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A hydro-climatological lake classification model and its evaluation using global data

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Abstract

For many of the world's lakes, particularly those in remote regions, an assessment of the basin's sensitivity to climate change is limited by the availability of appropriate hydrologic data. A regional steady-state lake water balance model was developed that uses simple, yet easily estimated or obtained, data to generate an aridity index (potential evapotranspiration to precipitation ratio) to predict changes in lake basin area to lake surface area ratio, a non-dimensional lake-basin property that can be easily obtained from digital maps. In the model, lake water balance components include precipitation, lake evaporation, and runoff into the lake. Both basin runoff and evaporation are incorporated in the analytical model using an empirical equation (based on the Budyko hypothesis) that utilizes the aridity index and a calibration parameter to account for vegetative influence. Observed records of lake to basin area ratio, as a function of their evapotranspiration to precipitation ratio, for a range of climates and land cover conditions, were plotted and compared to a family of calculated steady-state curves. Dividing the domain of calculated curves into regions of permanent, land-cover change sensitive, and ephemeral lakes allows for comparison of model predicted lake classification with lake sediment records. The impact of land cover and climate change on lake persistence is also discussed. The model is most applicable for closed basin lakes in sub-humid, semi-arid, and arid environments. The model can be used: (1) as a diagnostic tool to analyze lake response to climate change; (2) to assess environmental and anthropogenic factors leading to transient lake response; and (3) as a paleoclimatic research tool, to identify lakes that can potentially provide high-resolution paleorecords of water balance.

Keywords: Lake, Water balance, Paleorecord

1. Introduction

Understanding how climate change affects lakes is essential for managing water resources and the associated ecosystem services, as well as for interpreting lacustrine records of past climate variability. An increasing number of studies suggest that time series of data that span several hundred to several thousand years are necessary to understand the full range of natural climatic and hydrologic variability (Alley et al., 2003, Cook et al., 2007, Stine, 1994 and Woodhouse et al., 2009). Among the tools that expand the temporal framework to times prior to those recorded in the instrumental climate record are lake sediment cores, which can be used to reconstruct past hydrologic variation and how that variation affected ecosystem processes (Shapley et al., 2002, Stone and Fritz, 2006 and Whitlock et al., 2012). Multiple factors affect the sensitivity of a lake basin to different aspects of climate and the extent to which climate change is recorded in lake sediments (Bracht et al., 2008, Gasse et al., 1987 and Stone and Fritz, 2004). These include position within the landscape, size, bathymetry, groundwater connectivity, anthropogenic influences, as well as the magnitude, nature, and season-

ality of climate variation. Thus, climate patterns are more clearly inferred from certain types of lakes and in certain settings, but may be confusing or ambiguous in others (Fritz, 2008 and George and Hurley, 2003).

Lake models can be used to provide insight into how lakes respond to specific aspects of climate change through quantification of the hydrologic balance (Hostetler et al., 1994, Tate et al., 2004 and Zlotnik et al., 2009). Most prior modeling studies of lacustrine hydrology considered an individual lake or a small suite of lakes and their responses to changes in temperature, solar radiation, precipitation, or CO₂ (Hostetler et al., 2000, Vassiljev, 1998 and Vassiljev et al., 1995). However, such focused studies do not provide a large-scale picture of lake hydrologic response in relation to geographic location and regional climate conditions (Bennett et al., 2007, Sass et al., 2008, Vassiljev et al., 1995 and Webster et al., 2000). Other lake modeling studies have used general circulation models to reconstruct regional water balance at times in the past and compared model predictions with paleodata, including lake-level reconstructions, in order to better understand the mechanisms of regional climate change in the past (Kohfeld and Harrison, 2000 and Street-Perrott and Harrison, 1985).

We developed a steady-state, basin-lake water balance model that predicts basin area to lake area ratio (A') as a function of mean annual climate, quantified by an aridity index, Φ (mean annual potential evapotranspiration to precipitation ratio), expressed in a family of curves on an $A' - \Phi$ domain. Vegetation influences the basin runoff into a lake; therefore, we include the effects of basin vegetation within the model through an empirical calibration parameter. Based upon the vegetation-specific steady-state thresholds, we identify several lake classification regions defined on the $A' - \Phi$ domain: permanent (those that do not desiccate), land cover (LC) sensitive, and ephemeral (desiccates frequently). The model can be used to evaluate the extent to which lake level in a given basin (implicit in the A' value of a lake) responds to climate change relative to other non-climatic influences. Our approach is similar to that of Bowler (1981), in which a lake stability classification scheme, based upon water-balance components, was developed and implemented for Australian lakes. Bowler (1981) did not calculate runoff and evaporation explicitly but assigned values to these model parameters. However, in this paper we calculate runoff and evapotranspiration explicitly, using an aridity index based method that allows for climatic classification and incorporates vegetative influences.

This conceptual climatic lake model is designed to be simplistic, while requiring a minimum number of input parameters. The conceptual model relies on several base assumptions: (1) steady-state water balance, (2) uniform basin climate (including over lake and basin), (3) closed-basin lake system (including groundwater fluxes), (4) no anthropogenic influences, and (5) appropriate time-scale (some extremely large lakes may have long response times due to their storage capacities). Our methodology provides a means to identify other lake-basin hydrologic controls that influence lake-level variation, which could be critical to examine lake hydrology under limited hydrologic information. For example, the model can be used whether or not the lake has significant surface inflow or outflow, or whether groundwater fluxes are a substantial portion of the water budget. Also, the proposed model can be used to get insights on a lakes sensitivity to changes in the mean annual climate, and its potential to preserve a complete sediment record of climate history.

