Limnologica 51 (2015) 118–130

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.com/locate/limno

A sensitivity analysis of lake water level response to changes in climate and river regimes

Ali Torabi Haghighi*, Bjørn Kløve

Water Resources and Environmental Engineering Research Group, Faculty of Engineering, University of Oulu, PO Box 4300, FIN-90014 Oulu, Finland

ARTICLE INFO

Article history:
Received 15 December 2013
Received in revised form 3 February 2015
Accepted 9 February 2015
Available online 10 March 2015

Keywords:
Lake hydrology
Lake water level
River regime
Climate
Water balance

ABSTRACT

Lake water level regimes are influenced by climate, hydrology and land use. Intensive land use has led to a decline in lake levels in many regions, with direct impacts on lake hydrology, ecology and ecosystem services. This study examined the role of climate and river flow regime in controlling lake regimes using three different lakes with different hydraulic characteristics (volume-inflow ratio, CIR). The regime changes in the lakes were determined for five different river inflows and five different climate patterns (hot-arid, tropical, moderate, cold-arid, cold-wet), giving 75 different combinations of governing factors in lake hydrology. The input data were scaled to unify them for lake comparisons. By considering the historical lake volume fluctuations, the duration (number of months) of lake volume in different 'wetness' regimes from 'dry' to 'wet' was used to develop a new index for lake regime characterisation, 'Degree of Lake Wetness' (DLW). DLW is presented as two indices: DLW_1, providing a measure of lake filling percentage based on observed values and lake geometry, and DLW_2, providing an index for lake regimes based on historical fluctuation patterns. These indices were used to classify lake types based on their historical time series for variable climate and river inflow. The lake response time to changes in hydrology or climate was evaluated. Both DLW_1 and DLW_2 were sensitive to climate and hydrological changes. The results showed that lake level in high CIR systems depends on climate, whereas in systems with low CIR it depends more on river regime.

Introduction

In natural conditions, lake levels vary on different temporal scales from days to centuries (Chow-Fraser, 2005; Hofmann et al., 2008; Riis and Hawes, 2002; Wang and Yin, 2008; Cui et al., 2010). These changes in lake water levelsare due to many natural causes (climate, catchment area, topography, lake size) and anthropogenic pressures such as climate change, groundwater extraction or inflow regulation (Aroviita and Hämäläinen, 2008; Coops et al., 2003; Leira and Cantonati, 2008; Richter et al., 1997). A decrease in water level can influence the physical environment, biota and ecosystem (Leira and Cantonati, 2008), with impacts on a number of lake ecosystem functions (Coops et al., 2003; Wantzen and Junk, 2008; Paillisson and Marion, 2011; Da Silva et al., 2013). Severe impacts in lake ecological (Kahl et al., 2008) and socio-economic status have been reported for many large and small lakes worldwide, such as the Aral Sea in Asia (Erdinger et al., 2011; Glantz, 2007; Kamalov, 2003; Zavialov et al., 2003), Lake Chad in Africa (Coe and Foley, 2001; Guganesharajah and Shaw, 1984) and the Great Salt Lake (Bedford, 2009; Stephens, 1990) and the Salton Sea (Khan et al., 2013; Paillisson and Marion, 2011) in the United States. Different lakes or parts of lakes can display different responses to external impacts, with the littoral zone and its habitats typically being most easily affected (Aroviita and Hämäläinen, 2008; Baumgärtner and Mörtl, 2008; Coops et al., 2003). There is a need to better understand the vulnerability of lake water levels to external pressures and to develop methods to relate catchment water use to changes in lake levels. Potential impacts of climate change must also be better understood and predicted.

Abbreviations: CIR, capacity inflow ratio; SDSD, standard deviation of scaled data; P-E, effective precipitation; MLC, maximum lake capacity or volume; MAF, mean annual river flow; DLW, degree of lake wetness; NSP, number of months in which outflow from lake occurred; A.Ma, absolute maximum lake volume during 40-year simulation; A.Mi, absolute minimum lake volume during 40-year simulation; MMR, maximum–minimum volume ratio; AMR, absolutemaximum–minimum volume ratio; Bwh, hot-arid desert climate according to the Köppen climate classification; Cs, temperate with hot dry summer climate according to the Köppen climate classification; Aw, tropical savannah climate according to the Köppen climate classification; Bsk, cold, arid steppe climate according to the Köppen climate classification; Dfc, cold without dry season climate according to the Köppen climate classification.

* Corresponding author. Tel.: +358 294484333; fax: +358 294553 4507.
E-mail address: ali.torabihaghighi@oulu.fi (A. Torabi Haghighi).

http://dx.doi.org/10.1016/j.limno.2015.02.001
0075-9511/

The most obvious method to estimate lake levels is the water balance equation, where water input and output result in lake storage and water level changes (Bracht-Flyr et al., 2013; Crapper et al., 1996; Morrill et al., 2001; Soja et al., 2013; Tsubo et al., 2007). However, all water balance components cannot always be quickly assessed, such as evaporation due to expansion of irrigated areas or lake-groundwater interactions. A method that assesses general changes in lake level can be a useful tool in examining why different lakes have different lake level variation patterns and why the water disappears from some lakes. Assessment methods using climate data can provide important insights into variations in lake levels in different parts of the world (Bracht-Flyr et al., 2013). The aim of the present study was to determine how climate, river regime and lake hydrological properties independently influence lake water levels. For a given case, this can be done with hydrological modelling by perturbing locally observed climate and inflow (Zhu et al., 2010; Niedda et al. 2014). To provide general results for a range of different climate and river regimes, in this study we developed a new framework to examine the sensitivity of lake response by simulating combinations of known climates and river regimes for different lake sizes. We also developed a database containing 75 virtual cases for which water level changes were calculated for different climate and river inflow patterns using the new framework. In the approach, lake levels are simulated using the water balance equation, which results in mean monthly patterns of lake levels depending on climate, inflow and lake hydraulic properties (size, residence time). Such information on lake response increases the overall understanding of lake hydrology and can assist in the development of management approaches such as 'environmental flow concepts' for regulating and controlling water use in order to provide more stable water levels in lakes where this is a management target. In the past, environmental flow allocation has mainly been carried out for rivers(Tennant, 1976; Tharme, 2003), and this has not always maintained environmentally acceptable water levels in lakes (Cui et al., 2010; Kashaigili et al., 2007; Shang, 2008).

