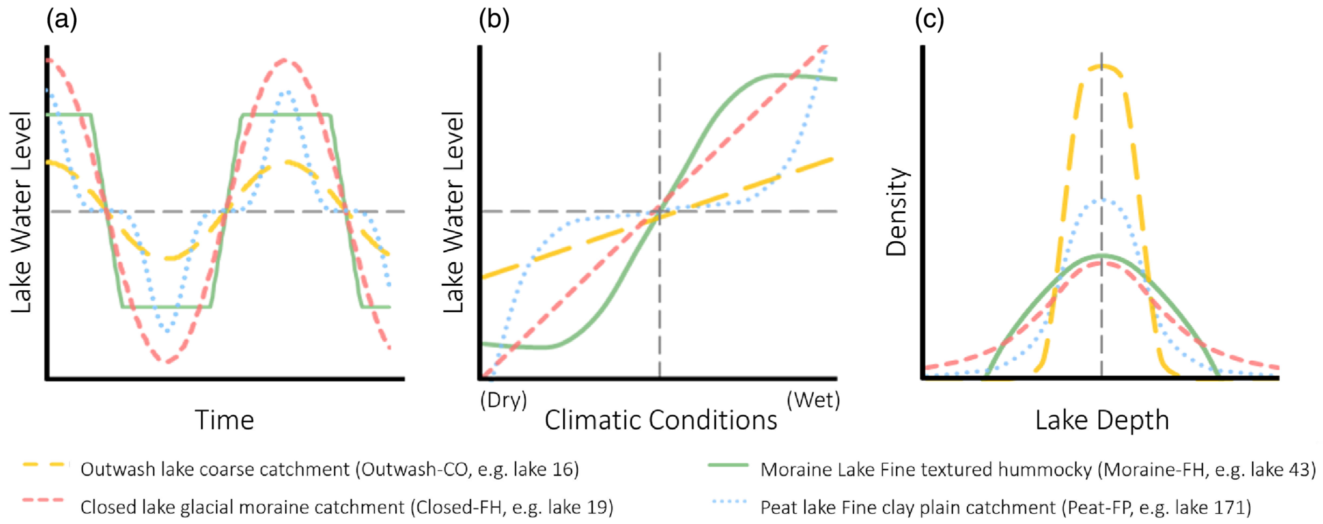

FIGURE 1 Hypotheses of (a) time series of lake water levels across decadal scale weather patterns; (b) lake water level response to long-term climatic gradient and; (c) subsequent distribution of lake water levels (assuming normally distributed weather patterns) for different glacial lake and catchment types. Hypotheses are founded upon extensive hydrogeologic research within the Boreal Plains to test the concept of hydrologic response areas or landscape units of homogenous hydraulic properties, applied to Boreal Plains lakes (Devito et al., 2012, 2016).

relation to catchment characteristics (Cobbaert et al., 2015; Plach et al., 2016), the question remains whether the full amplitude of WLF was observed because these studies were not sufficiently long to capture the full regional weather cycles and amplitude of WLF when comparing different glacial lake types within different surficial geologies.

Although the influence of interactions between climate and surficial geology on groundwater and surface water interaction is potentially large (Devito et al., 2023; Hokanson et al., 2019; Ireson et al., 2015) such interactions are not well documented for BP lake ecosystems despite the eco-region supporting a diversity of lake types and apparent eco-hydrological functionalities (Ireson et al., 2015). The importance of surficial geology on groundwater–surface water interactions and hydrologic connectivity has been shown in the BP (Ferone & Devito, 2004; Smerdon et al., 2005) and has given rise to the concept of hydrologic response areas (HRAs) or landscape units of homogenous hydraulic properties (Devito et al., 2017, 2023; Hokanson et al., 2019), which can be applied to lakes (Olefeldt et al., 2013; Plach et al., 2016). In Figure 1, we present hypotheses of climate–lake hydrological relationships for a range of lake types (Hutchinson, 1957) and catchment types as defined by the dominant HRA (Hokanson et al., 2019) in response to short- and long-term weather patterns typical of the BP to (1) aid in deciphering causes of lake hydrologic variation and separate multiple drivers that affect such lake hydrologic characteristics, and; (2) determine how HRAs, informed by surficial geology, may be utilized to regionalize lake hydrology and function. We first test if over the long term the total WLF amplitudes and impact on lake function and ecosystems may be similar across glacial lake and catchment HRA types in the BP. Closed glacial lakes with catchments dominated with fine textured and hummocky terrain that produce limited runoff would be expected to mimic the balance of P and PET with linear relationships between dry and wet cycles (van der Kamp et al., 2008). Alternatively in other lake-catchment settings, storage-driven thresholds and non-linear processes governing lake-catchment connectivity to the landscape may moderate or increase the magnitude of WLF (Figure 1a,c; Devito et al., 2023; Spence, 2010), with more complex and diverse non-linear relationships to weather patterns typical of the BP (hockey stick, step or sigmoid functions; Ali et al., 2013; Figure 1b).

The role of groundwater supply from coarse-textured terrain to glacial outwash lakes has been shown to influence water balances and potentially moderate lake WLF in the BP (Gibson et al., 2016; Hokanson et al., 2021; Figure 1) and other glacial outwash landscapes (Rosenberry et al., 2015; Winter et al., 2003). In glacial peat lakes, internal negative feedback mechanisms and peat hydraulic properties promote surface saturation and runoff from peatlands (Devito et al., 2023) and increased peatland connectivity to lakes may moderate WLF over the short term. Conversely, across decadal scales WLF responses may be magnified in lakes highly connected to peatland as high runoff from saturated peat will occur during extreme wet periods. This contrasts with high water holding capacity and cessation of baseflow from peatlands during prolonged drought conditions (Devito et al., 2023; Figure 1). Moraine lakes also differ in hydrologic function and WLF have been shown to respond strongly to climate due to threshold runoff responses from adjacent deciduous forests (Devito, Creed, Gan, et al., 2005; Thompson et al., 2015). However, the occurrence of both lake desiccation and outflow generation in shallow spilling moraine lakes is expected to constrain the amplitude of WLF relative to other lakes in the BP across long-term observations (Figure 1). This could be critically omitted if study periods do not span full meteorological cycles.

We utilize research at the Utikuma Region Study Area (URSA; Devito et al., 2016), an ideal location to study the interaction of landscape characteristics and weather patterns on lake WLF of the BP due to the diversity of glacial lake types that receive the same decadal meteorological signal. Herein, the overall objective was to understand the range and controls of spatio-temporal variability in lake hydrologic behaviour and function, and to determine how HRAs may be utilized to characterize lake basin and catchment hydrology to inform frameworks for regionalization of lake hydrology and WLF typical of the BP (Figure 1). The long-term lake studies were concurrent with hydrogeologic studies of the region (e.g., Hokanson et al., 2019) and specific lake catchments (e.g., Smerdon et al., 2007; Thompson et al., 2015) at URSA which represent variations in HRAs, as informed by geology, landcover, relief and landscape position, common to the sub-humid BP (Devito et al., 2016, 2023). We quantified the WLF response in 26 shallow lakes at URSA, which contrast in glacial lake types and catchment characteristics and location within HRAs, and received the same intra-annual (seasonal) and long-term inter-annual meteorological signal over 20 years (see Table 1). First, we conducted regional analyses to (1) determine if HRAs (surficial geology units) incorporate hypothesised topological and hydrological parameters that influence lake WLF. Second, we analysed high-frequency hydrometric monitoring of four lakes, representing the dominant lake-catchment HRA type to (2) characterize the spatial variability in amplitude and timing of WLF in response to seasonal and long-term weather patterns associated with different lake-catchment HRAs, and (3) examine the relative magnitudes of seasonal versus inter-annual variation in WLF and how initiation and length of sample period may impact comparative estimates. Finally, we analysed mid-summer maximum WL of 26 lakes during two 6- and 7-year periods to (4) assess the spatial variability of lake WL response within the HRAs to similar inter-annual variation in weather patterns. This characterization of shallow lake WLF will provide critical insights required for the classification and regionalization of lake functionality and developing frameworks to aid conceptualization of potential impacts of climate and anthropogenic disturbance on shallow lakes and their ecosystem health, habitat quality, and ecosystem services.

2 | DATA AND METHODS

2.1 | Study site

This study was conducted in the URSA (56° N, 115° W), within the Mid-Boreal Uplands ecoregion of the BP ecozone (Figure 2). The climate is continental, sub-humid with long-term annual average PET (517 mm) exceeding long-term annual average precipitation (483 mm), with >50% of annual precipitation falling in summer, June to August (Devito et al., 2016). Across the BP, inter-annual variability in precipitation results in multi-year oscillations of drying or wetting and significant increases or reductions in lake water depth and volume (i.e., Devito et al., 2023; Hokanson et al., 2019; Mwale et al., 2009; see also Section 1).

The region has low relief (<80 m) with deep (45–240 m) quaternary glacial deposits overlaying shale bedrock that limit regional groundwater interactions with lakes (Hokanson et al., 2019). The regional surficial geology varies spatially with roughly equal coverage of coarse-textured (CO) glacial–fluvial outwash, disintegration moraines with hummocky morphology and clay-silt rich substrates (FH) and clay-rich substrates of thrust moraines and glacio-lacustrine plains (FP) with many areas on the FP dominated with >1 m organic (peat) soils (Figure 2). The surficial geology has been categorized into three primary classes of HRAs representing broad similarities in local relief, water storage and transmission characteristics (Devito et al., 2012, 2016; Hokanson et al., 2019). Further description of HRA definitions, landforms, landcover, land use, runoff characteristics, and hydrogeology of the USRA are provided in Section 1.1.2.

The region has numerous shallow (0.5–5 m), naturally meso to eutrophic, cold polymictic lakes that vary in size, and cover ~10% of the landscape. Twenty-six study lakes were selected to cover the four main glacial lake origin types (Hutchinson, 1957; Figure 1), with roughly equal coverage across the three HRAs (Figure 2). The study lakes deliberately vary in landscape position, and potential groundwater and surface water interactions among and within lake types (Tables 1 and 2). See Section 1.2 for further description of the study lake basin morphometry and lake basin HRA and catchment characteristics.

2.2 | Methods

2.2.1 | Experimental design and sampling strategy

The experimental design tests for fundamental differences in lake hydrologic behaviour based on key hypothesised controls on catchment hydrological function within the thick low-relief glacial deposits and sub-humid climate of the BP (Figure 1) (Buttle et al., 2005; Devito et al., 2016; Devito, Creed, & Fraser, 2005; Devito, Creed, Gan, et al., 2005; Hokanson et al., 2019). This study was conducted over approximately two decades (1999–2018) to capture multi-year oscillations of wetting and drying that result in large ranges in lake water depths and volumes, typically observed on the BP (i.e., Devito et al., 2023). Lake hydrometrics were collected simultaneously for 26 study lakes selected strategically to represent the diversity in surficial geology, land cover, topography, lake geometry and lake types observed within the URSA and the BPs, (Table 1; see Table 2 and Figures S2 and S3 for sampling design and frequency) whilst receiving the same meteorological signal.

A regional analysis (i.e., Principal Component Analysis [PCAs], Figure 4) was conducted to assess the ability of HRAs (surficial geology) to incorporate hypothesised physiographic variables of basin geology and morphometry and catchment characteristics (Objective 1). Further to group lakes in order to test the influence of the dominant lake-catchment HRA type on potential spatial differences in hydrologic connectivity, water balance, and resulting WLF behaviour of the lakes as stated in Objective 2 (Fergus et al., 2022; Hokanson et al., 2021). The regional analysis was also used to determine the representativeness in lake morphometry and catchment characteristics of four detailed study shallow lakes compared with the remaining

TABLE 1 Lake-catchment classification and corresponding basin and catchment characteristics.

