LIMNOLOGY and OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 9999, 2022, 1–18

doi: 10.1002/lno.12097

Natural and anthropogenic controls on lake water-level decline and evaporation-to-inflow ratio in the conterminous United States

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Abstract

Lake water levels are integral to lake function, but hydrologic changes from land and water management may alter lake fluctuations beyond natural ranges. We constructed a conceptual model of multifaceted drivers of lake water levels and evaporation-to-inflow ratio (Evap : Inflow). Using a structural equation modeling framework, we tested our model on (1) a national subset of lakes in the conterminous United States with minimal water management to describe natural drivers of lake hydrology and (2) five ecoregional subsets of lakes to explore regional variation in water management effects. Our model fits the national and ecoregional datasets and explained up to 47% of variation in Evap : Inflow, 38% of vertical water level decline, and 79% of horizontal water level decline (littoral exposure). For lakes with minimal water management, Evap : Inflow was related to lake depth ($\beta = -0.31$) and surface inflow ($\beta = -0.44$); vertical decline was related to annual climate (e.g., precipitation $\beta = -0.18$) and water management ($\beta = -0.21$); and horizontal decline was largely related to vertical decline ($\beta = 0.73$) and lake morphometry (e.g., depth $\beta = -0.18$). Anthropogenic effects varied by ecoregion and likely reflect differences in regional water management and climate. In the West, water management indicators were related to greater vertical decline ($\beta = 0.38$), whereas in the Midwest, these indicators were related to more stable and full lake levels ($\beta = -0.22$) even during drought conditions. National analyses show how human water use interacts with regional climate resulting in contrasting impacts to lake hydrologic variation in the United States.

Altered lake hydrologic regimes resulting from dams, land use, and changing climate are recognized as significant and potentially widespread threats to lake integrity (Wantzen et al. 2008; Carpenter et al. 2011; Woolway et al. 2020). Lake water levels naturally fluctuate due to imbalances in water inputs (surface and groundwater inflows, precipitation) and outputs (surface and groundwater outflows, evaporation) that are related to watershed hydrology and climate characteristics. This hydrologic variation affects multiple physical, chemical, and biological processes defining lake structure, function, and ecosystem services (Leira and Cantonati 2008; Evtimova and Donohue 2016). However, human-related water management activities can substantially alter lake hydrologic regimes. Dams modify the magnitude and timing of water-level fluctuations (Leira and Cantonati 2008; Wilcox and Meeker 2011), and land use including irrigated agriculture and urban development consume and divert water to alter watershed hydrologic processes (Poff et al. 2006; Carlisle et al. 2019). Human-induced climate change is warming temperatures and altering precipitation patterns, a trend that will place greater stress on water resources and subsequently affect land and water management activities (Zohary and Ostrovsky 2011; Jeppesen et al. 2015; Wang et al. 2018). Disentangling the relative influence of natural and anthropogenic factors on lake hydrologic

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Additional Supporting Information may be found in the online version of this article.

Author Contribution Statement: All authors contributed to the conceptualization of the project through active participation in working group meetings. CEF compiled the NLA and geospatial data, performed the path analyses, and prepared the manuscript. CEF, JRB, PRK, AIP, RM, and PR developed the conceptual model of drivers of lake hydrology based on literature and expert opinion. GJG provided analytic support for the path analyses. MW and RAH compiled and processed geospatial data used in the HydrAP metric. All authors reviewed and edited the manuscript.

regimes is essential to determine the extent to which human actions may alter lake hydrologic condition.

Comprehensive lake-monitoring datasets and hypothesis-based conceptual models can aid in separating the multifaceted drivers that affect lake hydrologic characteristics. However, lake-monitoring programs do not commonly record information on hydrologic characteristics, and lakes with hydrologic records tend to be large natural lakes (Sahoo et al. 2013; Gronewold et al. 2016; Chang et al. 2017) or constructed reservoirs (Rougé et al. 2021). These incomplete observations give a biased representation of hydrologic variation across the landscape. Furthermore, lake hydrology is affected by multiple geoclimatic, hydrologic, and anthropogenic factors that vary among lake types and regional settings (Kraemer et al. 2020). These complex relationships can make it challenging to attribute causes of lake hydrologic variation without guiding hypotheses, appropriate analytic techniques, and comprehensive lake and geospatial datasets.

In this paper, we used a national lakes' dataset and modeling approach that address these concerns. Specifically, we examined the factors promoting variation in lake and reservoir hydrology across the conterminous United States (CONUS) using the National Lakes Assessment (NLA) 2007 and 2012 surveys (USEPA 2009, 2016) that each sampled ~ 1000 lakes and reservoirs spanning a range of size and anthropogenic disturbance gradients. The NLA collects information on lake water-level decline and evaporation-to-inflow ratio (Evap : Inflow), an estimate of the proportion of inflowing water that leaves the lake through evaporation. These variables have been used to assess lake hydrologic condition (Brooks et al. 2014; Kaufmann et al. 2014a; Fergus et al. 2020) and are associated with multiple ecosystem properties (e.g., nearshore habitat condition; Carmignani and Roy 2017) and processes (e.g., nutrient and carbon cycling; Jones et al. 2018). We modeled variation in lake hydrologic variables using structural equation models because they provide a scientific framework to evaluate complex multivariate theoretical relationships with empirical data (Grace et al. 2010). We developed and tested a lake hydrologic metamodel grounded in theory and supported by literature that included hypothesized pathways by which lake, landscape, climate, and human-related water management indicators operate and interact with one another to affect lake hydrologic characteristics (Fig. 1a; Table S1).

Anthropogenic climate change likely affects lake hydrology through complex pathways (Wine and Davison 2019; Kraemer et al. 2020). Separating the effects of natural climate variation from anthropogenic climate change, however, is beyond the scope of this study, which lacks long-term lake hydrologic observations to explicitly assess climate change impacts (Jeppesen et al. 2014). Rather, we focus our analyses on land and water management as indicated by dam infrastructure and land use, which have been shown to have pronounced effects on both lake and stream hydrology (Haddeland et al. 2014; Carlisle et al. 2019; Wine et al. 2019). We used the human hydrologic alteration potential (HydrAP) metric (Fergus et al. 2021) in our model to represent anthropogenic factors that have the potential to significantly alter lake hydrologic characteristics. The HydrAP metric integrates information on dam capacity, land use activities, and topographic relief to rank lakes on a gradient of potential anthropogenic hydrological alteration.

We applied the lake hydrologic model to address three hypotheses. First, we expected that in lakes with minimal water management presence, natural meteorological and hydrologic processes would drive lake water balance, and these relationships would be relatively robust among ecoregional settings. Second, we hypothesized that in lakes with human-related water management presence, the direction and magnitude of anthropogenic effects would vary across ecoregional settings. To address these hypotheses, we applied the model nationally to lakes with minimal water management presence as indicated by low-capacity dams and minimal land use in their immediate catchment to establish baseline expectations of geoclimatic drivers of lake hydrologic characteristics. We then applied the model to five ecoregional subsets of lakes that span the full range of management intensity to evaluate how water management and regional climate may affect lake hydrologic characteristics differently across CONUS. Finally, we hypothesized that water management effects may vary with drought and wetter-than-normal conditions (Magilligan and Nislow 2005; Giuliani et al. 2016), and that these interactions could obscure climatic effects on lake hydrologic characteristics (Jones 2011). We compared our base lake hydrologic model to a model with an interaction term between water management and drought and evaluated model fit. With these analyses, we quantify the relative influence of natural and water management factors on lake hydrologic characteristics that support lake ecosystems under changing environmental conditions.

Methods

We applied a structural equation modeling framework to examine the multifaceted drivers of lake hydrologic variation across CONUS. Our analytic workflow consisted of (1) developing a conceptual metamodel of general lake hydrologic drivers (Fig. 1a), (2) adapting the metamodel to a path analysis model using variables from national datasets (Fig. 1b), and (3) testing our hypothesized model by examining model fit and evaluating hypothesized pathways. Below we describe the model structure, the datasets, and analytic steps.