The main objective of this study was to analyse the response of lakes to different climate patterns and flow regimes. The framework developed was used to assess how climate, river regime and lake capacity inflow ratio affect lake water levels and volumes. Different scenarios were simulated and the lake response evaluated for 225 scenarios(75 cases each analysed with three initial conditions). To assist in the evaluation, an index, the 'Degree of Lake Wetness' (DLW),was developed to show past water level characteristics of lakes.

Materials and methods

Lake levels were simulated with a water balance equation for different lakes (L1-L3), river flow (R1-R5) and effective precipitation (C1-C5). The simulations were carried out for 75 cases (3 lake sizes x 5 river flow regimes x 5 effective precipitation monthly time series) for 40 years. Each simulated scenario was denoted using the RxCyLz code, where x represents the river regime type, y the type of climate and z the lake type (Appendix A). To account for the main water fluxes, a general water balance model was used to test the impacts of different river flow regimes, climate patterns and capacity inflow ratios (CIR, see section "Simulation and comparison of lake responses") on water level for lakes with different depth-area-volume relationships. For a general comparison, the river flow from five rivers was scaled to $100 \times 10^6\,m^3\,yr^{-1}$ to obtain lake inflows with similar magnitude and different regime. The effective precipitation was used as a proxy for different climates, from hot-arid to cold-wet, using input data from real weather stations located in the selected river catchments.

River flow and climate data

Case rivers and lakes

Three model lakes (L1-L3) differing in size, topography and area–volume–depth curve were selected as cases to test the methodology (Fig. 1). These lakes (Tammijärvi (L1), Isojärvi (L2) and Puula (L3)) are located in the Kymi river basin in southern Finland. Their respective volume is 0.024, 0.30 and 3.0 km^3 and their respective area 9.81, 18.33 and 330.76 km^2. In the present work, we only used geometry data on the lakes(any set of lakes with variable size could have been selected).

The case rivers (R1-R5) were selected from five different climate zones (C1–C5) based on the Köppen climate classification method (Peel et al., 2007), in order to represent a wider range of river regimes and climate conditions (Table 1). The Colorado river (R1) after the Hoover Dam (with basin area 447 400 km^2) in Nevada State was used to represent a hot-arid climate ('hot-arid desert (Bwh)') (C5) (Table 1). The Colorado river regime is regulated by the presence of a large number of hydropower reservoirs, the largest being the Hoover Dam (35.2 km^3 volume, 640 km^2 water area). The river Kymi in Finland (R2) displays low variation in discharge (Fig. 2a) from a cold-wet climate ('cold without dry season (Dfc)) (C1). The Kymi flow regime is affected by a large lake (river discharge after lakes Päijänne and Ruotsalainen, the second largest lake system in Finland, with an area of about 1080 km^2) and is regulated by 12 hydropower plants in the river, with a series of dams. The Kor river (R3), which is the main river in the Bakhtegan lake watershed in southern Iran, with a catchment area of about 27 000 km^2, represented a moderate climate ('temperate with hot

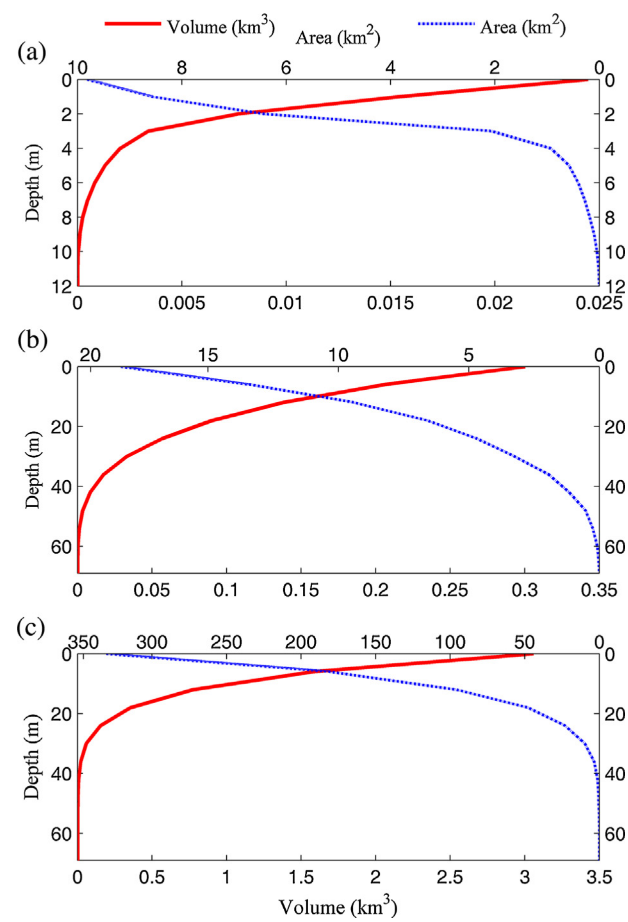

Fig. 1. Depth-area-volume curves for lakes: (a) Tammijärvi (L1), (b) Isojärvi (L2) and (c) Puula (L3) in Finland (http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp).