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Lake Water Levels and Associated Hydrologic Characteristics in the Conterminous U.S.

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Research Impact Statement: Probability survey of U.S. lakes showed water-level decline is common but variable across years (60%–20%). Lake water residence times were < 1 year for most lakes and less variable across years.

ABSTRACT: Establishing baseline hydrologic characteristics for lakes in the United States (U.S.) is critical to evaluate changes to lake hydrology. We used the U.S. Environmental Protection Agency National Lakes Assessment 2007 and 2012 surveys to assess hydrologic characteristics of a population of ~45,000 lakes in the conterminous U.S. based on probability samples of ~1,000 lakes/yr distributed across nine ecoregions. Lake hydrologic study variables include water-level drawdown (i.e., vertical decline and horizontal littoral exposure) and two water stable isotope-derived parameters: evaporation-to-inflow (E:I) and water residence time. We present (1) national and regional distributions of the study variables for both natural and man-made lakes and (2) differences in these characteristics between 2007 and 2012. In 2007, 59% of the population of U.S. lakes had *Greater than normal* or *Excessive* drawdown relative to water levels in ecoregional reference lakes with minimal human disturbances; whereas in 2012, only 20% of lakes were significantly drawn down beyond normal ranges. Water isotope-derived variables did not differ significantly between survey years in contrast to drawdown. Median E:I was 20% indicating that flow-through processes dominated lake water regimes. For 75% of U.S. lakes, water residence time was less than one year and was longer in natural vs. man-made lakes. Our study provides baseline ranges to assess local and regional lake hydrologic status and inform management decisions in changing environmental conditions.

(KEYWORDS: lakes; surface water hydrology; monitoring; water-level drawdown; water stable isotopes.)

INTRODUCTION

Lake water-level fluctuations influence nearshore habitat structure, within-lake biogeochemical processes, and community composition (Leira and Cantonati 2008; White et al. 2010; Zohary and Ostrovsky 2011; Evtimova and Donohue 2016) and thus have important implications for lake ecology and management. These fluctuations may be natural or the result of human activity. Water withdrawal and diversion for human purposes can significantly lower water levels, especially in man-made lakes. Changing climate conditions that affect precipitation inputs and evaporative water-loss can alter water balance in both natural and man-made lakes. Pressures on lake water balance are expected to worsen with projected increased water-use demands, modified temperature and precipitation regimes, and frequency of extreme weather events (e.g., flooding and prolonged droughts) (IPCC 2014; Jeppesen et al. 2015; Wang et al. 2018). These pressures may result in water-

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level fluctuations beyond normal historic ranges, which can significantly alter lake physical, chemical, and biological conditions (Wilcox and Meeker 1991; Wilcox and Meeker 1992; Hambright et al. 2004; Leira and Cantonati 2008; Zohary and Ostrovsky 2011; Gaeta et al. 2014; Lu et al. 2018).

Despite the importance of lake water levels and water-balance to lake function, hydrologic status for the vast majority of inland lakes across the United States (U.S.) remains unknown. Lake hydrologic studies tend to be conducted on individual lakes or groups of lakes within a restricted region and often are initiated because of an environmental concern of human interest (van der Kamp et al. 2008; Gibson, Birks, Yi, Moncur, et al. 2016; Jones et al. 2016). These focused studies do not provide an adequate description of hydrologic status in the wider lake population. In addition, standardized indicators of lake hydrologic alterations that can be applied in multi-lake, single-visit monitoring programs are lacking. Only a small proportion of U.S. lakes have physical water-level benchmarkers and/or gauges, and alternative methods are needed to measure water levels for broad-scale lake hydrologic assessments. Without standardized measures and baseline hydrologic values, the magnitude and extent of potential changes to lake water levels are difficult to determine.

Lake hydrologic assessments require statistically rigorous survey designs employing probability site-selection to represent the true population of lakes (Peck et al. 2013). In probability-based surveys, sampled lakes have known probabilities of selection from the target population, which allow inference to the population of interest. Nonprobability-based lake surveys, in which sites are selected by judgement or convenience, have typically over sampled large lakes and under-represent small lakes in the population (Peterson et al. 1999; Wagner et al. 2008; Stanley et al. 2019). These and other often unintentional sampling biases can distort perceptions of lake hydrologic condition and have implications for lake management decisions and macro-scale limnologic studies. Small lakes (<1 km^2) make up the majority of lakes globally (Downing et al. 2006), and their physical and morphological characteristics differ from those in large lakes. As a result, the hydrology of small lakes can differ substantially from that of large lakes (Read et al. 2012), further resulting in often complex and sometimes nonintuitive responses to climatic variation and environmental disturbances (Hostetler and Bartlein 1990; Coops et al. 2003; Kraemer et al. 2015; Winslow et al. 2015). For example, Winslow et al. (2015) found a size-dependent difference in lake water temperature response to climate, such that lake warming rates were greater in large lakes (>0.5 km^2) compared to small lakes (<0.5 km^2), which may be related to wind-sheltering effects on shallow lake mixing. Sampling biases in nonprobability surveys can ignore significant proportions of lakes in the population and may distort the perception of true lake hydrologic distributions and trends. Assessing lake hydrologic status and condition in the U.S. lake population requires quantifying hydrologic variation in statistically representative sampling at regional and national scales.

In this study, we describe the hydrologic characteristics of natural and man-made lakes across the conterminous U.S. based on the 2007 and 2012 U.S. Environmental Protection Agency (USEPA) National Lakes Assessment (NLA) datasets. The NLA applied standardized field and analytical methods to quantify attributes of sample lakes selected using a probability survey design (USEPA 2017). The NLA survey design enables us to describe characteristics of U.S. lakes using rigorous statistical inference from the sampled lakes (~1,000 lakes per survey) to the national population of ~45,000 lakes having surface area ≥ 0.04 km^2 (USEPA 2009; USEPA 2016). The NLA surveys have been used to assess physical, chemical, and biological condition of U.S. lakes (e.g., Kaufmann, Peck, et al. 2014; Stoddard et al. 2016; Leech et al. 2018). Additionally, the NLA surveys include lake hydrologic measures related to water balance: lake water-level drawdown and water stable isotope ratios. NLA's field measures of drawdown quantify water-level deviation from the apparent full pool level. The term drawdown is commonly used to describe water level declines on reservoirs and lakes where levels are intensively managed. Throughout this article, however, we use the term drawdown to refer to seasonal or long-term water level declines resulting from natural and/or anthropogenic factors in both natural and man-made lakes. We used water stable isotope ratios (δ^2H, δ^{18}O) in the NLA to quantify lake water balance attributes: evaporation-to-inflow (E:I) and water residence time (τ) (Brooks et al. 2014). In this study, we ask: (1) What are the national and regional distributions of lake drawdown and water balance parameters in natural and man-made lakes across the conterminous U.S.? and (2) What are the differences in these lake hydrologic characteristics between the 2007 and 2012 survey years? We expect that lake hydrologic characteristics vary among lake types (natural, man-made) and across regional settings. The results from this study provide a geospatial framework for future efforts to better understand the regional contexts associated with variation in lake hydrologic characteristics. Lake management and broad-scale limnologic studies will benefit from this baseline knowledge of hydrologic condition to better evaluate, predict, and respond to the effects of changing land use and climate on the ecological integrity of lakes.

METHODS

NLA Survey

The NLA uses probability-based survey designs to assess the ecological condition of U.S. lakes. Probability weights assigned to NLA sites are used to make statistically rigorous estimates (with quantified uncertainty) of characteristics of the population of lakes in the conterminous U.S. (Peck et al. 2013; USEPA 2017). Lakes in the NLA were selected using a spatially balanced, randomized systematic design that is stratified by ecoregion and lake size class (Peck et al. 2013). The sample frame is based on lake polygon features in the National Hydrography Dataset (NHD) Plus Version 1 (1:100,000) (USGS 2001) and includes both natural and man-made lakes and ponds. The surveys exclude the Laurentian Great Lakes, the Great Salt Lake, commercial treatment ponds, and coastal and ephemeral lakes.

The NLA populations included all NHD permanent waterbodies with surface area ≥ 0.04 km^2, estimated maximum depth ≥ 1 m, and ≥ 0.001 km^2 of open water (USEPA 2009). The 2012 NLA lake definition and sample frame expanded to include lakes between 0.01 and 0.04 km^2 in surface area (USEPA 2016). The 2007 NLA survey sampled 1,028 lakes that represented a population of approximately 45,600 lakes in the conterminous U.S.; the 2012 NLA survey sampled 1,038 lakes that represented a population of ~66,800 lakes (Figure 1; Table 1). To keep the size classes the same between survey years, we excluded lakes < 0.04 km^2 in the NLA 2012, which resulted in 951 sampled lakes representing ~44,200 lakes in the population. Approximately 30% of lakes sampled in NLA 2007 were resampled in NLA 2012 (n = 348 lakes). The 2007 lakes that were resampled in 2012 were selected with an equal probability within each of the 48 state strata and were relatively evenly distributed across the conterminous U.S. (USEPA 2017).

All lakes were sampled once within the time period of May through October each survey year, and about 10% of lakes were visited twice within a survey year (USEPA 2017). We used the first visit measurements in our status and change assessments and other studies used the repeat visits to estimate precision (Brooks et al. 2014; Kaufmann, Hughes, et al. 2014). Lakes were visited randomly within a state, with adjustments for weather and accessibility during the season, so the resulting order of sampling may

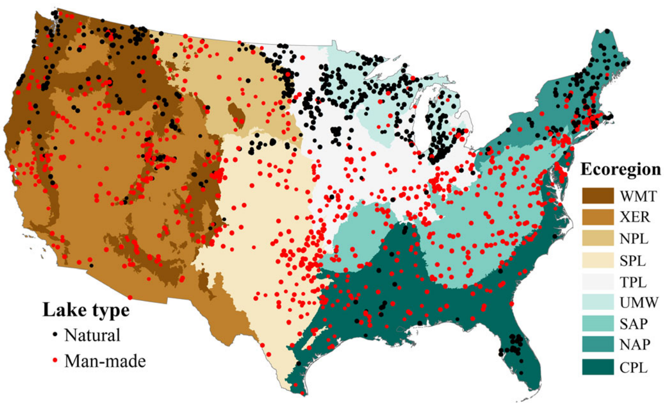

FIGURE 1. National Lakes Assessment (NLA) 2007 and 2012 natural and man-made lake sample sites ($\geq$0.04 km^2 surface area) distributed across nine aggregated ecoregions in the conterminous U.S. The number and spatial distribution of sample sites in NLA 2007 (n = 1,028) were similar to NLA 2012 (n = 951 lakes $\geq$ 0.04 km^2). Sample sites in the probabilistic survey design were used to make inference to target lake populations. Lakes are grouped into two types: *Natural* (black) and *Man-made* (red). Nine-aggregated Omernik Level-III ecoregions moving from west to east: WMT, Western Mountains; XER, Xeric; NPL, Northern Plains; SPL, Southern Plains; TPL, Temperate Plains; UMW, Upper Midwest; SAP, Southern Appalachians; NAP, Northern Appalachians; CPL, Coastal Plains.

exhibit latitudinal and elevation patterns. The 2007 and 2012 NLA datasets are available at https://www.epa.gov/national-aquatic-resource-surveys/nla. More information about the NLA survey design can be found in the NLA 2012 Technical Report (USEPA 2017).

