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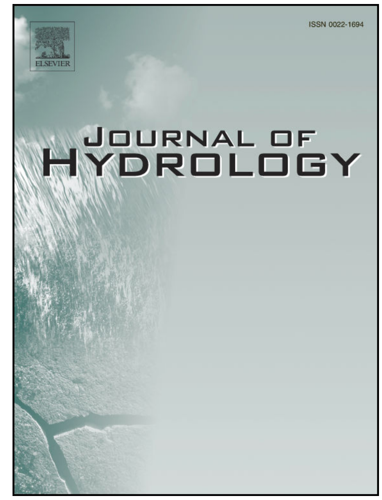

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MULTI-YEAR CLIMATE MEMORY IN SHALLOW LAKE WATER LEVELS

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

[1]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.; samantha.n.leader@gmail.com, ORCID ID 0000-0002-4545-1169, n.kettridge@bham.ac.uk, ORCID ID 0000-0003-3995-0305, d.m.hannah@bham.ac.uk, ORCID ID 0000-0003-1714-1240

[2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada T6G, Carl.Mendoza@UAlberta.ca, ORCID ID 0000-0002-2731-0004

[3]Department of Biological Sciences, University of Alberta, Edmonton, AB, T6G 2E3, Canada. ORCID ID 0000-0002-8216-0985

[4]Canadian Rivers Institute, University of New Brunswick, Fredericton, Canada, P.O. Box 4400, Fredericton, NB, E3B 5A3, Canada.

*Corresponding author: Nicholas Kettridge, School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK, B15 2TT

Email: n.kettridge@bham.ac.uk

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Abstract

Landscape hydrologic memory of meteorological cycles can have an important impact on catchment hydrological responses by propagating clustering of wet or dry conditions into extreme events. The non-linear and hysteretic hydrologic response functions driven by memory are often only studied at shorter temporal scales (event, season) despite larger interannual hydrologic responses evident in some systems. Within the Canadian Boreal, lakes and lake water levels provide an important indicator that can be used to assess the role of landscape memory on catchment hydrological function. Landscape memory has also been hypothesised to control the hydrological dynamics of shallow lake ecosystems that are also important biogeochemically and ecologically. Here we combine measurements of lake water levels in 26 lakes of varying type at varying temporal frequencies within the glaciated sub-humid Boreal Plain, to examine the impact and variability of interdecadal, decadal, multi-year, intra-annual memory on lake water levels. We show multi-annual hysteresis of precipitation-lake water levels with varied characteristics in space and time. These spatial variations in landscape memory are driven by differences in storage capacities controlled by heterogeneity in glacial landforms, wetland-forest landcover and lake properties. Thus, the propensity for drought years or wet years to persist or accumulate into extreme landscape drying or wetting varies significantly between different lake-landscape characteristics. We show how landscape memory is crucial to project lake water levels by defining spatial variability of the impact of periods of meteorological drought and deluge vital for understanding system sensitivity, duration of recovery and in turn infer resilience on Boreal Plain hydrology.

KEY WORDS: meteorological cycles; Boreal Plains; glacial landscapes; drought; water levels; hysteresis

1. Introduction

Typically, hysteresis in hydrology is observed and studied at an event scale, such as rainfall-runoff or storage-discharge for one storm or across a single year (Ali et al., 2015). However, landscape hydrologic memory of antecedent conditions in some systems can form multi-year climate memory and hysteresis loops otherwise known as long-range dependence, long-term persistence, or the 'Hurst' phenomenon (Hurst, 1951). Understanding this long-term hydrologic memory, hereafter termed memory, is important due to the impact on the timing, magnitude and clustering of extreme events (Khanal et al., 2019; Bunde et al., 2005), and the increase in the uncertainty of related hydrological processes (Koutsoyiannis, 2005). Lakes can act as important storage bodies in the landscape and are indicative of the landscape response (hysteresis, non-linear, threshold) to meteorological cycles observed in specific climates. Lakes thus act as important test beds to examine core conceptualisations of hydrological memory that operate at a catchment scale over multi-annual to decadal time periods. Antecedent storage in lakes also represents an important regulator of catchment connectivity and thus also drives further non-linearity and hysteresis of the hydrological system (Spence, 2010).

Geology impacts landscape memory by determining water storage and transmission capacities (Winter, 2001; Hokanson et al., 2019; Devito et al., 2023). The filling of depression storage (fill and spill) is a widely applied concept and form of memory in both the humid Boreal Shield and the semi-arid Prairie Pothole Regions. Within the Prairie Pothole Region this depression storage produces multi-year memory reflecting the balance of P to PET within isolated basins (Shook and Pomeroy 2011), whereas storage-driven seasonal responses in the Precambrian Shield bedrock lakes (Spence et al., 2019) are associated with variable connectivity processes such as gatekeeper lakes (Phillips et al., 2011). In contrast, water tables in coarse outwash lakes are driven by range in local to large scale groundwater flows (Smerdon et al.,2005; Hokanson, et al., 2021a), whereby memory is associated with lag, an autoregressive delay in response water level to climate, due to transit time through a catchment. While numerous studies have examined hysteresis responses in lakes, ponds and wetland water levels to climate (e.g. Hayashi et al., 2016; LaBaugh et al., 2018) or the influence of hydrogeological setting (Winter, 2001), few studies have attempted to characterise hysteresis characteristics (i.e. loop direction, shape, size) and their associated hydrological processes to assess the role of multi-annual memory across diverse hydrogeologic settings (Buttle, 2016).

We assess the role of multi-annual memory on shallow lake water levels within the Boreal Plain. Shallow lakes are ubiquitous in the low relief glaciated Boreal Plains (BP) of Canada. They are critical aquatic habitats (Morissette et al., 2018) that require effective management in response to extreme landscape and climate mitigation pressures (Price et al., 2013; Ireson et al., 2015). But Boreal Plain lakes likely exhibit a diversity of responses to decadal weather patterns because of their varied hydrogeologic settings (Leader et al., 2024; Leader et al., submitted WRR). Contrasts in storage and runoff result from thick glacial substrates that differ markedly in their texture, set within a sub humid climate with a strong and decadal climate signature (Devito et al.,2023; Hokanson et al., 2019). Lake responses to the climate signal result from spatially variable and interacting internal (lake) and external (landscape) controls on hydrology within the boreal plain (Leader et al., 2024; Leader et al.,submitted; Plach et al., 2016; Smerdon et al., 2007). These controls suggest the prevalence of multi-annual hysteresis of water levels of varying periodicities across multiple types of Boreal and glacial lake systems.

The aim of this paper is to evaluate how multi-year landscape memory of precipitation (P) varies spatially within shallow lake water levels (WL) across the range of lake-landscape types of the sub-humid Boreal Plains to address the following research questions:

1. What are the general characteristics of precipitation-water level (P-WL) hysteresis and how do they reflect hypothesised hysteresis loops based on different conceptualised storage-threshold relationships between different lake-landscape characteristics?
2. The significance of memory is different at different temporal scales, ranging from seasonal to interannual and therefore what additional insights are gained by considering landscape memory at multiple temporal scales?
3. Does landscape memory cause temporally different short term lake level response to weather due to position within the long-term meteorological cycles?

Differences in interannual hysteresis loops between Boreal Plain lakes are conceptualized by considering different landscape/lake memories to meteorological cycles (represented by cumulative departures from the long term mean). This is considered in the context of *a priori* conceptual understanding of the different response functions of surficial geologies typical of the BP (Table 1). We predict varying hysteresis loop types due to differing dominant sources of flow, transit times and storage-threshold mechanisms.

Landscapes with a low storage capacity are hypothesised to produce a short memory of climate, with rapid recovery following drought conditions (Devito et al., 2023; Ferone and Devito, 2004; Lukenbach et al., 2017). However, complex feedback mechanisms, i.e. due to rates of drying varying as a function of drought length and severity within peatlands between wetting and drying periods (Kettridge & Waddington, 2014), may produce irregular figure-eight shaped hysteresis loops. Shallow lakes are hypothesised to exhibit frequent resetting of landscape memory as the lakes spill and dry out. This will produce parallelogram loops due to periods of no lake level change due to threshold exceedance (Hokanson et al., 2021a; Thompson et al. 2015).

Difference in loop size is determined by the magnitude of lake level variability. High storage within closed fine textured lake basins connected to high storage catchments (Leader et al., 2024) are expected to produce the longest landscape memory and the large hysteresis loops (Shook and Pomeroy 2011). Whereas landscapes with larger scale groundwater flows (Leader et al., submitted; Hokanson et al., 2021a) could produce consistent low magnitude WL responses and subsequently smaller hysteresis loops. However, receiving lakes in low landscape positions may display complex temporal variability due to gatekeeper processes (Winter 1999; Gibson et al., 2002), with changes in landscape connectivity at different points along the meteorological cycle (Mwale et al., 2011). Differences in precipitation WL responses between lake types are hypothesised to be amplified under dry conditions. This is due to i) larger differences in catchment storage capacities ii) larger differences in ratios of runoff generating landscape to lake proportions and iii) the influence of within lake feedbacks (Hayashi and van der Kamp, 2007). During extended wet cycles, WL responses may synchronise as landscape storage deficits are filled and spatial differences in antecedent conditions become less important (Buttle 2016; Devito et al., 2023).

