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A new lake classification scheme for the Peace-Athabasca Delta (Canada) characterizes hydrological processes that cause lake-level variation

Laura K. Neary [a,*], Casey R. Remmer [a], Jadine Krist [a], Brent B. Wolfe [b], Roland I. Hall [a]

[a] Department of Biology, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
[b] Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada

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ABSTRACT

Study region: The Peace-Athabasca Delta, a Ramsar Wetland of International Importance in northeastern Alberta, is protected within Wood Buffalo National Park and contributes to its UNESCO World Heritage status yet is threatened by climate change and upstream energy projects.
Study focus: Recent drawdown of the delta's abundant shallow lakes and rivers has deteriorated vital habitat for wildlife and impaired navigation routes. Here, we report continuous measurements at ~50 lakes during open-water seasons of 2018 and 2019 to improve understanding of hydrological processes causing lake-level variation.
New hydrological insights for the region: Analyses reveal four patterns of lake-level variation attributable to influential hydrological processes, which provide the basis for a new lake classification scheme: 1) 'Drawdown' (≥15 cm decline) by evaporation and/or outflow after ice-jam floods, 2) 'Stable' lake levels (<15 cm change) sustained by rainfall, 3) 'Gradual Rise' by inundation from the open-drainage network, and 4) 'Rapid Rise' by input of river floodwater. River flooding during the open-water season is an under-recognized recharge mechanism yet occurred extensively in the Athabasca sector and appears to be a common occurrence based on the Athabasca River hydrometric record. Lake-level loggers show strong ability to track shifts in hydrological processes, and can be integrated with other methods to decipher their causes and ecological consequences across water-rich landscapes.

1. Introduction

Water security is a rising concern in western Canada, where climate warming has reduced snowpack and glacier volumes and altered the timing and amount of streamflow to downstream ecosystems (Bonsal et al., 2019; Debeer and Sharp, 2007; Hugonnet et al., 2021; Sauchyn et al., 2015; Tennant and Menounos, 2013; Wolfe et al., 2008). At the Peace-Athabasca Delta (PAD) in northeastern Alberta, major energy projects upstream pose additional potential threats to security of water supply (Lebel et al., 2011; Prowse and Conly, 2000; Prowse et al., 2006; Schindler and Donahue, 2006). These include regulation of Peace River flow for hydroelectric production which alters the seasonal distribution of discharge (Peters and Prowse, 2001) and withdrawal of

* Corresponding author.
E-mail address: lkneary@uwaterloo.ca (L.K. Neary).

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Athabasca River water within the Alberta Oil Sands Region which reduces discharge (Mannix et al., 2010). The delta's waterways provide important access to traditional territory of Indigenous people, and the hundreds of small (<1 km^2), shallow lakes furnish productive habitat for a diversity of wildlife where lake-level fluctuations influence population density (Hood, 2020; Straka et al., 2018; Vannini and Vannini, 2019; Ward et al., 2018, 2020). Eighty percent of the PAD is protected within Wood Buffalo National Park (WBNP), a UNESCO World Heritage Site, and the delta is a Ramsar Wetland of International Importance. Much of the remaining area is the traditional territory of the Athabasca Chipewyan First Nation (IR 201). Recent observations of lake drying and decline of river levels have led to a petition to include WBNP on UNESCO's List of World Heritage in Danger (MCFN, 2014), recommendations to improve understanding and causes of lake-level variations over space and time (WHC/IUCN, 2017), and an action plan to implement research and monitoring approaches to assess cumulative impacts and inform decision-making by stakeholders (WBNP, 2019).

The abundant shallow lakes of the PAD have been distinguished into three main hydrological categories (open-drainage, restricted-drainage, closed-drainage) based on differences in their connectivity to the river channel network, which exerts strong control on lake water balance in the low-relief terrain (PADPG, 1973; Peters et al., 2006; Pietroniro et al., 1999; Prowse and Demuth, 1996; Timoney, 2013; Wolfe et al., 2007). Open-drainage lakes occur at the lowest elevations and receive continuous to near-continuous river through-flow. Closed-drainage lakes occupy the highest elevations, are isolated from the channel network, and are thought to receive floodwaters only during episodic rise of water to extreme levels caused by ice-jam events on the Peace and Athabasca rivers and their distributaries. During intervals between ice-jam floods, maintenance of their water levels relies on input from snowmelt and rainfall to the lake and catchment to offset losses by evaporation. Restricted-drainage lakes have been characterized as occurring at intermediate elevations and they experience more frequent connectivity to rivers during ice-jam floods as well as periods of open-water elevated river flow that promote intermittent reconnection to distributary channels. The restricted-drainage category, thus, includes a broad lake class between the extremes of open- and closed-drainage lakes, and are presumed to be less prone to desiccation than closed-drainage lakes. 'Perched basin' is a frequently used term that includes both restricted- and closed-drainage lakes to distinguish isolated lakes in the landscape from open-drainage lakes connected to the river network, and to acknowledge a hydrological continuum exists. A hydro-limnological survey by Wolfe et al. (2007) further defined a subset of shallow perched basins as rainfall-influenced, based on their shallow depth and small water volume that promotes rapid desiccation by evaporation and refilling by rainfall events.

The three main hydrological categories described above were established decades ago during initial field surveys of the PAD when understanding of the hydrology of the landscape was incomplete. Systematic sampling of water isotope composition during spring, mid-summer and fall of a recent 5-year period (2015–2019) at a network of ~60 lakes and 9 river sites across the PAD has vastly improved our knowledge of hydrological processes regulating lake water balance and provided information on spatio-temporal patterns of variation in the influence of river floodwaters, precipitation and evaporation on lake water balance (Remmer et al., 2020a). Results demonstrate greater heterogeneity of lake water balance than can be captured by the conventional use of the three hydrological lake categories. For example, water balance of restricted-drainage lakes can vary across the delta from positive to negative at the same time, and this also occurs for closed-drainage lakes. Seasonal and inter-annual variation is sufficiently high that perched basins may exhibit water balance characteristic of the closed-drainage category in some seasons and years and characteristics of the restricted-drainage category in other seasons and years. Notably, the systematic water isotope monitoring during summers of 2017–2019 captured recurring evidence of strongly positive lake water balance across central and southern (Athabasca sector) portions of the PAD due to input of river floodwaters during the open-water season. Among the extensive body of hydrological literature on the PAD, this mechanism of lake replenishment has rarely been reported, except for Peters et al. (2006, 2021) who also identified the effectiveness of high river-level events during the open-water season in recharging slightly elevated lakes in the Athabasca sector. Classification of lakes into open-, restricted- and closed-drainage categories, thus, does not explicitly distinguish lakes that are strongly influenced by open-water flooding from those influenced by ice-jam flooding or lateral connectivity stemming from other hydrological processes associated with the river channel network.

Knowledge of open-water flooding in the Athabasca sector, and influence of other hydrological processes on the delta's lakes, may be advanced by using water-level loggers to obtain continuous, real-time measurements of lake-level fluctuations. Such continuous measurements may be used to pinpoint the timing, magnitude and extent of open-water flooding and its influence on lake levels, metrics that cannot easily be captured using 'snapshot' measurements of water isotope tracers alone when periodic sample collection does not coincide with influential hydrological processes and events. Fergus et al. (2020) demonstrated the value of supplementing water isotope tracer information with singular measurements of lake-level drawdown based on high-water marks to develop a national-scale hydrological baseline for lakes across the conterminous United States. To our knowledge, however, water-level loggers have not been deployed for continuous lake-level measurements at multiple sites across a floodplain landscape as dynamic as the PAD, yet they present an approach that can broaden and enhance our understanding of influential hydrological processes and contribute useful information for lake monitoring programs.

Here, we utilize continuous hourly lake-level measurements at 48 lakes in 2018 and 53 lakes in 2019 across the PAD to elucidate the timing and magnitude of lake-level responses to key hydrological processes during the open-water season. The knowledge gained is used to refine hydrological categorization of lakes in the PAD. We also integrate the lake-level measurements with river hydrometric data and a digital elevation model to define the geographical area of the PAD inundated by open-water flooding in 2018 and 2019, thus improving upon estimates reported in Remmer et al. (2020a) based on three 'spot' measurements of water isotope composition per year. We also use long-term river hydrometric data to speculate on the frequency of open-water season lake flooding by the Athabasca River during the past four decades. Finally, we assess the utility of water-level loggers as a complementary lake monitoring tool to water isotope tracers and other approaches.

2. Study area

2.1. Peace-Athabasca Delta

Spanning an area of ~6000 km^2, the PAD is the world's largest freshwater boreal delta (Fig. 1; Peters et al., 2006). Elevational differences between lakes and rivers, and the complex hydrological pathways connecting them, create three distinctive hydrological 'regions' across the PAD: the northern relic Peace sector, the southern active Athabasca sector, and the central area occupied by large open-drainage lakes (Lake Claire, Mamawi Lake; PADPG, 1973 ; Wolfe et al., 2007). Based on the Canadian Digital Elevation Model (CDEM; accuracy = 0–10 m for the region), the light blue region spanning the central area of the delta in Fig. 1 represents areas between 205 and 210 masl, and broadly corresponds with the spatial extent of the 'open-drainage network'. This includes lakes Claire, Mamawi and Richardson (PAD 38), and the channels that connect them with the Athabasca and Peace rivers and the western end of Lake Athabasca (Timoney, 2013). The Peace sector has greater topographic relief than the Athabasca sector and possesses numerous bedrock inliers (>225 masl) that occur in the catchments of many lakes. Comparatively, only a narrow area of land in the southern margin of the Athabasca sector along the Athabasca River is elevated above 220 masl.