			Basin characteristics				Basin location		Topographic catchment characteristics							
Lake ID	Lake–catchment class	Glacial Lake type[a]	Area (ha)	P:A ratio × 100	Sill height (m)	Outflow[b]	Basin HRA[c]	Relative elevation (%)	Area (ha)	Slope (%)	Relief	Roughness	FH %	CO %	Dominant HRA	Wetland %
1	Outwash–CO	Outwash	11.2	2.78	2.5	Flow Thr	CO	22.5	1591	1.37	3.20	2.26	14	87	CO	70
5	Outwash–CO	Outwash	325	0.44	3.3	Flow Thr	CO	5.0	9056	2.08	3.97	2.28	26	75	CO	57
16[d]	Outwash–CO	Outwash	46.6	0.66	2.0	Flow Thr	CO	8.4	185	2.09	3.51	2.24	0	100	CO	34
17	Outwash–CO	Outwash	106	0.66	5.5	Spill[e]	CO	25.1	472	2.62	3.72	2.27	0	100	CO	35
201	Outwash–CO	Outwash	38.2	0.67	2.8	Flow Thr	CO	26.9	72.1	1.11	2.37	2.25	0	100	CO	23
206	Outwash–CO	Outwash	13.7	1.72	3.0	Flow Thr	CO	50.9	183	3.44	3.27	2.37	41	59	CO-FH	35
208	Outwash–CO	Outwash	3.7	1.95	1.5	Spill[e]	CO	26.9	17.9	2.98	2.57	2.19	0	100	CO	61
7	Closed–FH	Closed–perched	2.9	2.66	3.4	Closed	FH-CO[f]	69.2	63.2	4.08	3.74	2.20	35	76	CO-FH	1
11	Closed–FH	Closed–perched	1.1	3.5	2.5	Closed	FH-CO[f]	73.3	13.0	1.01	2.59	2.41	87	13	CO-FH	1
15	Closed–FH	Closed–perched	0.05	19.2	4.5	Closed	FH-CO[f]	77.2	7.8	2.45	2.67	2.24	0	100	CO	1
19[d]	Closed–FH	Closed–perched	3.7	2.19	4.7	Closed	FH-CO[f]	42.7	29.5	3.86	3.19	2.03	0	100	CO	11
27	Moraine–FH	Moraine	6.8	1.81	1.4	Spill	FH	85.0	43.7	1.90	2.64	2.26	68	32	FH	43
39	Moraine–FH	Moraine	6.4	1.38	2.5	Spill	FH	82.2	276	2.23	3.14	2.25	100	0	FH	44
40	Moraine–FH	Moraine	0.77	4.41	1.0	Spill	FH	94.8	8.2	3.42	2.27	2.18	100	0	FH	54
42	Moraine–FH	Moraine	1.4	3.46	2.3	Spill	FH	89.2	30.3	2.90	2.71	2.16	100	0	FH	32
43[d]	Moraine–FH	Moraine	1.3	4.88	0.8	Spill	FH	96.4	27.4	2.64	2.89	2.27	100	0	FH	29
48	Moraine–FH	Moraine	5.0	2.72	1.2	Spill	FH	97.0	79.8	3.00	3.17	2.24	100	0	FH	28
111	Moraine–FH	Moraine	5.9	2.16	2.0	Spill	FH	95.6	46.4	1.41	2.25	2.15	100	0	FH	37
59	Peat–FH	Peat[g]	24.1	0.94	2.2	Flow Thr	FP	72.3	167	1.17	2.33	2.09	38	0	FH	57
112	Peat–FH	Peat[g]	4.9	2.32	1.6	Flow Thr	FP	61.9	605	1.70	3.48	2.17	91	0	FH	45
118	Peat–FH	Peat[g]	9.1	1.39	1.6	Flow Thr	FP	55.6	44.5	1.22	1.93	2.10	55	0	FH	61
122	Peat–FH	Peat[g]	9.2	1.34	1.6	Flow Thr	FP	43.7	37.4	1.08	1.91	2.00	58	0	FH	39
121	Peat–FP	Peat[g]	8.7	1.23	1.5	Flow Thr	FP	38.8	56.3	0.88	1.26	2.05	0	0	FP	86
168	Peat–FP	Peat[g]	13.5	1.12	1.6	Flow Thr	FP	62.3	1849	0.62	2.93	2.05	1	0	FP	73
171[d]	Peat–FP	Peat[g]	10.8	1.15	1.0	Flow Thr	FP	62.3	82.3	0.71	1.68	2.02	0	0	FP	78
205	Peat–FP	Peat[g]	20.5	0.81	1.3	Flow Thr	FP	81.8	267	0.83	2.66	2.07	1	0	FP	61

Abbreviation: HRA, of hydrologic response area.

[a] Modified from Hutchinson (1957) glacial lake origin classification.

[b] Outflows coded ordinally as closed = 1, spill = 2, flow through = 3.

[c] Basin HRA included in PCA as Coarse Basin (1 or 0).

[d] Detailed sampling lake, high frequency of sampling.

[e] Spills through coarse grain berm.

[f] FH-CO, veneer of fine-textured deposits transitioning over glacio-fluvial outwash deposits, lakes are perched above outwash deposits (Hokanson et al., 2019, 2021).

[g] Peat lake type – organic sediments surround the entire lake shore, at least 25% of the perimeter has riparian peatland extending 100 m or more.

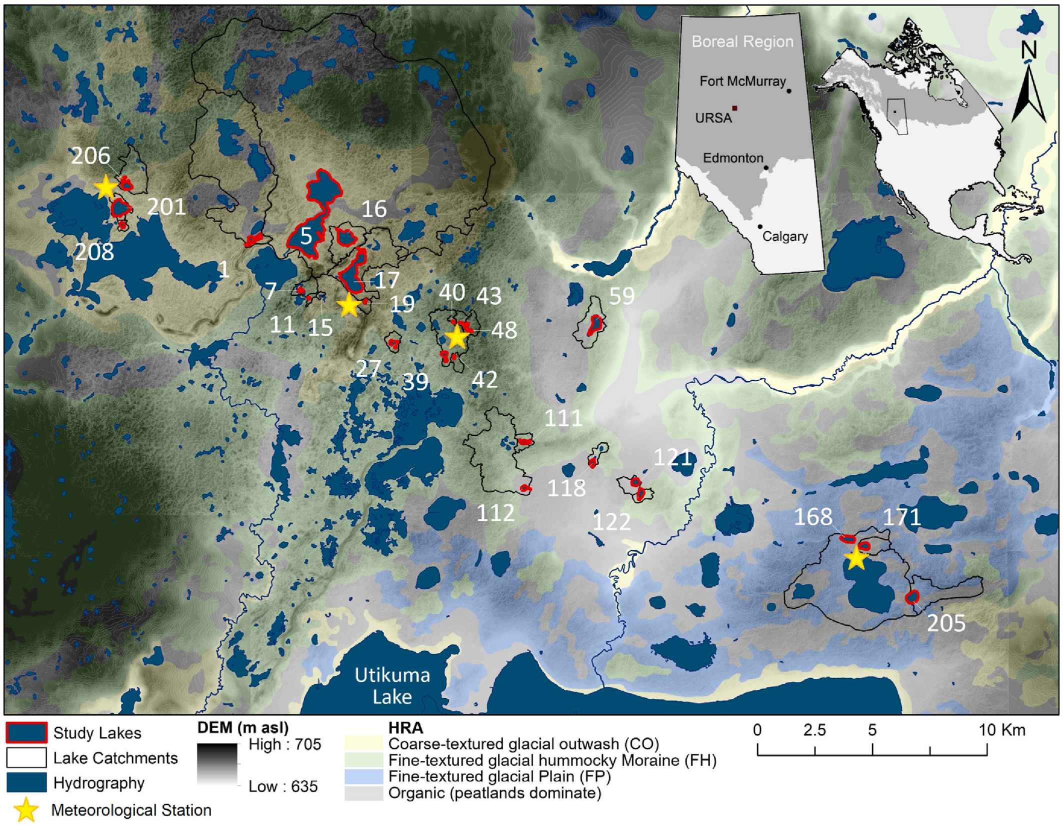

FIGURE 2 Site map of Hydrologic Response Areas (HRAs) derived from surficial geology; hydrography, topography and surface catchment boundaries of 26 study lake catchments in the Utikuma Region Study Area (URSA), within the Boreal plains ecozone of Canada within Alberta (Alberta Sustainable Resource Development, Alberta Environment, Alberta Community Development and Agriculture and Agri-Food Canada, June 2005). DEM, digital elevation model, m asl, metres above sea level.

22 lakes across the URSA. Parameters for lake attributes (area, perimeter, sill height, outflow type, lake HRA) and catchment or landscape attributes (relative elevation, area, slope relief, roughness, and wetland and HRA coverage) used in the analyses of the relationship of lake WLF to basin-landscape and meteorologic cycle interactions are listed in Table 1 and detailed in Section 2.3 and Table S2.

The lake hydrometric measures within this study comprise a high-frequency ‘detailed study’, and two high-breadth synoptics studies (Table 2). The detailed WL study was conducted using the four lakes, representative of the range of glacial lake types and catchment HRAs. The four detailed lakes were measured simultaneously at high frequency for 20 years to address Objective 2 (impact of HRA–Climate interactions) and Objective 3 (estimating period-related sampling bias). The high-frequency records of the selected lakes were further used to evaluate assumptions used within spatial analysis of the 26 synoptic lake survey study (i.e., use of maximum summer WLs; addressing data gaps).

Two broader synoptic surveys (6 and 7 years in length; Table 2) were conducted using instantaneous measures of mid-summer WLs on all 26 study lakes during the beginning and end of the 20-year study that included two series of weather conditions (Table 2 and Figure 3) Summer rainfall and runoff amounts (small or large) represent a large portion of annual inputs of BP lake water balance, and inter-annual oscillation in minimum and maximum lake levels are reflected in July WLs. It was assumed that mid-summer (July) WL measurements conducted during the two broader surveys incorporate sufficient time and oscillation in wetting and drying to assess relative spatial differences in inter-annual range and behaviour of lake WL within and between HRAs.

2.2.2 | Climatological measurements

All the study lakes are within 40 km of each other (Figure 2). Records from meteorological stations concurrently collected from two to four open locations along the transect from 1999 to 2018 show that the study lakes are subject to similar weather and climate conditions (Devito et al., 2016; Hokanson et al., 2021). Thus, precipitation and evaporation are assumed to be similar among the lakes (see Hokanson et al., 2019; Section 2.2.1 for details of meteorological measurements and calculations). A hydrologic year of 1 July to 30 June was utilized to measure accumulated precipitation prior to mid-summer lake levels that reflect inter-annual variations in lake level minimums and maximums (Figure 3). Inter-annual oscillations in wet and dry periods were based on a drought index for the study period where the precipitation cumulative deviation from the mean (1Yr-CDMP) was calculated using

TABLE 2 Experimental design, sampling strategy of the detailed study, and two synoptic surveys, and their climate conditions.

Experimental design considerations		Detailed study	Synoptic survey 1	Synoptic survey 2
Lake water level sampling period and frequency	*Period (years inclusive)*	1999–2018	1999–2004	2012–2018
	Duration (years)	20	6	7
	Sampling frequency	Continuous (automated logger with manual measurements)	Periodically each year (manual)	Annually (manual)[a]
	Sampling time of year	Throughout ice-free period	Throughout ice-free period	Final week June/ first week of July (assumed to be annual maximum level)[a]
	Hydrological monitoring equipment	3–9 referenced staff gauges per lake, and over 300 monitoring locations across the topographic catchment per lake, including piezometers and stilling wells[b]	1–2 referenced staff gauges	1–2 referenced staff gauges
Lakes sample size per Lake-Catchment classification	*Outwash-CO*	1 (Lake 16)	7	7
	Closed-FH	1 (Lake 19)	4	4
	Moraine-FH	1 (Lake 43)	7	7
	Peat-FH	0	4	4
	Peat-FP	1 (Lake 171)	4	4
	Total	4	26	26
Lake water level analysis/metrics	*Inter-annual range*	Calculated from a timeseries of maximum annual water level (occurs approximately end of June/start of July)	Calculated from a timeseries of maximum annual water level across both synoptic studies from measurements taken 1 June to 31 August in the earlier survey and the single July sample during the later survey[c]	
	Seasonal range	Calculated from a timeseries of mean daily water level	NA	NA
Climate Conditions		1Yr-CDMP oscillated between cumulative wet period, followed by cumulative dry period, then oscillated between moderate wet and dry, with near zero deviation from 1Yr-CDMP in 2012	Cumulative dry period with high drought index that proceeded prolonged wet condition early in the study	CDMP oscillated between moderate wet and dry

[a] Figure S3 details sampling frequency and *N* values per week per year (Weeks 23–36) per lake.

[b] Figure S2 details sampling network (number of hydrological monitoring sites).

[c] Based on analyses of inter-annual and seasonal of WL ranges in the four detailed study lakes and multiple summer samples in the early synoptic survey, inter-annual lake water level amplitude metrics were insensitive to length of sampling window within summer months (see Leader, 2021). Analysis from the detailed study indicates inter-annual maximum and minimum lake water levels occurred within the period of the two synoptic surveys.

a moving 365-day window from the long-term annual mean (1999–2018; Figure 3b). The ratio of long-term average PET (519 mm) and average annual P (PET/P) for each annual period (July to June) was used to further categorize wet, mesic, and dry periods previously established as <0.9, 0.9–1.15, and 1.15–1.8, respectively (Devito et al., 2012, 2016). The wet and dry periods correspond with 1Yr-CDMP of $>+100$ mm and <-100 mm, respectively.

2.2.3 | Lake hydrometric measures: Detailed and synoptic study

The elevation of WLs was measured at one or more referenced staff gauges secured to the deep sediment with known elevation (m amsl) at the edge of all 26 lakes and used to estimate the lakes depth of water at the centre (Lake Depth) during all sampling periods (Table 2 and Section 2.2.2). WL elevations were standardized to the maximum depth observed simultaneously at each lake during July 2012, when 1Yr-CDMP was approximately zero (4.5 mm). The deviation metric (WLD2012) was then used to compare long-term trends across lake basins and years.