NLA Lake Characteristics and Ecoregional Setting

Lakes in the NLA are divided into two lake origin types: *natural* and *man-made*, based on the classification developed for the surveys (USEPA 2012). NLA analysts determined lake origin using multiple lines of evidence such as field observations, maps with background imagery or topographic maps (e.g., Google Earth, Google Maps, GIS software), expert opinion, and other available records (e.g., history searches, “reservoir” in the lake name, Army Corps of Engineers reservoir database, etc.). Natural lakes were considered to be those that existed prior to European settlement, even if they currently have flow-control structures of some type; and man-made lakes were defined as water bodies intentionally created by humans by flooding constructed basins and/or damming river outlets where no lake existed prior to European settlement (USEPA 2009).

We used the NLA’s nine-aggregated Omernik Level-III ecoregions to delineate areas across the U.S. with similar geographic and climate features

TABLE 1. NLA 2007 and 2012 sample size (n) and inferred lake population size (P) and percent (%) of population in a survey year organized by lake type and ecoregion.

		2007			2012 size-adjusted $\geq 0.04\ km^2$			2012 original $\geq 0.01\ km^2$			Resampled 2007 and 2012
Category	**Class**	***n***	***P***	%	***n***	***P***	%	***n***	***P***	%	***n***
Lake type	Natural	434	26,633	58.5	420	26,469	59.8	457	34,440	51.5	150
	Man-made	594	19,004	41.6	531	17,798	40.2	581	32,419	48.5	198
Ecoregion + lake type											
WMT	Natural	73	2,691	5.9	74	1,911	4.3	90	3,209	4.8	19
	Man-made	75	572	1.2	76	1,064	2.4	79	1,338	2.0	24
XER	Natural	11	73	0.2	17	147	0.3	17	147	0.2	5
	Man-made	79	1,315	2.9	75	772	1.7	77	997	1.5	24
NPL	Natural	36	1,219	2.7	42	801	1.8	42	801	1.2	12
	Man-made	29	1,096	2.4	29	499	1.1	34	1,361	2.0	8
SPL	Natural	15	149	0.3	13	186	0.4	14	293	0.4	7
	Man-made	113	2,822	6.2	72	2,306	5.2	76	3,590	5.4	40
TPL	Natural	66	3,290	7.2	64	3,882	8.8	67	4,653	7.0	24
	Man-made	72	2,149	4.7	73	2,178	4.9	83	4,666	7.0	24
UMW	Natural	137	14,471	31.7	120	12,892	29.1	133	17,460	26.1	46
	Man-made	8	440	0.9	11	989	2.2	12	1,629	2.4	2
SAP	Natural	0	0	0	1	36	0.1	1	36	0.1	0
	Man-made	120	4,186	9.2	77	3,135	7.1	88	7,015	10.5	38
NAP	Natural	58	2,701	5.9	62	4,854	11.0	65	5,511	8.2	24
	Man-made	35	2,650	5.9	29	1,316	3.0	34	2,006	3.0	13
CPL	Natural	38	2,039	4.5	27	1,761	4.0	28	2,330	3.5	13
	Man-made	63	3,774	8.3	89	5,537	12.5	98	9,816	14.7	25
Total sampled lakes		1,028			951			1,038			348
Total target population lakes		45,637			44,268			66,859			

Note: Lakes are grouped into two types: *Natural* and *Man-made* and organized by nine-aggregated Omernik Level-III ecoregions ordered from west to east across the conterminous U.S. The target population and sample frame changed between survey years. NLA 2007 includes lakes $\geq 0.04\ km^2$, and the original NLA 2012 dataset includes lakes $\geq 0.01\ km^2$. NLA 2012 *size- adjusted* dataset drops lakes between 0.01–0.04 km^2 to match the size distribution in the NLA 2007 dataset. A subset of lakes (*Resampled*) were sampled in both the 2007 and 2012 surveys.

(Omernik 1987; Griffith et al. 1999) and summarize lake hydrologic characteristics. These aggregated ecoregions were initially based on stream macroinvertebrate assemblages at reference sites (Herlihy et al. 2008) and have proved an ecologically useful regionalization framework. Subsequently, all other USEPA National Aquatic Resource Survey assessments have used these aggregated ecoregions to report the ecological condition of freshwater systems in the conterminous U.S. The nine-aggregated ecoregions are Western Mountains (WMT), Xeric (XER), Northern Plains (NPL), Southern Plains (SPL), Temperate Plains (TPL), Upper Midwest (UMW), Southern Appalachians (SAP), Northern Appalachians (NAP), and Coastal Plains (CPL) (Figure 1).

We characterized flow network connectivity and morphology of NLA sample lakes based on attributes gathered from geospatial datasets and literature searches. Lakes were classified by freshwater connectivity (i.e., stream and upstream lake surface connections) using NHD lake and stream data layers and methods developed by N. Smith in Soranno et al. (2015). Lakes were grouped into three freshwater connectivity types: *Isolated* (headwater/seepage), *Drainage* (stream-connected lakes without connections to upstream lakes $\geq 0.1\ km^2$ in size), and upstream-drainage lakes — *UPLK* (stream-connected lakes with upstream lakes $\geq 0.1\ km^2$ in size) (Soranno et al. 2015; Fergus et al. 2017). Read et al. (2015) identified lakes in the NLA 2007 survey using these methods where NHD stream reach data were available (n = 906 lakes). This classification was not available for NLA 2012 lakes, but it is expected that these connectivity classes would not change significantly between years.

NLA field crews measured water depth at the approximate deepest location on each lake. However, maximum depths in lakes >50 m deep were not consistently measured or recorded by field crews. To address this limitation, we compiled published maximum depths for lakes with NLA field depth estimates ≥40 m and substituted the published values if the difference between the NLA measured depth and literature reported depth was >10% of the NLA estimate. We used this cutoff to accept the NLA field measured depth (which may be a better representation of depth at the time of sampling, especially in man-made lakes) if the differences were small (1–3 m difference). If differences were very large, we assumed the depth was beyond what the field crews could accurately measure and used the literature value. Maximum depth estimates were changed to literature values for only 24 lakes in NLA 2007 and for 8 lakes in NLA 2012.

NLA Lake Hydrology Variables

Lake Drawdown Measures. Horizontal and vertical water-level measurements are the distance and height, respectively, from the observed lake water level on the day of sampling to the apparent high-water marks based on field observations of the lake shoreline (Kaufmann, Hughes, et al. 2014). These lake drawdown measures estimate short- to medium-term declines in water levels from the full lake stage that may be caused by drought and/or water management activities over monthly to decadal time scales (Kaufmann, Hughes, et al. 2014). Crews visually estimated distances or used hand-held levels, survey rods, and laser rangefinders to measure horizontal and vertical lake level drawdown from the high water-mark locations at 10 equidistant stations around each lake. High-water mark locations were determined based on multiple lines of evidence, including the location of flotsam deposits, evidence of wave action, exposed lake bottom, and the extent and location of vegetation intolerant to frequent or prolonged inundation (USEPA 2017). We based our analysis on the mean values of the drawdown measures across the 10 stations on each lake. Field methods for drawdown were the same for the 2007 and 2012 surveys.

For some analyses, lake drawdown measures were scaled to account for the influence of lake morphology on absolute measures of drawdown. We scaled vertical drawdown as a proportion of lake depth by dividing by maximum lake depth, and horizontal drawdown as a proportion of the lake area by dividing by the square root of the lake's surface area (Table 2). We used these dimensionless, scaled metrics to examine associations between lake drawdown and the proportion of E:I while controlling for variation in lake morphology.

NLA Water-Level Condition. In addition to absolute water-level drawdown measurements, the NLA surveys evaluated the severity of lake drawdown in relation to the distributions of observed drawdown among least-disturbed (reference) lakes. Methods to estimate drawdown condition are detailed in the USEPA NLA 2012 Technical Report (2017) and parts are reiterated here. NLA analysts set criteria for *Normal*, *Greater than normal* (>*Normal*), and *Excessive* drawdown categories based on percentiles of the distribution of unscaled (absolute) horizontal and vertical drawdown in least-disturbed sites within each ecoregion of the surveys. Determination of least-disturbed sites was based on water chemistry, near-shore and surrounding human influences, and evidence of human water extraction and/or diversion (Herlihy et al. 2013; USEPA 2017). Details on NLA least-disturbed site selection are in the NLA 2012 Technical Report (2017) and Herlihy et al. (2013). Reference drawdown distributions were calculated separately for aggregated ecoregions NAP, SAP, UMW, and CPL. For the Central Plains (TPL, SPL, and NPL) and the West (WMT, XER), separate reference drawdown distributions were calculated for natural and man-made lakes. Vertical and horizontal drawdown were classified as *Normal* if values were ≤75th percentile of their respective reference distributions; *Excessive* if >95th percentile, and *Greater than normal* if in between. Reference drawdown distributions used to set drawdown condition class thresholds (NLA 2007 and 2012) are in the Supporting Information (Table S1). Overall, lake drawdown condition was considered *Normal* if both vertical and horizontal drawdown were classified as *Normal*; *Greater than normal* if one or both were *Greater than normal* (but not *Excessive*); and *Excessive* if one or both were *Excessive* (USEPA 2017).

Isotope-Derived Lake Hydrology Variables. E:I ratios and water residence time (Table 2) were calculated as described by Brooks et al. (2014) using water isotope mass balance models. Isotope-based E:I and water residence time measures can provide robust, first-order approximations of lake hydrologic characteristics that are useful for among-lake comparisons (Gibson, Birks, and Yi 2016).

We applied the same steps to derive E:I and water residence time for NLA 2012 lakes as was conducted in Brooks et al. (2014) for the NLA 2007 lakes. We provide a brief description of the approach below, and more details follow in the Supporting Information.

Water samples for all NLA chemical analysis were collected from the upper 2 m of water at the approximate deepest part of the lake to represent the well-mixed portion of the lake water column. Samples were shipped overnight to the Willamette Research Station in Corvallis, Oregon where subsamples were taken for water isotope analysis and sent to the nearby Integrated Stable Isotope Research Facility at the USEPA Pacific Ecological Systems Division. There, water isotope ratios (δ^2H, δ^{18}O) were measured on a laser absorption water vapor isotope spectrometer (Model 908-0004, Los Gatos Research, San

TABLE 2. Description of lake hydrologic and climate variables.

Variable	Units	Description
Horizontal drawdown	m	Horizontal drawdown distance (Horiz_{dd}) to apparent highwater mark calculated as a mean of measurements of exposed littoral bottom at 10 equidistant stations around the lake during the summer sample visit
Vertical drawdown	m	Vertical drawdown height (Vert_{dd}) to apparent highwater mark calculated as a mean of vertical height measurements at 10 equidistant stations around the lake during the summer sample visit
Scaled horizontal drawdown		Scaled $\text{Horiz}_{\text{dd}} = \text{Horiz}_{\text{dd}}/\left(\sqrt{\text{lake surface area}}\right)$
Scaled vertical drawdown		Scaled $\text{Vert}_{\text{dd}} = \text{Vert}_{\text{dd}}/\text{maximum lake depth}$
Evaporation-to-inflow (E:I)		Proportion of lake inflow that is evaporated. E:I = 0 no detectable losses to evaporation; E:I = 1 all (100%) inflow lost to evaporation (Brooks et al. 2014)
Water residence time	year	Water residence time within a lake based on water-isotope derived parameters, estimated lake volume, and modeled potential evapotranspiration from the lake surface (Brooks et al. 2014)
Change in response variables		Change in lake hydrologic response or weather from 2007 to 2012 survey years ($\Delta_y = y_{2012} - y_{2007}$)
Long-term precipitation	mm	30-year normal mean annual cumulative precipitation in the lake watershed (1981–2010) (PRISM Climate Group)
Long-term temperature	°C	30-year normal mean temperature in the lake watershed (1981–2010) (PRISM Climate Group)
Annual precipitation	mm	Cumulative precipitation during the survey water year (October of previous year to October of survey year) (PRISM Climate Group)
Mean temperature	°C	Mean temperature during the survey year (PRISM Climate Group)
PHDI		Palmer Hydrologic Drought Index — a measure of the severity of drought with positive values indicating wet periods and negative values indicating drought (National Oceanic and Atmospheric Administration). Estimated mean PHDI during the survey year
Lake drawdown condition class		Drawdown condition classes based on horizontal and vertical drawdown percentiles in least-disturbed (reference) sites: *Normal*, *Greater than normal*, *Excessive* (USEPA 2017)
Lake connectivity class		*Isolated*: Headwater or seepage lake with no inflowing streams *Drainage*: Lake with inflowing streams without connections to upstream lake(s) ≥0.1 km^2 *UPLK*: Lake with inflowing streams connected to upstream lake(s) ≥0.1 km^2 (Soranno et al. 2015)

Jose, CA, USA). All isotope values were expressed in standard δ notation relative to Vienna Standard Mean Ocean Water in parts per thousand (‰). Precision (one standard deviation) based on 55 sample duplicates was better than 0.2‰ and 0.1‰ for δ^2H and δ^{18}O, respectively. Accuracy based on 36 QC standards (not used in calibration) was -0.09 ± 0.2‰ for δ^2H, and 0.003 ± 0.06‰ for δ^{18}O. For more details on isotopic analysis please see Supporting Information.

We derived lake E:I from the following equation (Gibson and Edwards 2002; Gibson and Reid 2010).

$$\frac{E_L}{I_L} = \frac{(\delta_I - \delta_L)}{(\delta_E - \delta_L)}, \tag{1}$$

where I_L = inflow (m^3; i.e., surface water, groundwater, and direct precipitation) and E_L = lake evaporation (m^3). The isotopic values of inflow, lake water, and evaporation fluxes are δ_I, δ_L, and δ_E, respectively. δ_L was measured from the lake water sample; δ_I was estimated three ways: (1) annual lake point precipitation, (2) annual watershed precipitation, and (3) a regression slope method; and δ_E was estimated using the Craig-Gordon model for open-water evaporation (Craig and Gordon 1965). See Supporting Information for more details.

Water residence time (year; τ) was estimated from E:I estimates (from Equation 1), annual estimates of evaporation from the lake surface (m^3 yr; E), and lake volume (m^3; V) (Gibson et al. 2002).

$$\tau = \left[\frac{E}{I}\right]\left[\frac{V}{E}\right]. \tag{2}$$

For E from the lake surface, we used annual potential evapotranspiration estimated from temperature data (PRISM Climate Group) using the Hamon equation according to Wolock and McCabe (1999). Lake volume was estimated following methods in Hollister and Milstead (2010) using measured maximum lake depth and geographic data on the lake shoreline. The approach assumes that lake depth at any given location (Z) is a linear function of the distance from the shoreline (D) to more realistically represent variation within lake basin bottom shape.

$$Z = \frac{D \times Z_{\max}}{D_{\max}}. \tag{3}$$

Lake volume is estimated by calculating the volume (cell area × depth) within the lake polygon raster and summing across all cells within a lake. Previous work demonstrated that lake volume estimated using this distance method better captured "true" volume estimates that were based on bathymetry data than did estimates assuming a "conical" lake (Hollister and Milstead 2010). We used the lakemorpho: Lake Morphometry Metrics R package v. 1.1.0 (Hollister 2016) to estimate volume for the NLA lakes.

Inferred Population Estimates Analysis

We present national and regional estimates of lake horizontal and vertical drawdown, E:I, and water residence time inferred from the ~1,000 sampled lakes per survey year to the study population of lakes in the conterminous U.S. (~45,000 lakes) using the probabilistic survey weights. As part of the NLA survey design, weights were assigned to lakes based on their probability of being sampled from an explicitly defined target population of lakes and were expressed in units of lakes (i.e., the number of lakes they represent in the population). Weights differed across aggregated ecoregions and by lake area classes to reflect the regional variation in density of lakes and the greater abundance of small lakes relative to large lakes (USEPA 2017).

All analyses were performed with R statistical software (v. 3.3; R Core Team 2016). We used the spsurvey: Spatial Survey Design and Analysis R package developed for statistical analysis of probability-based survey data (Kincaid and Olsen 2016) to estimate target population statistics (e.g., mean, standard error, population percentiles). We calculated z-scores to test for significant differences among lake types and ecoregions from the inferred population means and standard error values. We performed two-way ANOVAs on the unweighted lake hydrology variables to test for the influence of lake type (natural vs. man-made), ecoregion (nine-aggregated ecoregions), and their interactions for each survey year. Lake drawdown measures and water residence time estimates were transformed (log10) to adjust for right-tailed skewed distributions (i.e., many lakes had little to no drawdown or short water residence times and few lakes had very large drawdown or long residence times). Although there were observations with zero drawdown, especially in 2012, many lakes had low and greater-than-zero drawdown values, and the log transformations resulted in near-normal distributions that we deemed satisfactory for analyses with assumptions of normality.

Difference between Survey Years Analysis

We examined differences in lake hydrologic characteristics between survey years using the subset of lakes that were sampled in both 2007 and 2012 (n = 348 lakes) and calculated the unweighted differences ($\Delta_y = y_{2012} - y_{2007}$). Restricting the comparison to only the resampled lakes eliminated the possibility that observed differences may have been caused by potential differences in the sample frame between survey years. We examined whether seasonal sampling date resulted in systematic differences in measured lake variables between surveys by calculating the difference in sample dates between years for individual lakes. Resampled NLA lakes were visited in 2007 and 2012 between May 9 to October 2, and sampling was slightly later in 2007 than in 2012 with a median difference of 8 ± 37 days. This indicates that most lakes were visited around roughly the same time of year, and there were no strong seasonality biases in sampling between years. To compare differences in lake hydrology between the 2007 and 2012 surveys, we calculated the mean difference in lake drawdown (log10), E:I, and water residence time (log10) and performed paired t-tests to determine whether mean differences were significantly different from zero. Results are presented as plots of unweighted sample mean differences with 95% confidence intervals by lake type within ecoregion.

We examined long-term climate characteristics and annual weather conditions for each sampled lake during the survey years to provide context for regional lake hydrologic patterns (Table 2). Baseline regional climate data include PRISM 30-year normal (1981–2010) mean annual total precipitation and mean annual temperature in the lake watersheds that are available for NLA lakes in the USEPA LakeCat dataset (Hill et al. 2018). In addition, annual climate characteristics during each survey water year (October of previous year to September of the survey year) were gathered from PRISM monthly data for 2006–2007 and 2011–2012 and summarized by lake watershed. We calculated cumulative precipitation and mean annual temperature for each survey year. Palmer Hydrologic Drought Index (PHDI) from U.S. National Oceanic and Atmospheric Administration (www.ncdc.noaa.gov) was used as a measure of the severity of drought relative to normal conditions, where positive values indicate wet periods and negative values indicate drought (Palmer 1965). PHDI is a modification from the original Palmer Drought Severity Index to account for longer-term dryness that may affect water storage, streamflow, and groundwater (Heim 2002). We calculated mean annual PHDI by averaging monthly PHDI values during the survey water year for each lake. We tested for significant differences in climate between survey years for the lakes that were sampled in both survey years (n = 348) by calculating differences in mean precipitation, temperature, and PHDI from 2012 to 2007 for each lake and summarized by ecoregion and lake type and performed paired t-tests.

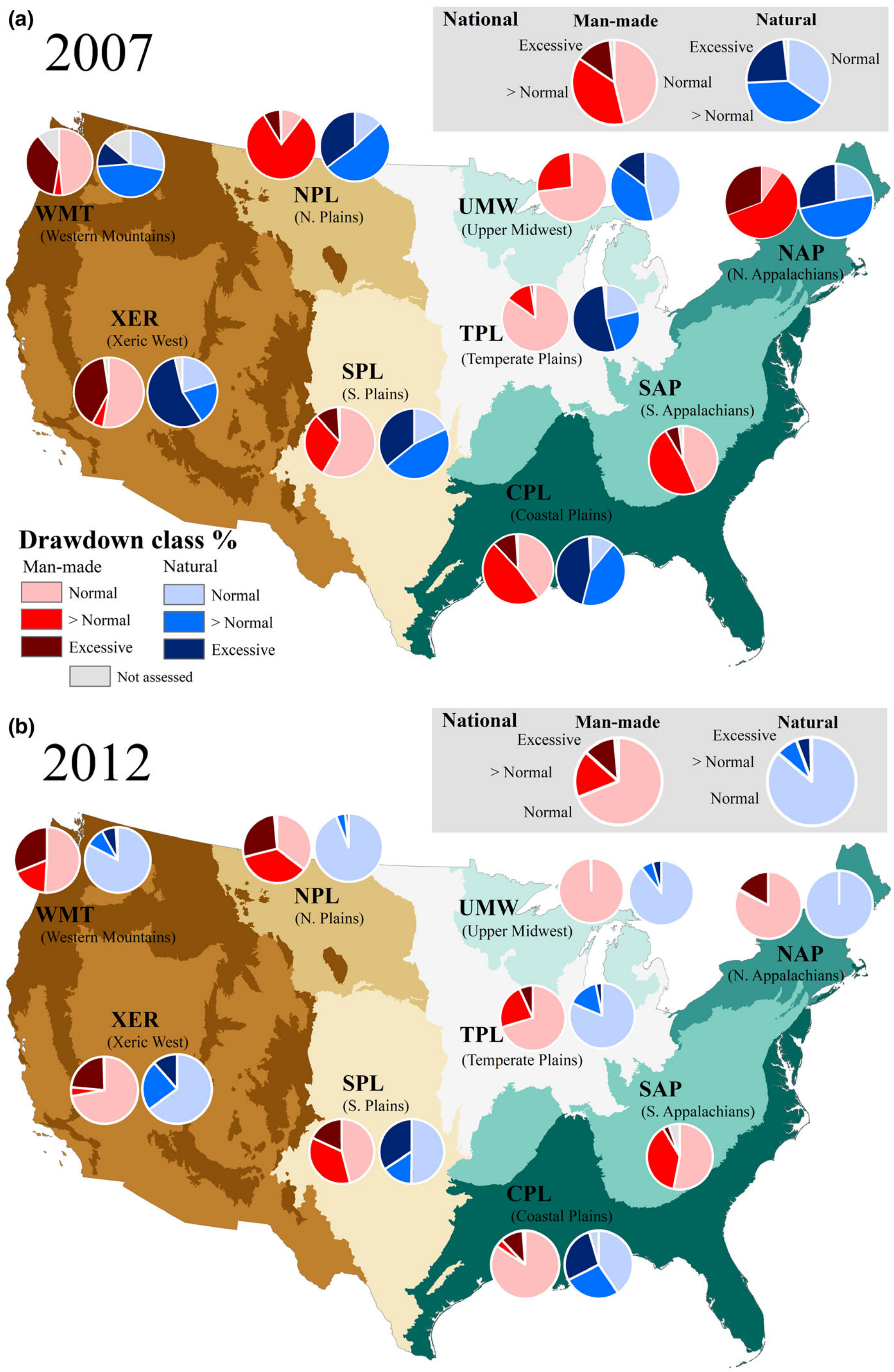

FIGURE 2. Population estimates of lake water-level drawdown condition class by lake type within aggregated ecoregions for the 2007 (a) and 2012 (b) NLA survey years. Lake drawdown condition classes (*Normal*, *Greater than normal*, and *Excessive*) are based on vertical and horizontal drawdown percentiles in least-disturbed reference sites within ecoregions (see Table S1). Drawdown class proportions were estimated for (a) NLA 2007 and (b) NLA 2012 ($\geq$0.04 km^2) target populations.

Precision of Lake Drawdown and Water Balance Variables

Kaufmann, Hughes, et al. (2014) and USEPA (2017) quantified the precision of NLA vertical and horizontal drawdown measurements based on analysis of repeat visits to lakes within the 2007 and 2012 surveys. They expressed precision as: (1) the pooled standard deviation of repeat visits (σ_{rep}), (2) precision relative to potential or observed range (σ_{rep}/Rg_{pot} and σ_{rep}/Rg_{obs}), and (3) the signal-to-noise ratio, where signal is among-lake variance and noise is within-lake variance during the same year and season ($S/N = \sigma^2_{lake}/\sigma^2_{rep}$). Precision analysis was based on NLA field measurements on a probability sample of 981 lakes (NLA 2007) and 1203 lakes (NLA 2012), with repeat sampling on random subsets of 90 and 88 of those lakes, respectively, during the summers of 2007 and 2012. They report that the drawdown index measurements themselves were moderate to relatively precise. With precision (σ_{rep}/Rg) between 0.052–0.084 m, the indices have the potential to discern differences between single lakes (or one lake at two different times) that are between 1/4th to 1/8th the magnitude of the observed ranges in the NLA. Despite large differences in drawdown between visits during the same sampling season, their signal-to-noise ratios ranged from 2.7 to 3.8, indicating that differences among lakes were substantially greater than those between visits to the same lake. Consequently, population distributions and associations are not greatly distorted by "noise" variance (Kaufmann et al. 1999).

Brooks et al. (2014) evaluated the precision of E:I and τ in the NLA 2007 estimates by calculating signal-to-noise ratios. They found that the signal-to-noise ratio for E:I was 11.5, indicating that the variance among lakes was 11.5 times as great as the variance within individual lakes between revisits in a sampling season. The signal-to-noise ratio for τ was 10.6, again indicating that national and regional distributions are minimally influenced by variance within individual lakes.

RESULTS

Water-Level Drawdown Patterns

National Patterns. Over 59% of U.S. lakes in the 2007 population were classified as having *Greater than normal* to *Excessive* water-level drawdown relative to absolute drawdown in least-disturbed reference lakes in their respective regions. More specifically, 20% of lakes were classified as having *Excessive* drawdown, 39% *Greater than normal*, and 39% *Normal* (<2% of lakes were not assessed in 2007). Among lake types, about 24% of natural lakes and 14% of man-made lakes were classified as having *Excessive* drawdown, with water-level drawdown exceeding the 95th percentile of drawdown levels in least-disturbed reference lakes (Figure 2a). Half the lakes in the U.S. had summer water-levels that were more than 0.18 m below the typical high water-line (vertical drawdown) and exposed more than 0.32 m of littoral bottom that is typically inundated under high-water conditions (horizontal drawdown) (Table S2). About 20% of U.S. lakes had negligible vertical and horizontal drawdown equal to zero. The maximum vertical and horizontal drawdown values measured in 2007 were 40 and 545 m, respectively, and both occurred on man-made lakes.

In contrast to drawdown patterns in 2007, more than 75% of lakes in 2012 had zero observed vertical and horizontal drawdown (Table S3). The majority of lakes (79%) had *Normal* drawdown relative to water levels in regional reference lakes; 12% were classified as *Greater than normal*, and only 8% had *Excessive* (1% were not assessed). In 2012, maximum measured drawdown again occurred in man-made lakes with vertical drawdown of 45 m and horizontal drawdown of 708 m.

Ecoregion Patterns among Lake Types. Lake water-level drawdown was substantially greater in certain ecoregions compared to the national levels and was related to lake type (two-way ANOVA with interaction $p < 0.001$; Table S4). In 2007, excessive drawdown beyond normal ranges occurred on natural lakes in XER, NPL, TPL, and CPL regions (35%–56%) and on man-made lakes in the western U.S. (WMT, XER) and in the NAP (30%–40%, Figure 2a). Within the WMT ecoregion, man-made lakes had substantially greater drawdown than their natural lake counterparts (*z*-scores $p < 0.05$) such that mean horizontal and vertical drawdown were about five times greater than drawdown on natural lakes (Figure 3a–3d).

In 2012, drawdown was minimal or absent across most ecoregions with some exceptions. Drawdown was small to nondetectable on both natural and man-made lakes in the UMW (Figure 2b). In contrast, more than half of natural lakes in the south central and southeastern U.S. (SPL and CPL), and similarly > 50% of man-made lakes in WMT, NPL, and SPL ecoregions had *Greater than normal* to *Excessive* drawdown. Man-made lakes in WMT and NPL ecoregions had significantly greater mean horizontal (16.4 m, 6.6 m) and vertical drawdown (2.8 m, 0.6 m) in 2012 than did their natural lake counterparts that had mean drawdown close to zero that year (*z*-scores $p < 0.05$, Figure 4a–4d).

E:I and Water Residence Time Patterns

Water balance parameters, E:I and water residence time (τ), had similar national and regional patterns both survey years. E:I estimated the proportion of water entering a lake (inflow) that was evaporated, such that lakes with E:I = 0 have no detectable losses to evaporation, whereas lakes with

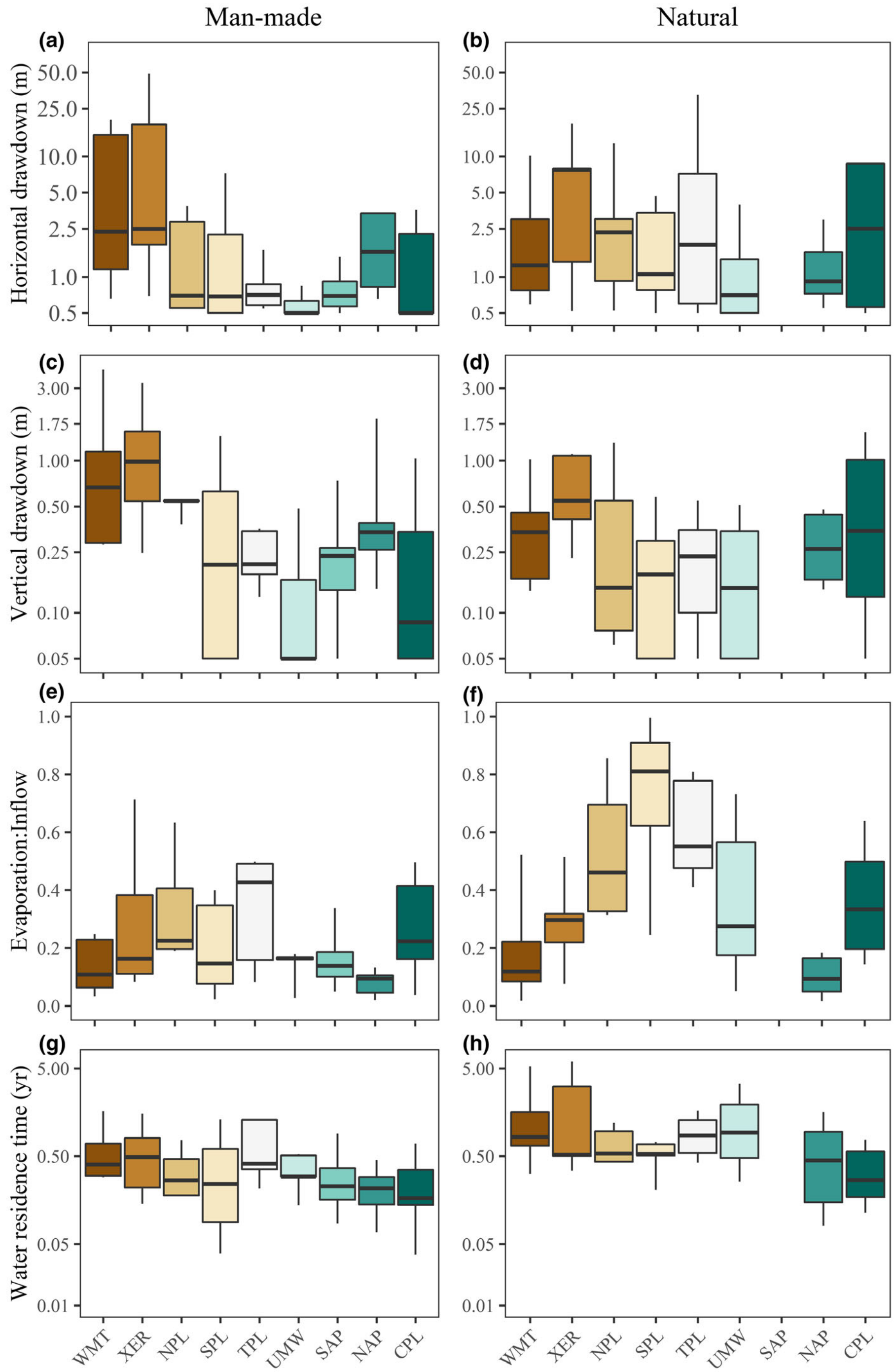

FIGURE 3. Population-inferred distributions of lake hydrologic characteristics for natural and man-made lakes by aggregated ecoregion in the NLA 2007 survey. Distributions are presented as boxplots (box midline = median, lower box = 25th percentile, upper box = 75th percentile, lower whisker = 10th percentile, and upper whisker = 90th percentile). Lake hydrologic variables include (a,b) horizontal and (c,d) vertical water level drawdown (m), (e,f) evaporation:inflow, and (g,h) water residence time (year). Ecoregions are arranged from west to east.

E:I = 1 lose 100% of inflow to evaporation and lakes with E:I > 1 are desiccating lakes. Median E:I values for all lakes were 0.21 in 2007 and 0.26 in 2012 (Tables S2 and S3) indicating that the majority of lakes in the U.S. can be characterized as flow-through, open drainage lakes (i.e., 21%–26% or less of inflowing water was lost to evaporation). Approximately a quarter of U.S. lakes in both survey years had E:I > 0.50 (i.e., more than 50% of inflowing water was lost to evaporation) signifying lakes with

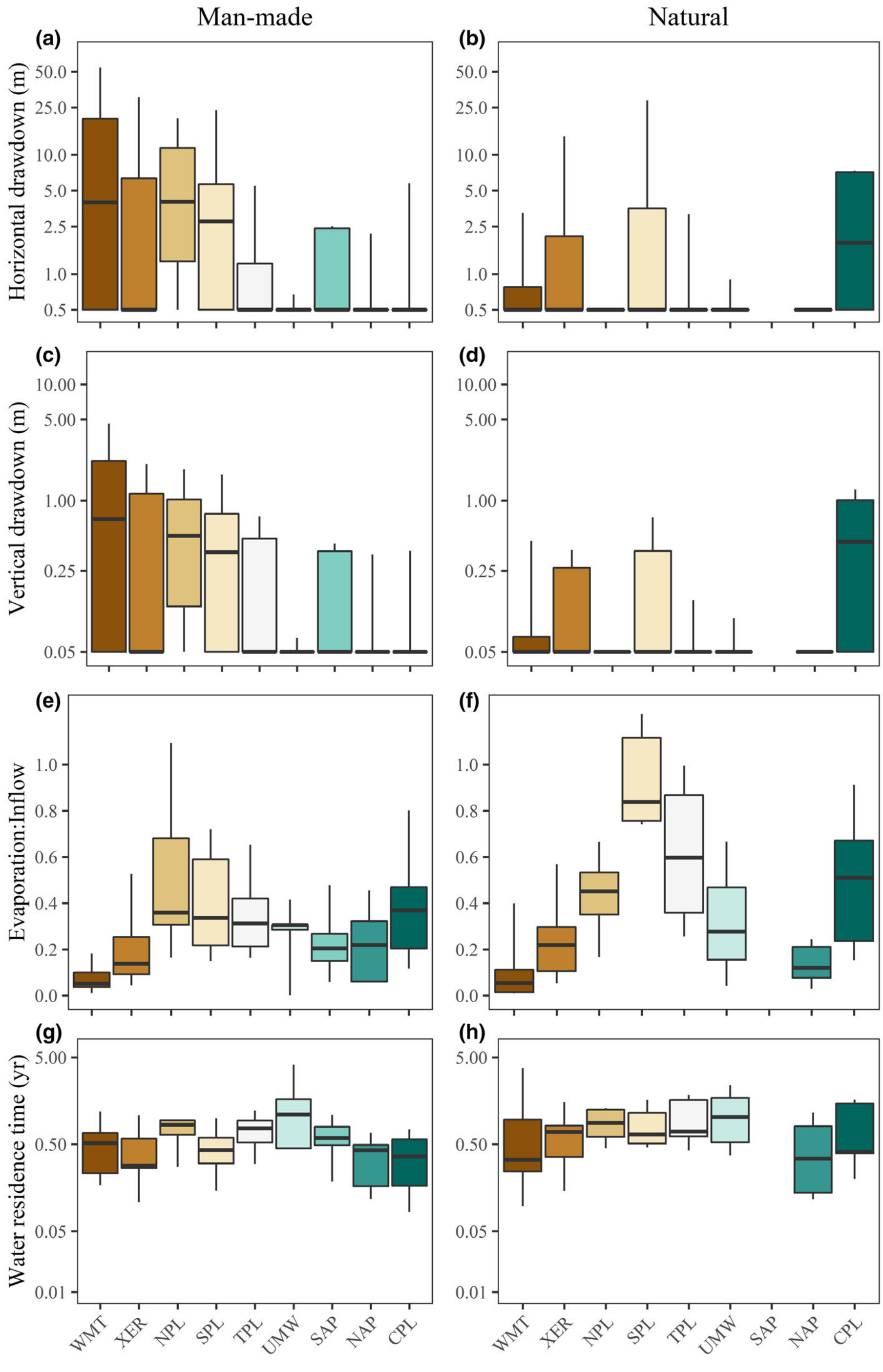

FIGURE 4. Population-inferred distributions of lake hydrologic characteristics for natural and man-made lakes (surface area ≥ 0.04 km^2) by ecoregion in the NLA 2012 survey. Distributions are presented as boxplots (box midline = median, lower box = 25th percentile, upper box = 75th percentile, lower whisker = 10th percentile, and upper whisker = 90th percentile). Lakes smaller than 0.04 km^2 were omitted in the 2012 plots to make the lake size ranges to be comparable with the 2007 survey ranges. Lake hydrologic variables include (a,b) horizontal and (c,d) vertical water level decline (m), (e,f) evaporation: inflow, and (g,h) water residence time (year). Ecoregions are arranged from west to east.

more hydrologically restricted drainage basins. Among ecoregions, E:I distributions were significantly greater in the plains (NPL, SPL, TPL, CPL) and UMW than in the west (WMT and XER) and northeast NAP ecoregions (z-scores $p < 0.05$; Figures 3e, 3f and 5e, 5f). Natural lakes had a greater portion of inflowing water leaving through evaporation (i.e., higher E:I) compared to man-made lakes across most ecoregions both survey years (z-scores $p < 0.05$, Tables S2 and S3).

When vertical drawdown was scaled relative to lake depth, scaled vertical drawdown was positively correlated (Spearman) with E:I for natural ($r = 0.29$, $p < 0.0001$) and man-made ($r = 0.13$, $p < 0.01$) lakes in both survey years (Figure S1), suggesting that evaporation may be an important driver of drawdown in lakes. However, these correlations were insignificant when examined within ecoregions, suggesting that regionally varying factors such as inflow/outflow characteristics of lakes and water management activities may influence lake evaporation relationships with drawdown.

Water residence time estimated from lake water isotopic composition, approximates the hydrologic residence time when samples were collected, rather than a residence time based on annual hydrologic budget measurements. For 75% of U.S. lakes, τ was less than one year (Tables S2 and S3). Water residence time distributions were longer in natural lakes (e.g., median NLA07 = 0.78 year) compared to man-made lakes (e.g., median NLA07 = 0.26 year). Water residence times varied across ecoregions and generally exhibited a pattern of longer-to-shorter τ moving from west to east across the U.S. (Figures 3g, 3h and 4g, 4h).

Differences in Hydrologic Characteristics between Survey Years

For resampled lakes, 45% were less drawn down, 10% were more drawn down, and 40% did not change drawdown condition class from 2007 to 2012 (5% were

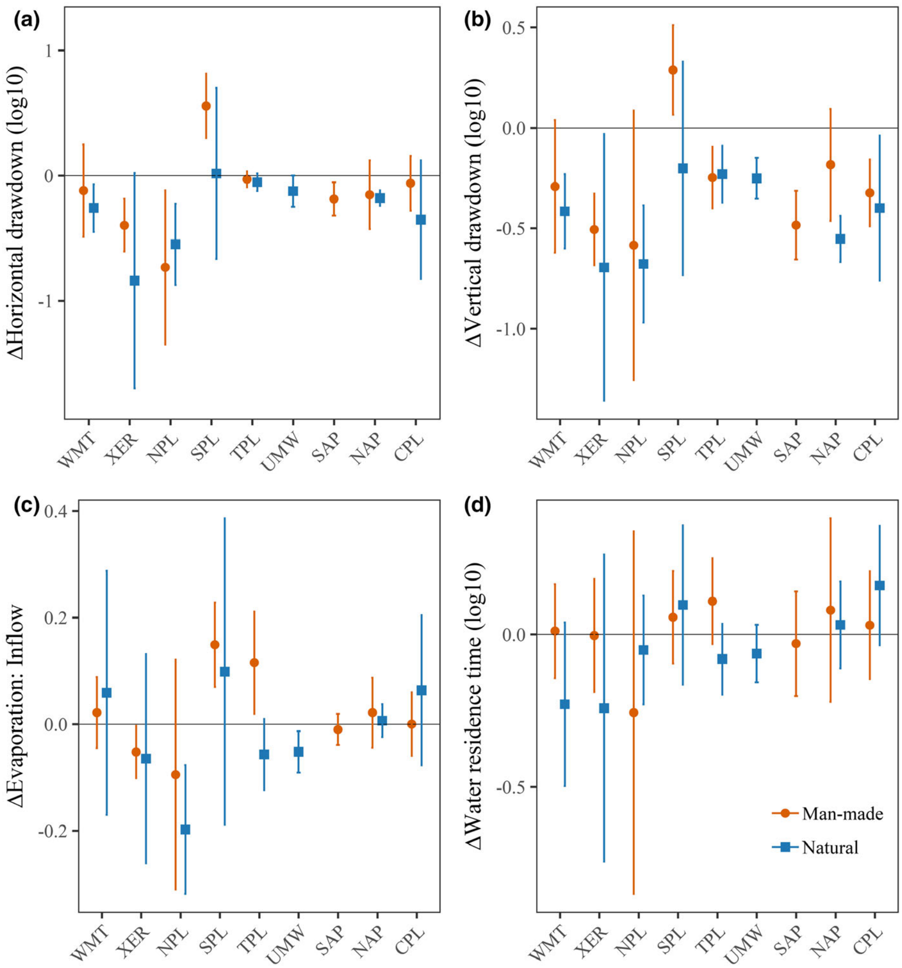

FIGURE 5. Difference in lake hydrologic characteristics between the 2007 and 2012 survey years in resampled natural and man-made lakes by ecoregion. Graphs represent the difference in (a) horizontal and (b) vertical water-level drawdown, (c) evaporation:inflow, and (d) water residence time in individual resampled lakes [$\Delta_y = (y_{2012} - y_{2007})$] that are unweighted (i.e., not population estimates of change) and averaged by lake type and ecoregion with 95% confidence interval error bars. Error bars that overlap zero indicate no statistically significant difference in values between survey years ($p < 0.05$). Positive values indicate an increase in values over time; and negative values indicate a decrease in values over time. Red circles = Man-made lakes; Blue squares = Natural lakes. Man-made lakes in the UMW and natural lakes in the SAP were omitted because of small sample sizes (respectively, $n = 2$ and $n = 0$ resampled lakes).

not assessed in one of the years). Among lake types, more natural lakes (57%) changed from *Excessive* or *Greater than normal* to a less drawn down class in 2012 compared to man-made lakes (35%). Natural lakes in northern ecoregions (WMT, NPL, TPL, UMW, NAP) and CPL were less vertically drawn down in 2012 by an average of 0.3 m (Figure 5b). But on man-made lakes, mean vertical drawdown remained high in 2012 in WMT (mean = 3.0 m), NPL (0.7 m), and NAP (0.3 m) and did not change significantly from mean drawdown in 2007 with confidence intervals overlapping zero (Figure 5b). Man-made lakes in SPL were the only group of lakes where vertical and horizontal drawdown were greater in 2012 compared to 2007 (Figure 5a and 5b).

Water balance parameters had similar distributions between survey years. Nationally, E:I in resampled lakes did not change (mean difference between years = 0.009 ± 0.022, pairwise *t*-test $t = 0.84^{n.s.}$). However, E:I in natural lakes in NPL and UMW was slightly lower in 2012 than 2007; and E:I was greater in man-made lakes in SPL and TPL in 2012 (Figure 5c). Water residence time within ecoregions did not change between survey years (Figure 5d).

We examined whether differences in lake hydrologic characteristics in resampled lakes were correlated with differences in sampling dates between survey years. Resampled NLA lakes were visited around the same time in the season in 2007 and 2012 with sampling occuring slightly later in 2007 than in 2012. However, differences in lake levels between the two surveys were not strongly correlated with the positive or negative differences in sampling date between years for either horizontal (Spearman correlation; $r = 0.01^{n.s.}$) or vertical drawdown ($r = 0.12$, $p = 0.04$).

Although examining potential causal factors was not a main objective of this study, we found that differences in drawdown and E:I were associated with differences in regional weather and drought conditions between the survey years. For the resampled lake locations, 2012 was a wetter year with cooler temperatures compared to 2007 (Figures 6, S2); and both survey periods were warmer and generally drier years compared to the long-term (30 year-average) mean temperature across ecoregions (Figure S2a, S2b). In 2012 mean precipitation was 911 mm compared with 854 mm in 2007; and mean summer temperature was 2° cooler (19.8°C) compared with 2007 (22.3°C). Mild to moderate drought conditions based on PHDI were more prevalent among ecoregions in the U.S. in 2007 compared to 2012. In resampled man-made lakes, change in E:I and change in vertical drawdown (scaled by depth) were negatively correlated with change in PHDI ($r = -0.39$; $p < 0.0001$ and $r = -0.35$; $p < 0.0001$; Figure S3a, S3b), such that E:I and vertical drawdown decreased under wetter conditions in 2012. However, in natural lakes, change in drawdown and E:I were not significantly correlated with change in PHDI.

DISCUSSION

Our study is the first to assess lake levels and water balance characteristics in the national population of ~45,000 lakes across the conterminous U.S. As expected, lake hydrology differed between natural and man-made lakes and among regions, with large water-level drawdown relative to reference conditions occurring on man-made lakes in the WMT and two Central Plains regions (NPL and SPL) and on natural lakes in the Southern and CPL. A greater proportion of inflowing water evaporated from natural lakes compared to man-made lakes. More than 75% of the population of U.S. lakes had water residence times of one year or less, with natural lakes having longer residence times compared to man-made lakes. Lake drawdown and proportion of evaporative water loss differed between the 2007 and 2012 surveys. The majority (59%) of U.S. lakes in 2007 experienced greater water-level drawdown compared to drawdown in least-disturbed reference lakes, in contrast to 2012 where only 20% of lakes had large drawdown relative to least-disturbed condition. Differences in drawdown and evaporative water loss between survey years were generally associated with differences in weather conditions: less drawdown and evaporation occurred in 2012 from 2007 in regions where precipitation increased and/or temperatures were cooler. However, these patterns were not consistent across the U.S., suggesting that lake basin characteristics and human activities may alter relationships between climate effects and lake hydrologic responses. This complexity underscores the importance of examining hydrologic patterns within local and regional contexts to assess influences on lake hydrologic condition across the nation. The results we report in this article establish baseline distributions of lake hydrologic characteristics for the population of lakes in the conterminous U.S. These national, regional, and reference distributions provide a context of observed and expected hydrologic characteristics to which results from individual lakes can be compared.

Patterns of Lake Hydrologic Characteristics in the U.S.

Documenting water-level drawdown and water balance parameters for a diverse population of U.S.

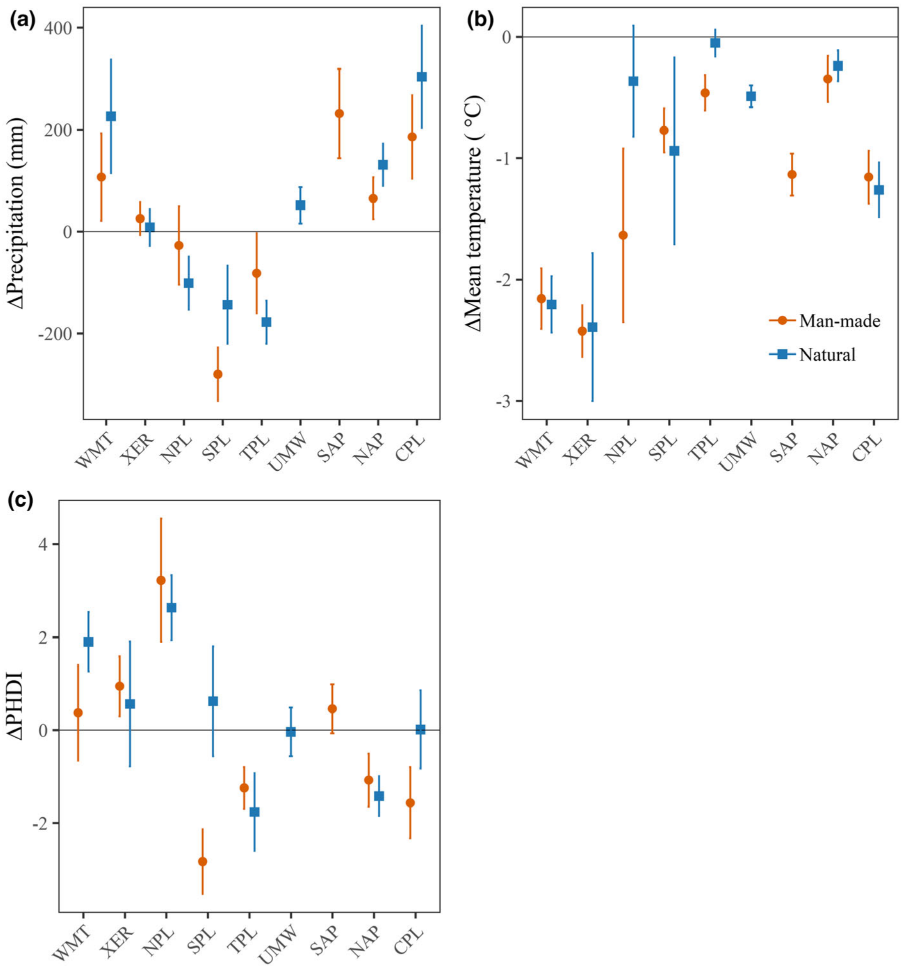

FIGURE 6. Difference in climate characteristics between the 2007 and 2012 survey years around resampled natural and man-made lakes by ecoregion. Graphs represent the difference in unweighted (a) annual cumulative precipitation (mm), (b) monthly-mean air temperature (°C), and (c) monthly-mean PHDI during the survey water year (October of previous year to October of sample year) within resampled lake watersheds between survey year [$\Delta_y = (y_{2012} - y_{2007})$]. Ninety-five percent error bars that overlap zero indicate no statistically significant difference in values between survey years ($p < 0.05$). Positive values indicate an increase in values from 2007 to 2012; and negative values indicate a decrease. Red circles = Man-made lakes; Blue squares = Natural lakes. Estimates for UMW man-made lakes and SAP natural lakes were omitted due to small sample size (respectively, $n = 2$ and $n = 0$ resampled lakes).

lakes has science and management implications under changing environmental conditions. Lake hydrologic characteristics are likely to be altered under projected changes in precipitation and temperature regimes. Lake water-level declines may become more prevalent with predicted increased lake evaporation under warmer climate scenarios (Wang et al. 2018). Water level declines have been observed on the Great Lakes and inland lakes within the region over the previous decade and may be due to evaporative water loss related to climate forcings (Sellinger et al. 2007; Gronewold and Stow 2014; Watras et al. 2014; Xiao et al. 2018). However, hydrologic response to climate change is expected to exhibit within- and across-region heterogeneity due to differences in lake morphometry, watershed hydrogeomorphology and land use/cover, baseline climate, and human water use activities (Blenckner 2005; Hay et al. 2011; Haddeland et al. 2014; O'Reilly et al. 2015; Byun et al. 2019). To better understand how lakes may respond to changing climate conditions requires identifying potential drivers of baseline variation in lake hydrology across lake types and regional settings.

The lake hydrologic variation observed in the U.S. is caused by both natural and anthropogenic processes that are hierarchically structured and can be difficult to tease apart. An in-depth analysis of the mechanisms behind these patterns is beyond the scope of this study but is a recognized future research direction. However, the general patterns we observed in likely drivers of lake hydrology across the U.S. inform ongoing and future research on the causes and ecological consequences of lowered water-levels on lake ecosystems.

Differences between Natural and Man-Made Lakes. Hydrologic characteristics in natural and man-made lakes were distinctly different, suggesting that drivers and processes that affect water levels should be examined for each lake type separately. Natural lakes tended to have smaller drawdown heights, less littoral exposure from drawdown, greater proportions of inflowing water leaving through evaporation, and longer water residence times than man-made lakes. These characteristics aligned with expectations based on differences in the mode of inflow and outflow between natural and man-made lakes (Hayes et al. 2017). Although many natural lakes have some kind of water control structure (e.g., Whittier et al. 2002 reported ~20% of natural lakes in the Northeast U.S. had dam-like structures or modifications at their outlets), water levels in natural lakes tend to reflect precipitation and evapotranspiration patterns (Zohary and Ostrovsky 2011). In contrast, dam and outlet management in man-made lakes can greatly modify water-level regimes and result in larger drawdown heights, greater littoral exposure distances, and less evaporative water loss than observed among natural lakes (Hill et al. 1998; Hirsch et al. 2014). In the NLA surveys, the majority of man-made lakes were situated within stream networks (~80% *Drainage* and *UPLK*; Table 3) and had drawdown and evaporative characteristics that are expected in reservoirs embedded within larger streams and rivers (i.e., more frequent and greater magnitude water-level drawdown and lower E:I compared to lakes outside of stream networks). Ultimately, these hydrologic differences between natural and man-made lakes have implications for characterizing lake response to climate change (Hayes et al. 2017) and their influence on macroscale hydrologic and biogeochemical cycles (Haddeland et al. 2006).

Ecoregional Patterns in Lake Drawdown. Ecoregional patterns in lake hydrology reflect variation in regional climate, watershed hydrology, and water management activities. However, the relative influences of these drivers on lake hydrology are difficult to separate. Human water management activities can increase or decrease water-level drawdown depending on the reservoir purpose and modify regional climate effects on lake and watershed hydrology (Biemans et al. 2011; Haddeland et al. 2014). Information on water management at NLA sample lakes is lacking in our assessment because the surveys did not explicitly identify the purposes of man-made lakes (e.g., hydroelectric, drinking water supply) and management data are difficult to acquire for small- to medium-sized lakes. However, large reservoir and water usage data in the U.S. can give insight into regional water management activities (Ruddy and Hitt 1990; Dieter et al. 2018) and help explain some of the observed patterns. In western regions of the U.S., drawdown heights on man-made lakes were large and greater than drawdown on natural lakes, suggesting that water management is an important driver of water level decline in these regions. Man-made lakes that are managed for irrigation, hydroelectric power, and/or flood control in western regions can experience large summer water-level drawdown (Ruddy and Hitt 1990; Dieter et al. 2018). Strong seasonality in precipitation, characterized by dry summers, high spring river levels, and precipitation as rain or snow in the fall and winter months, can lead to water regulation regimes in the western U.S. that result in large fluctuations in reservoir levels. These water management strategies may account for the large water-level decline observed and could be exacerbated by drought (Wu et al. 2018; Xiao et al. 2018). In contrast, in the TPL, man-made lakes had more full lake basins than did their natural lake counterparts. Higher water levels on man-made lakes in the TPL compared to the western U.S. may be related to more uniform annual precipitation patterns and management for stable water levels for domestic water supply and recreation use. Further studies are needed to examine what climate, landscape, and water management drivers promote regional variation in lake water-level drawdown.

Regional patterns in lake water-level drawdown not only provide important information about lake water balance but also have implications for assessing lake physical habitat, water chemistry, and biotic condition. Water-level fluctuations have been shown to influence lake temperature and stratification (Furey et al. 2004; Nowlin et al. 2004), which in-turn affect within-lake biogeochemical processes. In addition, nearshore habitat in the riparian and littoral zones are affected by water-level fluctuations that can alter substrate composition (Furey et al. 2004; Evtimova and Donohue 2016), littoral habitat complexity (Gaeta et al. 2014), macrophyte coverage and composition (Wilcox and Meeker 1991; Beklioglu et al. 2006; Cobbaert et al. 2015). These habitat changes subsequently affect the structure and composition of macroinvertebrate (Brauns et al. 2008) and fish assemblages (Gaeta et al. 2014). In fact, in the NLA 2007 survey, nearshore habitat condition was most altered compared to other aspects of lake physical and chemical condition, suggesting that degraded nearshore habitat is a threat equal to, if not more widespread than excess nutrients to U.S. lakes (Kaufmann, Peck, et al. 2014). These relationships highlight the need to monitor lake hydrologic

TABLE 3. Population-inferred lake morphology and freshwater-linkage characteristics of NLA 2007 natural and man-made lakes.

				% Freshwater-linkage type		
Scale	**Lake type**	**Lake area (km^2)**	**Lake depth (m)**	**Isolated**	**Drainage**	**UPLK**
National	All	0.14 (0.07, 0.37)	3.98 (2.45, 7.67)	35.0 ± 2.8	49.0 ± 2.8	15.9 ± 1.8
	Natural	0.17 (0.07, 0.42)	5.45 (2.49, 9.40)	47.0 ± 3.9	37.5 ± 3.8	15.5 ± 2.1
	Man-made	0.09 (0.06, 0.25)	3.45 (2.41, 5.75)	18.1 ± 3.7	65.4 ± 4.1	16.5 ± 3.0
Ecoregion						
WMT	Natural	0.08 (0.07, 0.18)	9.41 (7.33, 13.87)	43.4 ± 9.2	49.9 ± 9.0	6.7 ± 2.2
XER		0.90 (0.19, 2.78)	3.18 (2.36, 19.36)	8.6 ± 7.2	62.2 ± 15.4	29.2 ± 13.2
NPL		0.12 (0.08, 0.33)	2.13 (1.84, 2.48)	85.8 ± 5.2	9.1 ± 3.9	5.1 ± 2.6
SPL		0.30 (0.20, 0.59)	1.33 (1.15, 1.39)	42.7 ± 12.6	32.9 ± 10.7	24.4 ± 11.4
TPL		0.18 (0.05, 0.47)	2.44 (1.60, 3.46)	73.9 ± 7.8	12.4 ± 4.1	13.7 ± 6.9
UMW		0.22 (0.07, 0.42)	6.20 (3.67, 9.50)	44.4 ± 5.9	39.8 ± 5.9	15.7 ± 3.1
NAP		0.30 (0.13, 0.83)	6.45 (2.70, 11.44)	17.1 ± 6.4	55.8 ± 8.9	27.1 ± 7.2
CPL		0.10 (0.06, 0.30)	2.60 (2.26, 2.97)	42.1 ± 12.3	38.5 ± 11.3	19.4 ± 10.1
WMT	Man-made	0.10 (0.07, 0.50)	5.53 (2.95, 11.98)	18.3 ± 11.2	67.2 ± 11.0	14.5 ± 4.3
XER		0.43 (0.19, 0.93)	3.88 (2.66, 7.65)	19.9 ± 7.7	32.7 ± 7.4	47.4 ± 8.8
NPL		0.07 (0.06, 0.11)	1.97 (1.87, 2.44)	3.0 ± 1.9	92.6 ± 3.3	4.4 ± 1.9
SPL		0.09 (0.06, 0.14)	3.67 (2.56, 5.69)	20.2 ± 8.2	71.7 ± 8.3	8.1 ± 2.6
TPL		0.12 (0.07, 0.35)	5.72 (1.79, 7.00)	39.6 ± 19.0	44.3 ± 14.6	16.1 ± 6.6
UMW		0.19 (0.19, 0.64)	3.49 (3.44, 5.65)	—	14.1 ± 12.1	85.9 ± 12.1
SAP		0.09 (0.06, 0.18)	3.70 (2.79, 6.47)	16.1 ± 6.6	70.2 ± 7.6	13.7 ± 3.7
NAP		0.17 (0.05, 0.26)	2.88 (2.57, 5.77)	8.3 ± 5.2	57.3 ± 14.3	34.4 ± 16.4
CPL		0.06 (0.05, 0.15)	2.68 (2.09, 3.66)	21.9 ± 8.5	70.6 ± 8.5	7.5 ± 2.3

Note: Distributions of lake morphology characteristics in the target population are presented as median values (25th and 75th percentiles) by lake type and ecoregion. Lakes were grouped into three freshwater-linkage types defined by inflowing stream and upstream lake connections: *Isolated*, *Drainage*, and *UPLK*. Isolated lakes have no stream inflows. Drainage lakes have stream inflows and may or may not have outflows. UPLK lakes have stream inflows and are connected to upstream lakes (≥0.1 km^2). Percentages of freshwater-linkage types were inferred to the target population (±standard error).

characteristics to help managers meet conservation and water quality goals.