Conceptual metamodel underlying the lake hydrology path model

We developed the lake hydrologic model guided by theory and literature to characterize broad-scale relationships among landscape, climate, and anthropogenic variables on lake

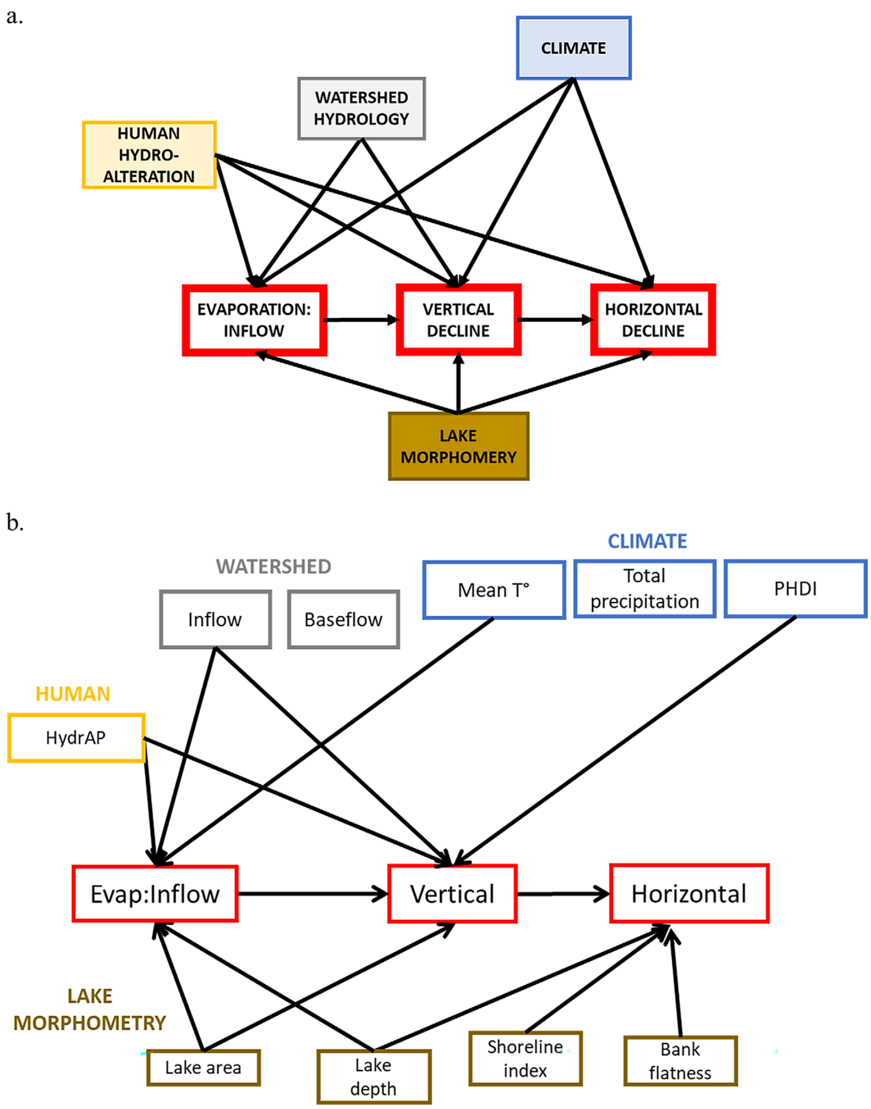

Fig. 1. Hypothesized drivers and their pathways affecting lake water-level decline and Evap : Inflow. (**a**) Metamodel of generalized lake, watershed hydrology, climate, and anthropogenic hydro-alteration predictors of lake hydrologic characteristics (red boxes). (**b**) Path analysis model adapting the metamodel to include measured lake, watershed hydrology, climate, and anthropogenic variables. Lake morphometry variables included lake surface area, maximum lake depth, shoreline development index, and bank flatness index. Climate variables included mean annual temperature (Mean T°), total annual precipitation, and PHDI. Human-related water management presence is represented by the HydrAP metric, an indicator of the potential for human hydro-alteration characterized by dam attributes and/or specific land use activities in the lake watershed.

vertical and horizontal water-level decline and Evap : Inflow. Lake hydrologic predictors were grouped into general driver classes relating to climate, watershed hydrology, lake morphometry, and human-related land and water management (Fig. 1a). Often these driver classes operate together in complex ways to affect lake and watershed hydrology. Variables in the model are coarse representations of underlying mechanistic processes and attributes that influence lake water balance. Theoretical background supporting the model structure is described in Table S1.

In our model, vertical water-level decline was treated as both a response variable and as a predictor of horizontal water-level decline. We hypothesized that vertical decline had a direct causal effect on horizontal decline because vertical decline is the common hydrological measure of depth change, while horizontal decline is a function of depth change and lake morphometry. Mechanistically, we expected climate and anthropogenic factors to act directly on depth change (vertical water levels), and for depth change to potentially result in exposing littoral areas (i.e., horizontal decline) based on lake basin morphometry (e.g., slope of the lake bottom). Examining these relationships together quantifies how lake morphometry affects the expression of water-level decline on the extent of littoral exposure.

Data

NLA surveys

Lake data came from the US Environmental Protection Agency NLA 2007 and 2012 surveys and can be accessed at the US EPA National Aquatic Resource Surveys web page, https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys. The NLA surveys are conducted every 5 yr to assess the ecological condition of lakes across CONUS using a probability-based survey design. The surveys sample natural and human-made lakes that are identified from the National Hydrography Dataset Plus (NHDPlus v.1 and 2; McKay et al. 2012) with target lakes spanning a range of sizes (≥ 0.01 to 1670 km^2) and geomorphic characteristics. About 30% of the lakes sampled in 2007 were resampled in 2012. We aggregated the NLA 2007 and 2012 datasets and excluded observations in 2012 for lakes that had been sampled in 2007 to create a continental dataset of 1716 lakes with independent observations for our analyses (Fig. 2).

Vertical and horizontal water-level declines were measured as the mean height or distance from the water-level line to the apparent high water mark at 10 equidistant stations around the lake during the summer sample visit (Kaufmann et al. 2014a). Lakeshore flooding was not reliably quantified in the NLA, and lakes with high water levels were characterized as having zero water-level decline (full pools). Evap : Inflow were calculated following methods described by Brooks et al. (2014) using water stable isotope values and mass balance models. Lakes with Evap : Inflow = 0 have all water entering the lake leaving as outflow, lakes with Evap : Inflow = 1 have all inflowing water lost to evaporation (100%), and lakes with Evap : Inflow > 1 are desiccating lakes with evaporation exceeding inflow. Details on lake water isotope collection, laboratory measurements, and Evap : Inflow estimation steps can be found in Brooks et al. (2014) and the NLA 2012 Evap : Inflow estimates in Fergus et al. (2020).

Lake morphometry attributes in the NLA included lake surface area, maximum lake depth, shoreline development index (an estimate of the sinuosity of the lake perimeter), and bank flatness index. Bank flatness index was the sum of stations recorded as having flat (< 5°) and gradual (5–30°) banks.

We grouped lakes into five ecoregions spanning CONUS that included the West, Great Plains, Midwest, Appalachians, and Coastal Plains (Fig. 2). These ecoregions are aggregations of Omernik Levell-III ecoregions that delineate the landscape

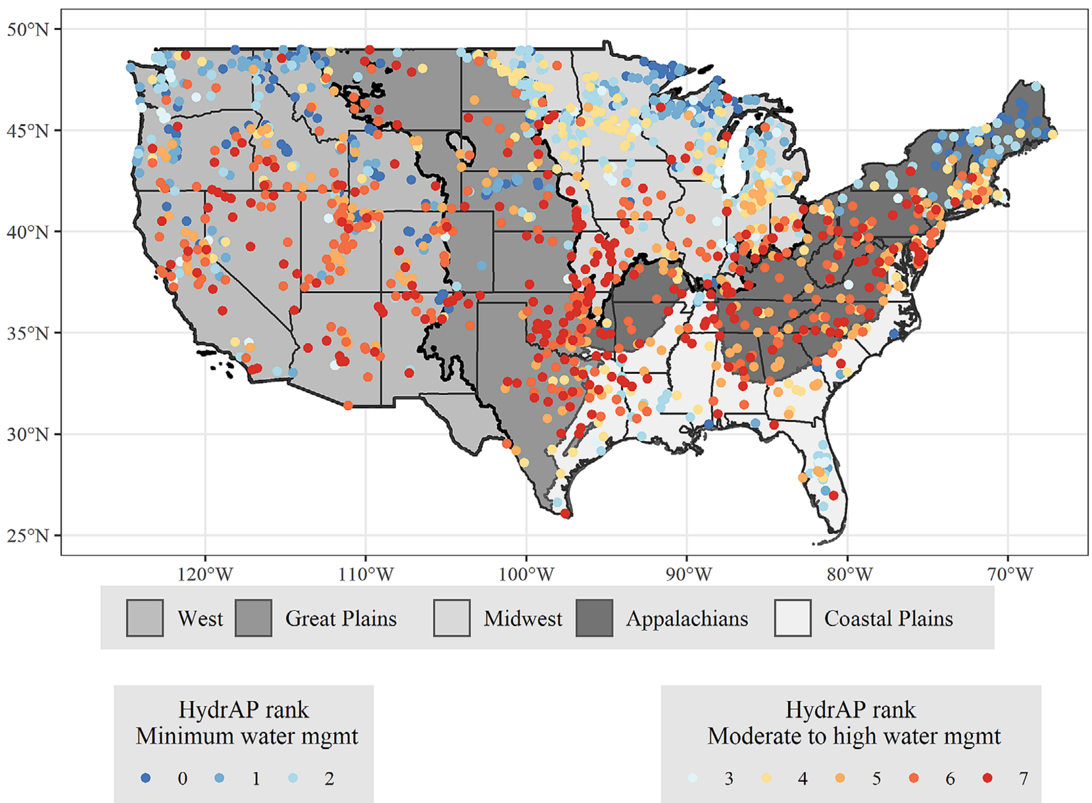

Fig. 2. Lakes from the NLA surveys colored by anthropogenic HydrAP across five ecoregions in the CONUS. The lake hydrologic model was tested on data subsets that included (1) a national subset of lakes with minimal water management presence (HydrAP rank 0–2; n = 553) and (2) by ecoregion that included the full range of water management presence (HydrAP rank 0–7). HydrAP ranks range from 0 to 7 where 0 indicates no water management presence and a 7 indicates great potential for hydro-alteration given dam infrastructure and land use activities (*see* the Methods section for more details). The aggregated dataset includes all lakes ≥ 4 ha in NLA 2007 (*n* = 1028) and nonresampled lakes ≥ 1 ha in NLA 2012 (*n* = 688).

into areas having similar natural geographic and climatic features (Omernik 1987; Herlihy et al. 2008).