In the earlier synoptic survey (1999–2004), instantaneous WL measurements were periodically measured between late ice on and autumn conditions. In the later synoptic survey (2012–2018) at least one WL measurement was conducted in the final week of June or first week of July. Based on analyses of inter-annual and seasonal of WL ranges in the 4 detailed study lakes and multiple summer samples in the early synoptic survey, inter-annual lake WL amplitude metrics

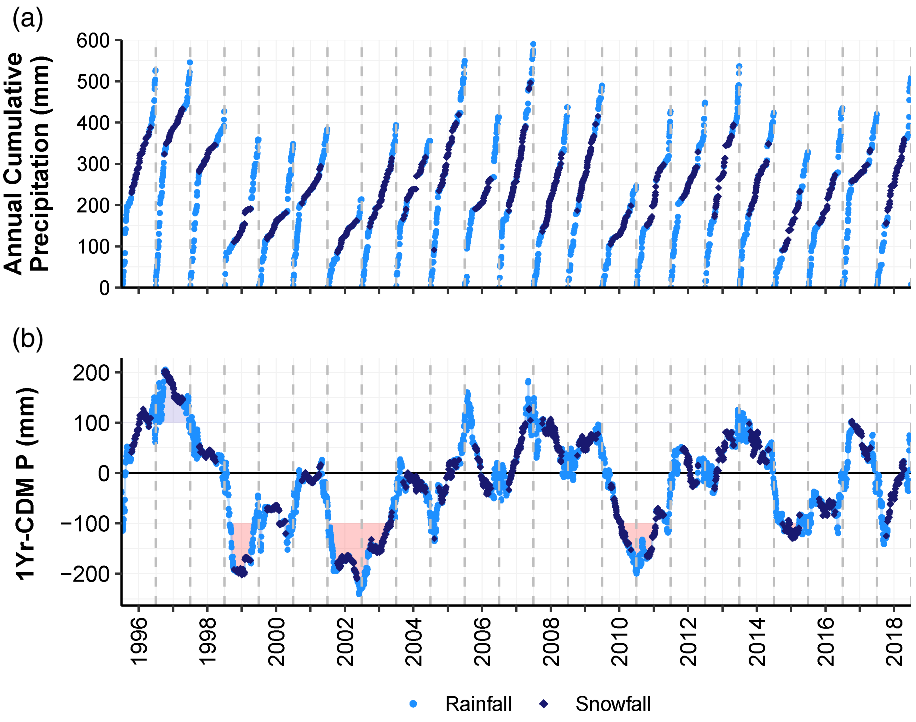

FIGURE 3 Precipitation of the Utikuma Region Study Area (URSA): (a) annual cumulative daily precipitation as snow (dark) and rain (light) 1996–2019 (hydrologic year commencing 1 July shown with dashed line); (b) precipitation 1-year cumulative difference from the long-term mean. Red area = dry 1Yr-CDMP <−100 mm; blue area = wet 1Yr-CDMP >100 mm.

were insensitive to length of sampling window within summer months (see Leader, 2021 and Figure S3). Summer rainfall and runoff amounts (small or large) represent a large portion of annual inputs of BP lake water balance, result in relatively continuous high water or lower WLs for a given year. Therefore, maximum summer WLs were derived from measurements taken 1 June to 31 August in the earlier survey are collated with single July sample during the later survey and assumed to reflect inter-annual range in WLs for each lake during the two sampling period.

For the four detailed study Lakes (lakes 16, 19, 43, and 171) WLs were measured multiple times throughout the ice-free period, and also logged continuously by pressure transducers within stilling wells associated with staff gauges with known elevations. Mean daily WLs were calculated during periods with continuous records and augmented with instantaneous WL measurements when continuous records were not available (Figure S3).

2.2.4 | Data analysis

Classification of lakes

A PCA and agglomerative and divisive hierarchical clustering (R Core Team, 2021; R 'cluster' package v2.1.1; Maechler et al., 2019) methods were utilized to assess the ability of HRAs to incorporate physiographic variables and further characterize parameters of basin geology and morphometry and catchment characteristics that influence lake hydrology. Physiographic variables included within the PCA are provided in Table 1 and reflect different topological, topographical, and typological parameters hypothesised to be important for lake hydrodynamics. Prior to analysis, all variables were tested for collinearity, scaled, and non-normally distributed variables were identified with Shapiro–Wilk normality tests and log transformed accordingly.

Patterns and behaviour in WLFs

For each of the four high-frequency study lakes (Figure 5), the importance of inter-annual versus seasonal fluctuations and the length and initiation of observations were determined by calculating the WL range (maximum WL minus minimum WL; Figure 6). For Intra-annual (seasonal) range, the maximum minus minimum WL was calculated for each year, using only years with 6 months or more data to prevent biases in seasonal range caused by low sample size (Figure 6a). For inter-annual range, the maximum minus minimum WL from 1999 to 2018 is calculated for each month (Figure 6b). Only months with 5 or more years of data are retained to prevent low inter-annual ranges caused by low sample size. To assess the effect of sampling window length and initiation (Figure 6c), the inter-annual approach was applied using all WL records. The 20-year range is a single value for the study period 1999–2018. The 5- and 10-year ranges are time series of 5- and 10-year windows commencing 1999–2014 and 1999–2009, respectively. The range value of a given window is represented on the initial year of that window (e.g., 1999–2003 window plotted at 1999).

Lake WL probability distribution functions (PDF) were calculated to provide WLF metrics for assessing inter-annual variation (Table 3). These are presented as a PDF plot for all recorded WLs for the study period to assess any threshold behaviour and the shape of the distribution of responses for the four high-frequency study lakes (Figure 7). This was then repeated for the 26 study lakes (Figure 8) using estimates of summer maximum WL across the two synoptic study periods and presented as boxplots for individual lakes and as a

TABLE 3 Water level fluctuation (WLF) metrics (Figures 7 and 9).

WLF metrics	Short description	Definition	Metric purpose
WLF % sill height	Fluctuations relative to the height at which the lake spills	Water level elevations expressed as a percentage of the basin sill height (i.e., lake depth divided by basin height)	Indicator for surface connectivity
WLF % maximum depth	Fluctuations relative to the maximum depth of water observed	Water level elevations expressed as a percentage of maximum observed water level elevation (i.e., lake depth divided by maximum observed lake depth)	Indicator for habitat stability
Lake depth	Fluctuations in lake depth	Depth of the water at the centre of the lake (i.e., water level elevation minus the elevation of the lake base at the centre of the lake)	Indicator for habitat stability and lake desiccation
WLD 2012	Fluctuations standardized to mean summer 2012 water levels	Water level elevations standardized to the maximum depth observed simultaneously at each lake during July 2012 (i.e., lake water level minus 2012 lake water level)	To compare long-term trends across lake basins and years and indicator for hydrologic memory (in July 2012, 1Yr-CDMP was approximately zero [4.5 mm])

PDF plot for grouped lakes within Lake-Catchment HRA classes (Figure 9).

3 | RESULTS

3.1 | Weather patterns

The 20-year records at the URSA study area show cyclical patterns in annual precipitation that fluctuated ±200 mm around the study period mean (415 mm) (Figure 3) and capture a full decadal weather cycle and multiple shorter inter-annual moisture cycles that are commonly observed within the BP (Devito et al., 2023; Thompson et al., 2017). Observation of annual snowfall and rainfall show that differences in summer season (June to August) rainfall largely contributed to observed inter-annual differences in annual P and 1-year CDMP. Wet periods (PET:P ratio <0.9; 1-YrCDMP >100 mm) were observed throughout the summers 1996 and 1997, and briefly in the summer of 2005 and again 2007. Dry years (PET:P ratio >1.2; 1Yr-CDMP <−100 mm) and mesic years (PET:P ratio 0.9–1.2; 1Yr-CDMP 100 to −100 mm) cycled approximately every 4 years. Multiple dry years were observed over the summers of 1998–1999 and from 2001 to 2003, with brief dry periods in 2010 and 2015.

3.2 | Lake and catchment characterization

PCA and hierarchical classification (Figure 4) cluster lake type-catchment HRA grouping into four groups and one sub-group (peat lakes transition between FP and FH catchments) based on lake and catchment physiographic parameters. The analysis also shows representativeness of the four detailed study lakes within the lake-catchment HRA groups. These clusters indicate there is a strong relationship of surficial geology with physiographic parameters defined within this study for assessing spatial differences in hydrologic behaviour of the lake based on basin characteristics and differences or similarities surrounding water source areas (see also hierarchical classification Figure S5). As a result, the lakes are grouped and classified based on a combination of the lake basin type and the dominant HRA of the connected catchment, which is important for describing the potential influencing of spatial patterns in hydrologic behaviour and resulting WLF of the lakes (Lake-Catchment Class; Table 1 and envelopes in Figure 4).

The seven outwash-CO lakes have basins located on coarse-textured deposits and are characterized by larger deeper lakes with higher sill heights. They are situated at low landscape positions (<50%) with both large surface and phreatic (groundwater) catchments dominated by CO HRAs. Although some outwash-CO lakes are as spill based on surface flow, during most periods they also function as flow-through as inflow and outflow seepage occurs through coarse mineral substrates and via diffuse near surface flow through wide alluvial fens (Table 1). Lake 208 is a small, narrow peat perimeter lake with an exceptionally small topographic catchment compared with the other outwash lakes, resulting in greater association with FH HRA class lakes. However, at a larger scale Lake 208 basin and its surface and phreatic catchment are located in CO HRA, and this lake receives large groundwater contributions (Hokanson et al., 2021).

The four Closed-FH lakes are situated at the transition of CO and FH HRAs and plot with PC2 values associated with CO HRAs. This group of lakes also share characteristics with Moraine-FH lakes, with greater topographic relief, slope, and sill heights produce small, closed basins. The lakes are in headwaters with hummocky morphology with ice-contact glacial-fluvial geology, and similar to FH HRAs, have deep (>10 m) fine-textured deposits overlaying coarse deposits not indicated on regional mapping, and thus, these lakes have perched groundwater function (Hokanson et al., 2019).

Moraine-FH lakes have smaller area and lower sill heights, and are associated with higher landscape positions, smaller catchments

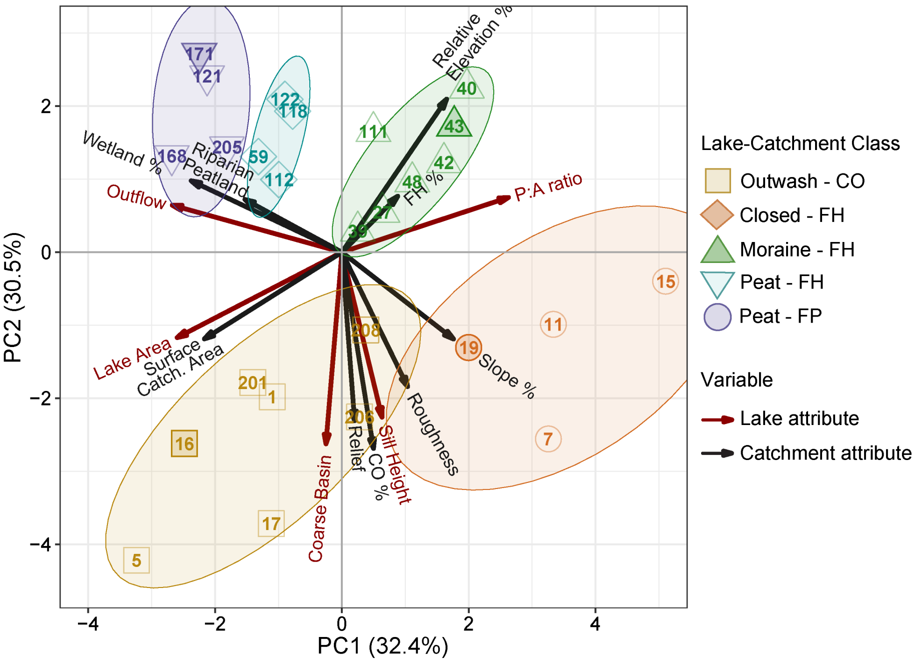

FIGURE 4 PCA of lake and catchment parameters (data given in Table 1) compared with lake-catchment topology of 26 study lakes in the Utikuma Region Study Area (URSA). Lake label colours indicate the hydrologic response areas class of lake-catchment based on dominant surficial geology, which closely correspond with types of lake formation and potential hydrologic connectivity. Detailed study lakes labels in bold.

areas with high roughness, and slope. Moraine-FH lakes are also surrounded by narrower riparian wetlands (peatland) and exhibit a greater proportion of forested upland. Lake recharge to regional aquifers is small, with some recharge to local aquifers (Thompson et al., 2015). Inflows and outflows occur intermittently as channelized or diffuse inflows and outflows in wider fens (Table 1).