In this paper first we describe the conceptual model. By using lake plotting position in a two-dimension space, we then evaluate lake sensitivity, which we define as the change in Φ or A' required to change a lakes plotting position to a different classification category. We evaluate our classification model against observations from 150 lakes, spanning six continents. We identify lakes whose dominant controls on lake level are climate and lake area/surface area interactions, or if other parameters are important in affecting lake-level variation. This model may be useful in evaluating sites for specific hydrologic or paleoclimate questions, regional controls on lake level, or lake response to land-use change.

2. Methods

2.1. Analytical model

The simplistic conceptual model is presented below. Model limitations are discussed as we present the model, as well as in the discussion section of the paper. The annual water balance of a closed lake basin can be written as (e.g. Street-Perrott and Harrison, 1985):

$$\Delta V = A_l(P_l - E_l) + R_b A_b + (G_i - G_o) \quad (1)$$

where ΔV is the net annual change in the lake volume, A_l is the lake surface area, P_l is precipitation over the lake, E_l is evaporation from the lake, R_b is the basin runoff generated uniformly

over the contributing area of the basin, A_b is the contributing basin area, and G_i, G_o are the groundwater fluxes in and out of the lake, respectively. Assuming that an equilibrium condition is attained between the fluxes of water into and out of the lake volume and that a net groundwater transfer is negligible, a closed-basin, steady-state lake water balance can be expressed as:

$$0 = A_l(P_l - E_l) + R_b A_b \quad (2)$$

A climatological classification of lake water balance should use some directly measurable lake and basin attributes, and an index that describes the regional climate, such that these properties can be plotted in a two-dimensional space, along with the predictions of the conceptual model. Earlier works on water-balance lake classification used lake to basin area ratio to further simplify Equation (3) into a non-dimensional form (Bowler, 1981; Street-Perrott and Harrison, 1985). In this model, instead of using a lake to basin area ratio, we prefer to use a basin area to lake area ratio. Thus, both sides of Equation (2) are divided by A_l to obtain this ratio. Using $A' = A_b/A_l$ as an area index, we obtain:

$$0 = P_l - E_l + R_b A' \quad (3)$$

In our simplified steady-state model we propose to estimate R_b and E_l from the Budyko hypothesis (Budyko, 1974). Budyko (1974) postulated that the mean annual actual evapotranspiration (ET_a) of a basin asymptotically approaches a very small value as climate becomes wetter, and approaches the mean annual precipitation over the basin (P) as climate becomes dry. When climate aridity is represented by $\Phi = ET_p/P$, where ET_p is the maximum or potential mean annual evapotranspiration, the hypothesis postulated by Budyko (1974) leads to the following limit conditions for ET_a/P :

$$\frac{ET_a}{P} = \begin{cases} F(\Phi) \rightarrow 0, & \Phi \rightarrow 0 \\ F(\Phi) \rightarrow 1, & \Phi \rightarrow \infty \end{cases} \quad (4)$$

where $F(\Phi)$ is an asymptotic function that could take various forms. The Budyko hypothesis has been widely used as a conceptual framework for examining basin water balance in a range of climates and environmental conditions, and for developing and validating regional hydrologic models (Milly and Dunne, 1994; Choudhury, 1999; Koster and Suarez, 1999; Atkinson et al., 2002; Farmer et al., 2003; Porporato et al., 2004; Zhang et al., 2001, 2004, 2008). The simplistic nature of this hypothesis provides an opportunity to relate the steady-state lake water balance model to climate.

For $F(\Phi)$ we use the model proposed by Zhang et al. (2001):

$$F(\Phi) = \frac{1 + w\Phi}{1 + w\Phi + \Phi^{-1}} \quad (5)$$

where w is an empirical parameter used to represent land cover and soil type. Assuming that P is in balance with R_b and ET_a on a mean annual basis and that inter-basin groundwater flow is negligible, basin water balance normalized with respect to precipitation becomes:

$$\frac{R_b}{P} + F(\Phi) = 1 \quad (6)$$

Solving for R_b gives:

$$R_b = P(1 - F(\Phi)) \quad (7)$$

In this simple model we propose to write Equation (3) as a function of three variables that can be directly estimated in a region: P , Φ , and A' . To limit the model to these variables, we made the following assumptions. First, using a single P , we assume that both the lake and the basin receive the same amount of mean annual precipitation ($P_l = P$). Second, we assume that the mean annual basin ET_p and lake evaporation E_l are identical. This neglects the role of heat storage in lakes, which is more

critical for deep lakes. The Food and Agricultural Organization (FAO), compares E_l with the potential rate of evapotranspiration for a reference grass crop (ET_R) over a year through the use of crop coefficients (Allen et al., 1998). The report suggests that in shallow waters (≤ 2 m) E_l can be as much as 5% higher than ET_R . For deeper waters where significant temperature changes in the lake profile could occur, E_l was reported 35% lower until mid-season, and up to 25% higher than ET_R after the middle of the growing season (Allen et al., 1998). However considering that over the mean annual time scales, the net change in the heat storage in a lake could be practically negligible, we argue that our assumption can be acceptable for a simplistic approximation of lake water balance applicable at the global scale. Using the aridity index, we can write $E_l = P\Phi$. Now substituting the expressions obtained for R_b and E_l into Equation (3), the steady-state lake-basin water balance reduces to:

$$0 = P(1 - \Phi) + P(1 - F(\Phi))A' \quad (8)$$

This model can be illustrated in Figure 1, where both lake and basin area are represented by boxes, governed by water balance, with basin runoff entering the lake area. Note that in the equations above, we showed how ET_a and R_b can be approximated from the Budyko hypothesis, and E_l from the aridity index.