Characterising such landscape memory within the context of the long-term meteorological cycle, and across common lake types will not only provide a greater understanding of the impact of memory on extreme landscape responses (drought and deluge), but will also significantly improve integration of antecedent conditions and associated hydrological processes within hydrological modelling at multiple temporal scales.

2. Study Area

The study was conducted in the Utikuma Region Study Area (URSA; 56°N, 115°W; Supplementary Figure S1, Leader et al., 2024), situated within the sub-humid Boreal Plains (BP) ecozone of Alberta, Canada, where long term annual average PET (513 mm) exceeds annual average P (483 mm; Plach et al., 2016; NRC, 2006). The region is exposed to strong decadal meteorological cycles, with wet years occurring infrequently on approximately 20 year cycle (Mwale et al., 2009), in addition to a pronounced seasonal weather cycle with cold winters (January temperatures of -14.5°C) and warm summers (July temperatures of 15.6°C; Thompson et al., 2015). Peak vegetation growth and evaporative demand overlaps with the majority of annual precipitation, with 60% falling the three months of June to August (Devito et al., 2005). Although contributing a smaller proportion of total annual precipitation, snowfall and snowmelt and the occurrence of heavy spring rains provide a crucial component of the water balance by replenishing soils and recharging groundwater (Devito et al., 2012).

The URSA is characterised by low relief deep (45-240 m), Quaternary deposits overlaying shale bedrock that limit regional groundwater interactions with streams and lakes (Hokanson et al., 2019; Plach et al., 2016). The surficial glacial deposits have been previously classified into three hydrologic response areas (HRAs) with similar storage and transmissivity properties: (1) coarse-textured glacial–fluvial outwash (CO); (2) fine-textured clay rich glacio-lacustrine plains (FP); (3) fine-textured hummocky moraine deposits (FH); (Leader et al.,2024; Hokanson et al., 2019).The overlying vegetation is characterised by a mosaic of forests, wetlands (peatlands), and ponds and shallow lakes that have been further discretized into hydrologic units (HU) representing contrasting soil-vegetation and hydrologic storage and transmission properties (Devito et al., 2012, 2017; Hokanson et al., 2020). Peatland wetlands are ubiquitous through the landscape and dominated by black spruce (Picea mariana) and tamarack (Larix laricina), whilst forestlands are characterized by trembling aspen (Populus tremuloides) or jack pine (Pinus banksiana) associated with surficial geology (NRC, 2006; Redding and Devito, 2011).

This study comprises of 26 study lakes located along a 40 km transect that covers the three HRAs typical of the Boreal Plains (Devito et al., 2023; NRC, 2006). Lakes were selected strategically to include the diversity in surficial geology, land cover, topography, lake geometry and lake types observed within the URSA and the Boreal Plain. This larger synoptic lake series include four detailed study lakes that represent the range of lake types in the URSA, and were sampled year round and at a higher frequency (Leader et al., 2024). The lakes were classified and grouped previously by Leader et al. (2024) based on the Hutchinson's (1957) glacial lake type and the dominant HRA of the connected catchment (Table 4). These include: (1) Outwash flow through lakes with the lake basin and associated surface and phreatic catchment located in coarse textured glaciofluvial HRA (Outwash-CO, includes detailed lake 16); (2) Closed basin lakes situated on HRAs designated as CO, but the headwater catchments have hummocky morphology fine-textured deposits overlaying (perched) coarse deposits not indicated on regional mapping (Hokanson et al., 2019) (Closed-FH, includes Lake 19); (3) Glacial moraine spilling lakes with basin and catchments on fine textured hummocky moraine HRAs (Moraine-FH; detailed lake 43); (4) peatland spilling lakes on glaciolacustrine clay plain with low relief catchments dominated by fine textured HRAs and large peatland coverage (Peat-FP, includes detailed lake 171); and (5) similar peatland spilling lakes on glaciolacustrine clay plain HRA but the connected catchments are dominated FH HRAs (Peat-FH). The areas of the lakes range 0.0005 to 3.2 km^2 and topographic or phreatic catchments range from 0.08 to 90 km^2 that vary from isolated headwater systems to large regionally connected systems and ranging in proportion of peatland and forestland cover (Leader et al., 2024; see Supplementary Information).

3. Methods

3.1. Climate variables and climate-driven temporal study design for memory testing

Climate data and variables

Daily precipitation and mean, maximum and minimum air temperatures have been monitored for 23 years (1995-2018) within the URSA and wider study region (see Supplementary Material section 2.1; Leader et al., 2024; Devito et al., 2016). Study lakes are all within 40 km of each other and were subject to similar weather and climate conditions (Devito et al., 2016; Hokanson et al., 2021). Records from 4 meteorological stations along the 40 km lake survey transect from 1999 to 2018 were collected (Figure S1, Leader et al., 2024).

Lag climate variables were devised to identify autoregressive responses associated with varying transit times, whereas cumulative climate variables are formulated to associate antecedent conditions and storage capacities with response. Precipitation lag value relative to the long-term mean (Lag P), and precipitation cumulative deviation from the long-term mean (CDM P) variables for memory periods of 0 – 5 years and 1 - 6 years respectively, were generated using the following equations (see Winter 2000; Hokanson et al. 2019):

Equation 1. $$\text{Lag}\ X\text{yr}\ d = \left(\sum_{d-X-1year}^{d-X} P \right) - \mu;$$

Equation 2. $$\text{CDM}\ X\text{yr}\ d = \left(\sum_{d-X}^{d} P \right) - (\mu \times X);$$

where *X* is the length of time for which the climate variable is calculated (in years), *d* is the date of the calculated climate variable, *P* is daily precipitation total (mm), μ is the long-term mean of annual precipitation (November hydrologic year), given as 444 mm for the study region. CDM P (mm) for 1 – 6 years is presented in Figure 1 for 1997-2019.

Lake water level data

The elevation of water levels were measured at 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 during all sampling periods (see Supplementary Material section 2.2 and Leader et al., 2024). In the earlier synoptic survey (1999-2004), instantaneous WL measurements were periodically measured between lake ice off and autumn conditions. In the later synoptic survey (2012-2018) at least one water level measurement was conducted in the final week of June or first week of July. Summer rainfall and runoff (small or large) represent a large portion of annual inputs to the BP lake water balance, thus the summer period represents relatively continuous high water levels or lower water levels for a given year. Therefore, maximum summer water levels were derived from measurements taken June 1st to August 31st in the earlier survey were collated with single July sample during the later survey that have previously been shown to reflect interannual range in water levels for each lake during the two sampling period (see also Leader et al., 2024). For the four detailed study Lakes (lakes 16, 19, 43, and 171) representing four different lake-catchment classifications (see Supplementary Material Table S1), water levels 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 water levels were calculated during periods with continuous records and augmented with instantaneous WL measurements when continuous records were not available. See Leader et al., (2024) for further information.

Climate-driven temporal study design

Analyses are conducted over four temporal scales for this study representing a trade-off between spatial and temporal scales (Table 2): 1) *Interdecadal scales*: World Satellite Imagery was obtained from Esri and combined with historical aerial photography of the URSA (8 images evenly disturbed across a 70-year period). Lake surface area was then delineated for each satellite image of Lake 19 and regression analysis conducted between lake area and CDM P 1-6yr (mm) to determine the effects of memory at interdecadal scales. 2) *Decadal scale*: Interannual summer water levels of 26 study lakes across 19 years - the full field-based measurement period - is used to assess spatial variability in responses at the decadal scale. Higher frequency sampling is required to analyse shorter term cycles, and these were limited to the analyses of trends in WL of the four detailed study lakes. 3) *Multi-year responses*: Interannual summer water levels of four detailed study lakes across multiannual wetting drying cycles. Three multi-annual periods were identified representing dry (2000-2004), dry-mesic (2008-2012) and mesic (2013-2018) conditions within the long-term climate cycle based on the 1-year cumulative departure from the long-term mean (wet, >100 mm P CDM; mesic, -100 mm < P CDM < 100 mm; dry, <-100 mm P CDM). 4) *Intra-annual*: For intra-annual analyses, 11 growing seasons (May 1st – September 30th) of the four detailed study lakes were identified and classified based on the directionality (wetting or drying) and value of the CDM P 1yr (mm) (Table 3) providing their context within the long-term climate. The variability and wet-dry cycles at different temporal scales are evident in the time series illustrated in Figure 1.