The remaining eight Peat lakes have shallow basins, located on fine-textured plains (FP), underlain and encircled by organic soil (peatland) with typically poorly channelized diffuse inflows and outflows through wide fens. The lake catchments are characterized by low relief and slope and large wetland (peatland) coverage that promote shallow runoff to the lakes. Groundwater inputs to the lake from mineral soil are minimal. Four peat lakes with the basin on FP HRAs have large riparian peatland coverage. In contrast, Peat-FP lakes with FH catchments have large aspen forest coverage. However, the catchments of peat lakes generally have lower slopes and greater wetland coverage compared with Moraine-FH lakes (Table 1), and herein classed as Peat-FH transition lakes.

3.3 | Detailed study lakes: Comparing patterns in WL across lake-catchment class

3.3.1 | Inter-annual versus seasonal variability

The variability in response of WLF of the four detailed study lakes to the long-term weather cycles is shown in Figure 5. Although in general inter-annual variability in lake WLs was associated with weather patterns over the 20 years, low WLs were not observed during the 1998–1999 meteorological drought that followed extreme wet weather in the previous 2 years (1996–1997). Further, poor concurrence in timing, magnitude and overall trend of lake WL patterns at seasonal, inter-annual, and decadal time scales was observed among the four lakes. Intra-annual and inter-annual variability was moderated in outwash-CO Lake 16 compared with the other lakes (Figure 6). There was considerable intra- and inter-annual variability in closed-FH Lake 19, and in contrast to other lakes, there was an overall decrease in lake WL over the study period. Little long-term trends in WL were observed in the Moraine-FH Lake 43 and Peat-FP Lake 171; however, the years with highest WL and recovery of WL following drought differed between lakes.

High-frequency observations over the study period show that inter-annual variability was greater than intra-annual (seasonal) variability in the detailed study lakes, except the outwash-CO Lake 16 (Figure 6a,b); the amplitude of long-term trends in WLF responding to weather patterns overwhelms the seasonal variability observed annually. A comparison of the year with greatest seasonal variability with the 20-year inter-annual range indicates that within year (seasonal) variability would be <29%, 56%, and 49% of the inter-annual variability in the detailed Closed-FH Lake 19, Moraine-FH Lake 43 and Peat-FP Lake 171, respectively. In the outwash-CO Lake 16 the seasonal variability is only 12% less than between year variability.

Inter-annual variability assessed by month (Figure 6b) demonstrates that summer months (May to August) result in the high ranges in inter-annual fluctuations, with a peak in July. These correspond with below or above normal late spring and summer rains that result in surplus or deficit relative to cumulative evapotranspiration losses (e.g., high intra-annual ranges associated with rainfall deficits in 2002 in Figure 6a). This pattern is not as evident for Outwash-CO Lake 16, rather the long-term range in WLF appears to be a function of seasonal variability that can mask the low amplitude long-term trends responding to weather patterns.

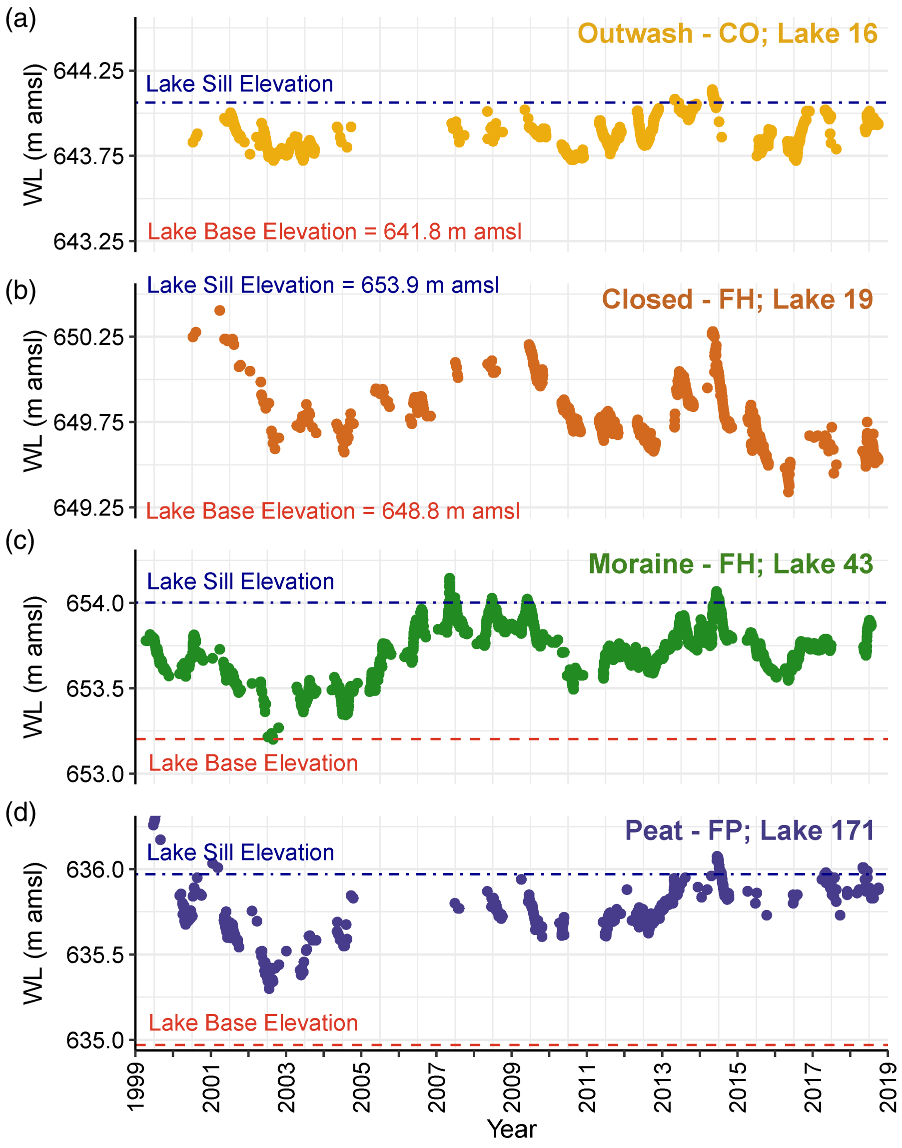

FIGURE 5 Lake water level (WL) observations 1999–2018 (above mean sea level) of four detailed study lakes in the Utikuma Region Study Area (URSA): (a) Lake 16 – Outwash-CO; (b) Lake 19 – Closed-FH; (c) Lake 43 – Moraine-FH; (d) Lake 171 – PeatFP. Lake sill and lake bottom elevations are given for each lake.

3.3.2 | Influence of sampling period of recorded WLF

Varying the length and starting point of the sampling window illustrates the importance of study length and study initiation relative to the long-term (decadal) climate cycle in determining the accuracy in the total magnitude of variability (Figure 6c). Using a 5- and 10-year study window would be insufficient to capture the full range in WLF observed across 19–20 years in all detailed study lakes and demonstrates how different initiation dates may result in different interpretations on lake stability. A 5-year study may under-predict variability by as much as 69% (0.7 m) in Peat-FP Lake 171; 56% (0.6 m) in Closed-FH Lake 19; 54% (0.22 m) in Outwash-CO Lake 16, and 46% (0.43 m) in Moraine-FH Lake 43. Conversely, short studies conducted following the 1996–1997 wet period that include the 2002–2003 dry period could represent the full range of conditions within the detailed Moraine and Peat lakes. However, comparisons drawn with detailed Outwash-CO and Closed-FH lakes for the same period may be limited due to spatial differences in storage memory and multi-year lag responses, and greater inter-annual variability captured at the end of this study period (2014) for these two detailed lakes.

3.3.3 | Characteristics of WLFs

Figure 7 shows the shape of WL PDF for the detailed study lakes which strongly corresponds with hypothesised distributions of different lake-catchment classes (Figure 1). The Outwash-CO Lake 16 WLs exhibit the narrowest range and distribution indicating low variability in WLF; WLs are maintained around the sill elevation and consistently produce outflow. As the deepest detailed study lake with the lowest range in depth (0.42 m), WLs in the Outwash-CO lake fluctuate through just 18% of its maximum observed storage.

WLF in the Peat-FP Lake 171 exhibit infrequent but potentially high magnitude exceedance of its sill, and similar drying behaviour of low frequency, high magnitude response, producing tapered tails

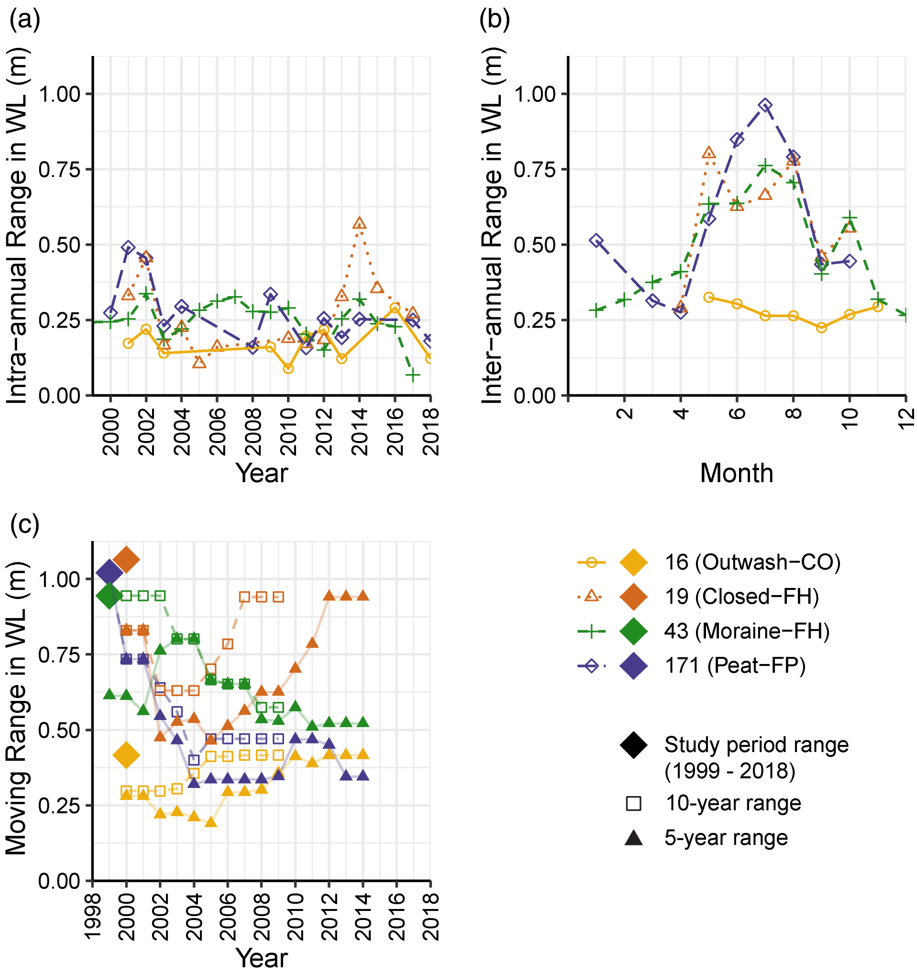

FIGURE 6 Metrics of lake water level fluctuations (WLFs) amplitude across different sampling periods: (a) Intra-annual (seasonal) range—maximum minus minimum lake WL within each year 1999–2018. Within each lake, only years with 6 months or more data retained to prevent low range caused by low sample size. (b) Inter-annual range—maximum minus minimum lake WL within each month from 1999 to 2018. Within each lake, only months with 5 or more years data retained to prevent low range caused by low sample size. (c) Inter-annual range across varied sampling windows—maximum minus minimum lake WL within sampling windows. The 20-year range is a single value for the study period 1999–2018. The 5- and 10-year ranges are time series of 5 and 10 year windows commencing 1999–2014 and 1999–2009 respectively. The range value of a given window is represented on the initial year of that window (e.g., 1999–2003 window plotted at 1999).

within its WL distribution. While WLFs are moderate for most changes in weather patterns, extreme fluctuations occur during drought conditions in 2002–2003, and in 1999 following the wet period of 1996–1997. This results in a high range in water depths (1.02 m), representing fluctuation through 75% of the maximum observed storage. The Moraine-FH Lake 43 also infrequently exceeds the sill; however, the PDF of this lake is restricted by both outflow generation and desiccation due to shallower depths. Thus, the lake fluctuates through 100% (0.94 m) of its maximum observed storage and so presents a more truncated distribution compared with the Peat-FP lake. The Closed-FH Lake 19 presents the widest distribution in depth and is the only detailed study lake not producing outflow due to high sill height. The Closed-FH lake is also a greater distance from drying out compared with the Moraine-FH lake due to deeper water depths. Subsequently, the Closed-FH lake fluctuates through only 66% (1.06 m) of its maximum observed storage.

Differences in WLD2012 (Figure 7d) between the detailed study lakes reinforces findings of differences in memory or lag response to weather patterns between lakes resulting in low synchrony in the timing of peaks and troughs. These echo findings of moving window ranges, whereby the Closed-FH lake WLD2012 is skewed towards positive values due to memory of the 1996–1997 wet period, dryer conditions in 2010–2011, and rapid wetting in 2014. In contrast, the detailed Outwash-CO, Peat-FP and Moraine-FH lakes exhibit skews towards negative WLD2012 values of varying degrees and distribution shapes, indicating different timing and magnitude responses to recurring drought conditions.