The basin to lake area ratio (A') required to maintain a steady-state balance of fluxes into and out of the lake can be calculated as a function of the aridity index by solving (8) for A' yielding:

$$A' = \begin{cases} \frac{\Phi - 1}{1 - F(\Phi)} & \Phi \geq 1 \\ 0 & \Phi < 1 \end{cases} \quad (9)$$

The behavior of this equation is illustrated on the $A' - \Phi$ domain for different values of w , representing different land use conditions (Figure 2). The energy line (vertical dashed line) separates the domain into energy and water limited climates, and the ranges of different climates classified with respect to Φ are indicated on the x-axis, according to Barrow (2006). Note that in Equation (8), $A' > 0$, if $\Phi > 1$. When $\Phi < 1$, the climate is energy limited and ET_p falls below P (Figure 2a). As a result, the model does not require A' in such humid regions where regional topography allows for closed depressions to store water. Thus, lakes in energy-limited regions, under a stationary climate, would be permanent, and their formation would solely be controlled by topography. In the water-limited portion of the $A' - \Phi$ domain, A' increases nonlinearly as climate becomes arid due to increasingly larger basin areas needed to compensate the growing evaporative demand.

To illustrate the role of land cover (LC) in the $A' - \Phi$ relation, we plot Equation (9) in Figure 2a for two typical values of w representing grass ($w = 0.5$) and forest ($w = 2.0$) (Zhang et al., 2001), and a low value of $w = 0.1$ to represent sandy soils and sparse vegetation (Wang et al., 2009). Conceptually we consider the region bound by the forest and sparse vegetation lines for a

Figure 1. This schematic simply illustrates the main conceptual model components. It also shows the relationship between the basin and lake components.

Figure 2. (a) $A' - \Phi$ relations for three typical values of w representing different land cover impacts, based on Zhang et al. (2001, 2004). The domain is separated into three different lake classification regions based on climate. The vertical dashed line separates the energy and water-limited environments. (b) Model sensitivity to land cover change, illustrated by plotting A^* (change in A' as a result of land cover change).

given Φ as a range of A' required to maintain lakes in a given climate. This threshold envelope between the forest and sparse vegetation increases as the climate becomes drier. This underscores the critical role of basin LC on lakes in arid climates. Conversely, in the sub-humid and energy-limited climates, the envelope between forest and sparse vegetation rapidly shrinks.

Lakes that fall above the forest threshold line can be considered permanent and insensitive to LC change as they have larger basin areas than required by the model. Lakes that fall below the lower threshold line can be considered ephemeral, as they have smaller basin areas than required by the model for sparse vegetation (LC). Ephemeral lakes would only form during the wet season or during wetter climate anomalies. We classify the lakes that fall between the upper and lower LC lines (threshold envelope) as LC sensitive lakes. In this region, lakes can be permanent, ephemeral, or conditioned on their LC type. For a given Φ , a lake with a forested basin that plots below the $w = 2.0$ threshold line would tend to show ephemeral behavior. We can further interpret the model results when individual lake data are calibrated with a w -value or a smaller range of w -values from basin runoff observations. In this case we expect that the smaller the observed A' of a lake compared to that calculated from Equation (9), the more frequently the lake will desiccate (or experience water losses) as a result of climate fluctuations. Conversely, with larger observed A' than required, the lake would be less susceptible to LC and climate change disturbances.

The conceptual model can also examine the impact of LC change on lake size. Figure 2b illustrates the impact of LC change on basin to lake area ratio (A') by plotting the percent change in A' as a result of LC change, calculated as:

$$A^* = \frac{A'_{\text{grassland}} - A'_{\text{forest}}}{A'_{\text{forest}}} * 100 \text{ or } A^* = \frac{A'_{\text{forest}} - A'_{\text{grassland}}}{A'_{\text{grassland}}} * 100 \quad (10)$$

The two curves represent land-use-change impacts from forest to grassland conversion and vice versa on A' (first equation is forest to grassland). Forested basin ET_a is larger than grassland ET_a . Under the same climate, a forested basin will need a larger A' (to maintain long-term steady-state water levels) than a grassland basin as it produces less runoff. In the case of grassland to forest conversion, a greater A' will be needed to maintain a lake water balance (positive A^*) (Figure 2b). Since increases in basin size are unlikely, the implication of this would be reduction of lake size or desiccation of the lake. When land cover changes from forest to grassland under a constant Φ , a lake would increase its size, leading to a reduction in A' (negative A^*) (Figure 2b). Interestingly, the conceptual model predicts that land-use change would have different impacts on A' depending on climate. A more dramatic impact of land cover change is predicted as climate gets drier, especially in the case of forest to grassland conversion. For example, for an aridity index of 4 (semiarid climate), forest to grassland conversion gives a ~65% increase in A' as the lake surface would grow and the basin area will remain relatively constant. Grassland-forest conversion would lead to more than a 180% decrease in A' , and the difference continues as climate becomes more arid.

2.2. Data

We use the model as a diagnostic tool to evaluate, in relation to vegetative conditions, the observed $A' - \Phi$ values of lakes, along with their records of desiccation frequencies globally to interpret certain lakes' sensitivity to climatic fluctuations. Lakes, over 150 globally, included in this study vary in location, surface area, volume, climate, and anthropogenic influence (Figure 3).