The directional movement of water in the delta is influenced by variation in water levels of the Athabasca and Peace rivers and Lake Athabasca (Fig. 1). Water enters the southern Athabasca sector via the north-flowing Athabasca River and its distributaries, including the Embarras River that carries water northward via Cree/Mamawi Creek into Mamawi Lake or via Fletcher Channel into Lake Athabasca. The Athabasca River and Lake Athabasca are typically at a higher elevation than the Peace River. Thus, for most of the time channels in the Peace sector (Rivière des Rochers, Chenal des Quatre Fourches, Revillon Coupé) carry outflow from Lake Athabasca northward to the Peace River and, ultimately, to the Slave River. In early spring, southward flow reversals can occur in these channels when Peace River water levels rise and, more typically, when ice-jams form.

2.2. Study lakes

The lakes from which water-level loggers (i.e., pressure transducers) were retrieved at the end of the open-water seasons (n_{2018} = 48, n_{2019} = 53) span surface areas from approximately < 1 km^2 to 38 km^2 (Richardson Lake / PAD 38) and are roughly divided between the Peace sector (n_{2018} = 22, n_{2019} = 24) and the Athabasca sector (n_{2018} = 26, n_{2019} = 29; Fig. 1, Table 1). Most (36/53) of the lake sites studied were included in a survey conducted in fall 2000 by Wolfe et al. (2007). The other 17 lakes (lakes M1 to M19) are a subset also sampled by community-based monitoring groups to track variation in muskrat abundance. The entire lake set is largely equivalent to that reported in Remmer et al. (2020a) and spans the range of lake hydrological conditions in the delta.

2.3. Meteorological conditions and spring ice-jam flooding in 2018 and 2019

Based on the 1981–2010 climate normal measured at the Fort Chipewyan airport station, mean monthly air temperatures range from − 20°C to 15 °C and average annual precipitation is ~365 mm (Fig. 2). Monthly temperatures during the two study years were similar to the climate normal with the following exceptions. In May-June 2018, average monthly air temperatures were warmer than the climate normal. This was followed by cooler-than-average air temperature in September. In 2019, air temperature was colder in February and warmer in March than the climate normal. Cumulative precipitation in 2018 (345 mm) was 20 mm less than the climate normal. Cumulative precipitation in 2019 (443 mm) exceeded the annual climate normal by late September. During the open-water season, substantial rainfall occurred in June 2018 (61 mm) and August 2019 (106 mm). Approximately 45 mm of rain was measured on August 14, 2019, which is far more than any other single day and unusual for the region.

Widespread ice-jam flooding in late April – early May 2018 delivered river floodwaters to nearly half of all lake sites (Table 1). The extent of river floodwaters was delineated by Remmer et al. (2020b) and includes a large central area within the Athabasca sector and small areas of the northern Peace sector. Of the lakes where we deployed water-level loggers, this event flooded 19 lakes (73%) in the Athabasca sector, and 8 lakes (36%) in the Peace sector. Spring flooding was more limited in 2019 and was detected in 8 (28%) of the Athabasca sector lakes and no lakes in the Peace sector where loggers were deployed (Table 1; Remmer et al., 2020a).

3. Methods

3.1. Field methods

Water-level loggers (Onset HOBO pressure transducers; Model U20–001–01, 4-m range, 0.3-cm accuracy) were installed at a central location of each lake in mid-May 2018 and 2019, shortly after ice-off (Fig. 1). Most study lakes have a simple bathymetry where maximum depth occurs near the center of the lake. Exceptions include oxbow lakes (PAD 15, 54), which are remnant river channels and where the thalweg is likely closer to the outer bank. For these two lakes, we deployed loggers equidistant from the shorelines on one of the arms, which are not at their deepest location. Each logger was attached to a 'rock-sock' anchor by zip-tie and a wooden float by nylon rope. Water pressure (psi) and temperature (°C) were recorded every hour until removed in mid-September of each year. GPS coordinates were logged immediately after each device was deployed to aid their retrieval and guide re-deployment at a consistent location the following year. In both years, a single logger was also deployed outside the field house in Fort Chipewyan to measure variation in local atmospheric pressure and air temperature. These data were used to convert water pressure readings at each lake to water depth (m) using the Barometric Compensation Data Assistant in the HOBOware software. RStudio v1.3.1073 (R Core Team,

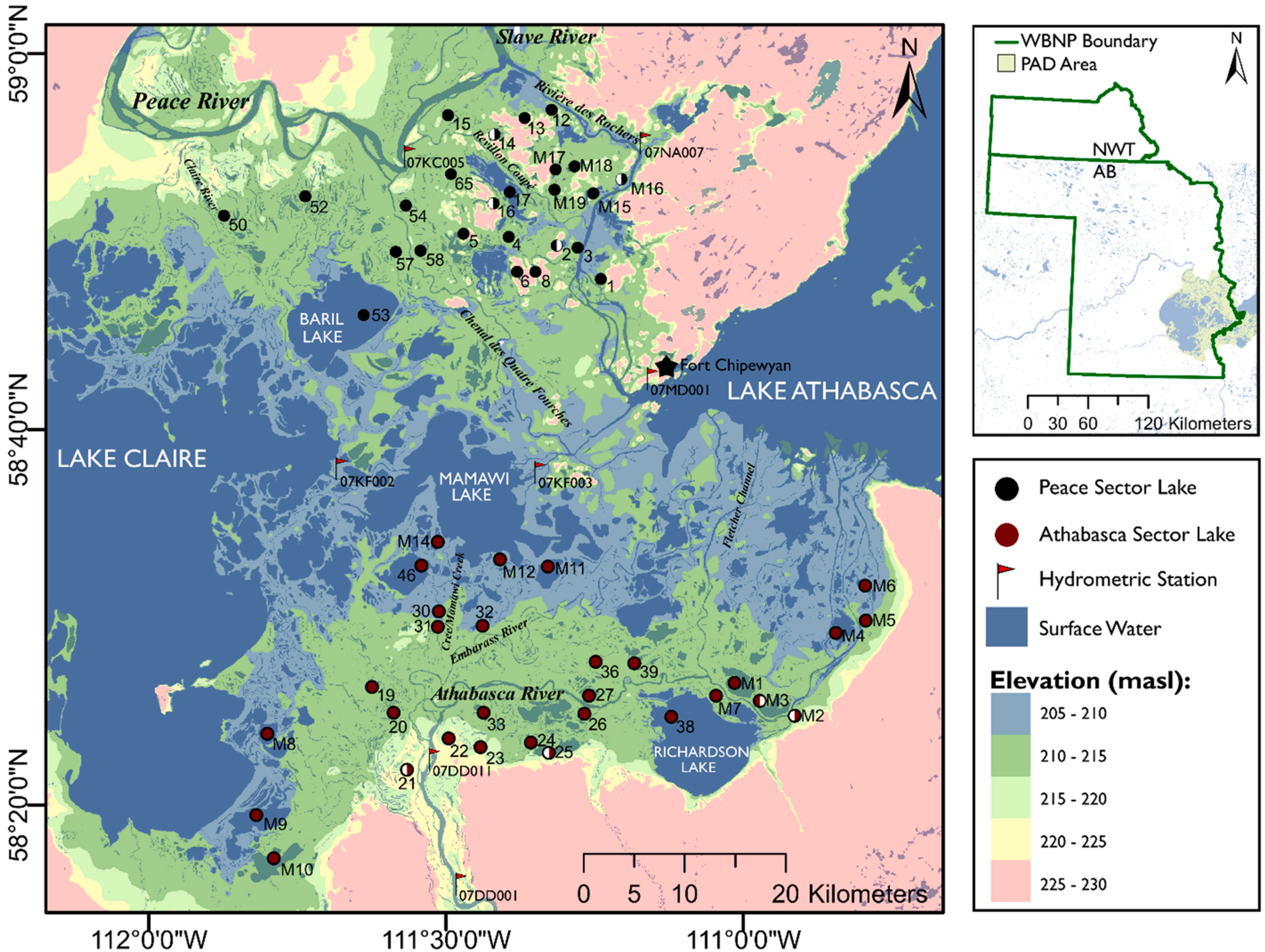

Fig. 1. Map showing locations of lake sampling sites within the Peace-Athabasca Delta, northern Alberta. Black circles identify lakes located in the Peace sector (n = 25) and red circles identify lakes located in the Athabasca sector (n = 30). Semi-circles indicate the year in which the lake-level logger was retrieved: left-filled semi-circles identify logger retrieved only in 2018, right-filled semi-circles identify logger retrieved only in 2019 and solid circles identify logger retrieved in both 2018 and 2019. Hydrometric stations operated by Environment and Climate Change Canada are indicated with red flags. Figure was created using ArcGIS Desktop version 10.7.1 and assembled by L. Neary using the following data sources (shapefiles): Government of Canada (national park boundaries: https://open.canada.ca/data/en/dataset/9e1507cd-f25c-4c64-995b-6563bf9d65bd; water bodies: https://open.canada.ca/data/en/dataset/448ec403-6635-456b-8ced-d3ac24143add; geospatial CDEM: https://maps.canada.ca/czs/index-en.html), PAD area: shapefile generated by J. Faber. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article)

Table 1
Summary of mean, initial, minimum, maximum and maximum-change of lake depth (above logger) in the Peace-Athabasca Delta for open-water seasons (May – September) of 2018 and 2019. Lakes that received spring floodwater in 2018 are indicated with an asterisk and lakes flooded in spring 2019 are bolded. Lake site names and their geospatial coordinates for this dataset are available online: https://doi.org/10.5683/SP2/D5TVYG.