3.4 | Synoptic lake study: Spatial WLF patterns

Time series of standardized Lake WLD2012 reveal diverse patterns and low concurrence in lake fluctuations spatially and temporally across the 26 study lakes despite experiencing similar weather patterns (Figure 8a). Although the amplitude and timing of peaks and troughs in WLD2012 differ between individual lakes, there are apparent trends within that differ among the lake-catchment classes as observed in the four-lake detailed study. These trends among lake-catchment classes are more apparent as a timeseries of WLF relative to sill height (Figure 8b), indicating the timing and potential scales of connectivity. The first synoptic survey shows no appreciable lowering of WL in any lake during the initial low drought index observed in 1999–2000, indicating high memory and lagged response to the extreme wet period of 1996–1997 in most lakes. WL response was rapid in most Peat-FP, Peat-FH, and Moraine-FH lakes to the second drought conditions that started in 2002. Extreme lowering of WL was observed in four peat lakes, with the greatest in the Peat-FH lake type. The lowering in WL responses to the drier 1 Yr-CDMP was

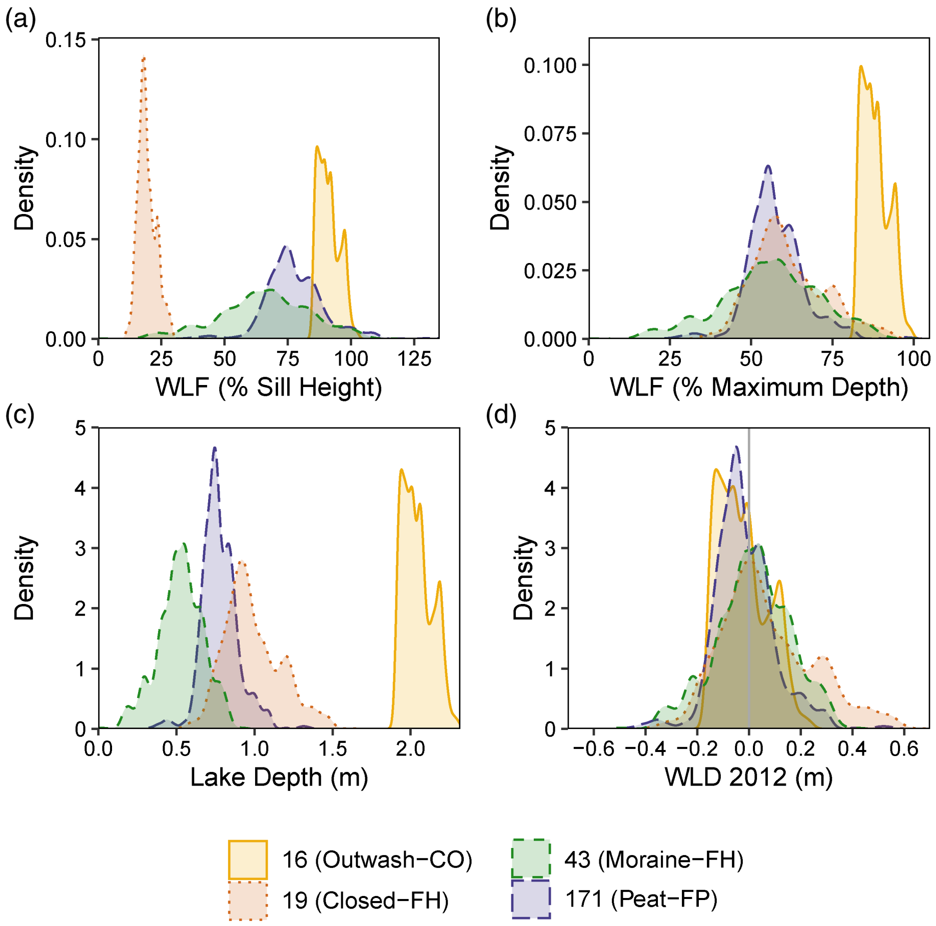

FIGURE 7 Probability distribution functions of the four detailed lake water level (WL) observations in the context of: (a) water depth as a percentage of potential storage (sill height) to indicate frequency or vertical distance to outflow; (b) water level fluctuation (WLF) as a percentage of maximum observed storage to indicate stability of lake depth; (c) water depth (m) to indicate frequency or distance to desiccation; (d) lake water level deviation relative to summer maximum levels in 2012 to indicate concurrence of lakes (positive values indicate higher water levels relative to 2012). Full metric definitions are provided in Table 3.

lagged in most outwash-CO lakes, compared with the other lake class, with lowest WLs occurring in 2003 or 2004. In the later synoptic survey following 2012, WL responses generally trended with the 1 year-CDMP, increasing with positive 1 year-CDMP in 2013 and 2014, then subsequently decreasing with negative 1 year-CDMP in 2015 and 2016. However, there is considerable variability between lakes of all classes during the 2011–2018 period.

Observations during 2005–2012 (between synoptic surveys) in selected lakes show moderate fluctuations in WL and indicate that comparisons of the earlier with the later synoptic survey period does represent the magnitude of WL variability over the study period (Figure 8). WLs in the outwash-CO lakes remained near or above WLDL2012 with no consistent longer-term trend apparent, with the exception of a low WL observed in one lake in 2003. WLs in Closed-FH lakes indicate a longer-term lowering trend, possibly in response to high memory with large accumulated water storage during the 1996–1997 wet period. No long-term trend in WL was apparent in Moraine-FH lakes over the study, with considerable WL fluctuation around the WLD2012 within and among this lake type. The Peat-FH, and to some degree the Peat-FP lakes indicate a larger drawdown, but rapid recovery to the cumulative drought cycles of 1999–2002, but little trend during the rest of the study.

The distributions of maximum summer lake WLD2012 for the combined 2000–2004 and 2011–2018 periods across the 26 study lakes largely mirror the findings of the main detailed study lakes within their HRA classification (Figure 9). Outwash-CO lakes display a narrow distribution and low range in fluctuations in both absolute depth and as a percentage of maximum storage. The Outwash-CO lakes fluctuated around their sill elevation for the study duration (Figure 9a), indicating frequent outflow annually. Peat-FP and Peat-FH and Moraine-FH lakes infrequently exceeded their sills while Closed-FH lakes did not exceed their sills within the study period. Closed-FH and Moraine-FH lakes exhibit the greatest percentage fluctuations relative to their maximum depth (Figure 9b); however, this appears to be a function of lake depth, where shallow lakes exhibit greater percentage fluctuations. In turn, these shallower lakes display the closest propensity to drying out (Figure 9c). While the characteristics of WLF relative to outflow and drying out are similar among lakes for each Lake-Catchment class, the absolute variability and WLD2012 is less distinct, indicating additional controls on magnitude responses and lag responses that vary within HRA classes (Figure 9d).

4 | DISCUSSION

4.1 | BP lakes WLs across space and time

4.1.1 | Inter-annual versus seasonal lake WL patterns

This study demonstrates the importance of long-term weather patterns in lake ecosystem functioning as inter-annual variability

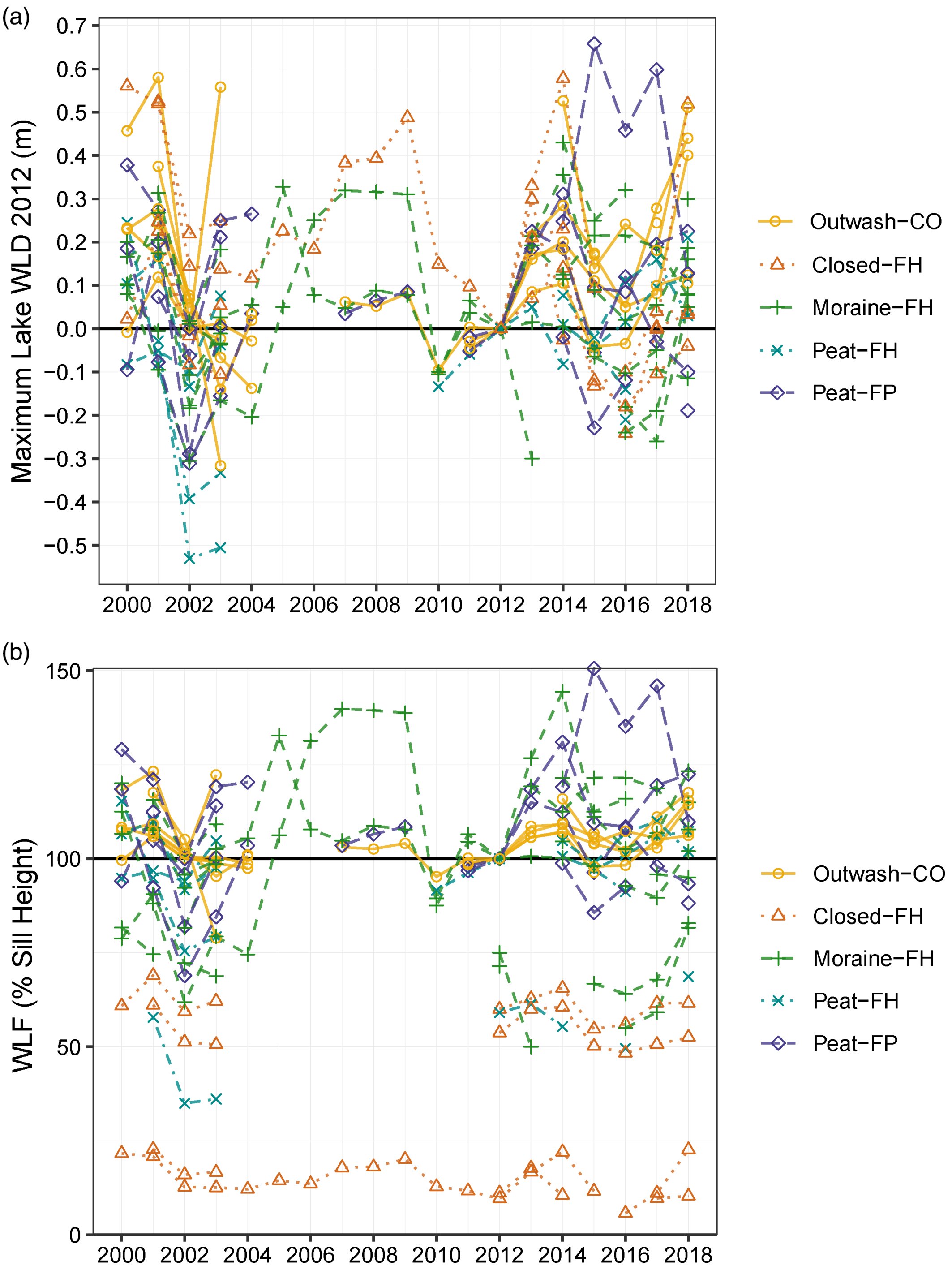

FIGURE 8 Maximum summer lake water levels 1999–2018 of 26 study lakes in the Utikuma Region Study Area (URSA), presented as: (a) deviation relative to 2012 lake water level; (b) water level fluctuation as a percentage of potential storage (sill height). Colour indicates lake-catchment classification (as per Figure 4, see also Table 1).

overwhelmed seasonal variability in BP lake WLs across a range of lake and catchment types. This contrasts the large control by seasonal weather patterns and snow melt in regions with higher precipitation and relief, such as the humid Boreal Shield (Oswald et al., 2011), snow-dominated Montane (Lee et al., 2015), Alaska (Arp et al., 2012) and European Boreal (Karlsen et al., 2019). In these hydro-geoclimatic settings, mean annual precipitation greatly exceeds mean annual evaporation and net precipitation frequently exceeds forest soil storage, producing significant runoff annually (Buttle et al., 2005) and maintain relatively stable lake WLF between years. In contrast, in the sub-humid boreal mean annual evaporation is similar to mean annual precipitation. Therefore, relatively small changes in annual precipitation may result in large changes in net atmospheric exchange. Further, poor drainage and large but heterogeneous landscape water storage