Lake-catchment (LakeCat) geospatial data

Watershed hydrology and climate variables came from the LakeCat dataset (Hill et al. 2018) and can be accessed at the US EPA LakeCat web page, https://www.epa.gov/national-aquatic-resource-surveys/streamcat-dataset-0. Watershed hydrology variables included modeled surface runoff (McCabe and Wolock 2011) and stream baseflow index—the percentage of streamflow that is attributed to groundwater discharge (Wolock 2003). Watershed runoff was multiplied by watershed area and scaled by lake area to estimate depth (m) of surface water inflow to a particular lake. Climate variables were derived from geospatial data layers following LakeCat processing steps and included mean annual temperature, total annual precipitation (PRISM Climate Group), and mean annual Palmer Hydrological Drought Index (PHDI – NOAA) for the water year (previous October to September of survey year). PHDI values indicate the severity of a wet (positive) or dry (negative) period and account for longer-term dryness related to local precipitation, temperature, and available water capacity of the soil that may affect water storage, streamflow, and groundwater levels. We selected this drought index for our model because it captures long-term drought conditions by calibrating temperature and precipitation variation over multidecadal periods (Wells et al. 2004; Dai 2011). Annual climate summaries were deemed an appropriate scale for an initial assessment of climate influences on lake hydrology in CONUS and future studies may consider examining seasonal climate phases associated with lake hydrologic regimes.

We characterized the degree of human-related water management presence on a lake using the HydrAP metric (Fergus et al. 2021). The HydrAP metric is an integrated measure of the potential for dams and specific land use activities (e.g., irrigated, tile drainage agriculture, total agriculture, and urban development) to alter lake hydrologic characteristics that can be applied across CONUS using information from the National Inventory of Dams and National Land Cover Database. The metric ranks lakes on a scale from 0 to 7 along a gradient of lake hydrologic alteration potential based on the premises that dams are primary drivers of anthropogenic hydro-alteration in lakes and land use activities are secondary drivers that alter watershed hydrologic flows. In the HydrAP framework, a score of 0 signifies lakes with no apparent dams or land use activities that could alter lake hydrology, and a score of 7 signifies lakes with large dams and/or intensive land use (such as irrigated agriculture, tile drainage agriculture, or urban development) with great potential to alter lake hydrology. The HydrAP metric serves as an indicator of potential anthropogenic hydrologic alteration on lakes and does not require actual measures of anthropogenic hydro-alteration such as dam operation records, which are not available for the majority of CONUS lakes.

Analytic framework and data analysis

We used path analysis models based on structural equation model techniques to evaluate our representation of lake, landscape, climate, and anthropogenic drivers on lake hydrologic characteristics. Path analysis is a statistical approach to model a priori hypothesized relationships among multiple interacting predictor and outcome variables via specific pathways (Lleras 2005). With this structure, the model simultaneously quantifies the relative strength of relationships within a network of drivers and responses. This approach is well suited to studying environmental systems by giving researchers a framework to specify how hypothesized predictors may affect responses through complex causal pathways (Grace et al. 2010). Path analysis models estimate both direct effects of predictors on responses and indirect effects in which predictor effects are transmitted through mediating variables. Calculating the total effect of a predictor by summing their direct and indirect effects on a response provides a more complete accounting of their influence on a response. Analytically, equations in the path analysis model are parameterized by finding solutions that minimize the difference between the model-implied and observed (sample data) covariance matrices (Riseng et al. 2011). This approach requires consideration of data sample size and model complexity, with more complex models (i.e., greater number of parameters to estimate) requiring larger sample sizes (Grace et al. 2012) to achieve adequate statistical power, model convergence, and minimize parameter estimate bias (Wolf et al. 2013).

We applied a path analysis model on a subset of lakes distributed across CONUS that had no-to-minimal human-related water management presence (HydrAP rank = 0–2, $n = 553$) (Fig. 2) to evaluate the relative influence of natural geoclimatic drivers on the lake hydrologic responses. We also applied the model separately on ecoregional datasets including lakes of all HydrAP ranks to examine whether anthropogenic effects on lake hydrologic characteristics varied across ecoregional settings and potentially interacted with drought indices (Fig. 2). Lakes in these ecoregional datasets spanned the full range of water management presence (HydrAP = 0–7) and ranged in numbers from 126 lakes in the Coastal Plains to 412 lakes in the Midwest ecoregions.

Data preprocessing steps and path analysis model estimation were performed in R version 3.6.3 using the packages *lavaan* (Rosseel 2012) and *psych* (Revelle 2019). Variables were assessed for skewness and transformed ($\log_{10}$) to meet assumptions of normality. Path analysis models were fit in *lavaan* using maximum likelihood estimation. Model performance was evaluated using several goodness-of-fit statistics and their thresholds that included robust Chi-square global test (p-value > 0.05), root mean square error of approximation (RMSEA ≤ 0.08), comparative fit index (CFI ≥ 0.95), and Tucker–Lewis fit index (TLI ≥ 0.95). A nonsignificant Chi-square test value indicates that the covariance structure of the model is not significantly different from the observed data and indicates a good model fit. The Chi-square statistic tends to be overpowered to detect trivial degrees of model misfit, and researchers therefore tend to examine several model performance measures to provide multiple lines of evidence of model fit (Hox and Bechger 1998).

Model coefficients and standard errors were derived from nonparametric bootstrap estimation with 1000 resamples, a reasonably large number of resamples for this modeling approach. Model coefficients were standardized to compare the effects of predictors with different ranges and units of measurement. The path analysis models included correlations among all exogenous predictor variables. From the model, we examined the direct, indirect, and total effects of the hypothesized predictors on lake hydrologic responses. We retained all pathways in the final models even when confidence intervals overlapped zero because our goals were to draw inference about the broad-scale drivers of lake hydrologic variation and not necessarily to maximize prediction in the dataset. Post-analysis, we examined modification index values to determine whether additional pathways would have improved model fit (with modification index threshold > 4 indicating improved model fit) but did not find compelling evidence to include any additional pathways.

We compared our base lake hydrology model with a model that included an interaction between HydrAP and drought index (PHDI). We used Bayesian information criteria adjusted by sample size to compare models, with smaller values indicating a more parsimonious model fit. We also evaluated the importance of the interaction term on lake hydrologic responses by examining the estimated total effect and confidence intervals.

Results

Path analysis model results for CONUS lakes with minimal water management presence

Model performance statistics showed that the path analysis produced a good model describing the hydrology of lakes with minimal water management presence based on a nonsignificant Chi-square statistic, RMSEA ≤ 0.08, and CFI and TLI values ≥ 0.95 (Table 1). The model explained 47% of variation in Evap : Inflow (R^2) but only 13% of variation in vertical water-level decline. Horizontal water-level decline was predicted well in the model with an R^2 of 0.62, which was mainly attributed to the strong direct effects of vertical decline as a predictor.

The pathways connecting predictors and lake hydrologic responses largely followed our expectations (Fig. 3). Lake Evap : Inflow was related to watershed hydrology and lake morphometry variables with similar magnitudes of effect (Fig. 4). The model indicated that large, shallow lakes with small amounts of inflowing water and warm annual temperatures had greater Evap : Inflow. However, we found that HydrAP increased Evap : Inflow, even though lakes had no-to-minimal

Table 1. Model performance measures of the lake hydrologic path analysis model. The lake hydrologic model was tested on (1) a national subset of lakes with minimal water management presence (HydrAP rank 0–2) and (2) on five ecoregional subsets that included the full range of water management presence (HydrAP rank 0–7). Model fit was evaluated using X^2 test of independence between the specified model and a saturated model, RMSEA, CFI, and TLI with good model fit indicated by small X^2 (a nonsignificant X^2 test indicates that the model covariance structure was not significantly different from the data and is a good model fit), RMSEA ≤ 0.08, CFI ≥ 0.95, and TLI ≥ 0.95. The variance explained by the model for each of the three lake hydrologic responses (evaporation-to-inflow: Evap : Inflow and vertical and horizontal water level declines) are indicated by the coefficient of determination (R^2). Good model fit criteria are in bold.