Site	Mean (m)		Initial (m)		Minimum (m)		Maximum (m)		Max. Change (cm)[a]		Lake-level Pattern[b]		Drainage Category[c]
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	
Peace sector													
PAD 1	1.10	0.80	1.09	0.89	1.00	0.71	1.24	0.91	-9.45	-17.16	S	D	c
PAD 2	1.10		1.18		0.99		1.19		-19.02		D		c
PAD 3	0.68	0.38	0.76	0.41	0.54	0.33	0.80	0.47	-22.56	-8.41	D	S	c
PAD 4	0.64	0.44	0.71	0.54	0.50	0.33	0.78	0.55	-20.24	-21.03	D	D	c
PAD 5	1.14	0.88	1.19	0.96	1.03	0.81	1.20	1.00	-15.48	-14.81	D	S	c
PAD 6	1.16	0.86	1.16	0.90	1.04	0.77	1.29	0.95	-11.80	-13.05	S	S	c
PAD 8 *	1.43	1.25	1.40	0.96	1.15	0.88	1.83	1.75	+ 64.13	+ 71.11	GR	GR	r
PAD 12	0.52	0.19	0.60	0.32	0.39	0.07	0.63	0.34	-21.43	-25.60	D	D	c
PAD 13	1.44	1.22	1.48	1.30	1.36	1.13	1.49	1.31	-11.46	-16.70	S	D	r
PAD 14 *		1.32		1.45		1.24		1.48		-21.09		D	r
PAD 15 *	1.38	0.90	1.37	0.99	1.32	0.81	1.44	1.00	-5.48	-17.59	S	D	c
PAD 16		0.38		0.43		0.28		0.48		-14.36		S	r
PAD 17	1.72	0.39	1.74	0.46	1.67	0.30	1.76	0.47	-7.06	-15.61	S	D	r
PAD 50 *	0.42	0.07	0.46	0.19	0.29	0	0.55	0.19	-16.61	-18.50	D	D	c
PAD 52	0.89	0.53	0.91	0.59	0.74	0.43	1.00	0.61	-17.04	-15.79	D	D	r
PAD 53	0.95	0.57	0.93	0.63	0.67	0.46	1.12	0.76	-25.88	-16.80	S	D	p
PAD 54 *	3.64	1.88	3.54	1.85	3.54	1.84	3.71	1.92	-0.58	-0.46	S	S	r
PAD 57	0.93	0.63	1.02	0.78	0.79	0.50	1.03	0.79	-23.32	-27.55	D	D	c
PAD 58 *	0.67	0.31	0.70	0.41	0.53	0.20	0.75	0.42	-17.04	-21.03	D	D	c
PAD 65	1.08	0.82	1.09	0.88	1.01	0.74	1.13	0.89	-7.77	-14.08	S	S	
M15	1.12	0.61	1.15	0.67	1.05	0.54	1.17	0.69	-9.75	-13.78	S	S	
M16		0.92		1.00		0.84		1.02		-16.22		D	
M17 *	1.04	0.72	1.08	0.79	0.94	0.63	1.11	0.82	-13.72	-15.79	S	D	
M18 *	1.37	1.11	1.45	1.19	1.28	1.01	1.45	1.21	-17.10	-18.32	D	D	
M19	1.09	0.71	1.13	0.77	1.00	0.63	1.15	0.80	-12.95	-14.33	S	S	
Athabasca sector													
PAD 19 *	1.06	1.00	1.21	1.06	0.91	0.89	1.21	1.09	-29.66	-17.53	D	D	c
PAD 20 *	1.87	0.53	2.11	0.71	1.67	0.41	2.11	0.71	-43.56	-29.87	D	D	r
PAD 21 *		0.61		0.71		0.49		0.72		-22.07		D	r
PAD 22 *	1.89	0.88	1.86	0.86	1.78	0.79	2.01	1.00	-7.40	-7.13	S	S	r
PAD 23 *	2.05	1.20	2.18	1.27	1.91	1.09	2.19	1.28	-27.46	-17.74	D	D	r
PAD 24 *	1.43	1.28	1.52	1.12	1.26	1.03	1.52	1.96	-25.66	+89.18	D	SR	r
PAD 25 *		1.23		0.90		0.82		2.24		+138.53		SR	o
PAD 26 *	1.06	1.32	1.32	0.94	0.83	0.83	1.78	2.41	+88.42	+154.59	SR	SR	o
PAD 27 *		1.28		1.27		1.21		1.42		-6.07		S	r
PAD 30 *	1.03	0.79	1.06	0.69	0.92	0.56	1.44	1.41	+45.48	+79.74	SR	SR	r
PAD 31 *	1.17	1.23	1.22	1.01	1.03	0.90	1.81	2.12	+68.03	+117.10	SR	SR	r
PAD 32 *	1.16	0.89	1.20	0.97	1.03	0.81	1.27	0.98	-17.10	-16.34	D	D	r
PAD 33 *	1.22	1.13	1.62	0.40	0.70	0.33	2.13	2.52	+141.09	+179.83	SR	SR	r
PAD 36 *	1.23	0.98	1.44	0.94	1.11	0.88	1.44	1.11	-33.56	-6.31	D	S	r
PAD 38 *	0.99	1.35	1.26	0.90	0.50	0.64	1.41	2.24	+56.51	+140.79	SR	SR	o
PAD 39 *	1.22	0.90	1.48	0.94	1.05	0.81	1.48	0.94	-43.16	-12.68	D	S	r
PAD 46 *	1.47	1.33	1.79	0.89	1.21	0.81	1.79	2.13	+46.45	+121.71	SR	SR	o
M1	1.15	1.21	1.24	1.11	1.05	1.03	1.25	1.40	-19.17	+31.85	D	SR	
M2		1.28		1.31		1.20		1.34		-10.49		S	
M3	0.63		0.71		0.54		0.72		-16.58		D		
M4	0.61	0.37	0.69	0.48	0.51	0.29	0.69	0.50	-18.50	-19.23	D	D	
M5	1.21	1.22	1.19	1.20	1.17	1.10	1.24	1.50	-2.62	-9.45	S	S	
M6	0.60	0.41	0.66	0.46	0.50	0.30	0.72	0.53	-16.03	-15.48	D	D	
M7	1.06	1.06	1.26	0.86	0.92	0.72	1.34	1.63	+33.28	+84.52	SR	SR	
M8	1.01	0.76	0.89	0.87	0.88	0.65	1.45	0.94	+45.10	-22.07	GR	D	
M9	0.89	0.65	0.85	0.75	0.80	0.56	1.06	0.79	+19.57	-18.75	GR	D	
M10	1.30	0.63	1.53	0.81	1.03	0.45	1.60	1.05	+51.24	+39.56	GR	GR	
M11	0.77	0.63	0.70	0.71	0.68	0.57	0.84	0.71	-2.10	-14.36	S	S	
M12 *	1.23	1.09	1.24	0.98	1.13	0.91	1.35	1.28	+16.49	+37.12	GR	SR	
M14 *	1.30	1.30	1.55	1.11	1.14	1.01	1.80	1.75	+41.54	+69.16	GR	SR	

[a] Maximum Change (in centimeters) was determined as Minimum - Initial for Drawdown and Stable lakes and as Maximum - June 14 water level for Gradual Rise and Sharp Rise lakes;
[b] Water-level pattern defines the main water-level trends observed in Figs. 3 and 4 (D: drawdown; S: stable; GR: gradual rise; SR: sharp rise);
[c] Hydrological drainage categories based on isotopic and limnological data (c: closed; r: restricted; o: open; p: very shallow (Zmax < 50 cm) rainfall-influenced) from Wolfe et al. (2007). Sites without drainage designation were not included in Wolfe et al. (2007).

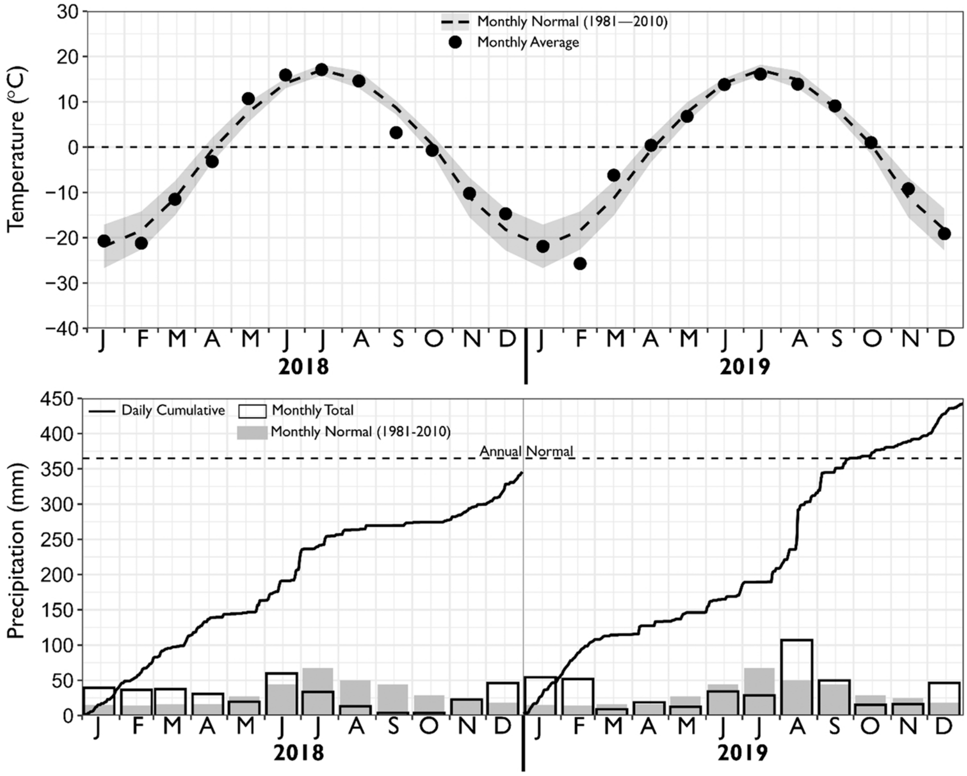

Fig. 2. Meteorological data for January 1, 2018 to December 31, 2019 recorded at the Fort Chipewyan Airport, Fort Chipewyan, Alberta, Canada (ID: 3072659). The upper panel includes average monthly air temperatures (°C) with respect to the monthly climate normal (1981–2010; ID: 3072658) identified by a black dashed line surrounded by grey area representing standard deviations. The lower panel includes cumulative daily precipitation (mm) for 2018 and 2019 represented by the solid black line and black-outlined bars representing monthly total precipitation, with respect to the climate normal (1981–2010) precipitation (grey bars). The annual climate normal (1981–2010) total precipitation is identified by a horizontal dashed line.