3.3. Data Analysis

Autocorrelation and cross correlation were undertaken in R (R Core Team, 2021). Daily and annual climate records of URSA were tested to establish whether the cyclical meteorological patterns produced autocorrelation (Supplementary Figure S1). For interannual summer water levels analyses, the average summer water level is correlated with precipitation and cumulative precipitation corresponding with the July 1 to June 30 hydrologic year, and a lag of 1 corresponds to 1 year. Where higher frequency water levels are tested, the cumulative precipitation (CDM P) relative to the long-term mean was correlated against water levels of the same day.

4. Results

4.1. Interdecadal memory

Historic satellite imagery of the Closed-FH Lake 19 has revealed more than 4-fold change in lake surface area extent since 1951 due to interdecadal water level fluctuations (Figure 2), ranging from 9674 m^2 in 2011 to 38930 m^2 in 1977, with perimeter varying two-fold between these records (476 m – 933 m). Climate-lake water level correlation strength and significance were considerably greater with longer cumulative climate variables of CDM P 4yr ($r = 0.88$, $p = 0.004$), CDM P 5yr ($r = 0.88$, $p = 0.0042$) and CDM P 6yr ($r = 0.87$, $p = 0.0047$) than one-year cumulative deviation from the long term mean in precipitation (CDM P 1yr; 444 mm; $r = 0.63$, $p=0.093$). Relatively low lake surface area occurred in 1951 despite above average rainfall for that year (74mm CDM P 1yr) as landscape antecedent conditions reflect a long-term precipitation deficit following 8 consecutive years of below average rainfall (CDM 6yr P = -320mm in July 1951). Similarly, 1965 surface water area is greater than expected for a CDM 1yr P value of -88 mm. Instead, 1965 lake water levels reflect memory of ~10 years of above average rainfall and thus a CDM 6yr P value of +210mm. This clearly demonstrates the importance of multi-annual memory of climate within this landscape, whereby clustering of wet or dry years propagate into extreme wetting and drying of the landscape.

4.2. Decadal scale - Spatial variability in memory between different lake-landscape characteristics across 19 years

Interannual summer lake water level response to annual precipitation totals (July 1 hydrologic year) produced hysteresis loops in all 26 study lakes (Figure 3). Graphical comparisons reveal high variability in the shape, size and direction of hysteresis loops spatially among lakes (see summary in Table 4). The varied characteristics of hysteresis loops indicate that complex and spatially variable memory is present in the landscape in time and in space.

A consistent response is observed across URSA in the dry year of 2002, where large decreases in water levels occur in all lakes (Figure 3 and 4,). However, the subsequent responses to wet conditions in 2003 vary substantially between lakes. This is exemplified by shallow Moraine-FH lakes, some of which dried out in 2002. These lakes could not dry further and produced parallelogram shaped loops. Peat-FP lakes display the greatest lake water level increases in 2003, producing elliptical or rapid-wetting figure-eight loops. In contrast, Outwash-CO lakes are the only class to display continued drying in 2003 in most lakes. Comparisons of loops for two of the 6-year cycles (period 1: 1999-2004 and period 3: 2013-2018) demonstrate consistent hysteresis responses between periods in some lakes and highly contrasting responses in others (Figure 3). This occurs due to the similar CDM P 1yr pattern for each period, enabling landscapes with low memory to produce consistent hysteresis loops (e.g. Moraine-

FH or Peat-FP and Peat-FH lakes 122, 121, 118), whereas lakes associated with longer CDM P control display contrasting hysteresis loops between periods (e.g. Closed-FH lakes 7, 15, 19). Therefore, systems with greater memory produced larger hysteresis loops and shallower water levels or desiccation in the long-term dry period of 2000-2005.

For each CDM P length (1-5 years), the cross-correlation function (CCF) value is displayed for the optimal lag (highest CCF) in Figure 4. The magnitude of CCF, the association with CDM precipitation periods and the variability in response between lakes differs between different lake-catchment classes. Cross correlation plots of Outwash-CO lakes demonstrate high similarity between lakes, with the exception of lake 1. Generally, Outwash-CO lakes produced highest CCF values for CDM P 1-3yrs with 0 lag, whereas the largest lakes (5 and 17) exhibit higher CCF for longer CDM variables. Closed-FH lakes that typically located in headwaters and/or perched above the CO HRA (Lake 11, 19, 15 and Moraine-FH lake 48) exhibit the poorest CCF values and longest lags, signifying poor association with climate at decadal scales due to interactions with antecedent moisture. Peat lakes with FP or FH catchments are positioned in plateau or extensive valley regions with low relief and with larger lake surface area for their fine-textured surficial geology class (39, 27, 42 & 121, 118; Leader et al, submitted) also exhibited low CCF and low synchronicity between lake types. In contrast, small and spilling, high landscape positioned Moraine-FH lakes (40, 43, 111, and peat-FP lake 171) produced high CCF values at 3year CDM**.** Of the peat lakes, lakes with catchments dominated by FH HRA's (59, 112 and 122) produced high CCF values at varying CDM variables. In contrast, peat lakes with large catchments dominated by FP HRA and peatlands (168 and 205, Peat-FP) produces low CCF values, which could signal complex response patterns as a function of variable hydrologic connectivity with continuous wetland distribution.

4.3. *Multi-year responses*: placing shorter-term responses in context of the long-term climate

Multi-year hysteresis loop plots plotted for the four detailed study lakes (Figure 5) demonstrate contrasting responses between each lake and between each 5/6 year time period. In each period, Closed-FH lake 19 produces the largest hysteresis loops due to the greatest water level declines with no recovery of water levels in 2000-2004 and continued drying in 2008-2012 (Supplementary Figure 6). Moraine-FH Lake 43 produces similar limited recovery of water levels in 2000-2004 and 2008-2012, however the magnitude of responses is varied between years. Lower declines in 2002 and greater recovery was possible in 2003 due to the lake desiccation in summer 2002, whereas higher antecedent water levels within the dry/mesic period enables greater drying in 2009-2010. Similarly, Peat-FP lake 171, in low relief plateau landscape position and peatland dominated catchment, produces highly variable responses between periods, producing a large figure-eight hysteresis loop 2000-2004, and a linear, low magnitude response in 2008-2012. In contrast, the water levels in low landscape position Outwash-CO lake 16 do not decline to the same magnitude during dry periods, and also show an increase during dry years which could reflect lagged response to meteorological cycles.

Regression analysis of high frequency detailed lake water level data against CDM P for 1 to 3 years (Figure 6) generally indicates higher, but contrasting association with CDM 2yr P across all lake types. For the Closed-FH lake 19 and Moraine-FH lake 43 CDM 2yr P provides the highest association, whilst CDM 3yr P provide the highest association for the Outwash-CO lake 16 and Peat-FP lake 171. Whereas other lakes display improved linear relationships, Closed-FH lake 19 produces a hockey stick shape, with low gradient response under precipitation deficit conditions but high response under above average cumulative precipitation. Figure 6 also indicates individual years which have improved residuals when lake water levels are fitted within the regression analysis linearly to longer cumulative climate variables (e.g. 2001, 2003, 2014). Understanding which years fit poorly (high residuals) to CDM 1yrm which signifies presence of multi-annual memory supports interpretation from interannual analysis. Notably, CDM 3yr P significantly improves the residuals of high lake water levels for Outwash-CO lake 16 during the long-term dry climatic conditions in 2001. Meanwhile, large negative residuals of low water levels in 2003 for Peat-FP lake 171 and 2003-2004 for Moraine-FH lake 43 signify memory of dry conditions which are better predicted with CDM 2/3yr P. High water levels during the dry summer of 2014 are also better represented by CDM 2/3yr P across all four lake types due to memory of wet conditions within 2013, as is also true for 2009 in Closed-FH lake 19 and Moraine-FH lake 43 following prolonged above average precipitation 2005-2009.

4.4. Intra-annual Weather- Lake WL Responses

Comparison of intra-annual weather and lake WL, grouped by different weather multi-annual weather classes (Dry, Mesic Dry, Wet to Mesic, Dry to Mesic, Mesic to Wet; Figure 7) demonstrates differing annual lake WL responses between years that are driven by memory (Table 3). Similar short-term net precipitation totals in dry years 2002 and 2010 (pink 'Dry' segment; Figure 7) produced comparable rates in lake levels decline through the year, however, lake water levels display greater magnitude rewetting responses to rainfall events in 2010 when in a wetter long-term meteorological cycle. Contrasting responses between lakes to rainfall events in 2002 reiterates the rapid post-drought recovery rate of peatland systems (Peat-FP lake 171) shown in 2003 and 2004 of Supplementary Figure 6 and 7. However, intra-annual data provides evidence for greater post-drought rewetting in Peat-FP lake 171 in late summer, when growing season evaporative demand is high but precipitation is typically low. Moraine-FH Lake 43 displays the greatest magnitude of water level declines within 2010, which implies lower retention of wet conditions 2005-2009 due to lake outflow generation during this period. Years 2003 and 2011 (green 'Dry to Mesic'; Figure 7) also have a comparable short term mesic climate and wet summer. Peat-FP Lake 171 continues to wet up the greatest in 2003 following the prolonged precipitation deficit, whereas under mesic long-term conditions, Moraine-FH lake 43 and closed-FH lake 19 display the greatest increases in lake levels, suggesting changes in the precipitation-lake water level gradients with CDM P value.