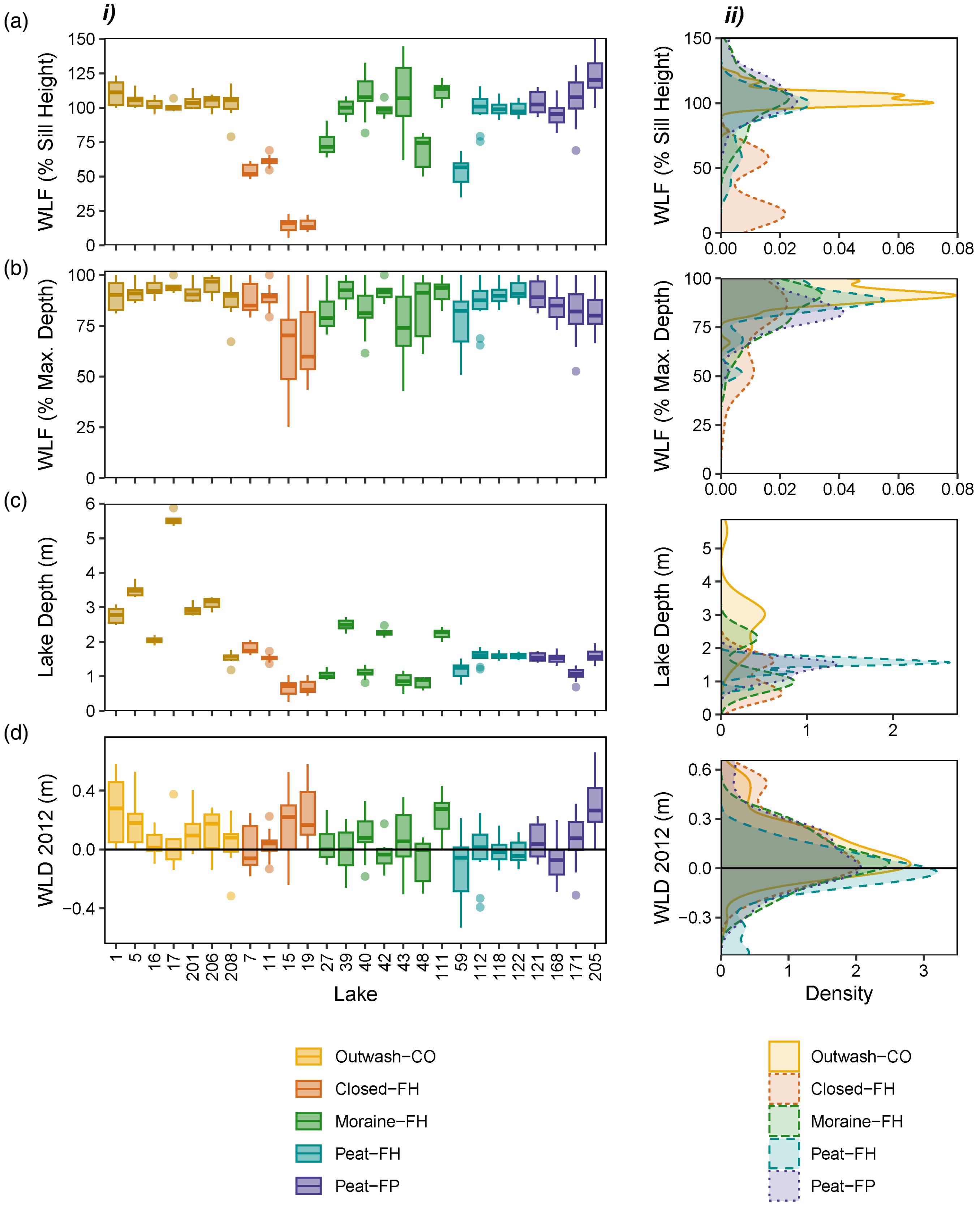

FIGURE 9 Maximum summer (1 June to 31 August) lake water level observations 1999–2018 above mean sea level of 26 study lakes in the Utikuma Region Study Area (URSA) as: (i) boxplots for individual lakes and (ii) probability distribution function plots for lake-catchment classifications. Lake WL observations are given in the context of: (a) water depth as a percentage of potential storage (sill height) to indicate frequency or vertical distance to outflow; (b) water depth as a percentage of maximum observed storage to indicate stability of lake depth; (c) water depth (m) to indicate frequency or distance to dying out; (d) lake water level relative to levels in 2012 to indicate concurrence of lakes responses to climate (positive values indicate higher water levels relative to 2012). Colour indicates lake-catchment classification. Full metric definitions are provided in Table 3.

result in large inter-annual variation in runoff trending with regional weather patterns (Devito, Creed, & Fraser, 2005; Devito et al., 2023). Therefore, peak WLs within a given year reflect the seasonal weather pattern superimposed onto the long-term weather patterns that fluctuate between surplus and deficits in regional moisture on ∼4-year -cycles, with wet years returning on about a 20-year cycle in the BP (Mwale et al., 2011). Moreover, we show that large differences in inter-annual variability are driven by summer WLs, signifying the importance of precipitation timing relative to evaporative demand within the growing season, in contrast to systems where spring snowmelt drives WLF.

Storage-driven memory of lakes is a widely understood phenomenon in semi-arid closed Prairie depression basins (van der Kamp et al., 2008), where waterbodies vary immensely from transient ponds to semi-permanent lakes (Hayashi et al., 2016; Shook & Pomeroy, 2011). In turn, concepts of controls due to landscape position and depression storage derived within the Prairies may lend to BP lakes better than non-linear threshold-mediated runoff dynamics developed in Boreal Shield studies (Oswald et al., 2011; Spence & Woo, 2006) and across northern catchment studies (Ali et al., 2015) where seasonal fluctuations (snow melt) dominate. In Prairie basins, lake WLF reflect long-term (inter-annual) cumulative departures from the long-term average of precipitation (CDMP; van der Kamp et al., 2008), similar to the relationship observed between CDMP signals and groundwater levels and meso-catchment runoff in BP landscapes (Devito et al., 2023; Hokanson et al., 2019). Although spatial differences in landscape storage give rise to long-term trends in hydrological responses across the glaciated continental plains, understanding lake function and landscape connectivity in the BP is further complicated by the fact that large portions of the landscape are covered with peatlands with less storage and hydrologic memory (Devito et al., 2023), and together with surficial geology influence both long-term and seasonal catchment responses, lake inputs and lake WLF.

4.1.2 | Spatially diverse hydrological threshold behaviours

We observed predicted differences in WL dynamics among the detailed study shallow lakes located in different HRAs, derived from surficial geology classifications (Devito, Creed, Gan, et al., 2005; Winter, 2001). This suggests that surficial geology incorporates important lake and catchment parameters that control WLF patterns and characteristics, consistent with meso-scale catchment runoff (Devito et al., 2023), groundwater levels (Hokanson et al., 2019), lake-groundwater dynamics (Hokanson et al., 2021; Plach et al., 2016) and long-term soil moisture and catchment runoff modelling (Carrera-Hernández et al., 2012; Thompson et al., 2017).

However, the synoptic survey results show there is considerable variability in the amplitude of WLF among lakes within surficial geology classes, strongly suggesting that addition factors are interacting with surficial geology to produce observed patterns in lake water dynamics. Most notably, landscape position likely influences lake budget inputs from groundwater and cumulative surface water from peatlands (Hokanson et al., 2021; Thompson et al., 2015). Spatially diverse amplitudes of WLF and varied temporal responses to weather patterns have been observed in Prairie (Hayashi et al., 2016) and glaciated northern Wisconsin lake complexes (Perales et al., 2020) located in different landscape positions within relative homogenous glacial deposits. Fergus et al. (2022) also demonstrated inconsistent effects of drought on lakes across North America due to heterogeneity in relation to landscape position and lake flow-through status. Within the detailed study lakes, Outwash-CO Lake 16 and Peat-FP Lake 171 are situated within a lower regional and local landscape position, respectively, receiving more continuous groundwater inputs through coarse surficial deposits or connected peatlands that can support lake WLs and maintain inundation. Therefore, the coarse-textured glaciofluvial outwash lakes (CO) exhibited the narrowest range and distribution of WLs, corresponding with the behaviour of groundwater patterns in BP coarse outwash systems (Hokanson et al., 2019, 2021; see also Figure 1). The fine-textured glaciolacustrine plains lake (FP) also exhibited moderated WLs for a wide range of annual weather conditions, corresponding with observations of regulated hydrologic conditions in peat-dominated systems (Ferone & Devito, 2004; Kettridge & Waddington, 2014).

The contrasting hydrological patterns between the detailed study sites, and the complexity in lake WL responses across surficial geologies classes (HRAs) in the synoptic survey demonstrates the need for hydro-geoclimatic frameworks that examine the interaction of short- and long-term weather patterns with geology as well as landscape position, and dominant land covers (peatland vs. deciduous forests) on lake WLF. Such frameworks would aid in extrapolating empirical findings to ungauged lakes, set the context for conceptual and numerical modelling and aid in best management practices to assess and mitigate potential anthropogenic and climate change impacts (Winter, 2001).

4.2 | Stability assessments: Importance of long-term observations concurrent with lake types

Measures of inter-annual variability across different timeframes clearly show that the estimated magnitude of WL variability can be an artefact of observation length and initiation day in BP lakes. Our results indicate that short-term studies (<10 years) are insufficient to capture the range in WLs that can be associated with full multi-decadal meteorology that is typical of the continental sub-humid regions (Mwale et al., 2009). Moreover, the non-linear relationship between weather pattern and hydrometrics in some lake types shows that shorter studies initiated on different dates of the same study lakes can result in different interpretations of hydrologic behaviour as a product of the initial WL position and lag response within long-term weather patterns. Further, spatial differences in lag responses to meteorological cycles suggest that short-term studies of diverse lake types could capture lakes in different phases and thus not necessarily responding to current weather conditions recorded within the study or the same scale of weather cycle (annual, multi-annual, decadal; Devito et al., 2012).

Artefacts of study timing and length have long been speculated as the cause for conflicting findings in lake stability. While there has long been a demand for more long-term hydrology observations to fully understand northern catchments (Laudon et al., 2017; Tetzlaff et al., 2017), this study shows that for accurate assessment of extremes in BP shallow lake WLFs, observations covering approximately two decades are required to capture a full long-term meteorological cycle. Observations of long-term WLF in Prairie ponds (Hayashi et al., 2016; LaBaugh et al., 2018) and Wisconsin lakes (Perales et al., 2020) with comparable climate and glacial geology indicate that similar observation windows are required. Subsequently, we suggest that climate-landscape controls can only be explained upon approaching these observations with a priori knowledge of heterogeneities in hydrogeoclimatic setting in large spatial datasets (Devito, Creed, Gan, et al., 2005; Hokanson et al., 2019; Winter, 2000). Doing so allows for placing a lake of interest in the context of their potential phase response to the long-term weather pattern based upon the surficial geology and dominant land cover associated with the lake basin and the landscape source waters.

We provided Figure 1 as a priori visualization of hypothesised hydrologic relationships associated with HRAs, which highlight the importance of threshold behaviour that may not be captured under a study observing a narrower range of annual weather conditions (Figure 1b). While spatial differences in storage-driven connectivity and thus memory will result in far more complex temporal patterns than posited (Figure 1a), our results support hypothesised climate-lake level hydrologic relationships across long-term weather cycles. Most strikingly, moving 5-year WL ranges erroneously indicate that Peat-FP is the least variable lake-catchment type based on observations commencing in 2014, yet the most variable within 5 years commencing in 1999. The former conforms with the common understanding of stability in peat systems. However, both Peat lake types (Peat-FP & Peat-FP) displayed threshold behaviours with infrequent and short-term high magnitude WLF under extreme climatic conditions. Such thresholds in WLF can be expected in lakes receiving relatively large contributions to the water balance from connected peatland areas because of the hydraulic properties of peat (Kettridge et al., 2016; Waddington et al., 2015). Peat has high water holding capacity that maintains antecedent moisture, promoting rapid saturation and runoff responses during extreme wet cycles (following the 1996–1997 wet periods) but also provides base flow contributions with normal and initial drying weather conditions (Kettridge et al., 2017). In contrast, during extreme droughts (2002–2003 driest period), peat will hold and conserve water, resulting in the cessation of inputs and desiccation of flow through lakes (Ferone & Devito, 2004). The actual water storage and memory of extreme desiccation are low (in contrast to forest uplands) as peatland antecedent moisture and resulting runoff rapidly responds to small rain events and receiving lake WLs rapidly recover. The large distribution of peatlands concurrent with sub-humid and cyclic wet-dry periods is a characteristic unique to the BP. The resultant control on threshold WLF responses in lakes, has been observed in regional catchment runoff studies (Devito et al., 2023), illustrating the need to consider lake catchment characteristics and length of observation periods in regionalizing extremes in WLF and overall lake function in this hydrogeoclimatic setting.

Conventionally, Moraine-FH lakes are considered to respond greatest to climatic conditions, however, lower spill height and basin storage results in minimal memory. Following the 1996/1997 wet period, Moraine-FH lakes likely experienced outflow losses reducing maximum levels. Further, with shallow depths, water the amplitude of WL decline is truncated with drying out in 2002 resulting in lower variability in Moraine-FH lakes compared with Peat-FP lakes. Similarly, the selected length of study results in conflicting conclusions of WLF magnitudes in the Closed-FH lake basins due to high memory of the wet 1996/1997 period, which declines over a very long period by evaporation (van der Kamp et al., 2008), followed by rapid wetting in 2014. Subsequently, 5- and 10-year ranges show increasing interannual variability in the Closed-FH lake WL throughout the study period, whereas the Moraine-FH and Peat-FP lake WL decrease in variability throughout the study period. The long-term amplitude and periodicity of WLF in the Closed-FH lake may be much greater. Trends in WLF of over 3 m amplitude and over several decades have been observed in closed Prairie lakes (van der Kamp et al., 2008). Conversely, timing and length of study are of less significance in Outwash-CO lakes, which corresponds with observations in low interannual variability. Lower 5- and 10-year ranges at the beginning of the study could signify diminishing buffering capacity of groundwater as an extended lag response to the 1996–1997 wet period, which could be restored upon the next wet period. These findings clearly emphasize the need for long-term studies in order to produce and apply landscape frameworks.