Data for lake surface area, watershed area, potential evapotranspiration, and precipitation come from a variety of sources and methods, including publications, GIS measurements of basin and lake area, and data from the International Water Management Institute (IWMI, <http://www.iwmi.cgiar.org>), the Northern Temperate Lakes Long Term Ecological Research (LTER, <http://www.lter.limnology.wisc.edu>), Experimental Lakes Area (ELA, <http://www.experimentallakesarea.ca>), World Lake Database (WLD, <http://www.ilec.or.jp>), the

Table 1. Lake data sources, see text for definition of acronyms.

Continent	Data source
Africa	Ayenew, 2003, Bergonzini, 2004 and Hamblin et al., 2004 Kutzbach, 1980, Nicholson and Yin, 2002 and Song et al., 2002
Asia	Morrill, 2004 and Qin and Huang, 1998, WLD, IWMI
Australia	Bowler (1981), IWMI, WLD
Europe	George et al., 2000 and Vassiljev, 1998 Vassiljev et al. (1995), IWMI, WLD
North America	Allen, 2005 and Hostetler and Giorgi, 1995, NOAA, LTER, ELA, USGS NED files
South America	Blodgett et al., 1997 and Hastenrath, 1985, Kessler (1983), WLD

National Oceanographic and Atmospheric Administration (NOAA, <http://www.ncdc.noaa.gov>), and United States Geological Survey NED files (<http://www.seamless.usgs.gov>) (Table 1). Limitations in data availability and type prevented using the same methodology to calculate each parameter. Lakes range in size from small ponds ($\leq 1 \text{ km}^2$) to large lakes, such as Baikal, Titicaca, and the African Rift Valley Lakes (greater than $10,000 \text{ km}^2$). Drainage basin sizes also vary widely, but larger lakes generally have large drainage basins. Precipitation and potential evaporation values also vary, ranging from less than 20 mm/year to several thousand mm/year . The variable with the greatest range of uncertainty is potential evaporation, as it is estimated using a wide variety of methods and with different timescales. However, exact values are not vital, as the model mainly explores the relationships and relative changes among the variables considered.

Many of the lakes included in the analyses have paleorecords or lake-level records that give an indication of the frequency of lake desiccation, which we use to estimate the desiccation interval. Using potential lake desiccation intervals provides another tool for evaluating the model, as the position of the lake relative to the line describing steady-state conditions should indicate its propensity to stabilize in each of the three different states. The majority of desiccation intervals were obtained from the literature or paleorecords. Many permanent North American lakes that formed after the last gla-

Figure 3. Locality map of the different lakes used in the $A' - \Phi$ threshold model. Every continent was included in the study, with the exception of Antarctica. Some geographic regions are either over or under represented in the model, resulting from data availability.

cial period were given a maximum desiccation interval of 10^3 . Other lakes that we could not obtain data for were given the value of $\geq 10^3$, as this is an intermediate value.

3. Results

Figure 4 plots $A'-\Phi$ curves for different w -values and data for all considered lakes. The line marked, $w = 2.5$, approximates highly vegetated forest conditions, or finer soil texture, while the line marked, $w = 0.1$, approximates sparse to bare vegetation (Wang et al., 2009). We refer to these upper and lower end member lines as representing the threshold envelope for which lakes are most sensitive to land cover changes. The steady-state condition for an individual lake is heavily dependent upon the basin land cover, thus for individual lakes it may be important to consider a smaller, land cover specific, envelope rather than the entire range between sparse vegetation and forest lines. However, since we discuss the plotting position of lakes in relation to their desiccation intervals, we have not further examined the land cover condition of each lake individually.

As climate gets drier, there is a clear decrease in the desiccation interval of the lakes. In Figure 4, the majority of the lakes that have long desiccation intervals (referred to as permanent lakes with respect to the current climate) tend to plot either in the $\Phi \leq 2$ region, or above the forest land cover line. Under the current climate, the permanent existence of these lakes is arguably not sensitive to their land cover conditions. A land cover change from forest to grass or vice versa would not lead to desiccation of the lakes classified as permanent.

Lakes that have short desiccation intervals (referred to as ephemeral lakes) tend to plot below the sparse vegetation curve. All of the lakes that show annual dry-ups plot in this portion of the lake classification domain. These lake data plotting positions are consistent with the lake classification regions defined by the conceptual model and the lake domains denoted in

Figure 4. Lakes plotted on the $A'-\Phi$ domain along with Equation (9) for a range of climates. The solid lines illustrate the effect of land cover for the two end-member vegetative possibilities, dense forest ($w = 2.0$) and sparse vegetation ($w = 0.1$). The dashed lines plot predicted A' as a function of Φ threshold values that result from different basin vegetative cover (w -values). The gray box represents the range of $A'-\Phi$ values for ELA and LTER lakes. The gray oval encompasses several southwestern US lakes. Labeled lakes are discussed in the paper. The number labels correspond to the following lakes: (1) Baikal, (2) Crater, (3) Crevice, (4) Foy, (5) George, (6) Keilambete, (7) Malawi, (8) Qinghai, (9) Titicaca, and (10) Windermere. The lakes are grouped by potential desiccation time. Lakes that desiccate frequently tend to plot far below the $A'-\Phi$ thresholds, while lakes that never/rarely desiccate plot above of the threshold lines. Theoretically, lakes that plot within the envelope would be the most sensitive to land-use change.

Figure 2. We suggest that the farther away a lake plots from the limits of the land cover-sensitive envelope (higher or lower A'), the more likely that other factors, such as local topography and hydrologic conditions, gain importance in lake dynamics. Many of these lake data plotting positions are consistent with the steady-state conditions of the conceptual model and the lake domains denoted in Figure 2a. However, some lakes deviate from these trends, which will be discussed below.