Four short-term 'wet to mesic' years (light blue segment; Figure 7) were identified within the study period, each with contrasting growing season P and long-term meteorological cycles. Within these years, both 2009 and 2014 represent dry summers following prolonged wet periods and lake outflow generation in spilling lakes, and produce near linear drying trends throughout the growing season in all lakes. Drier long-term conditions in 2014 than 2009 (111 mm drier CDM 3yr P; 401 mm drier CDM 5yr P) result in steeper gradients and greater magnitude decreases in lake water levels. Under these dry conditions we also observe a change in order of the gradient and magnitude response of each lake in comparison to mesic and wet years. Outwash-CO Lake 16 exhibits the lowest drying rate in 2009, but highest in 2014, which could reflect greater association with the long-term climate. Rates and patterns are similar between lakes 43, 19 and 171, however Peat-FP lake 171 water levels dry at a slow rate, diverging from closed-FH lake 19 and Moraine-FH lake 43 in mid-August, whereas lake Closed-FH 19 displays greater rates of water level decline in 2014 than Peat-FP lake 171 and Moraine-FH lake 43 throughout the whole growing season. In contrast to 2009 and 2014, mesic summers in the wet years of 2008 and 2012, frequent rainfall events produce several anticlockwise hysteresis loops in all lakes. In both 2008 and 2012, Outwash-CO lake 16 shows early season declines in lake water level while other lakes are stable or increasing, but also exhibits late summer increases when other lakes are drying. In both 2008 and 2012, Moraine-FH lake 43 displays the lowest lake level decline across the growing season and greatest wetting in response to rainfall events, whereas Peat-FP lake 171 produces larger anticlockwise loops towards a drier state.

5. Discussion

Within this study, multi-annual hysteresis of precipitation-lake water levels clearly demonstrate the importance of understanding interannual landscape memory of climate within the sub-humid plains regions of the circumpolar Boreal Forest. Further, different insights are gained through analyses at different temporal scales, with memory evident from interdecadal to intra-annual scales (Table 2). The varied characteristics of hysteresis loops (Table 4) indicate that complex and spatially variable memory is present. These spatial variations in landscape memory are driven by differences in storage capacities (Table 1), which is in turn governed by landscape properties, such as surficial geology, landcover and landscape position (Leader et al., 2024; Devito et al., 2023). Thus, the propensity for drought years or wet years to persist or accumulate into extreme landscape drying or wetting varies significantly between different lake-landscape characteristics.

Peatland lakes on fine plains (Peat-FP) HRAs demonstrated the rapid recovery following drought (Figure 2 and 7) due to low storage capacities and subsequently short memory of dry conditions of connected peatlands within the lake catchment (Lukenbach et al., 2017; Hokanson et al., 2021b; Devito et al., 2023). In contrast, desiccation in many moraine spilling lakes in fine hummocky (Moraine-FH) HRAs restricted the magnitude of lake water level declines and memory of drought, but low water levels persisted one to two years following droughts (Figure 2 and 7). This implies longer landscape memory of dry conditions within Moraine-FH systems, which fits with current conceptual understanding of deep hillslope soils, high infiltration rates, high evaporative demand and subsequent long runoff return periods (Redding & Devito, 2008; Hokanson et al. 2021b). On the other hand, under mesic or wet climatic conditions Moraine-FH and Closed-FH lakes produced greater increases in lake water levels than Peat-FP lakes (Figure 7), indicating non-linear precipitation-lake water level response functions with CDM 1yr P value (Figure 4, Table 4). Small, high landscape positioned Moraine-FH lakes produced a strong cross correlation with CDM 3yr P (Figure 4, Table 4) as spilling and desiccation frequently 'reset' memory. Closed basins (Closed-FH) produced poor cross correlations, and a hockeystick shaped response function with a near zero gradient response to CDM 1yr P < 0 mm, but high responses to above average long-term precipitation (Figure 4, Table 4). This echoes findings within the PPR, whereby depressional shallow lakes exhibit longer memory as they can only dry via evapotranspiration due to the absence of lake outflows (Hayashi and van der Kamp 2007). Within Outwash-CO lakes, high cross correlation with lagged and longer cumulative precipitation variables reflects the dominance of groundwater as a control on lake water levels within this glacial landform on the BP (Smerdon et al., 2007; Hokanson et al., 2021a, Figure 4, Table 4). As such, intra-annual patterns of Outwash-CO lake water levels often contrast with patterns in lakes on fine textured HRAs due lags in seasonal dynamics (snowmelt recharge) superimposed on to a lagged response to long term dry conditions (Carrera-Hernández et al., 2011).

While some consistencies in precipitation-lake water level hysteresis characteristics and cross correlation were identified within lake classifications (Figure 4, Table 4), the generally poor cross correlation in a high number of lakes across the 18-year record could signify the complex interaction of lake basin memory and antecedent storage of the upslope catchment (Devito et al., 2023). Detailed investigative analysis comparing within year responses of similar short term climatic conditions (Figure 7) demonstrate that seasonal climate is an important driver for within year water level patterns, but landscape memory of long-term climate and threshold runoff responses govern the magnitude and gradient of these patterns (Mwale et al., 2011). This echoes findings of short-term studies that specify that precipitation timing and magnitude relative to PET, rather than annual precipitation totals defined runoff (Devito et al., 2005; Redding & Devito, 2008). Yet slight differences in antecedent soil moisture or groundwater position can propel a hydrologically disconnected catchment into one that yields high proportions of annual runoff in one storm event (Devito et al., 2005; Devito et al., 2023; Hokanson et al., 2021b). Thus understanding of antecedent conditions is crucial as proximity to storage thresholds results in disproportionate effects of precipitation events on discharge (Devito et al., 2023, Devito et al., 2023, Spence, 2010; Holecek 1988). Antecedent conditions also determines the connectivity between wetlands, modifying contributing area (Shaw et al., 2012). Consequently, it is difficult to directly define or infer hydrological processes from analysis that spans multiple climate cycles in landscapes with capacity for high memory. Simultaneously, it is challenging to gain a full understanding of a system's hydrologic function without observing response under a range of climatic conditions where non-linearities exist. Instead, shorter term interannual or intra-annual analyses should be placed within the context of the long-term meteorological cycles, where comparisons of responses at different antecedent conditions will provide stronger evidence of landscape memory and associated hydrological processes.

5.1 Implications for land management

A direct consequence of multiannual memory is that clustering of wet or dry climatic years can propagate into extreme wetting and drying of the landscape (Khanal et al., 2019). Multi-annual landscape memory of climate within the Boreal Plains demands greater understanding of the heterogeneity of glacial deposits and land covers and subsequent contrasts in storage and transmissivity processes governing antecedent moisture conditions of the connected catchment to accurately model lake water level responses, groundwater levels or landscape runoff over prolonged periods (multiannual to multidecadal), especially under drought or deluge (Devito et al. 2005, 2023; Holecek 1988; Hokanson et al., 2019). Thus, this knowledge is essential for land management practices at hydroclimatic periods when both uncertainty in hydrological processes is at its greatest (Koutsoyiannis, 2005) and water resource management is at its most critical. Yet one of the main limitations of previous BP research is the limited understanding of dynamic controls such as landscape memory (Devito et al., 2023). While research focusing solely on 'static' landscape characteristics controls such as landcover proportions, lake geometry and surficial geology have provided crucial knowledge for conceptualising hydrologic landscapes, static controls cannot fully explain temporal variations in both interannual and intra-annual water level patterns. The important control of storage in catchment hydrograph non-linearity has previously been recognised within the BP (Holecek 1988; Devito et al. 2005, 2023; Wells et al. 2017; Hokanson et al., 2021b), and a plethora of concepts have been defined to describe these non-linear processes (e.g. Ali et al., 2013; Shaw et al., 2012; Spence, 2007). Approaches presented within this study to examine landscape memory could have applicability to many continental and plains Boreal regions globally. However, this is the first study to characterise landscape memory through both interannual and intra-annual water level analysis across heterogeneous hydrogeoclimatic settings typical of the Boreal Plains.

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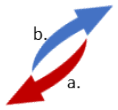
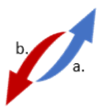
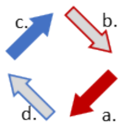
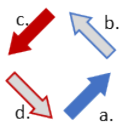
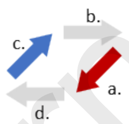
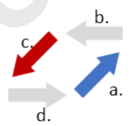
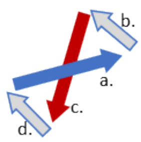
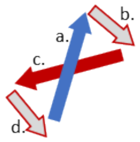
Table 1. Hypotheses and references to plausible systems for hysteresis climate-lake level responses.