4.3 | Implications for determining stability and interpreting lake resilience

Defined as low deviation from its average state, stability in lake systems is commonly inferred from the magnitude of WLFs (Bayley & Prather, 2003; Cobbaert et al., 2015). From our findings, we highlight two limitations with using this metric to define lake stability. The first being methodological, where studies of insufficient length may produce values unrepresentative of true long-term variability between lakes as outlined above. The second challenge is in determining what metric of variability to use in defining stability in lake WL, or by extension, to interpret lake resilience. Despite identifying diverse hydrologic behaviour between lakes in different HRAs, absolute magnitude of lake variability is comparable across the study region, therefore the periodicity and timing of fluctuations may be of greater importance for inferring stability. Stability is often associated with hydrological thresholds such as drying out or outflow generation which shape habitat characteristics (Cobbaert et al., 2015; Sass et al., 2007). These represent important markers both ecologically and chemically, by governing habitat availability, the movement and concentration of nutrients, and the downstream supply of water. As a result, lakes are often considered unstable or exhibit low resilience if they dry up, perhaps based on observations, largely in humid landscapes, of rapid terrestrialization of lake area by riparian peat triggered by drought (Ireland et al., 2012; Warner et al., 1989). However, drying out may be part of a lakes natural cycle, as observed in Prairie ponds (Euliss et al., 2004; Euliss Jr. et al., 2014) that rely on negative feedback mechanisms to enable rapid recovery following droughts and thus shape the resilience of the given lake. Furthermore, the high community richness, diversity, and productivity of BP ecosystems are a result of heterogeneity in lake habitats. This is derived from spatially and temporally diverse lake depth responses as a result of range in landscape position and relative controls of surface and groundwater interacting with weather patterns (drought to deluge; Euliss et al., 2004; Perales et al., 2020). Given the dominance of inter-annual WLF, and that WLF may be operating on different timescales due to the interaction of long-term weather patterns with spatial differences in storage-driven memory, the long-term interactions of hydrological thresholds and how they shape landscape resilience could be overlooked in studies covering a short time periods (e.g., <10 years). Given the subhumid climate, but presence and interaction of extensive peatlands with heterogeneity in glacial geology of the BP, extrapolating current resilience and stability studies may require an integration of concepts of pond terrestrialization developed in humid climates (Ireland et al., 2012; Tsyganov et al., 2019; Warner et al., 1989) with pond continuums in semi-arid Prairie landscapes (Euliss et al., 2004; Euliss Jr. et al., 2014). Representation of the full range in dynamics of lake WLF will aid in (1) defining important basin storage properties and internal inputs (P and E) versus external hydrometric parameters; (2) interpreting the influence of study period and initiation of previous studies; (3) improve our understanding of the controls on stability and resilience of long term hydrologic and ecosystem function of shallow lakes of the BP and; (4) assess the potential influence of land use and climate change.

ACKNOWLEDGEMENTS

Funding was provided by Natural Sciences and Engineering Research Council of Canada Collaborative Research and Development Grants to KJD (CRD238050-00, CRDPJ337273-06, and CRDPJ477235-14) with industry partners Syncrude Canada, Canadian Natural Resources, AlPAc Forest Industries, Tolco Forest Ind., and Ducks Unlimited Canada Boreal Program, and by Natural Environment Research Council (NERC) funding to SL and NK through the Data Risk and Environmental Analytica Methods (DREAM) Centre for Doctoral Training. We thank Wayne Bell, Debbie Bryant and Gunther Tondilier for initial installation and monitoring and Kelly Hokanson, Mika Little-Devito, Sarah Percsadus, and Emily Pugh for long-term maintenance; and to Carolynn Forsyth for camp facilities at the ArtisInn.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

S. Leader https://orcid.org/0000-0002-4545-1169
N. Kettridge https://orcid.org/0000-0003-3995-0305
D. Hannah https://orcid.org/0000-0003-1714-1240
C. Mendoza https://orcid.org/0000-0002-2731-0004
K. J. Devito https://orcid.org/0000-0002-8216-0985

REFERENCES

Ali, G., Oswald, C. J., Spence, C., Cammeraat, L., McGuire, K. J., Meixner, T., & Reaney, S. M. (2013). Towards a unified threshold-based hydrological theory: Necessary components and recurring challenges. *Hydrological Processes*, *27*(2), 313–318.

Ali, G., Tetzlaff, D., Mcdonnell, J. J., Soulsby, C., Carey, S., Laudon, H., Mcguire, K., Buttle, J., Seibert, J., & Shanley, J. (2015). Comparison of threshold hydrologic response across northern catchments. *Hydrological Processes*, *3591*(June), 3575–3591. https://doi.org/10.1002/hyp.10527

Arp, C., Whitman, M., Jones, B., Kemnitz, R., Grosse, G., & Urban, F. (2012). Drainage network structure and hydrologic behavior of three lake-rich watersheds on the arctic coastal plain, Alaska. *Arctic, Antarctic, and Alpine Research*, *44*(4), 385–398. https://doi.org/10.1657/1938-4246-44.4.385

Bayley, S. E., & Prather, C. M. (2003). Do wetland lakes exhibit alternative stable states? Submersed aquatic vegetation and chlorophyll in western boreal shallow lakes. *Limnology and Oceanography*, *48*(6), 2335–2345. https://doi.org/10.4319/lo.2003.48.6.2335

Buttle, J. (2006). Mapping first-order controls on streamflow from drainage basins: The T3 template. *Hydrological Processes*, *20*(2006), 3415–3422. https://doi.org/10.1002/hyp

Buttle, J. M., Creed, I. F., & Moore, R. D. (2005). Advances in Canadian forest hydrology, 1999-2003. *Hydrological Processes*, *19*(1), 169–200. https://doi.org/10.1002/hyp.5773

Carey, S. K., Tetzlaff, D., Seibert, J., Soulsby, C., Buttle, J., Laudon, H., McDonnell, J., McGuire, K., Caissie, D., Shanley, J., Kennedy, M., Devito, K., & Pomeroy, J. W. (2010). Inter-comparison of hydro-climatic regimes across northern catchments: Synchronicity, resistance and resilience. *Hydrological Processes*, *24*(24), 3591–3602. https://doi.org/10.1002/hyp.7880

Carrera-Hernández, J. J., Smerdon, B. D., & Mendoza, C. A. (2012). Estimating groundwater recharge through unsaturated flow modelling: Sensitivity to boundary conditions and vertical discretization. *Journal of Hydrology*, *452-453*, 90–101. https://doi.org/10.1016/j.jhydrol.2012.05.039

Cheng, F. Y., & Basu, N. B. (2017). Biogeochemical hotspots: Role of small water bodies in landscape nutrient processing. *Water Resources Research*, *53*(6), 5038–5056. https://doi.org/10.1002/2016WR020102

Cobbaert, D., Wong, A., & Bayley, S. E. (2014). Precipitation-induced alternative regime switches in Shallow Lakes of the Boreal Plains (Alberta, Canada). *Ecosystems*, *17*, 535–549. https://doi.org/10.1007/s10021-013-9741-5

Cobbaert, D., Wong, A. S., & Bayley, S. E. (2015). Resistance to drought affects persistence of alternative regimes in shallow lakes of the Boreal Plains (Alberta, Canada). *Freshwater Biology*, *60*(10), 2084–2099. https://doi.org/10.1111/fwb.12633

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? *Hydrological Processes: An International Journal*, *19*(8), 1705–1714. https://doi.org/10.1002/hyp.5881

Devito, K., Mendoza, C., & Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. Implications for Watershed reconstruction.

Devito, K. J., Creed, I. F., & Fraser, C. J. D. (2005). Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. *Hydrological Processes*, *19*(1), 3–25. https://doi.org/10.1002/hyp.5776

Devito, K. J., Hokanson, K. J., Moore, P. A., Kettridge, N., Anderson, A. E., Chasmer, L., Hopkinson, C., Lukenbach, M. C., Mendoza, C. A., Morissette, J., Peters, D. L., Petrone, R. M., Silins, U., Smerdon, B., & Waddington, J. M. (2017). Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. *Hydrological Processes*, *31*(15), 2737–2751. https://doi.org/10.1002/hyp.11213

Devito, K. J., Mendoza, C. A., Petrone, R. M., Kettridge, N., & Waddington, J. M. (2016). Utikuma region study area (URSA) – Part 1: Hydrogeological and ecohydrological studies (HEAD). *The Forestry Chronicle*, *92*(1), 57–61. https://doi.org/10.5558/tfc2016-017

Devito, K. J., O'Sullivan, A. M., Peters, D. L., Hokanson, K. J., Kettridge, N., & Mendoza, C. A. (2023). Runoff threshold responses in continental boreal catchments: Nexus of subhumid climate, low-relief, surficial geology, and land cover. *Water Resources Research*, *59*(11), e2023WR034752. https://doi.org/10.1029/2023WR034752

Euliss, N. H., Jr., Mushet, D. M., Newton, W. E., Otto, C. R. V., Nelson, R. D., LaBaugh, J. W., Scherff, E. J., & Rosenberry, D. O. (2014). Placing prairie pothole wetlands along spatial and temporal continua to improve integration of wetland function in ecological investigations. *Journal of Hydrology*, *513*, 490–503. https://doi.org/10.1016/j.jhydrol.2014.04.006

Euliss, N. H., Labaugh, J. W., Fredrickson, L. H., Mushet, D. M., Laubhan, M. K., Swanson, G. A., Winter, T. C., Rosenberry, D., & ONelson, R. D. (2004). *The wetland continuum: A conceptual framework for interpreting biological studies* (p. 269). USGS Northern Prairie Wildlife Research Center.

Fergus, C. E., Brooks, J. R., Kaufmann, P. R., Pollard, A. I., Herlihy, A. T., Paulsen, S. G., & Weber, M. H. (2021). National framework for ranking lakes by potential for anthropogenic hydro-alteration. *Ecological Indicators*, *122*, 107241. https://doi.org/10.1016/j.ecolind.2020.107241

Fergus, C. E., Brooks, J. R., Kaufmann, P. R., Pollard, A. I., Mitchell, R., Geldhof, G. J., Hill, R. A., Paulsen, S. G., Ringold, P., & Weber, M. (2022). Natural and anthropogenic controls on lake water-level decline and evaporation-to-inflow ratio in the conterminous United States. *Limnology and Oceanography*, *67*(7), 1484–1501. https://doi.org/10.1002/lno.12097

Ferone, J. M., & Devito, K. J. (2004). Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology*, *292*(1–4), 75–95. https://doi.org/10.1016/j.jhydrol.2003.12.032

Gibson, J. J., Birks, S. J., Yi, Y., Moncur, M. C., & McEachern, P. M. (2016). Stable isotope mass balance of fifty lakes in central Alberta: Assessing the role of water balance parameters in determining trophic status and lake level. *Journal of Hydrology: Regional Studies*, *6*, 13–25. https://doi.org/10.1016/j.ejrh.2016.01.034

Gibson, J. J., Yi, Y., & Birks, S. J. (2019). Isotopic tracing of hydrologic drivers including permafrost thaw status for lakes across northeastern Alberta, Canada: A 16-year, 50-lake assessment. *Journal of Hydrology Regional Studies*, *26*(August), 100643. https://doi.org/10.1016/j.ejrh.2019.100643

Hayashi, M., van der Kamp, G., & Rosenberry, D. O. (2016). Hydrology of prairie wetlands: Understanding the integrated surface-water and groundwater processes. *Wetlands*, *36*(S2), 237–254. https://doi.org/10.1007/s13157-016-0797-9

Hokanson, K. J., Mendoza, C. A., & Devito, K. J. (2019). Interactions between regional climate, Sur fi cial geology, and topography: Characterizing shallow groundwater Systems in Subhumid, low-relief landscapes. *Water Resources*, *55*, 284–297. https://doi.org/10.1029/2018WR023934

Hokanson, K. J., Rostron, B. J., Devito, K. J., Hopkinson, C., & Mendoza, C. A. (2021). Landscape controls of surface-water/groundwater interactions on shallow outwash lakes: How the long-term groundwater signal overrides interannual variability due to evaporative effects. *Hydrogeology Journal*, *30*(1), 251–264. https://doi.org/10.1007/s10040-021-02422-z

Hutchinson, G. E. (1957). *A treatise on limnology. I*. Geography, Physics, and Chemistry. Wiley.

Ireland, A. W., Booth, R. K., Hotchkiss, S. C., & Schmitz, J. E. (2012). Drought as a trigger for rapid state shifts in kettle ecosystems: Implications for ecosystem responses to climate change. *Wetlands*, *32*(6), 989–1000.