Prior knowledge of lake conditions in comparison to whether a lake plots in the permanent, land change sensitive, or ephemeral domain is useful in identifying possible controls on the hydrological conditions for a given lake. Based on the steady-state $A' - \Phi$ curves and lake plotting positions, we interpret that certain lakes are more sensitive to climatic perturbations than others. For example, a lake that plots significantly below the land change sensitive envelope would require a larger increase in precipitation relative to evapotranspiration (i.e. decreases in Φ) to prevent the lake from desiccating.

The Australian saltpan lakes (Buchanan, Gaillee, Gardiner, and Frome) and American southwestern lakes would require a substantial change in climate to become permanent (see Figure 4 caption to distinguish lake symbols). Conversely, a lake that plots only slightly below the sparse vegetation line would require only a small increase in precipitation to change from a basin that is losing water to a permanent lake. Thus, the saltpan lakes of Australia and ephemeral lakes of southwestern US have a higher probability of desiccating than many other lakes, as shown in Figure 4, resulting from both the high potential evapotranspiration and lack of a sufficiently large basin to compensate for evaporative losses. In the figure, lakes tend to group by desiccation interval (as indicated by the paleorecords), suggesting the large-scale importance of climate relative to local factors.

4. Discussion

Of the 171 lakes included within the study, lakes that plot within each category are: 125 permanent, 14 land cover change-sensitive, 28 ephemeral, and four that plot at the boundary of the sensitive to change envelope. In the $A'-\Phi$ domain presented in Figure 4, in agreement with the conceptual model, the majority of the lakes with annual desiccation intervals plot within the ephemeral region of the domain, while a significant number of the lakes that exhibit infrequent desiccation plot within the permanent region. However, several data points do not plot within the expected model domain.

Some of the lakes that desiccate infrequently plot within the ephemeral domain, while some ephemeral lakes plot within the land change sensitive domain (Figure 2). According to the conceptual model, lakes that plot within the threshold envelope are mainly dominated by surface water inflows and may be considered to be in steady-state with climate. The lakes that do not fall within this envelope are not in steady-state conditions and may be gaining or losing volume. Alternatively, these lakes may be in steady state conditions, but their water balance is affected by other water fluxes, that are not accounted for in the conceptual model, such as groundwater fluxes or anthropogenic influences. In general, lakes that deviate from model predictions can be used to evaluate whether critical model assumptions are violated and thus whether hydrologic controls not included in the conceptual model are important in affecting lake-level dynamics. In the following paragraphs, we provide some examples.

Lake Turkana, which is one of the world's largest permanent and alkaline desert lakes, plots within the ephemeral lake region. It is likely that Lake Turkana violates the second assumption of uniform climate across the lake basin region. The main water source for Lake Turkana, the Omo River, flows 620 miles before reaching the lake, and originates in much wetter regions

than Lake Turkana itself. Crater Lake, Oregon, USA and the LTER, Wisconsin, USA, lakes likely violate the third assumption of closed lake basin systems, as they likely have significant groundwater fluxes. These lakes plot within the energy-limited portion of the permanent lakes domain, do not have surface water outlets, and receive greater amounts of precipitation than necessary to maintain lake-levels. In both settings, losses to the regional groundwater systems are important components of the regional lake water balances (Redmond, 2007; Webster et al., 1996) and this hydrologic connectivity likely causes the lakes to fluctuate in level more than the model predicts. For example, Crater Lake loses more than 100 cm/year to seepage (Redmond, 2007). Similarly, Lake George, Australia, which plots within the land cover change-sensitive region, exhibits frequent, decadal, desiccation and also likely violates the third conceptual model assumption because its water balance is affected by groundwater seepage (Jacobson et al., 1991).

Lake Qinghai is an example of a lake that violates the fourth assumption, lack of anthropogenic impacts. Lake Qinghai plots near the land cover change-sensitive domain, but decreased from 4980 km² to 4304 km² between 1908 and 1986 (Qin and Huang, 1998). The decrease in Lake Qinghai surface area may largely be attributed to significant loss of riverine inputs, because many tributary streams, such as the Buha River, are now dry as a result of anthropogenic water extractions (Li et al., 2007). The plotting position of Lake Qinghai puts it in the boundary between the sensitive and ephemeral lake regions, illustrating the very sensitive nature of this lake to changes in climate and land use.

Issyk-kul, Lake Balkhash, Mono Lake, and the Aral Sea are within semi-arid to arid regions and plot within the ephemeral region of the domain. These large lakes are more stable than some geographically similar, smaller lakes. Violation of both the fourth and fifth assumptions, the lack of anthropogenic influence and the massive water storage capacities of these lakes may prevent or slow desiccation. While more stable than other smaller regional lakes, these lakes are currently shrinking as a result of climate change, in some cases compounded by anthropogenic use (Aizen et al., 2007; Gao et al., 2011; Micklin, 2007; Qin and Huang, 1998). (Note that paleolimnologic evidence suggests that the Aral Sea has desiccated in the past (Aizen et al., 2007)). We do not intend to minimize anthropogenic changes to these lakes, but rather emphasize the importance of managing water resources in basins that are likely to be sensitive to natural climate perturbations. Therefore, we suggest that the lakes that plot in the ephemeral region of the $A'-\Phi$ domain are a prime focal point for sustainable management because severe declines or desiccation are likely.