Extent	X^2 (df)	RMSEA (90% CI)	CFI	TLI	n	R^2		
						Evap : Inflow	Vertical	Horizontal
$\text{CONUS}_{\text{low HydrAP}}$	**4.12 (5)** **$p = 0.53$**	**0.001 (0, 0.06)**	**1.00**	**1.00**	510	0.47	0.13	0.62
West	**9.04 (5)** **$p = 0.11$**	**0.05 (0, 0.10)**	**1.00**	**0.97**	357	0.36	0.38	0.79
Great Plains	12.35 (5) $p = 0.03$	**0.08 (0.02, 0.14)**	**0.98**	0.87	225	0.35	0.10	0.71
Midwest	16.81 (5) $p = 0.005$	**0.08 (0.04, 0.12)**	**0.98**	0.88	412	0.42	0.18	0.57
Appalachians	**6.68 (5)** **$p = 0.25$**	**0.04 (0, 0.10)**	**1.00**	**0.98**	261	0.31	0.36	0.70
Coastal Plains	13.69 (5) $p = 0.02$	0.12 (0.05, 0.19)	**0.96**	0.75	126	0.56	0.18	0.62

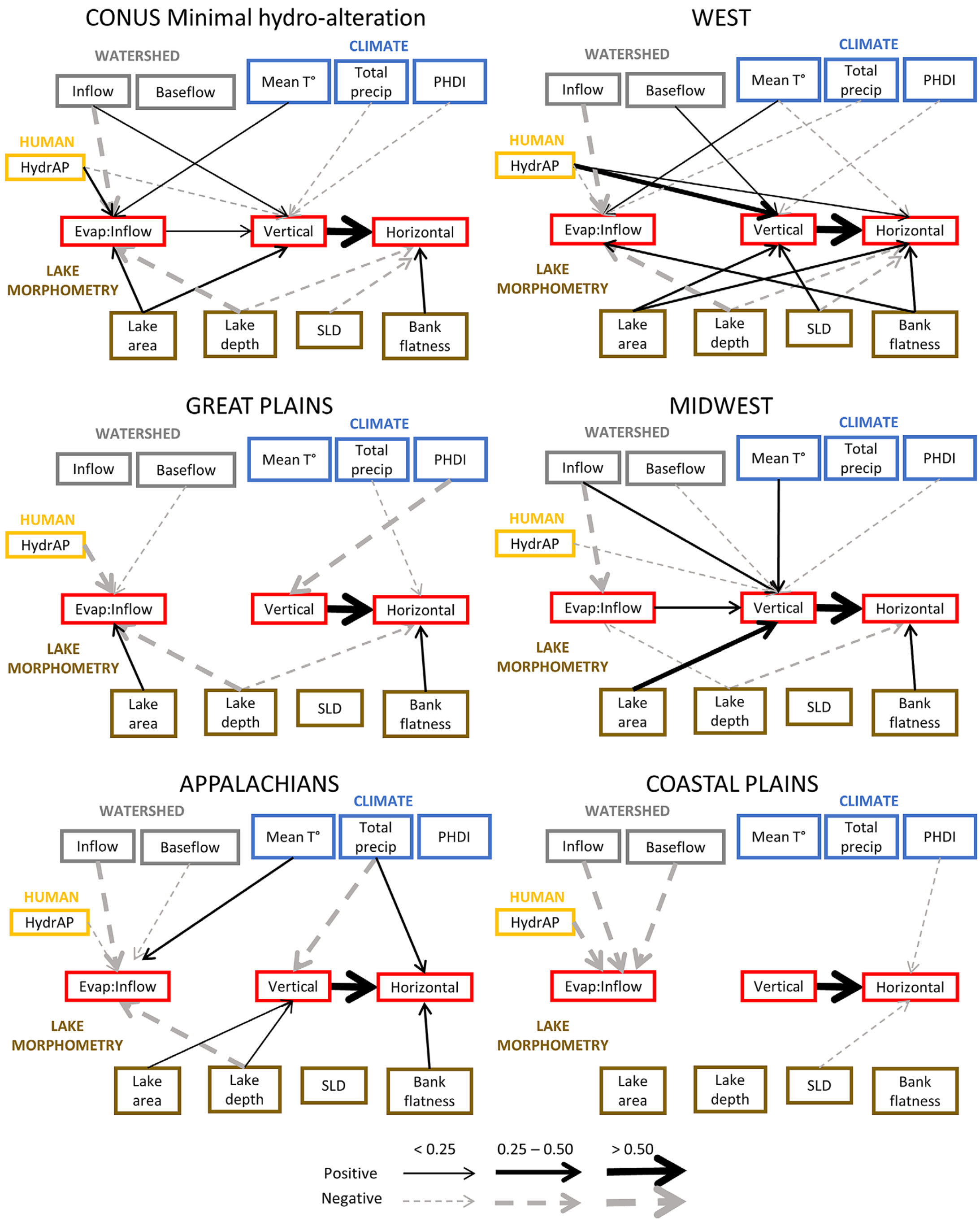

Fig. 3. Path analysis models showing direct standardized effects of predictors on lake hydrologic characteristics for a national subset of lakes in the CONUS with minimal water management presence (HydrAP < 3) and lakes with full range of water management presence (HydrAP 0–7) by ecoregion. Lake hydrologic response variables are outlined in red boxes and include Evap : Inflow and vertical and horizontal water-level decline. Predictor variables are colored by driver class: lake morphometry, watershed hydrology, climate, and human drivers. Arrows between variables represent significant standardized direct effects based on 90% confidence intervals not overlapping zero where the arrow width indicates the relative magnitude of the standardized effect. Note the path models only depict direct effects among variables and not their total effects (direct + indirect) in the model (see Figs. 4, 5, and S1). SLD = shoreline development index.

water management infrastructure, suggesting that even small levels of anthropogenic presence may affect lake water balance.

Vertical water-level decline was related to lake size and climate variables. Lakes with larger surface areas (standardized total effect $\beta = 0.21$) and drier conditions during the survey

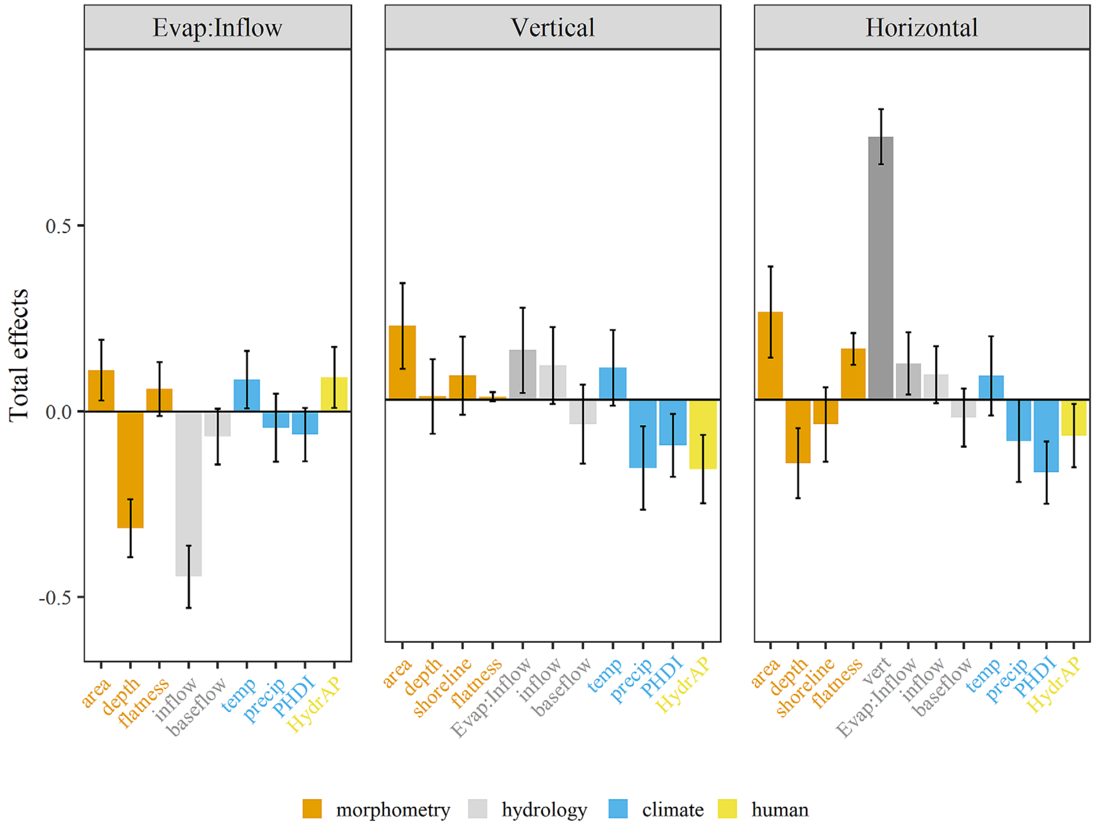

Fig. 4. Total effects of predictors on lake Evap : Inflow and vertical and horizontal water-level decline from the national dataset of lakes with minimal water management presence. Total effects are the sum of standardized direct and indirect effects. Model effects were estimated by bootstrap resampling. Error bars represent 90% confidence intervals. Predictor variables are colored by theme: lake morphometry, watershed hydrology, climate, and human.

year (PHDI $\beta = -0.13$; annual precipitation $\beta = -0.19$) had greater vertical declines. Lake Evap : Inflow was related to increased vertical decline ($\beta = 0.14$), suggesting that lakes with more hydrologically restricted basins were more susceptible to water-level decline when anthropogenic effects were minimized. HydrAP at minimal levels tended to reduce water-level decline and promote lake-level stabilization ($\beta = -0.19$ for vertical decline).