Climate-WL Hysteresis Loop Shape and Direction			Definition	Theorised Cause/ Process	Hypothesised Lake/ Landscape Type
Linear/ Narrow Ellipse	Clockwise		Linear or near linear response function with minimal lag in water level response to climate	▪ Lower capacity for cumulative memory or lag ▪ Low storage ▪ Surface runoff dominated ▪ Localised flowpaths	Boreal shield lakes: impermeable bedrock, high rainfall results in low storage deficits and runoff dominated systems (based on multi-annual response – memory is expected intra-annually)
	Anti-Clockwise				
Diamond	Clockwise		Exhibits periods of a negative relationship between cumulative precipitation and lake water levels (arrows b and d)	▪ Cumulative memory of previous climatic conditions or lag responses ▪ Response to external disturbance or an extended lag e.g. beaver dam build and break ▪ High storage ▪ Long transit times ▪ Groundwater dominated ▪ Snowmelt	Coarse outwash lakes: groundwater dominated systems results in long transit times
	Anti-Clockwise				
Parallelogram	Clockwise		Exhibits periods of no change in water level despite significant changes to cumulative precipitation (arrows b and d)	▪ Threshold exceedance, e.g. lake desiccation, lake outflow ▪ Variable catchment connectivity, e.g. upstream storage deficits, upstream gatekeeper lakes	Shallow hummocky moraine low storage capacity lakes: lake spilling and desiccation Prairie Potholes Region: coalescing and desiccating lakes
	Anti-clockwise				End lakes/ receiving lakes: Wetting lag due to catchment storage deficits, ephemeral peatland connectivity, or gate keeper lakes upstream; drying lag due to groundwater supply
Figure-eight	Slow wetting, rapid drying		Exhibits both clockwise and anticlockwise loops caused by differing rates of wetting and drying response to the same climate gradient (arrows a and c). May	▪ Rapid drying and slow wetting – productive, low drought resilient landscape, e.g. forest dominated	Forest dominant systems: rapid drying due to high evaporative demand, large storage (forest upland hummocks) results in slow rewetting and high memory

		contain diamond or parallelogram loops.		
Rapid wetting, slow drying			▪ Rapid wetting and slow drying – efficient, high drought resilient landscape, e.g. peatland dominated	Peatland dominant systems: rapid wetting due to low storage, slow drying due to negative feedback mechanisms, results in quick recover from drought Isolated systems: can only dry via ET

Key:

Climate and lake levels wetting

Lake levels wetting under drying climate

No lake level change under wetting climate

Climate and lake levels drying

Lake levels drying under wetting climate

No lake level change under drying climate

Table 2. Spatial and temporal scales of analyses, and corresponding objectives, insights and results figures/tables.

Data duration, frequency and	Data type	Lake sample size	Relevant Objective			Key insight/finding	Relevant Figure
			Obj. 1 Characteristics of hysteresis loops	**Obj. 2** Memory at different temporal scales	**Obj. 3** Long-term memory impact on short-term response		
Interdecadal 1951-2013	Water levels from georeferenced satellite imagery & DEM	1 lake: Lake 19 (closed-FH)		✓		Demonstrates multi-annual memory - clustering of wet or dry years propagate into extreme wetting and drying of the landscape.	Figure 3
Decadal 2000-2018	Mean annual summer water levels	26 lakes All classes	✓	✓		High variability in the shape, size and direction of hysteresis loops spatially between lakes = complex and spatially variable memory is present in the landscape in time and in space (see also Table 1 and Figure 1).	Figure S5
	Cross correlation functions between climate variables and WLs		✓	✓			Figure 4 & Table 4

Multi-year 2000-2018 3x 4/5 year loops (see Figure 2 for key to climate periods)	Mean annual summer water levels	4 main lakes (4 classes)	✓		Hysteresis loops indicate contrasting responses between each lake and between each 5/6 year time period.	Figure 5
	Continuous/high frequency water levels	4 main lakes (4 classes)	✓	✓	The best cumulative precipitation variable differs between lakes. Years of cumulative wet or cumulative dry conditions (2003, & 2014) exhibit high residuals for CDM 1yr, which improve for multi-year climate variables.	Figure 6
Intra-annual for ice-free period	Continuous/high frequency water levels	4 main lakes (4 classes)	✓	✓	Contrasting responses between years that are driven by memory	Figure 7

Table 3. Summary of climate in key study years used to classify short term climate for use in analysis, corresponding with Figure 2. Annual and multiannual CDM variables are calculated from 1st July (relative to 1920-2018 1yr average 444 mm); CDM growing season is given for May 1st – September 30th (relative to 1920-2018 average 303 mm). Conditional formatting provides a wetness indicator for each variable for each year; red = dry, blue = wet, white = mid.

CDM 1yr Trend	Year	1yr P	CDM 1yr P	CDM Growing Season P	CDM 3yr P	CDM 5yr P	Summary
Dry	2002	214	-230	-91	-389	-487	Dry year, dry summer, dry long-term climate
	2010	244	-198	-108	-159	-43	Dry year, dry summer, mesic long-term climate
Mesic	2004	356	-88	-14	-369	-528	Mesic to dry year, mesic summer, dry long-term climate
	2001	385	-59	-147	-240	-155	Mesic to dry year, dry summer, dry-mesic long-term climate
Dry to	2003	393	-50	-17	-340	-521	Dry to Mesic year, mesic summer, dry long-term climate
	2011	427	-17	32	-169	-30	Dry to Mesic year, wet summer, mesic long-term climate
Wet to Mesic	2014	424	-20	-132	77	-138	Mesic year, dry summer, mesic-wet long-term climate
	2008	437	-7	-11	103	126	Mesic year, mesic summer, wet long-term climate
	2012	449	5	-28	-213	-172	Mesic year, mesic summer, dry long-term climate
	2009	492	48	-104	188	263	Mesic year, dry summer, wet long-term climate
Mesic	2018	516	72	-6	40	-95	Wet year, mesic summer, mesic-wet long-term climate

Table 4. Summary of precipitation-lake water level hysteresis characteristics and best cross correlations between cumulative precipitation variables and lake water levels in 26 lakes across 5 lake-catchment classes (see supplementary Figure S6).

	Class Attributes	***Dominant Loop Type***	***Lag/CDM cross correlation***	***Relating Process to Class Response***
Peat-FP	*Large flat plains, large riparian peatland, peatland dominated catchments*	*Figure-eight dominated*	▪ *Largest lake/catchment and receiving catchment = low CCF (168)* ▪ *Headwater plateau lakes = 3yrs CDM, varying lag (171, 205)*	*Peatland storage, feedback mechanisms and ephemeral connectivity = complex response patterns to varying connectivity*
Peat-FH	*Large riparian peatlands, FH catchments but large Peatland cover*	*Figure-eight dominated*	▪ *Catchments with larger peatland proportion = high CCF, 0 lag, varying CDM (59, 112)* ▪ *Catchments with larger lake proportion = low CCF (118, 122, also FP lake 121)*	*Peatland storage, feedback mechanisms and ephemeral connectivity = complex response patterns to varying connectivity*
Moraine-FH	*Shallow lakes, smaller surface areas, with small, hummocky forest dominated catchments*	*Mixed loop types*	▪ *High CCF, 3yr CDM, 0yr lag in Small, spilling, high positioned FH (40, 43, 111)* ▪ *Very low CCF in larger, low positioned FH catchments (39, 27, 42 & 121, 118)*	*CDM/lag varies with point in long term weather cycle due to antecedent storage deficits (therefore differs between lakes due to varying capacity spatially)*

Closed-FH	*Closed systems, hummocky forest catchments*	*Mixed loop types*	▪ *Poor CCF* ▪ *High lags*	*High storage = poor association with weather*
Outwash-CO	*Groundwater dominated*	*Diamond and figure- eight loops*	▪ *High CCF (except Lake 1).* ▪ *CDM1-CDM3, 0yr lag* ▪ *Larger lakes (5 and 17) associated with higher cumulative landscape memory.*	*Long transit times = lag and cumulative deficit in meteorological cycle*