The model can help to identify lakes that might produce highly resolved lake-level reconstructions that reflect climate driven fluctuations in the hydrologic budget. In the conceptual model explored in this paper, ideally, lakes that are sensitive to climate variation should plot near the threshold envelope, as these lakes require the smallest perturbations in potential evapotranspiration or precipitation to switch from one domain to another (e.g., land cover change sensitive to permanent). This can be further refined for individual lakes if enough is known about the land cover or vegetation of the basin to constrain the w -values. Comparison of the model to paleolake records shows that many "classic" sites used for lake-level reconstructions plot near the land cover adjusted $A'-\Phi$ threshold line. Lakes, such as Lake Titicaca and Lake Malawi (African Rift Valley), plot almost on the threshold line, suggesting that these lakes are quite sensitive to climate fluctuations. Both of these lakes have highly resolved records that show large fluctuations in lake depth (Baker et al., 2001; Cohen et al., 2007; Fritz et al., 2007). Several other lakes that plot within or near the threshold envelope, including Lake Balkal, Lake Keilambete, and Foy Lake, also have highly resolved

paleorecords that suggest these lakes are quite sensitive to variation in the hydrologic balance (Bowler, 1981; Mackay, 2007; Stevens et al., 2006). Timescale is an important consideration in evaluating lake sensitivity to changes in hydrologic balance; lakes may not be particularly sensitive to yearly or decadal fluctuations in climate, but may provide high lake sensitivity on longer timescales (e.g. Shinneman et al., 2010).

The conceptual model also may be used to approximate the magnitude of climate change that produced lake-level patterns evident in paleorecords, particularly during lake inception and desiccation. The model approximates steady-state conditions for lake size and basin size, under non-transient climate. However, lakes often persist throughout a variety of climate regimes, which affect Φ and A' . For example, the Great Salt Lake is a remnant of a large paleolake called Lake Bonneville, which occupied parts of the Great Basin region during pluvial periods in the past. It may be possible to estimate the aridity index during the Pleistocene inception of Lake Bonneville, (maximum surface area, 51,300 km²), although the region is currently a salt flat (Benson et al., 1992). The basin was not included in our plot, because many model parameters could not be measured, but it would be likely plot below any of the land cover-specific threshold lines. However, during lake inception, Φ would be considerably lower, which would produce incoming fluxes that were greater than outgoing fluxes, and thus lake formation. This change in Φ would move the lake position within the threshold envelope, and provide a semi-quantitative, estimation of climatic change. Pollen records from surrounding regions could be used to estimate w at lake inception to more accurately predict paleo- Φ values.

5. Conclusions

In this paper a lake water balance equation that predicts the basin to lake surface area ratio (A') for a given climate, characterized by an index of aridity (Φ , potential evaporation to precipitation ratio), and basin soil and land cover conditions is developed, which is most appropriate for closed basin lakes in non-humid climates. Based on the conceptual model a lake hydro-climatological classification idea is presented that stems from the work of Bowler (1981). Our classifications separate the $A'-\Phi$ domain into ephemeral, permanent, and land cover change-sensitive lake regions. The model presented here is applied to multiple lakes to identify sites where surface area/basin area and evapotranspiration/precipitation are dominant controls on water level. Lakes that have strong alternative controls on lake level, such as the influences of groundwater, morphometry, or those with significant outflow generally do not plot as the steady-state conditions would suggest. These parameters were not included in the model, because typically they are not known or easily estimated for most lakes.

The model suggests that a wide variety of lakes have some sensitivity to precipitation-evapotranspiration changes, as these lakes either plot within or near the threshold envelopes. Some of this sensitivity is based on the land cover of the lake basin, which is incorporated in the model with the w -value. We used lakes around the globe to interpret their current status, as well as potential factors that may cause deviation from model predictions in relation to their paleorecords. Interestingly, the conceptual model has successfully identified the lakes that are known to be permanent and ephemeral in relation to their paleorecords that give desiccation intervals and lake level trends. Lakes that plot within the threshold envelope are most likely sensitive to land use change.

The model can be used both to estimate past aridity index values or to estimate which lakes are likely to produce high-resolution lake-level paleorecords. Thus the model may be useful in planning paleoclimatic studies based on lacustrine records, as well as identifying modern lakes where climate has

a large influence on surface water hydrology and lake level. As our conceptual model identifies the impact of climate stress on lake hydrology, it may be used for both lake water management purposes, as well as examining the potential impacts of future climates on lake level trends.

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Appendix A (Supplementary material) follows the References.

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Lake	Lat	Long	SA (km ²)	CA (km ²)	Precip(mm)	Evap (mm)
Africa						
Abiyata	7°30'N	38°30'E	203	10740	552	1653
Malawi	13°30'S	34°00'E	6400	6593	1350	1700
Massoko	9°20'S	33°45'E	0.4	0.5	1300	500
Rukwa	8°00'S	32°25'E	4000	78200	995	2000
Tanganyika	10°00' S	30°00' E	32600	197400	1302	1251
Victoria	1°25'S	33°10'E	68800	184000	1780	1591
Langano	7°37'N	38°42'E	230	2000	770	1921
Modern Chad*	13°00'N	14°00'E	25000	250000 0	500	1297
Paleolake Chad	13°0'N	14°0'E	350000	250000 0	391	1297
Shala	7°28'N	38°31'E	370	2300	627	2110
Turkana	3°03'N	36°01'E	6750	130860	250	2335
Ziway	8°00'N	38°49'E	440	7380	734	2022
Asia						
Ahung Co	31°20'N	92°5'E	3.6	100	430	760
Aral	45°00' N	60°00' E	66500	100646 0	200	1317
Baikal	53°30'N	108°10'E	31500	557000	677	1321
Balkhash	46°32'N	74°52'E	16434	521000	187	1141
Ba Be	22°02'N	105°04'E	4.5	454	1445	1354
Dal	34°02'N	75°04'E	21	316	655	957
Dong-hu	30°03'N	114°02'E	28	97	1450	1037

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
Issuk-kul	42°30'N	77°30'E	6236	28127	258	984
Phewa	28°01'N	83°05'E	5	110	1556	1151
Qinghai	37°00' N	100°00' E	4304	29691	378	1459
Australia						
Buchanan	21°38'S	145°52'E	115	3110	227	3000
Eyre	28°30'S	137°20'E	9790	131600 0	500	1297
Frome	30°37'S	139°52'E	2550	24500	232	1300
Gaililee	22°19'S	145°50'E	260	500	360	3000
Gairdner	34°57' S	118°08'E	4520	11180	350	1900
George	35°4'S	149°25'E	150	906	600	1050
Gregory	25°38'S	119°58'E	387	33160	300	1669
Keilambete	38°12'S	142°52'E	2.7	4.1	400	900
Torrens	31°02'S	137°51'E	5640	27000	186	1500
Tyrrell	35°21'S	142°50'E	155	647	323	890
Woods	17°43'S	139°30'E	423	25300	302	1600
Europe						
Amara	45°13'N	27°17'E	1.5	47	429	836
Balta Alba	45°02'N	27°02'E	11.0	91.6	429	836
Banyoles	42°08'N	2°45'E	1.1	11.4	804	937
Bassenthwait he	54°39'N	3°13'W	5.3	237	1300	500
Blelham Tarn	54°24'N	2°59' W	0.1	4	1918	500

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
Chervonoje	52°2'N	27°5'E	40.0	353	656	663
Esthwaite Water	54°21'N	2°58'W	1.0	17	1912	500
Grasmere	49°04'N	1°15'W	0.6	28	2553	500
Karujarv	58°23'N	22°13'E	3.3	16.1	238	235
Kirjaku*	59°15'N	27°35'E	0.2	30.8	238	235
Lake Bysjon	55°40'N	13°32'E	0.2	0.9	587	619
Loch Shiel	56°05'N	5°04'W	20.0	234	1300	500
Vijandi	58°20'N	25°35'E	1.6	66.8	238	235
Windermere (NB)	54°21'N	2°56'W	8.1	198	1300	500
Windermere (SB)	54°21'N	2°56'W	6.7	32	1300	500
North America						
Crater	42°56'N	122°06'W	53.2	67.8	1692	1270
Crevice	47°52'N	113°39'W	0.1	0.2	356	1100
Foy	48°5'N	114°15'W	0.9	13.6	406	1100
Great Salt	40°42'N	112°23'W	4400	89000	419	1349
Mono	38°0'N	119°0'W	227	1800	355	1981
Morrison	44°36'N	113°02'W	0.1	2	406	1100
Pyramid	40° N	119°30'W	430	2620	500	1300
Reservoir	45°07'N	113°27'W	0.2	2.8	381	1100

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
Sammamish	47°33'N	122°03'W	19.8	255	800	818
Washington	47°37'N	122°15'W	87.6	1274	799	1234
Yellowstone	44°30'N	115°30'W	360	7100	516	973
Southwest						
Animas	32°28'N	108°54'W	374	5670	250	1840
Cloverdale	31°00' N	108°00' W	102	460	410	1780
Encino	34°00' N	105°00' W	96	620	350	1370
Estancia	34°45'N	106°03'W	1125	5050	310	1270
Goodsight	32°19'N	108°45'W	65	590	250	1830
Otero	32°32'N	105°46'W	745	126000	250	1660
Pinos Well	34°27'N	105°38'W	82	560	360	1320
Playas	31°50'N	108°34'W	49	1120	270	1900
Sacramento	32°45'N	105°46'W	86	780	250	1650
San Agustin	33°52'N	108°15'W	786	3880	290	1150
Trinity	33°40'N	106°28'W	207	4240	250	1590
LTER						
Allequash	46°02'N	89°37'W	1.7	6.3	800	1000
Arrowhead	45°54'N	89°41'W	0.4	2.4	800	1000
Beaver	46°12'N	89°35'W	0.3	4.6	800	1000

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
Big	46°09'N	89°46'W	3.3	10.4	800	1000
Big Crooked	46°02'N	89°51'W	2.7	6.0	800	1000
Big Gibson	46°08'N	89°33'W	0.5	1.1	800	1000
Big Muskellunge	46°01'N	89°36'W	3.6	7.8	800	1000
Boulder	45°08'N	88°38'W	2.2	14.3	800	1000
Brandy	45°54'N	89°42'W	0.4	1.0	800	1000
Crampton	46°12'N	89°28'W	0.3	0.7	800	1000
Crystal	46°00'N	89°36'W	0.4	1.8	800	1000
Diamond	46°02'N	89°42'W	0.5	1.2	800	1000
Flora	46°10'N	89°39'W	0.4	2.2	800	1000
Heart	46°05'N	89°16'W	0.1	0.5	800	1000
Ike Walton	46°02'N	89°48'W	5.7	13.2	800	1000
Island	46°06'N	89°47'W	3.6	12.5	800	1000
Johnson	46°08'N	89°31'W	0.3	1.7	800	1000
Katherine	45°48'N	89°42'W	2.1	6.6	800	1000
Kathleen	45°14'N	88°38'W	0.1	0.3	800	1000
Katinka	46°12'N	89°47'W	0.7	1.6	800	1000
Lehto	46°01'N	90°02'W	0.3	7.4	800	1000
Little Crooked	46°08'N	89°41'W	0.6	3.2	800	1000
Little Spider	45°58'N	89°42'W	0.9	2.1	800	1000
Little Sugarbush	46°01'N	89°51'W	0.2	0.8	800	1000