2019) software and external packages (pracma, lubridate, ggplot2) were used to calculate and graph daily (24-hour) running means (Borchers, 2019; Grolemund and Wickham, 2011; Wickham, 2016). From this point forward, we simply refer to the water depth measurements as 'lake level' or 'lake-level patterns or variation'.

3.2. River hydrometric data and Canadian digital elevation model

Water-level data were obtained from hydrometric stations maintained by the Water Survey of Canada (https://wateroffice.ec.gc.ca/) for river sites (Athabasca River (07D001, 07DD011), Peace River (07K005), Rivière des Rochers (07NA007)), Lake Claire (07KF002), Mamawi Lake (07KF003), and Lake Athabasca (07KF003) to compare to our lake-level data (Fig. 1). Hydrometric data for the Peace River were unavailable during early spring 2018 because river ice damaged the hydrometric station.

A Canada-wide digital elevation model (CDEM) was included as a map layer in ArcMap 10.7.1 to explore and visualize relations between elevation and spatial distribution of lake-level patterns. The CDEM was created in 2016 by the Department of Natural Resources Canada and is accessible online at: https://maps.canada.ca/czs/index-en.html. The coverage and resolution of the CDEM varies according to latitude and uses the North American Datum 1983 as a reference system for horizontal coordinates. Elevations are orthometric and expressed relative to mean sea level (Canadian Geodetic Vertical Datum 1928). For the study region, the CDEM offers a spatial base resolution of 0.75″ x 0.75″ arc seconds and a measured altimetric accuracy of 0–10 m.

3.3. Classification of lake-level patterns

Based on visual observation of individual lake-level patterns, geographical location and simple numerical analyses, study lakes were sorted into the following four categories for 2018 and 2019: 1) 'drawdown' (≥15 cm decline), 2) 'stable' (<15 cm decline), 3) 'gradual rise' and 4) 'sharp rise'. Lake-level decline was calculated as the minimum lake level subtracted by the initial lake level at the time of logger deployment (Table 1). Initial lake level was selected as the benchmark, rather than maximum lake level, because the latter is time dependent and varies from lake to lake. The threshold used to separate lakes into the drawdown versus stable categories (15 cm) was based on approximation of the median drawdown for lakes in 2018 and 2019 (17.0 cm and 16.2 cm, respectively; Fig. 3).

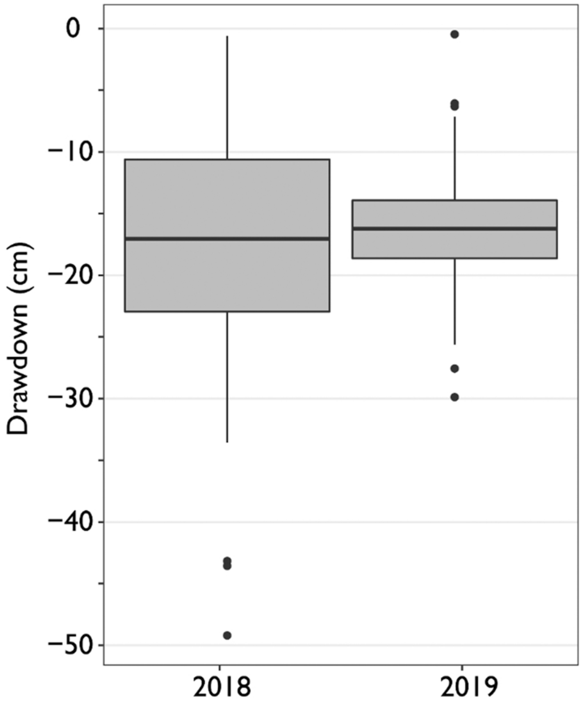

Fig. 3. Boxplot showing variation in maximum drawdown of lake level in 2018 and 2019 for lakes that did not display a gradual or sharp rise.

Temporal patterns of 'gradual rise' and 'sharp rise' were visually discernable as lake levels that increased slowly or rapidly, respectively. For study lakes located adjacent to large open-drainage lakes (i.e., Claire and Mamawi), we also visually assessed for lake-level correlation between the study lake and adjacent open-drainage lake as evidence of gradual rise due to inundation by rising levels in the open-drainage network. Estimates of maximum lake-level change for gradual and sharp rise lakes (Table 1) were obtained from the lake-level maximum subtracted by the lake level measured on June 14th for both years. June 14th was selected to minimize the potential effects from spring flooding and is ~24 h before the earliest lake-level rise associated with open-water flooding.

4. Results

Lakes in both sectors of the PAD displayed lake-level variations of the stable, drawdown and gradual rise categories during 2018 and 2019 (Figs. 4, 5). However, only lakes in the Athabasca sector exhibited the sharp-rise pattern in lake levels during 2018 and 2019 (Figs. 4, 5). Given this difference and previous research demonstrating lake water balances contrast greatly between the Peace and Athabasca sectors (Wolfe et al., 2007; Remmer et al., 2020a), we present and describe the results separately for each sector. We also report spatial distribution of lake-level patterns with respect to land-surface elevations and proximity to active river channels.

4.1. Peace sector

Including both study years, 25 lakes in the Peace sector fell into the drawdown category, which is more than any of the other categories (Fig. 4A, B). Ten lakes (45.5%; PAD 2, 3, 4, 5, 12, 50, 52, 53, 57, 58) displayed drawdown in 2018, and 15 lakes (68.2%; PAD 1, 4, 12, 13, 14, 15, 17, 50, 52, 53, 57, 58, M16, M17, M18) in 2019. Seven of the lakes fell into the drawdown category in both years. All but one of the drawdown lakes is elevated above 210 masl (Fig. 6). Baril Lake (PAD 53) is the sole exception located within the 205–210 masl range. Baril Lake also shows higher frequency variation compared to other lakes in this category possibly due to its larger fetch that generates greater wind-driven lake-level fluctuation. In 2018, lake-level decline began at lakes in this category in early July and continued until loggers were retrieved in mid-September. In contrast, lake-level decline began earlier in 2019 (mid-May) and ended earlier (mid-August) when substantial rainfall coincided with a sudden small rise in lake levels (4.8 ± 1.2 cm). Among the lakes in this category, PAD 50 drew down sufficiently to expose the logger to the atmosphere after mid-July 2019. Two of the 10 drawdown lakes in 2018 shifted to the stable category in 2019 (PAD 3, 5).

The next most common lake-level category in the Peace sector was stable (Fig. 4C, D). In 2018, 11 lakes (50.0%; PAD 1, 6, 13, 15, 17, 54, 65, M15, M17, M18, M19) exhibited this behaviour. Of these, four lakes (PAD 15, 54, M17, M18) received ice-jam floodwaters in the spring (Remmer et al., 2020b). Eight lakes (33.3%; PAD 3, 5, 6, 16, 54, 65, M15, M19) fell in this category in 2019 when spring flooding was less extensive. Lakes in the stable category are situated east of the Chenal des Quatre Fourches and span a range of elevations (205–225 masl; Fig. 6). Lakes in the stable category displayed a sudden small rise (5.0 ± 0.9 cm) coincident with the major

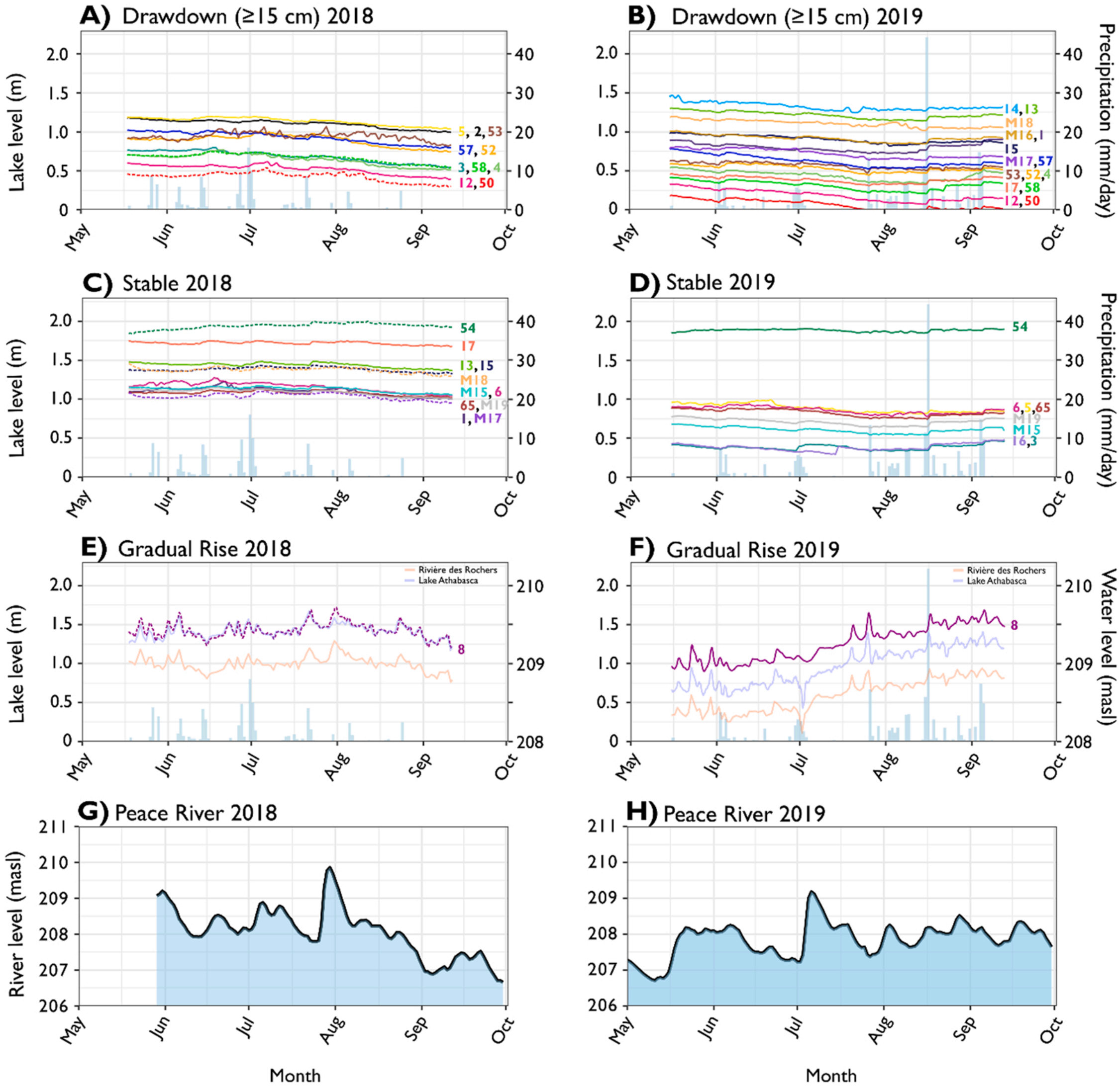

Fig. 4. Temporal patterns of lake-level variation in the Peace sector (Panels A – F) from May to October during the open-water seasons of 2018 (left column) and 2019 (right column): Drawdown (A, B), Stable (C, D) and Gradual Rise (E, F). Hydrometric data showing the water-level variation of Lake Athabasca (ID: 07MD001) and the Rivière des Rocher (ID: 07NA007) are included in panels E and F. Also shown in A – F (as vertical light-blue bars) is daily precipitation (mm) measured at Fort Chipewyan Airport (ID: 3072659). Panels G and H show the daily water level of the Peace River (masl) in 2018 and 2019, measured below the Chenal des Quatre Fourches (ID: 07KC005). Dotted lines in panels A, C and E are lakes that received floodwater during the spring 2018 ice-jam flood prior to logger installment (Remmer et al.; 2020b).

rain event in mid-August 2019, as observed for lakes in the drawdown category. Six of the 11 stable lakes in 2018 shifted to the drawdown category in 2019 (PAD 1, 13, 15, 17, M17, M18).

One lake in the Peace sector, PAD 8, exhibited a gradual rise in lake level, which coincided with the rise and fall of Lake Athabasca and its outlet channel, the Rivière des Rochers, but not with variation of Peace River levels (Fig. 4E–H). This lake is connected to the Rivière des Rochers via a single distributary channel (Chilloney's Creek), which serves as both an inflow or outflow depending on relative water levels of PAD 8 and the Rivière des Rochers.

None of the lakes in the Peace sector displayed a sharp rise in lake level in 2018 and 2019, and temporal patterns of lake-level variation in the three other categories show little to no association with variation of Peace River levels during the open-water season (Fig. 4G, H).

4.2. Athabasca sector

Similar to the Peace sector, drawdown was the most common lake-level pattern in the Athabasca sector during the two study years

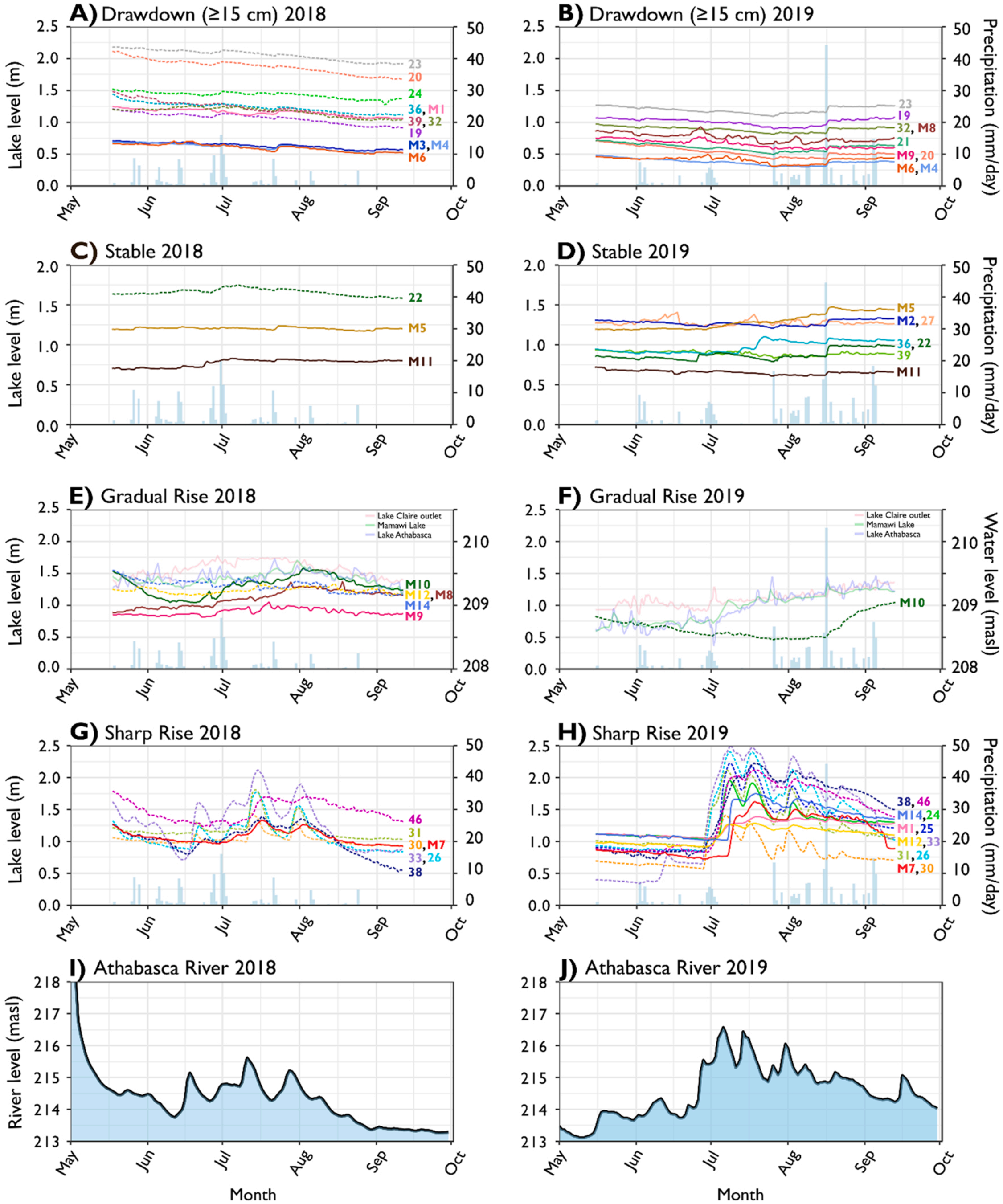

Fig. 5. Temporal patterns of lake-level variation in the Athabasca sector (Panels A – H) May to October during the open-water seasons of 2018 (left column) and 2019 (right column): Drawdown (A, B), Stable (C, D), Gradual Rise (E, F) and Sharp Rise (G, H). Hydrometric data showing the water-level variation of the three largest lakes that comprise the open-water network including Lake Claire, Mamawi Lake and Lake Athabasca (ID: 07KF002, 07KF003, 07MD001, respectively), are included in panels E and F. Also shown in A-H (as vertical light-blue bars) is daily precipitation (mm) measured at Fort Chipewyan Airport (ID: 3072659). Panels I and J show the daily water level of the Athabasca River (masl) in 2018 and 2019, measured at Embarras Airport (ID: 07DD001). Dotted lines in panels A, C, E, F, G, and H are lakes that received floodwater during the spring (prior to logger installment; Remmer et al.; 2020a, 2020b).

(Fig. 5A, B). Eleven lakes fell in this category in 2018 (42.3%; PAD 19, 20, 23, 24, 32, 36, 39, M1, M3, M4, M6) and 10 lakes in 2019 (34.5%; PAD 19, 20, 21, 23, 32, M4, M6, M8, M9). Six lakes fell into this category in both study years. The timing and duration of lake-level decline was comparable to that observed in the Peace sector in both study years. Of the 11 drawdown lakes in 2018, 8 received floodwaters during the spring prior to logger deployment. Lakes in the drawdown category in 2018 and 2019 are situated across a wide

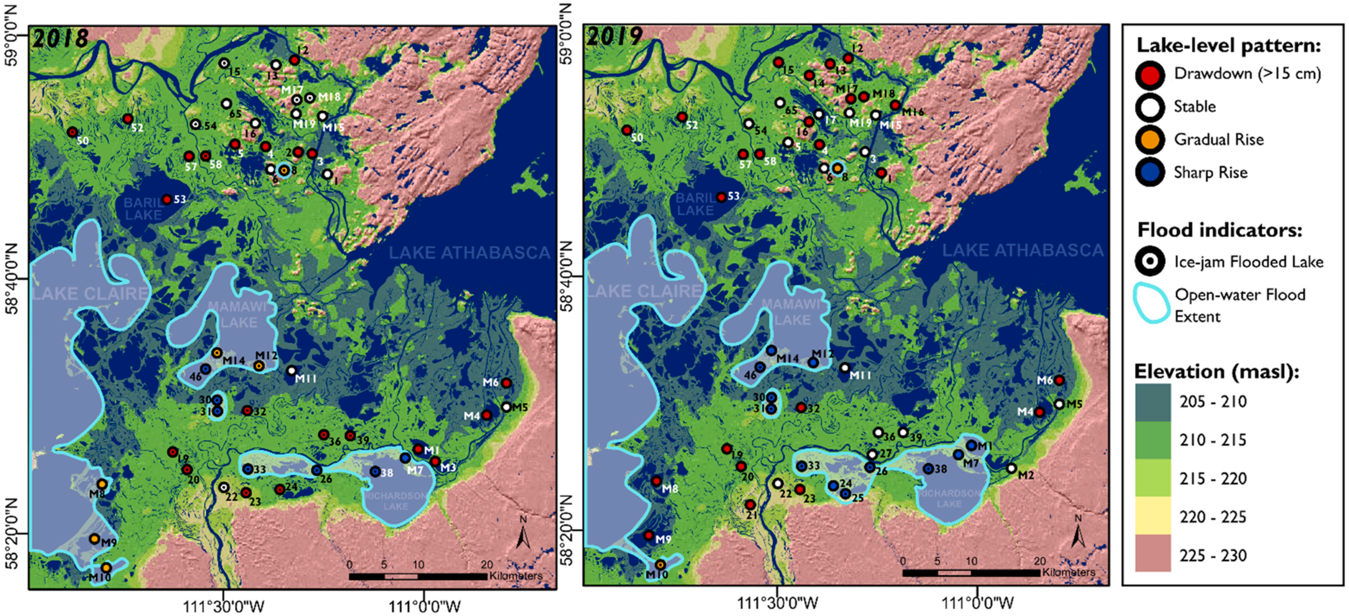

Fig. 6. Maps showing location of lake-level patterns (left:2018; right 2019) and estimated open-water flood extent incorporating lakes inboth gradual rise and sharp rise categories, superimposed on land surfaceelevation of the Peace-Athabasca Delta, Alberta. Figurewas created using ArcGIS Desktop version 10.7.1 and assembled by L. Nearyusing the following data sources (shapefiles): Government of Canada (waterbodies: https://open.canada.ca/data/en/dataset/448ec403-6635-456b-8ced-d3ac24143add; geospatial CDEM: https://maps.canada.ca/czs/index-en.html).

range of elevations (205–225 masl; Fig. 6). Three of the drawdown lakes in 2018 displayed a different lake-level pattern in 2019; one was classified as stable and two as sharp rise.

In contrast to the Peace sector, relatively few lakes fell into the stable category in the Athabasca sector in 2018 and 2019 (Fig. 5C, D). This includes 3 lakes in 2018 (11.5%; PAD 22, M5, M11) and 7 lakes in 2019 (24.1%; PAD 22, 27, 36, 39, M5, M6, M11). All but one of these lakes are situated above 215 masl (Fig. 6). The exception, M11, is located southeast of Mamawi Lake at 205–210 masl. All three of the lakes in 2018 remained in the stable category in 2019.

Five lakes (19.2%; M8, M9, M10, M12, M14) displayed gradual rise of lake level in 2018 and one lake (3.4%; M10) fell in this category in 2019 (Fig. 5E, F). Lake-level variations in these lakes coincided with those of the open-drainage network (lakes Claire, Mamawi and Athabasca; Fig. 5E, F). Fewer lakes with gradual rise in 2019, compared to 2018, corresponds with 0.5 m lower peak lake levels in the open-drainage network (Fig. 5E, F). In 2019, lake level at M10 declined gradually between mid-May and early August, similar to lakes in the drawdown category, and then rose gradually after mid-August when adjacent Lake Claire reached maximum lake level. Lakes in the gradual rise category are situated at elevations between 205 and 210 masl and occur south-east of Lake Claire (M8, M9, M10) and along the southern edge of Mamawi Lake (PAD M12, M14; Fig. 6). In 2019, M12 and M14 shifted to the sharp rise category, and M8 and M9 exhibited the drawdown pattern.

Several lakes in the Athabasca sector displayed sharp rises of lake level, which was not observed in lakes of the Peace sector (Fig. 5G, H). In 2018, 7 lakes (26.9%; PAD 26, 30, 31, 33, 38, 46, M7) fell into this category, with two to four sharp rises evident in late June, early July, mid-July and early August. These same 7 lakes, plus 5 others (41.4%; PAD 24, 25, M1, M12, M14), displayed sharp rises in early July, mid-July, late July and early August in 2019. In most instances, lake levels declined markedly after each rise and coincided with sharp rise and fall in Athabasca River levels during both years, suggesting open-water river flooding is the cause of these lake-level variations (Fig. 5I, J). Exceptions to this include three lakes where lake level did not decline markedly after a sharp rise (PAD 46 in 2018, M1 and M12 in 2019). Prolonged high lake levels in PAD 46 and M12 may reflect inundation by rising levels of adjacent Mamawi Lake after input of river floodwaters in July. M1 lacks an adjacent open-drainage lake, which suggests the peak river levels in early July 2019 only briefly exceeded the sill elevation for this lake on one occasion, and the lake remained bank-full thereafter. Maximum rise of lake level ranged from 31 to 170 cm, with a mean of 73 cm in 2018 and 104 cm in 2019 (Table 1). River floodwaters reached more lakes in 2019 when the Athabasca River (at Embarras Airport) reached a maximum level of ~216.5 masl, 1.1 m higher than the maximum level in 2018 (~215.4 masl) (Fig. 5). In both years, open-water flooding occurred south of the Athabasca River, and along downstream portions of Cree/Mamawi Creek and adjacent to Mamawi Lake (Fig. 6).

5. Discussion

Continuous hourly lake-level measurements at ~50 lakes across the Peace-Athabasca Delta during two open-water seasons (2018, 2019) revealed four distinctive patterns of lake-level variation: drawdown (≥15 cm decline), stable (<15 cm decline), gradual rise and sharp rise. The number of lakes that displayed each lake-level pattern differed between years and sectors of the PAD. In the Peace sector, drawdown and stable patterns were equally prevalent in 2018 (n = 10 and 11, respectively), but drawdown was more common than stable in 2019 (15 and 8, respectively). In the Athabasca sector, drawdown was the most prevalent pattern in 2018 (10), followed by sharp rise (7) and gradual rise (5). In 2019, sharp rise (12) was most common, followed by drawdown and stable (9 and 7, respectively). Lakes in the stable and drawdown categories consistently occur at elevations greater than 215 masl in the Peace sector, in contrast to the Athabasca sector where lakes with these lake-level patterns were located across a range of elevations (205–220 masl). Gradual rise lakes consistently occur at low elevations (205–210 masl) and are situated adjacent to Lake Claire and Mamawi Lake in the Athabasca sector, whereas the sole gradual rise lake in the Peace sector possesses a connection to the Rivière des Rochers via Chill-oney's Creek. Lakes that had a sharp rise of lake level were only found within the Athabasca sector at low elevations (205–215 masl)

Table 2
Lake level functions for the four lake-level categories. Bolded terms identify the dominant hydrological process for each category. Former drainage categories for lake sites that overlap with Wolfe et al. (2007) are included for comparative purposes. Lake sites that do not overlap are designated as "uncategorized".

Category	Lake Level Functions	Former Drainage Categories (#)
Drawdown	LL(f): [IJF + S_m + R_f – O – **E**]	-closed (11) -restricted (11) -rainfall-influenced (1) -uncategorized (9)
Stable	LL(f): [IJF + S_m + $\mathbf{R_f}$ – O – E]	-restricted (8) -closed (5) -rainfall-influenced (1) -uncategorized (7)
Gradual Rise	LL(f): [IJF + S_m + R_f + **ODN** – O – E]	-restricted (1) -uncategorized (5)
Sharp Rise	LL(f): [IJF + S_m + R_f + **OWF** – O – E]	-open (4) -restricted (4) -uncategorized (4)

LL = lake level, IJF = ice-jam floodwaters, Sm = snowmelt, Rf = rainfall, ODN = open-drainage network, OWF = open-water floodwaters, O = surface outflow, E = evaporation.

and adjacent to active river channels (Athabasca and Embarras rivers, Cree/Mamawi Creek).

Lakes in the PAD have long been recognized to span a broad hydrological spectrum and be potentially influenced by several processes including snowmelt, ice-jam flooding, rainfall, open-water flooding, water-level fluctuations in the open-drainage network and evaporation (PADPG, 1973; Peters et al., 2006; Pietroniro et al., 1999; Prowse and Demuth, 1996; Remmer et al., 2018, 2020a, 2020b; Wolfe et al., 2007, 2008). Lake-level variations are a sensitive measure and a direct consequence of the relative influence of many of these hydrological processes. Based on systematic lake-level patterns (Figs. 4, 5) and their spatial distribution (Fig. 6), we propose a new hydrological classification system for lakes in the PAD, defined by key hydrological processes (Table 2).