Horizontal water-level decline was mainly driven by vertical decline ($\beta = 0.73$), surface area ($\beta = 0.24$), lake depth ($\beta = -0.18$), and bank flatness ($\beta = 0.14$) (Fig. 4). Shallow lakes with gently sloping banks had greater horizontal decline (littoral exposure) compared to deep, steep-sided lakes. The path analysis model revealed indirect effects of lake area, cumulative precipitation, drought (PHDI), Evap : Inflow, and HydrAP on horizontal decline that were mediated through vertical decline (Table S2).

Ecoregion path analysis model results

The lake hydrology model fit four out of the five ecoregion datasets relatively well based on model performance measures with RMSEA ≤ 0.08 and CFI ≥ 0.95 (Table 1). The model did not fit the Coastal Plains well (RMSEA $= 0.12$), nor did the modification index values identify sensible pathways to add to improve model fit. The poor model performance in the Coastal Plains may be related to the low sample size relative to the model complexity ($n = 126$; parameters to estimate $= 100$). In the four other ecoregions, the lake hydrologic model accounted for between a third to almost half of the variation in Evap : Inflow (Table 1). Vertical water-level decline was moderately to weakly explained by the models with R^2 values up to 0.38 in the West and only 0.10 in the Great Plains. The model explained over half of variation in horizontal water-level decline with R^2 values ranging from 0.57 (Midwest) to 0.79 (West) that again were mainly attributed to the strong direct effects of vertical decline in the model.

We found that ecoregional setting influenced the strength of connections between drivers and lake hydrologic responses especially with regard to anthropogenic effects (Figs. 4 and S2). Lake Evap : Inflow decreased with increasing inflow and greater lake depth. Surface inflow was a dominant driver of lake Evap : Inflow except in the Great Plains where baseflow index had a greater effect. This relationship indicates that groundwater may be a significant component of lake water

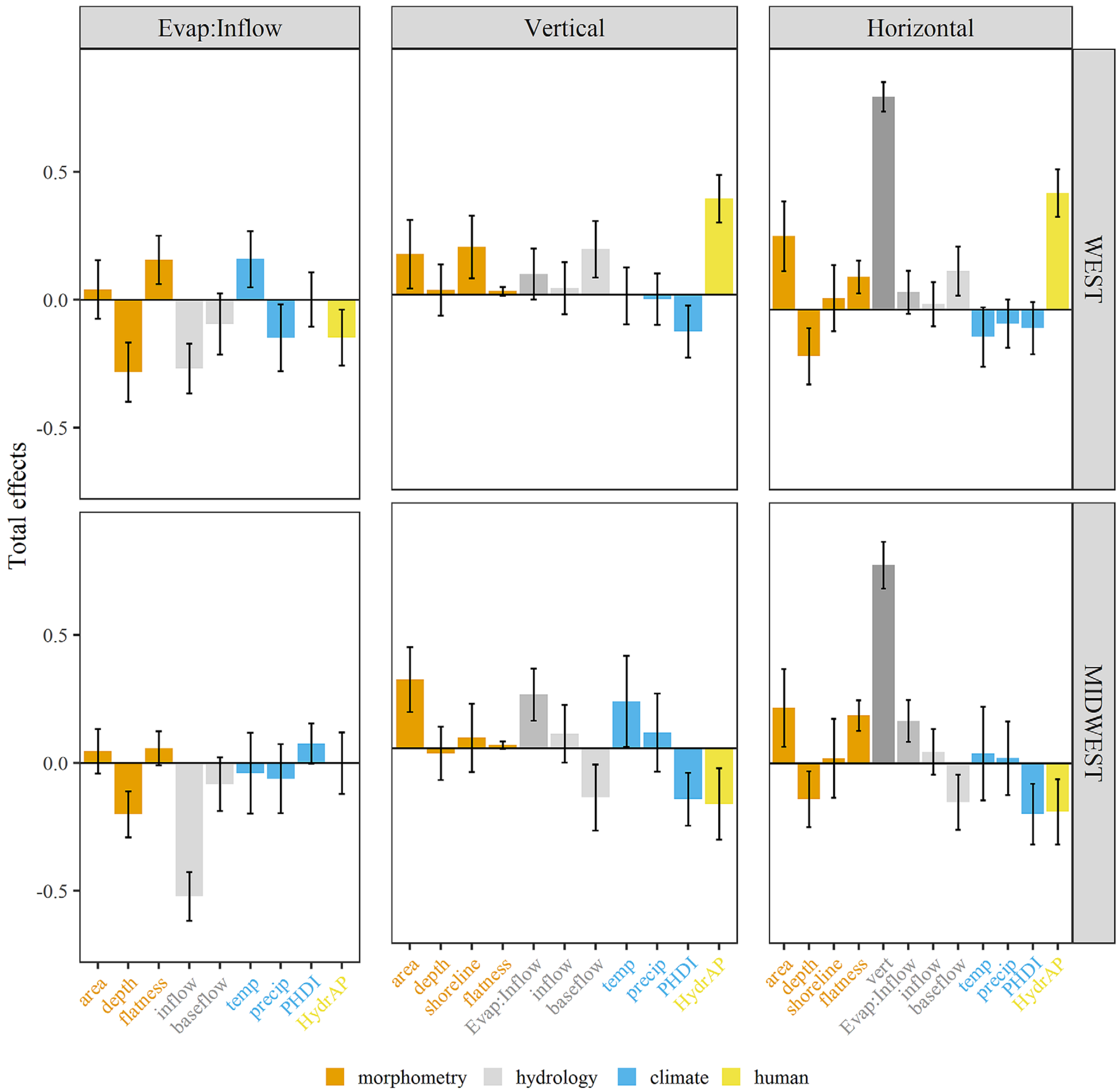

Fig. 5. Total effects of predictors on lake Evap : Inflow and vertical and horizontal water-level decline in the West and Midwest. Total effects are the sum of standardized direct and indirect effects. Model effects were estimated by bootstrap resampling. Error bars represent 90% confidence intervals. Predictor variables are colored by theme: lake morphometry, watershed hydrology, climate, and human.

balance in the Great Plains. The HydrAP metric was associated with lower Evap : Inflow across most ecoregions, a reversal of the positive relationship observed for CONUS lakes with minimal water management presence. This association implies that humans tend to build water control infrastructure or have land use activities near river-connected, flow-through lakes.

Vertical water-level decline was predicted well in the two mountainous regions of CONUS, the West and Appalachians, but by different predictors. In the West, HydrAP had the greatest total effect on vertical decline ($\beta = 0.38$) (Fig. 5). But in the Appalachians, vertical decline was most strongly related to annual precipitation ($\beta = -0.36$) and was not related to HydrAP (Fig. S1). In the Great Plains, the inverse drought index (PHDI) was the only significant predictor of vertical decline ($\beta = -0.27$). Horizontal water-level decline was positively associated with vertical decline and bank flatness in all four ecoregions with good model fit: West, Great Plains, Midwest, and Appalachians (Figs. 4 and S2).

Comparison of West and Midwest ecoregions

We compared the West and Midwest results to explore regional heterogeneity in the drivers of lake hydrologic characteristics in two ecoregions with distinct lake hydrologic characteristics and potentially divergent water management practices. Western lakes had greater water-level decline (e.g., mean vertical decline = 1.83 m, standard deviation [s] = 4.6) and low Evap : Inflow values (mean = 0.18, s = 0.18) compared to other CONUS ecoregions (Fig. S2). In contrast, Midwestern lakes had small-to-moderate water-level decline (e.g., mean vertical decline = 0.19 m, s = 0.39) and high Evap : Inflow values (mean = 0.30; s = 0.28). The lake hydrologic model explained some of this variation, but the types of drivers, their magnitude, and the direction of their effects varied among the two ecoregions.