Ecoregion E:I and Water Residence Time Patterns. Regional patterns in E:I are likely associated with regional climate conditions and may also reflect among-region heterogeneity in lake morphometry and freshwater connectivity attributes. In regions where E:I was high, natural lakes commonly had morphological and hydrologic connectivity traits that exacerbate the influence of warm air temperatures on evaporative water loss. Natural lakes in the plains regions (NPL, SPL, TPL, and CPL) tended to be shallow and isolated from surface stream connections and consistently had higher E:I compared with natural lakes in other regions. Lake depth has been shown to be negatively associated with lake E:I with shallow lakes having greater E:I compared to deep lakes (Brooks et al. 2014). Mathematically, E:I should not be related to either lake depth nor area. But this association may be due to the correlation between depth and inflow in natural lakes across the U.S. in the NLA surveys, such that deeper lakes tend to have greater inflow (Spearman correlation, $r = 0.28$, $p < 0.001$). Lakes that are less hydrologically connected to streams have been reported to have greater evaporation signals in water isotope values compared to lakes that are more hydrologically connected (MacKinnon et al. 2015). In the NLA survey, *Isolated* lakes were twice as evaporatively enriched compared to stream-connected lakes: median E:I in 2007 *Isolated* = 0.51; *UPLK* = 0.20; *Drainage* = 0.17. Natural lakes in the plains regions may experience greater E:I than those in other regions because of warmer regional climate, shallow lake depths, and lack of freshwater-linkages. Furthermore, we found positive correlations between E:I and scaled lake water-level drawdown, implying that declines in lake water levels may be associated with water loss due to evaporation. Evaporation can be a dominant factor in lake hydrologic budgets, and there is a need to better characterize how lake morphology, connectivity, and regional climate conditions can influence evaporative water loss in lakes (Sahoo et al. 2013).

Around 75% of lakes in the U.S. had water residence times of approximately one year or less in both survey years. These estimates are similar to modeled hydrologic residence times reported for U.S. lakes (median 0.8 year; Messager et al. 2016) and lakes in the Great Lakes region (median 1.63 year; Hanson et al. 2018). Independently derived water residence times for the NLA lakes using modeled runoff (McCabe and Wolock 2011) were similar to the isotope-based residence times and followed the same patterns as in Brooks et al. (2014) such that median modeled τ were shorter (0.31 year in 2012) than median isotope-based τ (0.58 year in 2012). Lake τ did not exhibit strong regional patterns, unlike water-level drawdown and E:I. Variation in water residence time may be more strongly influenced by local lake and watershed attributes rather than regional-scale characteristics. Large, deep seepage lakes with small watersheds have been observed to have longer residence times compared to moderate sized lakes with large stream-connected watersheds (Brooks et al. 2014; Messager et al. 2016; Hanson et al. 2018). Lake morphology and watershed attributes have been shown to exhibit weak spatial autocorrelation at macroscales and a great deal of within-region variation (Lapierre et al. 2018) and may explain the lack of regional patterns observed. The range of lake water residence times reflect variation in lake and watershed characteristics across the U.S.

E:I and water residence time quantify important lake hydrologic characteristics that are related to lake biogeochemistry and ecology. Brooks et al. (2014) found a positive relationship between E:I and total nitrogen concentrations in lakes sampled in NLA 2007, and higher E:I has been related to more eutrophic lake conditions (Wolfe et al. 2007; Gibson, Birks, Yi, Moncur, et al. 2016). In addition, lake evaporative characteristics and water residence time have been associated with decoupling lake hydrologic and carbon processes and thus can be significant factors in assessing the role of lakes in regional and global carbon cycles (Jones et al. 2018; Zwart et al. 2018). Greater knowledge of the regional distributions of lake E:I and water residence time will assist with understanding hydrologic attributes that promote variation lake water quality and clarify the role of lakes in a variety of earth system processes.

Differences in Lake Hydrologic Variables between Survey Years

Differences in lake hydrologic variables between the 2007 and 2012 surveys provided insight on the sensitivity of lake levels and water balance parameters (i.e., E:I and water residence time) to inter-annual climate conditions. Between-year variation in water-level decline was greater on natural lakes than man-made lakes, suggesting that natural lakes are more responsive to changes in weather. Natural lakes had less vertical drawdown in 2012 (a cooler, wetter weather year) compared to 2007, whereas large drawdown persisted on man-made lakes, particularly in western regions. Dam and outlet structures can significantly alter lake and stream hydrology and potentially mask effects from climate or weather (Jones et al. 2012; Hayes et al. 2017). Overall, the 2007–2012 changes in evaporative concentration and water level decline suggest that water levels in natural lakes may be more responsive to temperature and precipitation in a given year, whereas water levels in man-made lakes may be more strongly influenced by water management and indirectly by weather conditions in western U.S. regions.

In contrast to lake water-level drawdown, isotope-derived water balance parameters were more stable between survey years. E:I estimates in resampled lakes were similar in both survey years (median = 0.26) and only increased or decreased in regions that experienced drought or wetter than normal conditions. The consistency in E:I between survey years suggests that isotope analyses quantify hydrologic characteristics that are temporally integrated, or those that are driven by relatively stable lake morphological characteristics. Lake morphometry (e.g., maximum depth, surface area) attributes are less variable over time than are weather and climate conditions and may moderate variation in lake E:I and residence time, leading to more conservative values over the time period between survey years. Lake water levels, on the other hand, may be more responsive to extreme and in-frequent weather events than are the hydrologic characteristics derived from water-isotope analysis. Extreme runoff events can lead to a rapid rise in lake water levels but have been shown to have minimal lasting influence on water-isotope-derived hydrologic characteristics that reflect more prolonged climatic conditions (Remmer et al. 2018).

We found that differences in lake hydrology were not consistently associated with differences in regional climate between survey years. This was not surprising given the short temporal frame and the range of hydrogeoclimatic settings and variety of lake morphologic types in the NLA. Two years of observations is insufficient to detect associations between lake hydrologic characteristics and climate over time. In addition, climate effects on lakes at broad spatial extents are highly variable due to underlying lake, watershed, and regional variation (McCullough et al. 2019). Environmental factors such as lake morphology and freshwater-linkages may interact with land cover and water management to affect lake hydrology in unexpected ways. These influences can obscure and complicate lake hydrologic response to drought (Jones 2011; Jones et al. 2012), and must be considered to improve our understanding of lake responses to changing water management and climate conditions over broad geographic extents (Molinos and Donohue 2014). Given the importance of climate effects on lake hydrology, further research is needed on seasonal temperature and precipitation patterns that influence the timing and magnitude of key watershed hydrologic characteristics. These seasonal hydro-climatic characteristics are shown to be particularly important in high latitude and high elevation lakes that have water levels influenced by snowpack and ice cover (Xiao et al. 2018; Byun et al. 2019).

With observed annual average temperatures increasing and warming projected to continue, particularly in northern central regions in the U.S. (Vose et al. 2017), it is likely that lake water loss due to evaporation will increase (Wang et al. 2018; Xiao et al. 2018) and place more demand on water resources (Jones et al. 2016). By contrast, some regions in the U.S. have experienced increased runoff due to increased precipitation (McCabe and Wolock 2011). These trends are predicted to continue in the Midwest region (Byun et al. 2019), possibly preventing water level decline in lakes. It is expected that water management activities will respond and interact with underlying regional changes in climate conditions, and consequently mitigate or amplify climate effects on lake hydrologic integrity. But it is uncertain how natural and human factors will interact to affect lake hydrology.

Currently the NLA datasets, with two years of data over a five-year period, lack the temporal observations to examine trends in lake hydrology in relation to changing climate conditions. But what they lack in temporal records they make up for in spatial coverage. The national assessments establish baseline distributions of lake hydrologic characteristics that are reflective of the diverse lake morphological types and regions in the U.S. With these datasets and additional geospatial information, future studies can examine local and regional landscape and climatic factors that influence the regional variation in lake drawdown and E:I described in this paper.

CONCLUSIONS

We assessed lake hydrologic status for ~45,000 lakes distributed across the U.S. in the first national survey to quantify hydrologic characteristics related to lake water levels and water balance. We present the range of lake drawdown height, littoral bottom exposure, and isotopically derived water balance values derived from diverse lake waterbody types that are representative of the nation's lakes for two contrasting years. Incorporating hydrology variables into lake monitoring programs is essential for assessing hydroecological status and trends such as nutrient enrichment of lakes exacerbated by evaporation. Quantifying regional and continental variation in lake hydrologic characteristics is a prerequisite to understanding local and regional controls on lake levels and ultimately, predicting and managing the changes on water quality, habitat, and biota that may occur in the face of changing land use activities, human water demands, and climate conditions.

Data Availability

The 2007 and 2012 NLA datasets can be found at https://www.epa.gov/national-aquatic-resource-surveys/nla.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Text file of methods of deriving water stable isotope variables, figure of scaled drawdown vs. E:I, figure of distribution of weather conditions, figure of lake hydrologic variables vs. drought, and tables of reference criteria, distributions of population inferred lake hydrologic variables, and two-way ANOVA results.

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