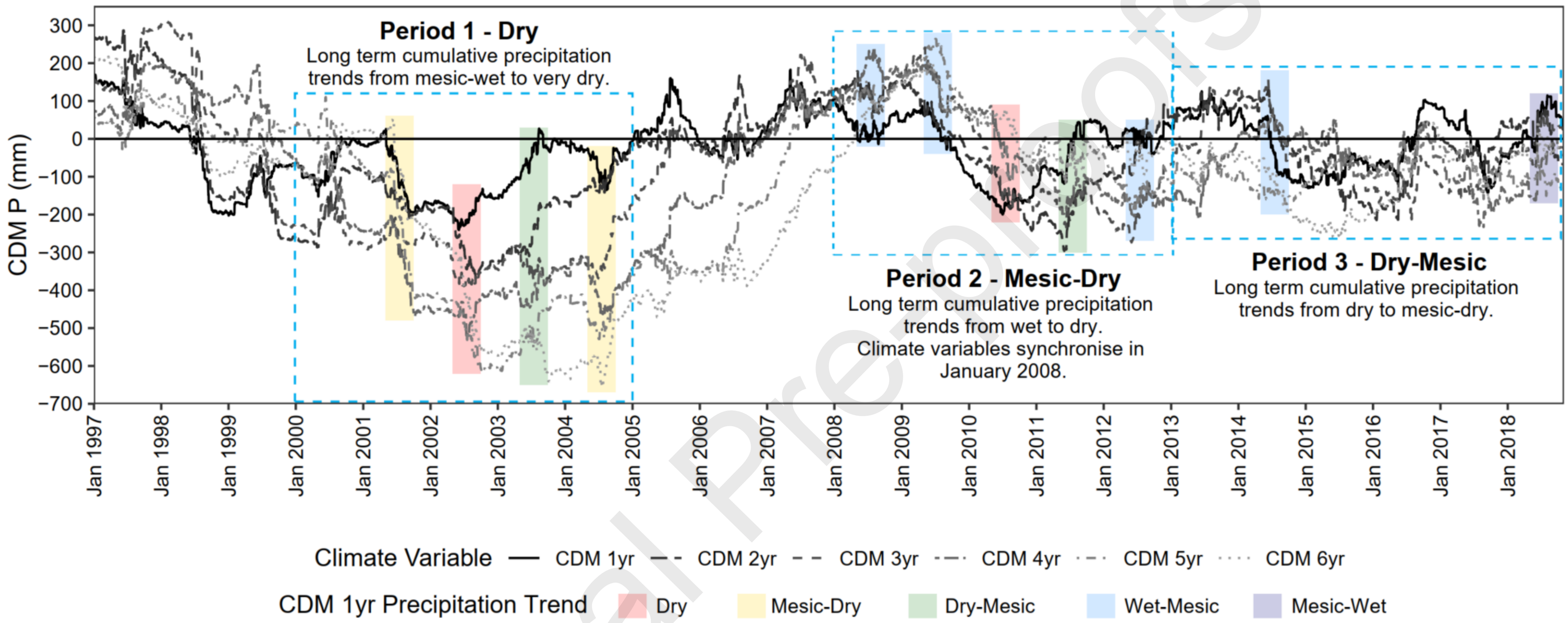


Figure 1. Climate of the URSA during the study period given as the difference in cumulative precipitation from the long-term mean (444 mm $year^{-1}$). Cumulative precipitation is calculated as a daily moving window for 1 to 6 years (see equation 1). Figure annotations delineate the paper's temporal methodology by dividing the 19-year climate record, which span one long-term climate cycle, into three periods of multi-annual wetting-drying cycles. Intra-annual patterns are then examined by placing short term climate (CDM 1yr P and within year growing season P) within the context of long-term climate (CDM 2-6yr P).

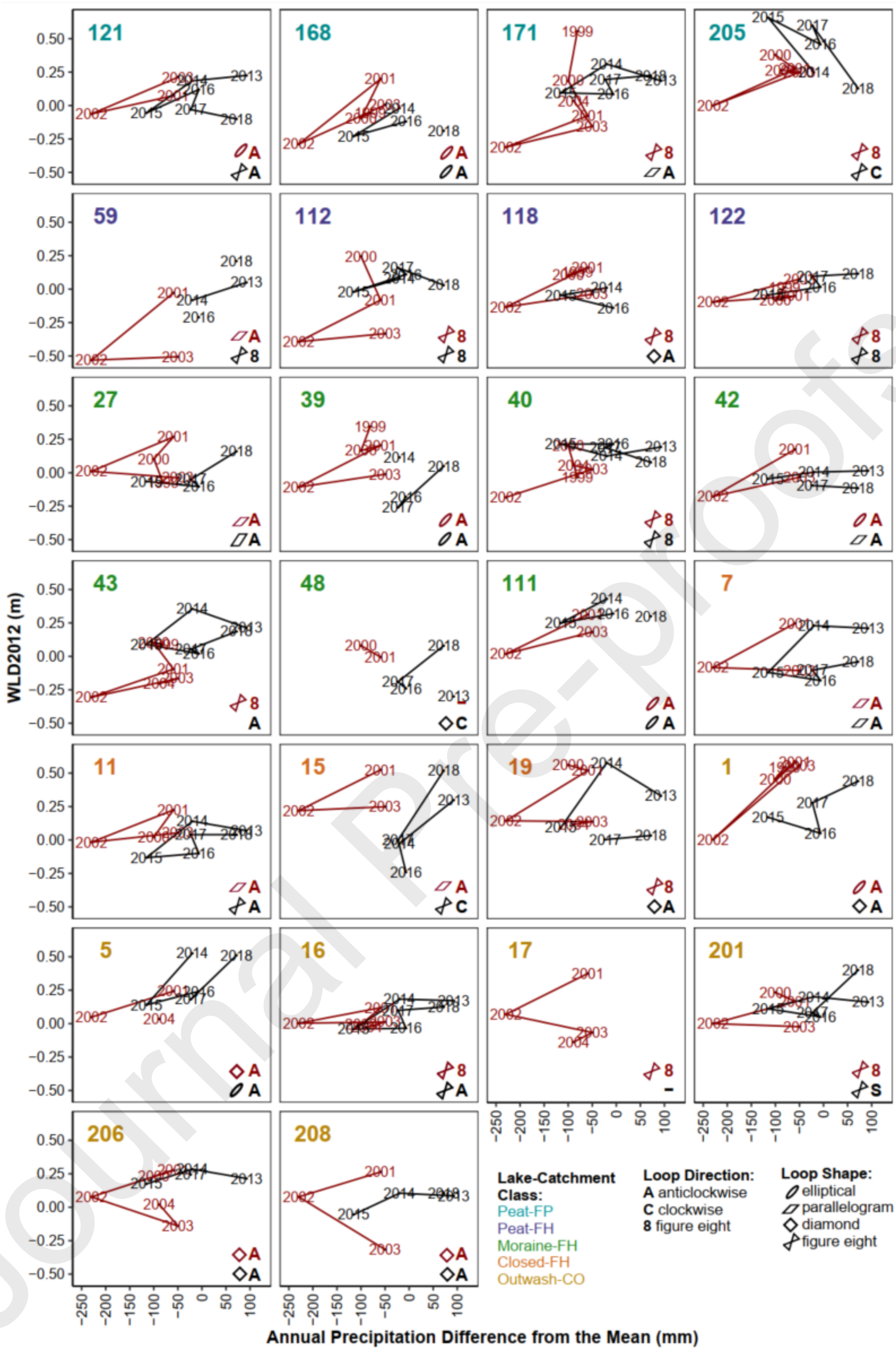


Figure 2. Hysteresis loops of annual precipitation relative to mean summer water levels relative to 2012 (WLD2012) in 26 study lakes (red: 1999-2004 – long term climate transitioning from wet to very dry; black: = 2013-2018 – long term climate mesic). Lakes are presented in order of their classification (Leader et al., Submitted). Each loop is classified in shape and direction.