5.1. Hydrological processes that define a new lake categorization system for the PAD

During the open-water season, we identify a singular dominant hydrological process, among the several processes operating across the PAD, that defines each of the four new lake hydrological categories (Table 2). 1) Drawdown lakes are strongly influenced by evaporation, as reflected by their consistent, gradual lake-level declines throughout the summer that exceed 15 cm. However, because ice-jam floodwaters in 2018 raised lake levels of several drawdown lakes in the Athabasca sector, surface outflow also may have contributed to their lake-level decline early during the open-water season. 2) Stable lakes did not experience substantial drawdown (< 15 cm) because of summer rainfall that offset evaporation. Lake morphology and catchment characteristics, including watershed-to-lake area and surface area-to-volume ratios, and localized rainfall events, may explain the differing relative influence of rainfall, its associated runoff and evaporation on drawdown and stable lakes. These factors are difficult to quantify because of the low relief terrain and there is only one meteorological station (Fort Chipewyan airport) in this remote region. 3) Gradual rise lakes are characterized by inflow due to hydrological connectivity with adjacent large open-drainage lakes (principally lakes Claire and Mamawi) and distributary channels of the open-drainage network. 4) Sharp rise lakes correspond with rise of the Athabasca River beyond its flood stage, identifying open-water season flooding as the main hydrological process that characterizes these lakes. Ice-jam flooding and snowmelt can influence all lakes across the delta during the early open-water season (PADPG, 1973; Prowse and Conly, 1998; Timoney, 2013). However, these hydrological processes are not readily identified in the lake-level records because loggers cannot be installed until after ice-off and thus after snowmelt and ice-jam flooding have occurred.

The new lake hydrological classification scheme offers distinct advantages over the conventional closed-, restricted- and open-drainage categories. Table 2 lists the number of lakes in our study set that fall into the former drainage categories based on water isotope and water chemistry data from 2001 (Wolfe et al., 2007). Closed-drainage lakes (and their subset of rainfall-influenced lakes) have now been partitioned into drawdown and stable lakes based on the prevailing influence of evaporation and rainfall, respectively. The broad spectrum of restricted-drainage lakes is reflected by distribution among all four of the new categories, further demonstrating that restricted-drainage lakes are influenced by a wide range of hydrological processes. A distinct advantage is that the new categories distinguish formally restricted-drainage lakes that receive open-water flooding via direct inflow of Athabasca River water (i.e., sharp rise lakes) versus inundation or connection with the open-drainage network (i.e., gradual rise lakes). Conventionally, three lakes have been identified as open-drainage (Claire, Mamawi, Richardson; Timoney, 2013), but they span two of the four new categories proposed here. Lakes Claire and Mamawi displayed gradual rise of lake levels, as would be expected of large, through-flow lakes in flat terrain that receive inflow from rivers with sharply rising lake levels. However, lake levels rose sharply at Richardson Lake (PAD 38) during open-water seasons of 2018 and 2019. Lake levels at PAD 25, 26 and 46, identified as open-drainage by Wolfe et al. (2007), also rose sharply. Thus, the new lake classification system identifies the non-uniform influence of hydrological processes in this previously defined category of open-drainage lakes. It also reveals that a broad suite of hydrological processes influence lake levels in the delta and shifts in several of these processes can lead to lake-level drawdown. These include climate-induced increase in duration of the open-water season and increased evaporation, reduced open-water flooding and decline of precipitation.

5.2. Characterization of open-water flooding

Recently, substantial open-water flooding was detected in the Athabasca sector using seasonal measurement of water isotope compositions (Remmer et al., 2020a) and remote sensing (Peters et al., 2021). Hourly lake-level data improves our understanding of the influence of this hydrological process by capturing the precise timing that floodwaters enter a lake, the magnitude of lake-level rise and the spatial extent of flooding. In 2018, open-water flooding of sharp rise lakes coincided with increases in the water level of the Athabasca River during 2–3 intervals in mid-June, mid-July and late July, which raised levels by 0.33–1.41 m (Fig. 4; Table 1). In 2019, open-water flooding occurred during 3–5 intervals, including three in July and two in early August, which raised levels of sharp rise lakes by 0.31–1.79 m (Fig. 5; Table 1). Each one of these flood events occurred during an interval of one to two weeks. Continuous lake-level measurements demonstrate that multiple pulses of river floodwater may enter lakes in the Athabasca sector during the open-water season potentially resulting in lake-level increases exceeding 1.5 m. Given that most lakes are < 1 m deep, and some are less than 0.5 m deep, open-water flooding is clearly an important recharge mechanism for lakes in the Athabasca sector. High levels of the Athabasca River in 2018 and 2019 also promoted gradual rise of water levels at Mamawi Lake and Lake Claire, which inundated nearby basins (gradual rise lakes; Figs. 4, 5). Although the Athabasca River peaked at ~216.5 masl in 2019, more than 1 m higher than in 2018 (~215.4 masl), spatial extent of floodwaters was similar (Fig. 6). Flooded regions captured by sharp rise lakes include along the southern margin of the delta and the Cree/Mamawi Creek corridor in the Athabasca sector, and likely define the areas most susceptible to the direct effects of open-water flooding. Our interpretation of the spatial extent of open-water flooding includes gradual rise lakes (Fig. 6), which were indirectly influenced by the high discharge on the Athabasca River via the open-drainage network. Notably, open-water flooding did not extend to the terminus region of the Athabasca River, which includes the traditional territory of the Athabasca Chipewyan First Nation located adjacent to the WBNP boundary at the southeastern edge of the PAD, likely due to diversion of flow through Cree/Mamawi Creek caused by the Embarras Breakthrough in 1982 (Kay et al., 2019; Wolfe et al., 2008). Indeed, the lake-depth data reveal that drawdown is common among lakes at the Athabasca River terminus in the absence of open-water flooding (e.g., M1, M3, M4, M6; Figs. 5, 6). This is an important finding because it identifies systematic lake-level drawdown which has negative consequences for land users and access to traditional lands. We consider the spatial extent of open-water flooding depicted in Fig. 6 to be more accurate than that approximated in Fig. 4 of Remmer et al. (2020a), in part because the latter is influenced by the timing of water sample collection for isotope analysis.

Periodic ice-jam flooding in spring is well known as an important source of replenishment for lakes in the PAD (Prowse and Conly, 2000; Prowse and Lalonde, 1996; Timoney et al., 1997) and causes of reduced frequency of this hydrological process have been subject to much debate given concerns of lake-level drawdown during recent decades (e.g., Beltaos, 2018; Wolfe et al., 2020). Less attention has been placed on the frequency of open-water flood events probably because, unlike ice-jam floods, they are difficult to predict or observe as they typically generate smaller, more localized flooding and can occur at any time during the open-water season. We examined the Athabasca River hydrometric record at the Old Fort gauging station (ID: 07DD011; Fig. 1) to assess the frequency of potential open-water flood events equivalent to or greater than 2018 and 2019 since the Embarras Breakthrough in 1982 (Table 3; Fig. 7). We utilized data recorded at Old Fort hydrometric station because the station at Embarras Airport only reports water levels since 2014. At Old Fort station, peak water level was ~214.5 masl during 2018 and ~215.4 masl during 2019. The water-level record of the Athabasca River at this station shows that the 2018 threshold has been exceeded during 16 years since 1982 (42% of years), demonstrating that open-water flooding of similar or greater magnitude as 2018 has been a common occurrence during the past 38 years. Given that peak water levels of the Athabasca River have exceeded the 2019 threshold during only 8 of those years (21%), it is likely that open-water flooding has infrequently extended to the Athabasca River terminus during this time. This interpretation is consistent with paleolimnological records that depict reduced influence of river floodwaters in this region of the Athabasca sector since 1982 (Kay et al., 2019). The record at Old Fort station also shows an extended interval of low peak summer river levels during 1998–2010. Since then, peak river levels have exceeded the 2018 threshold in at least 6 years since 2011 (note missing data for 2014

Table 3
Annual maximum open-water season level (m) of the Athabasca River between May 30 and August 17 measured at the Old Fort gauging station (ID: 07DD011) from 1982 to 2019. Note that data are not available (NA) for 2014 and 2015.