The lake hydrology model explained similar levels of variation in Evap : Inflow in the West and Midwest (Table 1), but the magnitudes of the driver effects differed by ecoregion (Fig. 5). In the West, depth (β = −0.28) and inflow (β = −0.27) had similar magnitudes of total effects on lake Evap : Inflow. But in the Midwest, inflow (β = −0.52) had twice the magnitude of effect on Evap : Inflow compared to lake depth (β = −0.20). The HydrAP metric was negatively associated with lake Evap : Inflow in the West, but there was no relationship in the Midwest.

Vertical decline in lakes in the West was most strongly related to HydrAP and lake morphometry and moderately related to annual drought (Fig. 5). Water management presence (HydrAP) was associated with large vertical decline (β = 0.38), and HydrAP effects were over twice as large as drought effects (β = −0.15). These relationships suggest that the effects of human-related water management on lake levels exceeded the direct effects of annual climate in the West during the survey periods. In contrast, vertical decline in Midwest lakes was mainly related to annual climatic variables, and HydrAP had moderate effects relative to the other driver classes. Warm mean annual temperature (β = 0.19) and drier-than-normal conditions (β = −0.20) during the survey year were associated with vertical decline. Lakes with greater water management presence in the Midwest had smaller vertical water-level declines (HydrAP: β = −0.22), which suggest that water management may promote full and stable lake levels. The contrasting effects of HydrAP in the West and Midwest imply that regional water management strategies may result in different outcomes on lake water levels.

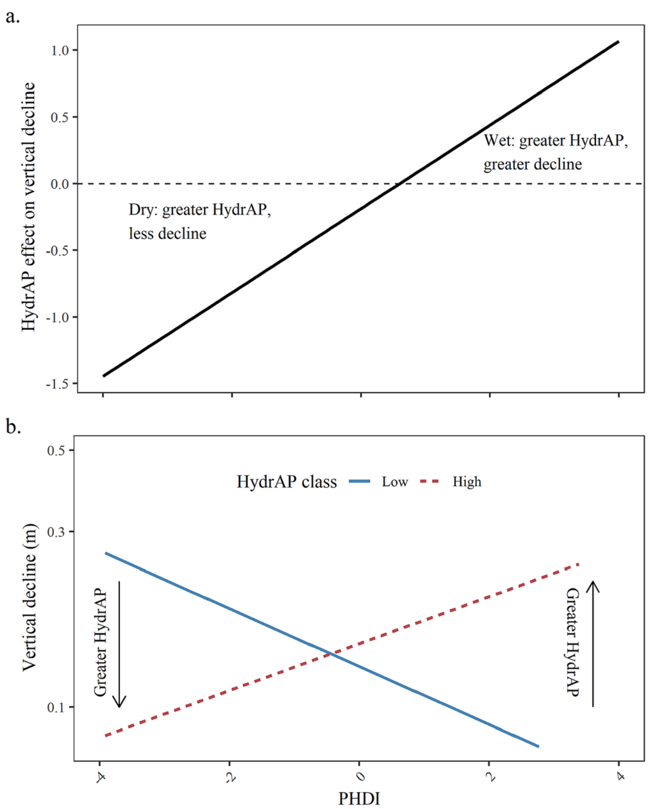

Fig. 6. Graphical representation of the interaction between anthropogenic HydrAP and PHDI on vertical decline in the Midwest. (**a**) Effect size curve of HydrAP on vertical decline at different levels of PHDI. (**b**) Vertical decline and PHDI relationships for lakes binned into low (< 3) and high (> 5) HydrAP classes. PHDI indicates the severity of wet (positive values) and dry (negative) periods: normal conditions (0 ± 0.5), drought (−0.5 to −4), wet (0.5–4). During normal climatic conditions, HydrAP has little effect on vertical decline in the Midwest. However, during drier- and wetter-than-normal conditions, the direction and magnitude of HydrAP effects on vertical decline changes. During dry conditions, lakes with greater HydrAP have less water-level decline in contrast to lakes with low HydrAP. These relationships reverse during wet conditions—lakes with greater HydrAP have greater vertical decline and lakes with low HydrAP have less decline.

Anthropogenic land and water management interaction with drought on lake hydrology

The HydrAP*PHDI interaction term improved model fit only in the Midwest ecoregion (Table S3). In the Midwest, HydrAP*PHDI had positive effects on vertical and horizontal water-level declines (Fig. 6a). Under drought conditions, lakes with greater water management presence tended to have fuller lake levels compared to lakes with less water management presence. In contrast, under wetter-than-normal conditions, lakes with greater water management presence had larger water-level declines than those with less water management presence (Fig. 6b). These contrasting relationships suggest that water management activities in the Midwest may dampen the lake level response to drought and flood by artificially maintaining full lake levels during drier-than-normal periods and lowering lake levels during wetter-than-normal periods.

Discussion

The lake hydrologic model, supported by national and regional datasets, illustrated how multiple lake, landscape, climate, and water management factors promote variation in water balance characteristics in CONUS lakes and reservoirs. We found that in lakes with minimal water management, water levels and Evap : Inflow were related to natural lake morphometry, watershed hydrology, and climate drivers that followed expected relationships. However, even at minimal levels, anthropogenic land and water management indicators affected lake water levels and Evap : Inflow. When viewed by ecoregion, the magnitude and direction of water management effects differed, demonstrating the need to consider the regional context when assessing anthropogenic effects on lake hydrologic characteristics across broad spatial extents.

Natural drivers of lake water-level decline and Evap : Inflow in CONUS

We expected lake hydrologic characteristics to be driven by climatic variables that interact with lake and watershed attributes (Blenckner 2005) in the absence of major human-related water management infrastructure and land use. The model results supported these expectations and demonstrate how natural morphometry and hydroclimatic drivers affect lake hydrologic characteristics across CONUS.

Lake evaporation : inflow in our model decreased with increasing surface inflow and maximum lake depth, in agreement with observations from minimally disturbed lake studies (Gibson and Edwards 2002; Gibson et al. 2016). Surface inflow in our model was derived from precipitation, watershed soils, and land cover (McCabe and Wolock 2011), and it therefore represented a more direct water input to lakes across ecoregions and disturbance gradients compared to climate variables alone. Lake depth may indirectly affect lake evaporation by influencing the synchrony of seasonal water and air temperatures (Hostetler and Bartlein 1990; Blenckner 2005). However, the strong relationship between lake depth and Evap : Inflow in our model may be attributed to the positive correlation between maximum lake depth and surface inflow ($r = 0.22$, $p < 0.01$) since evaporation from lakes is an areal process (Jones et al. 2018). Lake surface area was positively related to Evap : Inflow, supporting evaporation being controlled by surface area extent, but interestingly lake depth was consistently a stronger predictor than lake area. Collectively, climate-driven differences in surface inflow interact with heterogeneity in lake morphometry to promote variation in Evap : Inflow. We expected that climate variables would be related to lake Evap : Inflow, but mean annual temperature was the only significantly related climatic variable in the model, and its positive relationship was weak. Seasonal climate metrics might better capture climatic variation that affects lake hydrologic processes, particularly in temperate regions in CONUS. In prairie lakes, winter precipitation was found to be a key component of lake water balance (Pham et al. 2009). In model simulations, the duration of winter ice cover was shown to affect lake evaporation with shorter ice cover periods being associated with greater evaporation (Wang et al. 2018). Seasonal precipitation and temperature measures may better capture climate variation that affect lake hydrology, but defining relevant temporal scales in climate attributes across the CONUS extent is beyond the scope of this analysis.

Lake water-level declines can be driven by drought and significantly impair lake ecological conditions (Gaeta et al. 2014; Glassic and Gaeta 2019). However, the effects of drought are not consistent among lake types nor across ecoregions because of underlying heterogeneity in lake and watershed geomorphology (Blenckner 2005; Torabi Haghighi et al. 2016). We found that vertical and horizontal water-level declines in CONUS lakes were related to less annual precipitation, greater drought, and more hydrologically restricted lake basins as indicated by Evap : Inflow. In the Great Plains and Appalachian ecoregions, climate variables, above all other driver classes, were the dominant controls of water level decline. Water level fluctuations are common in the Great Plains, where periodic drought and large-scale climate systems promote hydrologic variability throughout the year (Leira and Cantonati 2008). Topographic and soil composition in the Appalachians may make surface hydrology more responsive to precipitation (Gnann et al. 2021). In addition, the landscape position of a lake can explain variable drought effects with perched (i.e., groundwater separated), seepage lakes exhibiting greater water-level declines during drought compared to drainage lakes lower in the landscape (Webster et al. 1996, Hanson et al. 2018, Perales et al. 2020). Although we did not have landscape position measures to include in our model, we used lake Evap : Inflow as an isotopic indicator of lake flow-through status. Lakes with high Evap : Inflow values (i.e., hydrologically restricted basins) had greater water-level declines compared to lakes with low Evap : Inflow values (flow-through, drainage lakes) when minimizing water management presence. Lake Evap : Inflow could be a useful attribute for identifying lakes that are vulnerable to declining levels resulting from drought and changing climate.

Lake water levels fluctuate naturally in response to climate variation, and lake ecosystems are adapted and benefit from these natural fluctuations (Coops et al. 2003; Leira and Cantonati 2008). Some littoral plant communities are adapted to periodic drying and flooding and rely on these perturbations to support life history stages (Mortsch 1998). However, prolonged littoral exposure caused by horizontal water-level declines can degrade nearshore habitat structure and alter biotic community composition (Zohary and Ostrovsky 2011; Kaufmann et al. 2014b; Carmignani and Roy 2017) and may significantly impair CONUS lake condition (Kaufmann et al. 2014b). We found that horizontal decline in CONUS lakes was driven by vertical decline and lake basin morphometry, such that shallow, large lakes with gently sloping banks had greater littoral exposure. Lake basin shape and flushing characteristics have been associated with lake vulnerability to desiccation from altered flows and climate (Gibson et al. 2016; Torabi Haghighi et al. 2016). Understanding how morphometric attributes influence the expression of horizontal water-level decline is critical to assess potential climate-related impacts on lake ecological condition.

The magnitude of horizontal decline is predetermined largely by the amount of vertical decline and the slope of the littoral bottom. Mechanistically, we expected climatic drivers to primarily act on the water surface area to affect water depth and for climate to indirectly affect horizontal decline through vertical decline. We explored the relative importance of vertical decline and the indirect influences of climatic drivers on horizontal decline by running a separate model that removed the connection between vertical and horizontal water-level decline. The revised model fit the data relatively well (Chi-square = 2.70 n.s.; RMSEA = 0.03; CFI = 1.00; TLI = 0.99) and explained only 16% of variation in horizontal decline compared to 62% in the original model that included vertical decline as a predictor. The other predictors of horizontal decline had similar total effects (surface area [$\beta = 0.24$], lake depth [$\beta = -0.17$], bank flatness [$\beta = 0.15$], and drought [$\beta = -0.21$]) as compared to the original model and explained similar levels of variation as vertical decline (13%). The revised model illustrates that our geoclimatic and anthropogenic drivers explained similarly low levels of variation in vertical and horizontal decline, and we need to explore other measures to improve model performance in predicting lake water-level decline.

Land and water management infrastructure and activities are widespread among CONUS lakes (Fergus et al. 2021). Although we attempted to minimize human-related water management effects by examining a subset of lakes with low HydrAP values; even so, over 70% of these 553 lakes had some level of anthropogenic disturbance. The prominent anthropogenic feature in these lakes was total anthropogenic land use in the immediate lake catchment: about 65% of low HydrAP lakes had small levels of agriculture and urban development in their direct drainage area (median = 13.8%, Q1 = 3.2%, Q3 = 31.1%). Only about 5% of low HydrAP-ranked lakes were reported to have dams, and these dams had limited abilities to alter lake water levels based on the ratio of dam height to maximum lake depth (median = 0.12, Q1 = 0.07, Q3 = 0.16). Small proportions of impervious surface in watersheds (Booth and Jackson 1997) and road and dam density (Eng et al. 2013) have been associated with altered stream flows, indicating that low levels of anthropogenic disturbance can impact the fate and transport of precipitation on a watershed. The HydrAP metric was negatively related to vertical and horizontal decline and positively related to Evap : Inflow nationally, suggesting that lakes with minimal water management presence were associated with more full pools and greater evaporation of inflowing water. In these lakes, land and water management practices may dampen natural water-level fluctuations and result in more stable, full lake pools. Collectively, these relationships demonstrate that anthropogenic disturbances to lake and watershed hydrology are ubiquitous and have measurable effects on lake water balance even at relatively small levels.

Anthropogenic effects on lake Evap : Inflow and water-level decline in regions of CONUS

The goals of land and water management practices are strongly affected by underlying regional geoclimatic variation that influences spatial and seasonal patterns of water abundance, as illustrated by the distribution and density of dams across the landscape (Smith et al. 2002; Doubek and Carey 2017; Fergus et al. 2020). We found that the magnitude and direction of anthropogenic effects on lake hydrology varied across CONUS ecoregions particularly in the West and Midwest ecoregions. Differences in HydrAP relationships in the West and Midwest may largely be attributed to dam presence (Fig. 7). In the West, lakes with dams had significantly greater vertical and horizontal water-level decline compared to lakes without dams. In contrast, lakes with dams in the Midwest had less horizontal water-level decline and lower Evap : Inflow. Lakes with large capacity dams (HydrAP 6–7) in the West were in areas receiving less long-term precipitation (30-yr normal mean) than the ecoregional mean (Fig. S3). In the West, water availability can be limited or highly seasonal and these dynamics affect where and how water storage infrastructure is used. According to the National Inventory of Dams, dams in the West tend to be used for irrigation, hydroelectric power, and water supply; and these purposes can result in large water-level fluctuations or even declines over multiple seasons. By contrast, in the Midwest ecoregion, lakes with dams were in areas that regularly received greater precipitation than the ecoregion mean, and these dams were designated for recreational purposes, fish and wildlife habitat, and water storage for farm ponds. Humans have altered lake hydrology in the Midwest by constructing outflow control structures, agricultural drain tiles, and urban stormwater infrastructure (Fausey et al. 1995; Green 2006; Carlisle et al. 2019). These modifications and water management practices retain water in lakes and can lead to artificially stable water levels. Ecoregional differences in climate, dam location, and the predominant purpose of dams in the West and Midwest provide insight into how human-related water management affects lake hydrology.

Land and water management activities affect watershed hydrology in variable ways that may amplify or dampen natural geoclimatic effects. Studies have shown that land and water management practices can mask and even exceed the effects of climate on lake and stream hydrology (Haddeland et al. 2014; Carlisle et al. 2019; Wine et al. 2019), but metrics of anthropogenic disturbance are needed to disentangle the relative influence of human and climate effects on hydrology. We used the HydrAP metric in this study, which integrates information on dam attributes and land use (urban development, total agriculture, irrigated agriculture, and tile drainage agriculture) to provide a more comprehensive measure of human hydrologic pressure. To better understand what specific land and water management features were most prominent across ecoregions, we subset lakes with moderate to high HydrAP scores (> 3) and examined distributions of the four main components used in the HydrAP ranks (Fig. S4). Dam height relative to maximum lake depth was similar among four out of the five ecoregions, but land use types varied. Lakes in the Midwest, Appalachians, and Coastal Plains had