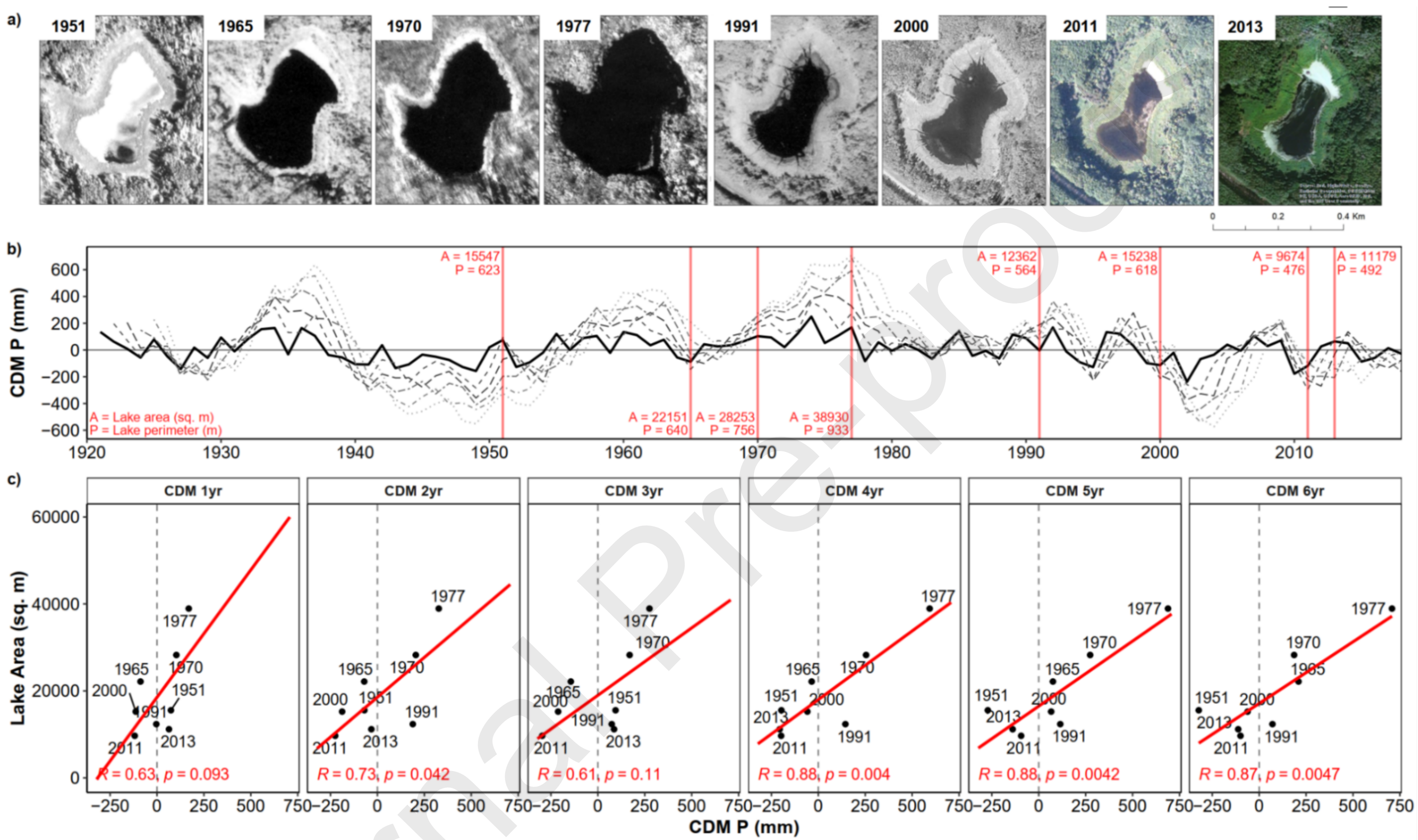


Figure 3. a) Satellite imagery of lake surface water extent (summer months, 1951-2013) within a forest dominated isolated basin with fine textured surficial geology with Closed-FH lake 19 perched over coarse deposits within the URSA, Alberta, Canada (see Hokanson et al., 2021a). b) Surface water area (denoted by 'A' for imagery years, m^2) and perimeter (denoted by 'P' for imagery years, m) is compared to the cumulative precipitation record of Fort McMurray (1920-2018) and c) Surface water area plotted against URSA precipitation record (1996-2018) for CDM P for 1-6 years (July 1st).

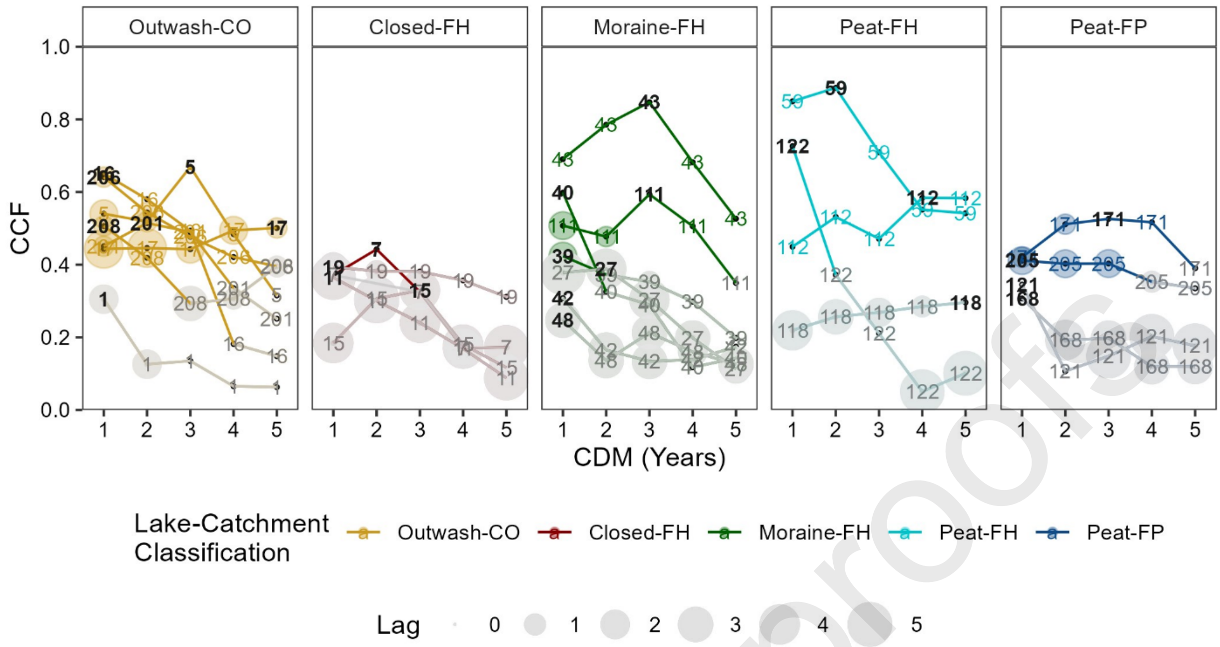


Figure 4. Maximum cross correlation function (CCF) value of water levels of each lake with CDM precipitation variable (years) combined with lag (years). CCF was calculated for each combination of CDM (1-5 years) and Lag (1-5 years) against mean summer (June-August) water levels relative to 2012 levels (WLD2012) at 26 study lakes; the optimal lag per CDM of each lake is presented. Labels denote the lake ID; black labels signify the best CCF per lake; coloured labels/points signify CCF ≥ 0.4; grey labels/points signify CCF < 0.4. Study lakes are presented in 5 groups representing their lake-catchment classification.

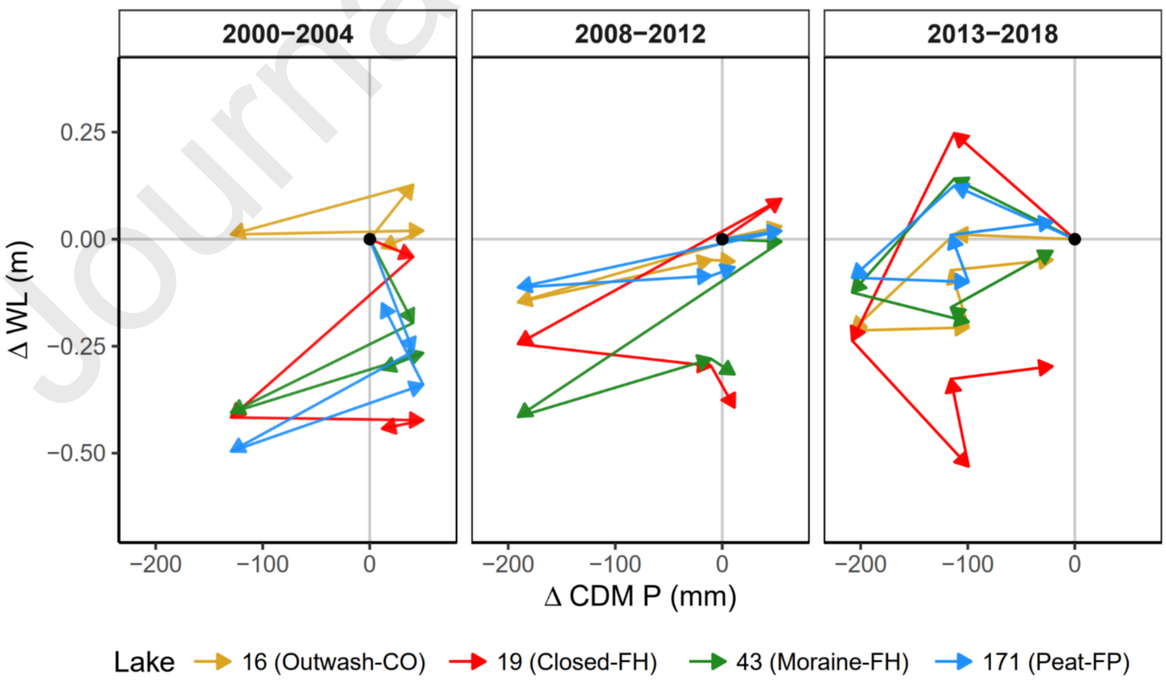


Figure 5. Hysteresis loops for three study periods at four detailed study lakes. CDM (mm) and WL (m) are given as 0 for the first time point in each multiyear period/loop. For concurrent multiyear change in 1-year cumulative difference from the mean in precipitation (CDM P mm) and associated time series change in lakes water levels see Supplementary Figure 7.