Ireson, A. M., Barr, A. G., Johnstone, J. F., Mamet, S. D., van der Kamp, G., Whitfield, C. J., Michel, N. L., North, R. L., Westbrook, C. J., DeBeer, C., Chun, K. P., Nazemi, A., & Sagin, J. (2015). The changing water cycle: The Boreal Plains ecozone of Western Canada. *Wiley Interdisciplinary Reviews: Water*, *2*(5), 505–521. https://doi.org/10.1002/wat2.1098

Karlsen, R. H., Bishop, K., Grabs, T., Ottosson-Löfvenius, M., Laudon, H., & Seibert, J. (2019). The role of landscape properties, storage and evapotranspiration on variability in streamflow recessions in a boreal catchment. *Journal of Hydrology*, *570*(March), 315–328. https://doi.org/10.1016/j.jhydrol.2018.12.065

Kettridge, N., Lukenbach, M. C., Hokanson, K. J., Hopkinson, C., Devito, K. J., Petrone, R. M., Mendoza, C. A., & Waddington, J. M. (2017). Low evapotranspiration enhances the resilience of peatland carbon stocks to fire. *Geophysical Research Letters*, *44*(18), 9341–9349. https://doi.org/10.1002/2017GL074186

Kettridge, N., Tilak, A. S., Devito, K. J., Petrone, R. M., Mendoza, C. A., & Waddington, J. M. (2016). Moss and peat hydraulic properties are optimized to maximize peatland water use efficiency. *Ecohydrology*, *9*(6), 1039–1051. https://doi.org/10.1002/eco.1708

Kettridge, N., & Waddington, J. M. (2014). Towards quantifying the negative feedback regulation of peatland evaporation to drought. *Hydrological Processes*, *28*(11), 3728–3740. https://doi.org/10.1002/hyp.9898

Kolding, J., & van Zwieten, P. A. M. (2012). Relative lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. *Fisheries Research*, *115-116*, 99–109. https://doi.org/10.1016/j.fishres.2011.11.008

Kraemer, B. M., Seimon, A., Adrian, R., & McIntyre, P. B. (2020). Worldwide lake level trends and responses to background climate variation. *Hydrology and Earth System Sciences*, *24*(5), 2593–2608.

LaBaugh, J. W., Rosenberry, D. O., Mushet, D. M., Neff, B. P., Nelson, R. D., & Euliss, N. H. (2018). Long-term changes in pond permanence, size, and salinity in prairie pothole region wetlands: The role of groundwater-pond interaction. *Journal of Hydrology: Regional Studies*, *17*, 1–23. https://doi.org/10.1016/j.ejrh.2018.03.003

Laudon, H., Spence, C., Buttle, J., Carey, S. K., McDonnell, J. J., McNamara, J. P., Soulsby, C., & Tetzlaff, D. (2017). Save northern high-latitude catchments. *Nature Geoscience*, *10*(5), 324–325. https://doi.org/10.1038/ngeo2947

Leader, S. N. (2021). Landscape controls on lake-peatland-forestland hydrology within the Boreal Plains (Doctoral dissertation, University of Birmingham).

Lee, S. Y., Ryan, M. E., Hamlet, A. F., Palen, W. J., Lawler, J. J., & Halabisky, M. (2015). Projecting the hydrologic impacts of climate change on montane wetlands. *PLoS One*, *10*(9), e0136385. https://doi.org/10.1371/journal.pone.0136385

Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M., & Hornik, K. (2019). Cluster: Cluster analysis basics and extensions.

Molinos, J. G., Viana, M., Brennan, M., & Donohue, I. (2015). Importance of long-term cycles for predicting water level dynamics in natural lakes. *PLoS One*, *10*(3), 1–12. https://doi.org/10.1371/journal.pone.0119253

Morissette, J. L., Kardynal, K. J., Bayne, E. M., & Hobson, K. A. (2018). Are boreal riparian bird communities unique? Contrasting riparian and upland bird assemblages in the Boreal Plain of Western Canada. *Wetlands*, *38*(6), 1299–1311. https://doi.org/10.1007/s13157-018-1054-1

Mwale, D., Gan, T. Y., Devito, K., Mendoza, C., Silins, U., & Petrone, R. (2009). Precipitation variability and its relationship to hydrologic variability in Alberta Davison. *Hydrological Processes*, *23*, 3040–3056. https://doi.org/10.1002/hyp

Mwale, D., Gan, T. Y., Devito, K. J., Silins, U., Mendoza, C., & Petrone, R. (2011). Regionalization of runoff variability of Alberta, Canada, by wavelet, independent component, empirical orthogonal function, and geographical information system analyses. *Journal of Hydrologic Engineering*, *16*(2), 93–107. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000284

Olefeldt, D., Devito, K. J., & Turetsky, M. R. (2013). Sources and fate of terrestrial dissolved organic carbon in lakes of a Boreal Plains region recently affected by wildfire. *Biogeosciences*, *10*(10), 6247–6265. https://doi.org/10.5194/bg-10-6247-2013

Oswald, C. J., Richardson, M. C., & Branfireun, B. A. (2011). Water storage dynamics and runoff response of a boreal shield headwater catchment. *Hydrological Processes*, *25*(19), 3042–3060. https://doi.org/10.1002/hyp.8036

Perales, K. M., Hein, C. L., Lottig, N. R., & Vander Zanden, M. J. (2020). Lake water level response to drought in a lake-rich region explained by lake and landscape characteristics. *Canadian Journal of Fisheries and Aquatic Sciences*, *77*(11), 1836–1845.

Plach, J. M., Ferone, J., Gibbons, Z., Smerdon, B. D., & Mertens, A. (2016). Influence of glacial landform hydrology on phosphorus budgets of shallow lakes on the Boreal Plain, Canada. *Journal of Hydrology*, *535*(May 2018), 191–203. https://doi.org/10.1016/j.jhydrol.2016.01.041

Price, D. T., Alfaro, R. I., Brown, K. J., Flannigan, M. D., Fleming, R. A., Hogg, E. H., Girardin, M. P., Lakusta, T., Johnston, M., Mckenney, D. W., Pedlar, J. H., Stratton, T., Sturrock, R. N., Thompson, I. D., Trofymow, J. A., & Venier, L. A. (2013). Anticipating the consequences of climate change for Canada's boreal forest ecosystems. *Environmental Reviews*, *21*(December), 322–365. https://doi.org/10.1139/er-2013-0042

Pugh, E. A., Olefeldt, D., Leader, S. N., Hokanson, K. J., & Devito, K. J. (2021). Characteristics of dissolved organic carbon in Boreal Lakes: High spatial and inter-annual variability controlled by landscape attributes and wet-dry periods. *Water Resources Research*, *57*(11), e2021WR030021. https://doi.org/10.1029/2021wr030021

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rosenberry, D. O., Lewandowski, J., Meinikmann, K., & Nutzmann, G. (2015). Groundwater-the disregarded component in lake water and nutrient budgets, part 1: Effects of groundwater on hydrology. *Hydrological Processes*, *29*(13), 2895–2921. https://doi.org/10.1002/hyp.10403

Sass, G. Z., Creed, I. F., Bayley, S. E., & Devito, K. J. (2007). Understanding variation in trophic status of lakes on the Boreal Plain: A 20 year retrospective using Landsat TM imagery. *Remote Sensing of Environment*, *109*(2), 127–141. https://doi.org/10.1016/j.rse.2006.12.010

Scheffer, M., Carpenter, S. R., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems review. *Nature*, *413*(October), 167–196. https://doi.org/10.1130/0-8137-2366-3.167

Shook, K. R., & Pomeroy, J. W. (2011). Memory effects of depressional storage in northern prairie hydrology. *Hydrological Processes*, *25*(25), 3890–3898. https://doi.org/10.1002/hyp.8381

Smerdon, B. D., Devito, K. J., & Mendoza, C. A. (2005). Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. *Journal of Hydrology*, *314*(1–4), 246–262. https://doi.org/10.1016/j.jhydrol.2005.04.001

Smerdon, B. D., Mendoza, C. A., & Devito, K. J. (2007). Simulations of fully coupled lake-groundwater exchange in a subhumid climate with an integrated hydrologic model. *Water Resources Research*, *43*(1). https://doi.org/10.1029/2006WR005137

Soulsby, C., Birkel, C., & Tetzlaff, D. (2016). Modelling storage-driven connectivity between landscapes and riverscapes: Towards a simple framework for long-term ecohydrological assessment. *Hydrological Processes*, *30*(14), 2482–2497. https://doi.org/10.1002/hyp.10862

Spence, C. (2010). A paradigm shift in hydrology: Storage thresholds across scales influence catchment runoff generation. *Geography Compass*, *4*(7), 819–833. https://doi.org/10.1111/j.1749-8198.2010.00341.x

Spence, C., & Woo, M. K. (2006). Hydrology of subarctic Canadian shield: Heterogeneous headwater basins. *Journal of Hydrology*, *317*(1–2), 138–154. https://doi.org/10.1016/j.jhydrol.2005.05.014

Stralberg, D., Arseneault, D., Baltzer, J. L., Barber, Q. E., Bayne, E. M., Boulanger, Y., Barber, Q. E., Brown, C. D., Cooke, H. A., Devito, K., Edwards, J., Estevo, C. A., Flynn, N., Frelich, L. E., Hogg, E. H., Johnston, M., Logan, T., Matsuoka, S. M., Moore, P., … Whitman, E. (2020). Climate-change refugia in boreal North America: What, where, and for how long? *Frontiers in Ecology and the Environment*, *18*(5), 261–270. https://doi.org/10.1002/fee.2188

Tetzlaff, D., Carey, S. K., Mcnamara, J. P., Laudon, H., & Soulsby, C. (2017). The essential value of long-term experimental data for hydrology and water management. *Water Resources Research*, *53*, 2598–2604. https://doi.org/10.1002/2017WR020838.Received

Tetzlaff, D., Soulsby, C., Buttle, J., Capell, R., Carey, S. K., Laudon, H., McDonnell, J., McGuire, K., Seibert, S., & Shanley, J. (2013). Catchments on the cusp? Structural and functional change in northern ecohydrology. *Hydrological Processes*, *27*(5), 766–774. https://doi.org/10.1002/hyp.9700

Thompson, C., Mendoza, C. A., & Devito, K. J. (2017). Potential influence of climate change on ecosystems within the Boreal Plains of Alberta. *Hydrological Processes*, *31*(11), 2110–2124. https://doi.org/10.1002/hyp.11183

Thompson, C., Mendoza, C. A., Devito, K. J., & Petrone, R. M. (2015). Climatic controls on groundwater-surface water interactions within the Boreal Plains of Alberta: Field observations and numerical simulations. *Journal of Hydrology*, *527*, 734–746. https://doi.org/10.1016/j.jhydrol.2015.05.027

Tsyganov, A. N., Kupriyanov, D. A., Babeshko, K. V., Borisova, T. V., Chernyshov, V. A., Volkova, E. M., Chekova, D. A., Mazei, Y. A., & Novenko, E. Y. (2019). Autogenic and allogenic factors affecting development of a floating sphagnum-dominated peat mat in a karst pond basin. *Holocene*, *29*(1), 120–129. https://doi.org/10.1177/0959683618804631

van der Kamp, G., Keir, D., & Evans, M. S. (2008). Long-term water level changes in Closed-Basin Lakes of the Canadian prairies. *Canadian Water Resources Journal*, *33*(1), 23–38. https://doi.org/10.4296/cwrj3301023

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology*, *8*(1), 113–127. https://doi.org/10.1002/eco.1493

Warner, B. G., Kubiw, H. J., & Hanf, K. I. (1989). An anthropogenic cause for quaking mire formation in southwestern Ontario. *Nature*, *340*(6232), 380–384. https://doi.org/10.1038/340380a0

Watras, C. J., Michler, J. R., & Rubsam, J. L. (2022). Monitoring the water balance of seepage lakes to track regional responses to an evolving climate. *Canadian Journal of Fisheries and Aquatic Sciences*, *79*(7), 1056–1063. https://doi.org/10.1139/cjfas-2021-0217

Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's Boreal Zone, 23(1), 78–131.

Winter, T. C. (2000). The vulnerability of wetlands to climate change: A hydrologic landscape perspective. *Journal of the American Water Resources Association*, *36*(2), 305–311. https://doi.org/10.1111/j.1752-1688.2000.tb04269.x

Winter, T. C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association*, *37*(2), 335–349.

Winter, T. C., Rosenberry, D. O., & Labaugh, J. W. (2003). Where does the ground water in small watersheds come from? *Groundwater*, *41*(7), 989–1000. https://doi.org/10.1111/j.1745-6584.2003.tb02440.x

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Leader, S., Kettridge, N., Hannah, D., Mendoza, C., & Devito, K. J. (2024). Diverse response of shallow lake water levels to decadal weather patterns in a heterogeneous glacial Boreal Plains landscape. *Hydrological Processes*, *38*(4), e15125. https://doi.org/10.1002/hyp.15125