Year	Maximum level (m)	Day of the Year	Julian Day Number (JDN)
1982	215.22	12-Jul	193
1983	214.17	29-Jul	210
1984	214.06	14-Jun	166
1985	214.74	05-Jul	186
1986	216.04	25-Jul	206
1987	213.85	09-Aug	221
1988	215.07	13-Jul	195
1989	215.09	10-Aug	222
1990	215.81	20-Jun	171
1991	214.36	17-Jun	168
1992	212.73	22-Jun	173
1993	212.86	31-Jul	212
1994	214.35	12-Jul	193
1995	214.94	17-Aug	229
1996	215.83	07-Jun	159
1997	217.39	01-Jul	182
1998	213.62	07-Jul	188
1999	214.37	15-Jul	196
2000	214.22	30-Jul	212
2001	214.82	01-Aug	213
2002	212.75	06-Jul	187
2003	214.45	29-Jun	180
2004	213.99	18-Jul	200
2005	213.37	01-Jun	152
2006	213.52	01-Jun	152
2007	213.93	13-Jun	164
2008	213.96	19-Jun	171
2009	214.09	16-Jul	197
2010	212.53	22-Jun	173
2011	215.64	16-Jul	197
2012	215.54	01-Aug	214
2013	215.84	17-Jun	168
2014	NA	NA	NA
2015	NA	NA	NA
2016	214.06	16-Jun	168
2017	214.97	17-Jun	168
2018	214.55	11-Jul	192
2019	215.45	05-Jul	186

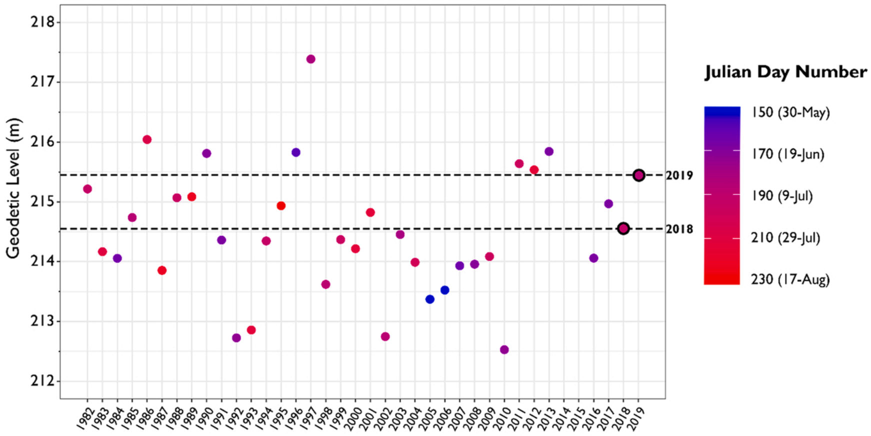

Fig. 7. Maximum water-level (masl) of the Athabasca River recorded between May 30 and August 17 at the Old Fort gauging station (ID: 07DD011) from 1982 to 2019. The colour of the points indicates the date (Julian Day Number) when each of the annual open-water season peaks occurred. Horizontal dashed lines and black-outlined coloured points indicate the peak water level recorded in the summer of 2018 (214.5 m) and 2019 (215.4 m). Note that data are missing for 2014 and 2015.

and 2015). We also note that the timing of peak water level at Old Fort station in any given year may span a ~6-week interval. Such marked seasonal and annual temporal variation in peak river levels of the Athabasca River and associated open-water flooding highlights the importance of monitoring the frequency of these important recharge events using continuous lake-level recorders.

5.3. Implications for monitoring

Given projected declines in summer discharge of east-flowing rivers fed by high-elevation glaciers and snowpack in the Rocky Mountains (Chernos et al., 2020; Debeer and Sharp, 2007; Hugonnet et al., 2021; Tennant and Menounos, 2013), peak summer levels in the Athabasca River and associated open-water flooding at the PAD are likely to decline in coming decades. If so, frequency of lakes in the 'sharp rise' and 'gradual rise' categories will decrease and shift to the 'stable' and/or 'drawdown' categories depending on

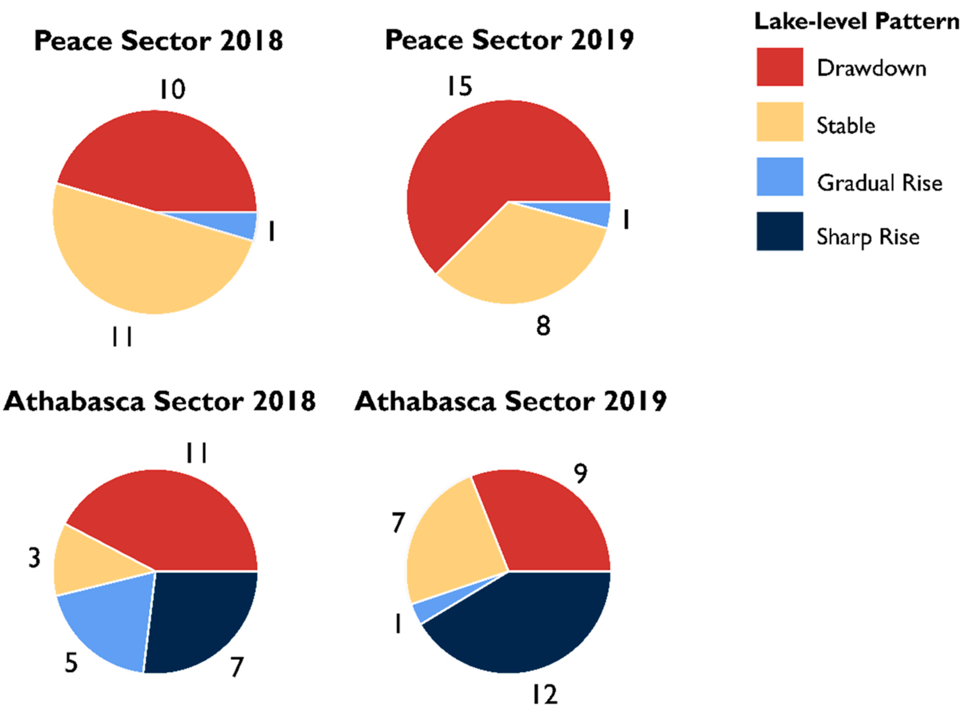

Fig. 8. Pie charts summarizing the distribution of the four lake-level patterns by sector (Peace vs Athabasca) and year (2018, 2019). Values identify the number of lakes represented by each pie slice.

amount of rainfall runoff and evaporative water loss. Combined with predicted declines in ice-jam flood frequency (Beltaos and Bonsal, 2021; Lamontagne et al., 2021) and longer duration of the open-water season promoting greater evaporative water loss (Barnett et al., 2005; Schindler and Donahue, 2006), lake levels are likely to decline across broad areas of the PAD.

Ongoing monitoring of lake levels can inform stewardship decisions for Wood Buffalo National Park, a priority of the federal Action Plan (WBNP, 2019), and ensure long-term sustainability of the delta's ecosystems during the ongoing climate crisis. For example, lake-level monitoring has become an effective management tool for the North Saskatchewan Watershed Alliance to track long-term water-level trends at 33 lakes across the province of Alberta (Islam and Seneka, 2015; NSWA, 2017). Analogous to Fig. 1a in NSWA (2017), we summarize the number of lakes in each hydrological category using pie charts to demonstrate how these data can be used to track the influence of shifting hydrological conditions across sectors and years (Fig. 8). This end-product highlights the importance of open-water flooding (sharp rise lakes) in the Athabasca sector and evaporation (drawdown lakes) in the Peace sector. The approach captured marked increase of drawdown lakes in the Peace sector and sharp rise lakes in the Athabasca sector between 2018 and 2019, which suggests strong potential for ongoing lake-level monitoring. We recommend lake-level monitoring be integrated with other hydrological monitoring tools, such as water isotope tracers and remote sensing imagery, to quantify relative importance of ice-jam flooding, snowmelt and evaporation on lake water balance (Remmer et al., 2020a, 2020b) and to corroborate the spatial extent of river flooding and lake drying (Pavelsky and Smith, 2008; Peters et al., 2021; Töyrä and Pietroniro, 2005). Combined use of these approaches can strengthen monitoring of dynamic lake-rich landscapes, such as the PAD, and better characterize the varying influence of hydrological processes and the timescales at which they operate. Given sufficient financial resources, transferability of this approach to similar remote freshwater landscapes is possible, such as the nearby Slave River Delta (Brock et al., 2007) and Saskatchewan River Delta (MacKinnon et al., 2015), although there may be site-specific hydrological processes to consider such as the influence of seiche events on Great Slave Lake on the former.

At the PAD, wildlife abundance, aquatic habitat, and limnological conditions are strongly regulated by hydrological processes that cause changes in lake levels. Muskrat, for example, is a culturally important and 'keystone' species used to track aquatic habitat availability and ecological integrity of shallow lakes in the PAD (Straka et al., 2018; Ward et al., 2018, 2020). Muskrat abundance has been shown to respond rapidly to changes in freeze-up water levels as they rely on vegetation under ice to survive throughout winter (Virgil and Messier, 1997). Density of muskrat houses increased by two orders of magnitude after spring flooding in 2014 and slowly declined during subsequent drier years as water depth declined (Straka et al., 2018). Lake level rise caused by input of turbid floodwater dramatically reduces water clarity, concentrations of dissolved nutrients, organic carbon and ions, and biomass of phytoplankton and macrophytes at seasonal timescales or longer (Wiklund et al., 2012). Flooding that causes rapid rise of lake levels is likely to result in greater reductions in these variables than flooding that causes gradual rise. Absence of recent flooding, on the other hand, leads to higher concentration of nutrients and ions, higher pH and greater penetration of solar radiation to the bottom of shallow lakes, leading to higher production of macrophytes, phytoplankton and their consumers. Such conditions characterize lakes in the stable and drawdown categories (Wiklund et al., 2012). Persistent drawdown of water levels eventually results in loss of littoral habitat and encroachment of terrestrial vegetation such as willow which impedes mobility of large wildlife (e.g., bison) and land users (Timoney, 2013). Spatio-temporal variation in lake types across the PAD supports an abundance and diversity of aquatic and semi-aquatic biota, yet climate change is predicted to increase proportions of lakes in the drawdown and stable categories at the expense of lakes in the gradual rise and rapid rise categories. Clearly, continued monitoring of lake-level variation, coupled with research on links with the ecological structure and function of the lakes, is important to inform about ongoing hydroecological changes in response to climate trends and other stressors.

CRediT authorship contribution statement

L. K. Neary: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **C. R. Remmer**: Investigation, Writing – review & editing. **J. Krist**: Formal Analysis, Investigation. **B. B. Wolfe**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **R. I. Hall**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100948.

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