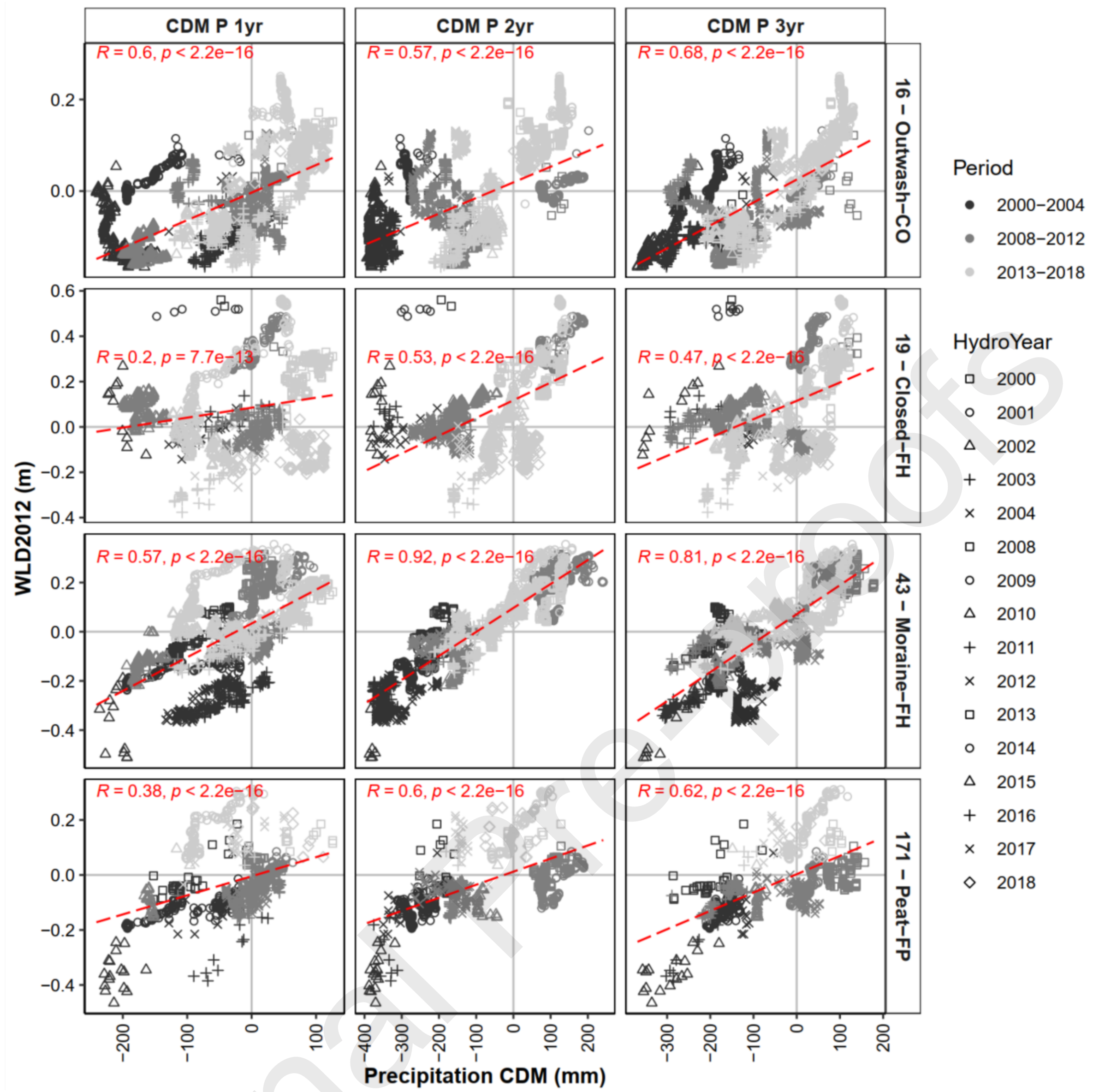


Figure 6. Scatter plots of Precipitation CDM variables (mm; 1-3 years) and lake water levels relative to mean summer 2012 levels (WLD2012; m) in four key study lakes across three time periods. Dashed red line represents a fitted linear model (LM) with associated the R and p coefficients given between climate variables and lake water levels.

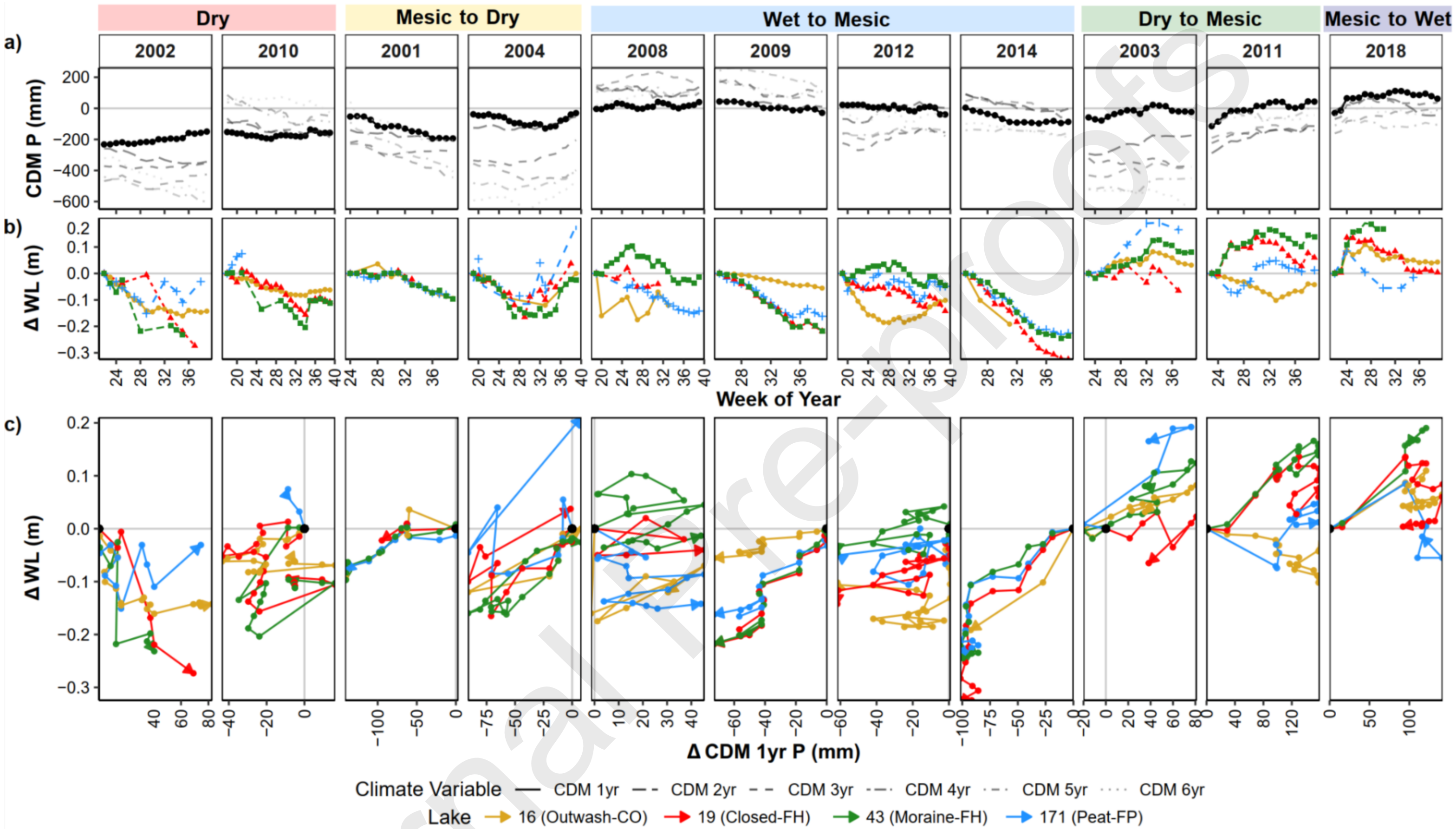


Figure 7. (a) Cumulative difference from the mean in precipitation (CDM P mm), cumulative for 1-6 years; b) lakes water level deviation from week X of year; (c) corresponding CDM P-WL hysteresis loops for figure a and b. Individual years representing drying, wetting and variable summers relative to the long term annual precipitation mean, within contrasting long term climatic conditions (see Figure 2 for further detail on climatic conditions) at four key study lakes.

- Landscape memory is crucial to project lake water levels in the Boreal Plain
- Measurement & analysis of lake water levels in 26 Boreal Plain lakes over two decades
- Interdecadal, decadal, multi-year, intra-annual memory impacts lake water levels
- Variations in memory driven by differences in lake-landscape storage capacities
- Shorter term analyses should be placed in the context of the long-term cycles