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
Little Trout	46°04'N	89°51'W	4.1	7.6	800	1000
Lower Kaubeshine	45°48'N	89°44'W	0.8	2.8	800	1000
Lynx	45°56'N	89°13'W	1.2	2.8	800	1000
McCullough	46°11'N	89°34'W	0.9	3.3	800	1000
Mid	45°51'N	89°39'W	1.0	2.7	800	1000
Minocqua	45°52'N	89°41'W	8.1	11.7	800	1000
Muskesin	46°01'N	89°54'W	0.5	1.3	800	1000
Nixon	46°05'N	89°33'W	0.5	9.6	800	1000
Partridge	46°04'N	89°30'W	1.0	3.3	800	1000
Randall	46°01'N	90°01'W	0.5	4.3	800	1000
Round	46°10'N	89°42'W	0.7	5.7	800	1000
Sanford	46°10'N	89°41'W	0.4	1.5	800	1000
Sparkling	46°00'N	89°41'W	0.6	1.1	800	1000
Statenaker	45°58'N	89°46'W	0.8	1.9	800	1000
Stearns	45°59'N	89°48'W	1.0	2.0	800	1000
Tomahawk	45°49'N	89°39'W	15.0	25.4	800	1000
Trout	46°02'N	89°40'W	15.7	23.6	800	1000
Upper Kaubeshine	45°47'N	89°44'W	0.7	2.1	800	1000
White Birch	45°39'N	91°09'W	0.5	1.0	800	1000
White Sand	46°05'N	89°35'W	3.0	5.5	800	1000
Wild Rice*	46°03'N	89°47'W	1.5	153.1	800	1000
Wildcat	46°10'N	89°37'W	1.4	4.1	800	1000

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
ELA						
93	49°40'N	93°43'W	5.5	60	684	525
106	49°40'N	93°43'W	3.7	121	684	525
109	49°40'N	93°43'W	14.9	42	684	525
110	49°40'N	93°43'W	5.3	34	684	525
111	49°40'N	93°43'W	9.6	339	684	525
114	49°40'N	93°43'W	12.1	58	684	525
115	49°40'N	93°43'W	6.5	119	684	525
149	49°40'N	93°43'W	26.9	94	684	525
164*	49°40'N	93°43'W	20.3	4984	684	525
165*	49°40'N	93°43'W	18.4	4802	684	525
191	49°40'N	93°43'W	19.4	338	684	525
220	49°40'N	93°43'W	1.6	20	684	525
221	49°40'N	93°43'W	9	82	684	525
222	49°40'N	93°43'W	16.4	204	684	525
223	49°40'N	93°43'W	27.3	260	684	525
224	49°40'N	93°43'W	25.9	98	684	525
225	49°40'N	93°43'W	4	31	684	525
226	49°40'N	93°43'W	16.1	97	684	525
227	49°40'N	93°43'W	5	34	684	525
239	49°40'N	93°43'W	56.1	391	684	525
240	49°40'N	93°43'W	44.1	720	684	525
260	49°40'N	93°43'W	34	166	684	525

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
261	49°40'N	93°43'W	5.6	42	684	525
262	49°40'N	93°43'W	84.2	1230	684	525
265	49°40'N	93°43'W	13.1	71	684	525
302	49°40'N	93°43'W	23.7	103	684	525
303	49°40'N	93°43'W	9.5	54	684	525
304	49°40'N	93°43'W	3.4	26	684	525
305	49°40'N	93°43'W	52	237	684	525
309*	49°40'N	93°43'W	2.6	560	684	525
310	49°40'N	93°43'W	49.7	539	684	525
373	49°40'N	93°43'W	27.6	83	684	525
375	49°40'N	93°43'W	18.9	231	684	525
377	49°40'N	93°43'W	26.7	2030	684	525
378	49°40'N	93°43'W	24.3	136	684	525
382	49°40'N	93°43'W	36.9	205	684	525
383	49°40'N	93°43'W	5.6	40	684	525
385	49°40'N	93°43'W	24.9	102	684	525
421	49°40'N	93°43'W	17	51	684	525
428	49°40'N	93°43'W	6	44	684	525
442	49°40'N	93°43'W	15.2	184	684	525
470	49°40'N	93°43'W	5.7	168	684	525
622	49°40'N	93°43'W	38.6	419	684	525
623	49°40'N	93°43'W	36	651	684	525
624	49°40'N	93°43'W	2	753	684	525
626*	49°40'N	93°43'W	27.9	388	684	525

Lake	Lat	Long	SA (km2)	CA (km2)	Precip(mm)	Evap (mm)
629	49°40'N	93°43'W	35.5	348	684	525
658	49°40'N	93°43'W	63.1	125	684	525
South America						
Amatitlan	14°08'N	90°06'W	15.2	368	1124	1150
Chapala	20°01'N	103°06'W	1112	52500	893	1601
Laguna de Rocha	34°04'S	54°01'W	72	1312	1073	1058
Paleo Tauca 1	13°28'S	72°02'W	22700	73500	600	1494
Poopo	18°33'S	67°05'W	1000	27700	250	1494
Paleo Tauca 2	13°28'S	72°02'W	20300	73500	310	1494
Titicaca	15°50'S	69°20'W	285006	580000	737	1270