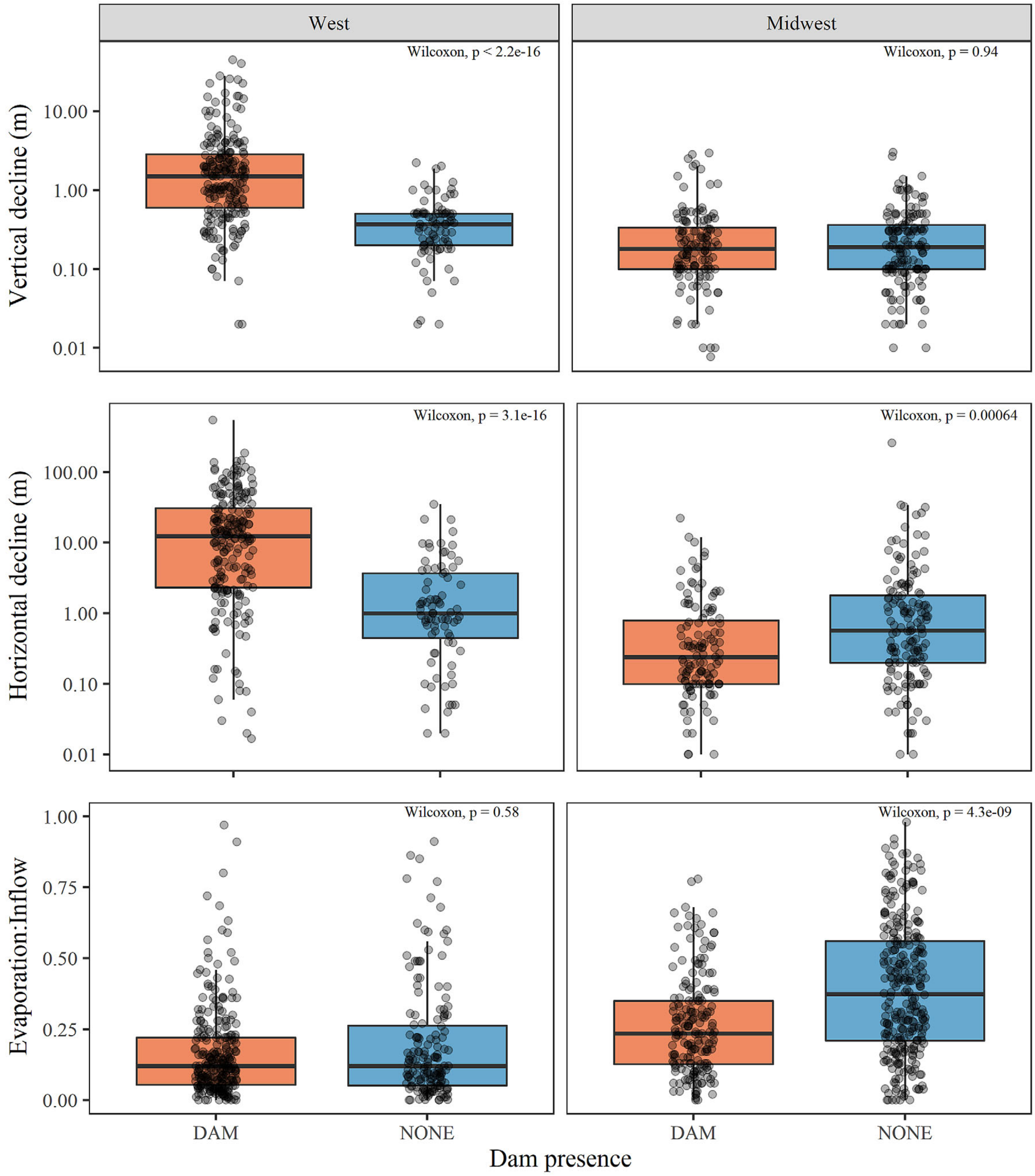

Fig. 7. Distributions of lake hydrologic response by dam presence for lakes in the West and Midwest ecoregions. Nonparametric Wilcoxon rank-sum tests for differences in lake hydrologic characteristics between lakes with and without dams.

greater percentages of urban development compared to lakes in the West and Great Plains. Specific agriculture types exhibited regional patterns with irrigated agriculture being more prevalent in the West, Great Plains, Midwest, and Coastal Plains and tile drainage agriculture being more prominent in the Midwest. Examining the individual components of the HydrAP metric provides some insight into the mechanisms promoting lake hydrologic variation.

The HydrAP metric is a measure of the *potential* for anthropogenic hydrologic alteration that relies on geospatial data that are spatially and temporally coarse and may not accurately characterize land and water management activities. For example, dam height scaled by maximum lake depth did not vary significantly across the five ecoregions, but dam effects on lake hydrology did vary. Ultimately, human decisions on dam operations determine how dams affect lake hydrology, but records on these activities are lacking. Measures of anthropogenic disturbances to hydrology at national extents may improve with advances in remote sensing technology to more accurately characterize human land use activities over time and with the development of data repositories on reservoir operation policies (Turner et al. 2021).

Interaction of anthropogenic and drought effects on lake hydrology

Water management practices have the potential to exacerbate or ameliorate drought and flood effects on lake hydrology. We found evidence for an interactive effect between HydrAP and drought severity index on lake water-level decline in the Midwest. In this ecoregion, dam infrastructure and land use activities minimized the response of lake levels to drought and flooding. This interaction indicates that water management practices in the Midwest can be responsive to intra-annual climate variation and may dampen drought and flood effects. Recreation and commercial interests may advocate for artificially stable lake water levels that can impair nearshore macrophyte community composition (Epstein 2017) and even cause ecological shifts from clear water to turbid states (Leira and Cantonati 2008). Water management infrastructure has the potential to be used as an adaptive management tool that can support efforts to protect lake biointegrity and meet human water needs with changing climate (Ehsani et al. 2017). Identifying how water management and drought effects interact can improve lake hydrologic predictions and assess the potential for water management infrastructure to support climate change resiliency.

Model limitations

The lake hydrology model is a coarse representation of the multifaceted drivers promoting regional variation in lake hydrologic characteristics across CONUS. Hydrologic responses in the model are snapshots of lake water-level decline and Evap : Inflow and do not capture fine-scale nor long-term lake hydrologic dynamics. However, these variables were measured on a diverse and representative range of lakes across CONUS to provide insights on hydrologic variation across lake types and ecoregional settings. Long-term lake hydrologic records are needed to understand how lake hydrology and its controlling factors may change over time, but long-term records are commonly available only on single or small groups of lakes of high human interest (Kann and Walker 2020). Consequently, little is known about hydrologic dynamics for most lakes. Others have recognized this challenge and are developing innovative solutions to fill this information gap. Low-cost in situ hydrologic observatories can collect accurate water balance measurements on small lakes and could be deployed and monitored by citizen scientists (Watras et al. 2019, 2021). Remote sensing technology with improved sensors and methods to quantify lake surface area dynamics (Eilander et al. 2014; Pekel et al. 2016; Pickens et al. 2020), in combination with citizen science lake-level observations can potentially expand the temporal and spatial coverage of lake water storage observations (Little et al. 2021).

The lake hydrologic model fit the datasets relatively well but did not account for a large proportion of variation in vertical water-level decline across CONUS. Water level decline and Evap : Inflow may be related to temporally dynamic variables that were not included in the model such as single storm events (Zohary and Ostrovsky 2011), specific water management release decisions (Coerver et al. 2018), or longer-term climate cycles. Observed lake-level declines may be related to antecedent lake levels in preceding years that are driven by climate cycles not necessarily included in our model. In the Upper Great Lakes region, lakes and aquifer water levels exhibited ~ 13-yr oscillation patterns attributed to changes in net atmospheric water fluxes, possibly connected to mid-North Pacific atmospheric circulation patterns (Watras et al. 2014). The NLA design is better suited to capturing spatial trends rather than temporal trends in lake-level variation, and regionally specific climate oscillations were not included in our model. While these temporal oscillations and their drivers are important to understand hydroclimatic effects on lakes, we expect that in the NLA dataset, the spatial variation across CONUS may exceed temporal signals that are likely conditioned to geographic region and local scale factors (McGregor 2017; Little et al. 2021). Other climate metrics besides the PHDI may capture climatic variation that drives lake water-level declines. Methods using moving mean time periods to derive deviations in precipitation found that monthly precipitation anomalies from 5-yr means were correlated with groundwater levels in Wisconsin (Smail et al. 2019). These methods may aid with metric development that characterizes climate variation at temporal scales relevant to water level fluctuations. In addition, surface and groundwater connections are important lake water balance components associated with declining lake water levels (Roach et al. 2013; Perales et al. 2020) but are not quantified at national extents. Integrating these different drivers into landscape-level analyses will require improved data resources and advance modeling techniques. Despite the model limitations, the path analysis approach provides an adaptable representation of lake hydrologic drivers from which we can make inference and predictions to a broad array of lake types distributed across the landscape.

Conclusions

The structural equation model analyses highlight general patterns to help us interpret and understand what promotes variation in lake hydrologic characteristics across CONUS. Lake water-level decline and Evap : Inflow are distinct hydrologic metrics driven by different landscape, climate, and anthropogenic predictors that exhibit variation over space. These distinctions should be considered when determining research and management objectives. Our path analysis model highlighted important causal pathways promoting lake hydrologic variation. We demonstrated that in the absence of water management, natural predictors have relatively consistent effects on lake hydrologic characteristics, but anthropogenic influences differ among ecoregions and can interact with climate conditions. Evolving human water needs coupled with changing climate may alter lake water-level fluctuations beyond natural ranges, with attendant impacts on lake habitat and biota. Our study, with observations at only one time point per lake, cannot evaluate climate change effects on lake hydrologic characteristics. However, the analyses identify ecoregions and lake types where climate has a greater influence on lake hydrologic characteristics relative to other drivers and may render lakes to be more responsive to changing climate conditions. Future studies can examine climate variation effects on CONUS lake hydrologic characteristics as the NLA monitoring data grows. The NLA will continue to provide a valuable spatial and eventually temporal resource to evaluate lake condition in the United States. Disentangling the relative effects of natural and anthropogenic drivers on lake hydrologic condition is essential to support lake assessment and management objectives under changing environmental conditions.

Data availability statement

The data that support the findings of this study are openly available in the US EPA ScienceHub at https://doi.org/10.23719/1526381

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Acknowledgments

We thank the various individuals and entities behind the NLA data collection, processing, and maintenance that include field crews, laboratory staff, data management and quality control staff, analysts, and many more from EPA, states, tribes, and federal agencies. We thank Drs. Abhishek Kumar, Patti Meeks, and Susan Holdsworth for constructive reviews of earlier drafts of the manuscript. Please contact nars-hp@epa.gov with questions specific to the EPA's NARS program. This manuscript has been subjected to Agency review and has been approved for publication. The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. This project was supported in part by an appointment to the Research Participation Program at the Pacific Ecological Systems Division, U.S. Environmental Protection Agency, administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and EPA.

Conflict of Interest

None declared.

Submitted 29 November 2021
Revised 11 March 2022
Accepted 23 April 2022

Associate editor: Grace M Wilkinson