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Can lake sensitivity to desiccation be predicted from lake geometry?

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SUMMARY

Declining lake levels (Aral Sea syndrome) can be caused by changes in climate, increased water use or changed regulation patterns. This paper introduces a novel lake geometry index (LGI) to quantify lake hydrological characteristics. The index was developed using a large representative dataset of lake hypsographic characteristics from 152 lakes and man-made reservoirs. Using the LGI index, lakes can be classified into five groups: groups 1–4 when LGI is 0.5–2.5, 2.5–4.5, 4.5–6.5 and 6.5–8.5, respectively, and group 5 when LGI is >8.5. Naturally shallow and vast lakes and wetlands fall into the first group and deep man-made reservoirs in narrow valleys are in group 5. The response of three different lake systems (LGI 0.75, 2.75 and 6.5) to different water flow scenarios was then simulated using the water balance equation. From this, the index 'potential lake area' (A_{pot}) was developed to show lake responses to changed hydro-climatological conditions. A_{pot} and LGI can be used to classify lakes into open or closed systems. Simulations showed that lakes with low LGI have a shorter response time to flow and climate changes. As a result, the impact of water balance restoration is faster for lakes with low LGI than for lakes with high LGI. The latter are also more vulnerable to climate variation and change.

1. Introduction

In arid regions, lakes and wetlands supply important ecosystem services, such as climate moderators and sources of food. Due to increasing water consumption in dry regions, lakes and other aquatic ecosystems are under increasing pressure (Coops et al., 2003; Torabi Haghighi et al., 2014; Yuan et al., 2015). In these regions, responses in lake water levels can be used as an indicator to assess the overall regional hydrological impacts of climate change, land use change and river regime modifications (Torabi Haghighi and Kløve, 2015b; Hassan and Jin, 2014; Jin and Feng, 2013; Moftakhari et al., 2013; Muvundja et al., 2014; Coops et al., 2003; Torabi Haghighi et al., 2014; Yuan et al., 2015). The Aral Sea in Central Asia (Crétaux et al., 2005; Erdinger et al., 2011; Glantz, 2007), Lake Chad in Africa (Guganesharajah and Shaw, 1984; Lemoalle et al., 2012) and Lake Urmia in Western Asia (AghaKouchak et al., 2015; Fathian et al., 2014; Hassanzadeh et al., 2012) are all lakes which are disappearing at an alarming rate due to intensive water use in their catchments.

Environmental flow is an approach allowing sustainable management of water resources where rivers, lakes and aquatic ecosystems are under quantitative pressure (Rathburn et al., 2009; Tharme, 2003; Walker, 2003; Young et al., 2000). There are several hundred methods for estimating environmental flow for rivers, which are typically classified within four different categories; hydrological, hydraulic, habitat and holistic (Tharme, 2003; Walker, 2003). However, previous studies of environmental flow conditions in lakes are scarce. In general, lakes typically reach an equilibrium state as a response to the given hydro-climatological conditions (Mason et al., 1994; Torabi Haghighi and Kløve, 2015b). This can either be a true equilibrium with water levels, volume and area constant, or a dynamic equilibrium with fluctuations regularly around the equilibrium. Changes in lake or surrounding catchment conditions (climate or hydrology) cause a transient response towards a new equilibrium where a new water level is established (Szesztay, 1974; Mason et al., 1994; Crétaux and Birkett, 2006; Torabi Haghighi and Kløve, 2015b). To find the response time, water balance equation was applied for lake simulating as widely used for this purpose (e.g. Kebede et al., 2006; Kakahaji et al., 2013; Ali et al., 2015; Kaiser et al., 2015).

In addition to climate and hydrological conditions, lake geometry can also play an effective role in how lakes react to changed inflows. The main objective of this study was to develop methods for evaluating the sensitivity of water level fluctuation (WLF) in lakes and man-made reservoirs to lake geometry in different flow alteration scenarios. The approaches developed were further extended to evaluate the response times of lakes to climate or flow

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changes. This study introduces the lake geometry index (LGI) and potential lake area (A_{pot}) to evaluate lake geometry and assess the state of lakes under changing climatological conditions and in different flow alteration scenarios. For this purpose, the geometry of 112 natural lakes and 40 man-made reservoirs was used to evaluate the LGI index. Further, monthly water balance simulations were used to assess the effect of flow alteration for three different lake geometries under the same hydro-climatic conditions.

2. Material and methods

2.1. Lake geometry index (LGI)

It summarizes the hypsometric curves of lake as a single index or number. To develop the lake geometry index (LGI), the volume-depth (height) curves of natural lakes or man-made reservoirs were converted to linear curves by applying a logarithmic scale for lake volume (see example in Fig. 1). The absolute value of the slope of this line was defined as the LGI. In natural lakes, the smallest volume occurred at the highest mean depth and the largest volume at the lowest mean depth and this appeared as a negative slope (Fig. 1b). For man-made reservoirs, the highest mean depth corresponded to the largest volume and the smallest volume to the lowest mean depth (Fig. 1c), resulting in a positive slope (Fig. 1d). Conceptually, LGI is a shape factor of lake basin (the depression occupied by a lake), which must be between 0 and infinity (tangent 0 and 90, respectively). With LGI, the hypsometric characteristics of lakes can easily be presented as an index (number) for very different type of lakes (from different volume lakes from deep to shallow lakes). Large number of data from lake and reservoirs were used to in order to show the variety of hypsometry based on the LGI and approve that our selected case studies (explain in Section 2.2.2) are different and belong to different geometry.

2.2. Case studies

2.2.1. Database on lakes and reservoirs for lake geometry classification

To test the LGI index, we used data from different types of lakes and reservoirs. The database consisted of hypsometric data in the form of area-volume-depth curves for 152 natural lakes and man-made reservoirs, 112 natural lakes from Finland (Oiva database) and 40 man-made reservoirs from Iran (Iranian Water Resources Management Company) (Appendix A). The range of depth (height) and volume of lakes and reservoirs are presented in Fig. 2. These data were used to demonstrate the variation in LGI and to classify the lakes into five different groups based on LGI value.

2.2.2. Cases for lake sensitivity analysis

A more detailed analysis was performed based on data from Lakes Bakhtegan and Tashk, natural terminal lakes in southern Iran (Fars province) and data from two reservoirs (hypsometric data from the Chahnime IV and Doroudzan reservoirs). Iranian lakes were selected as they are at risk of desiccation due to increased water use for e.g. irrigation and due to climate variability (Rashki et al., 2013; Aghakouchak et al., 2015; Torabi Haghighi and Klöve, 2015a). To compare these cases, the depth-area and depth-volume curves for the reservoirs were scaled so that all systems had equal maximum volume or area to Lake Bakhtegan. This

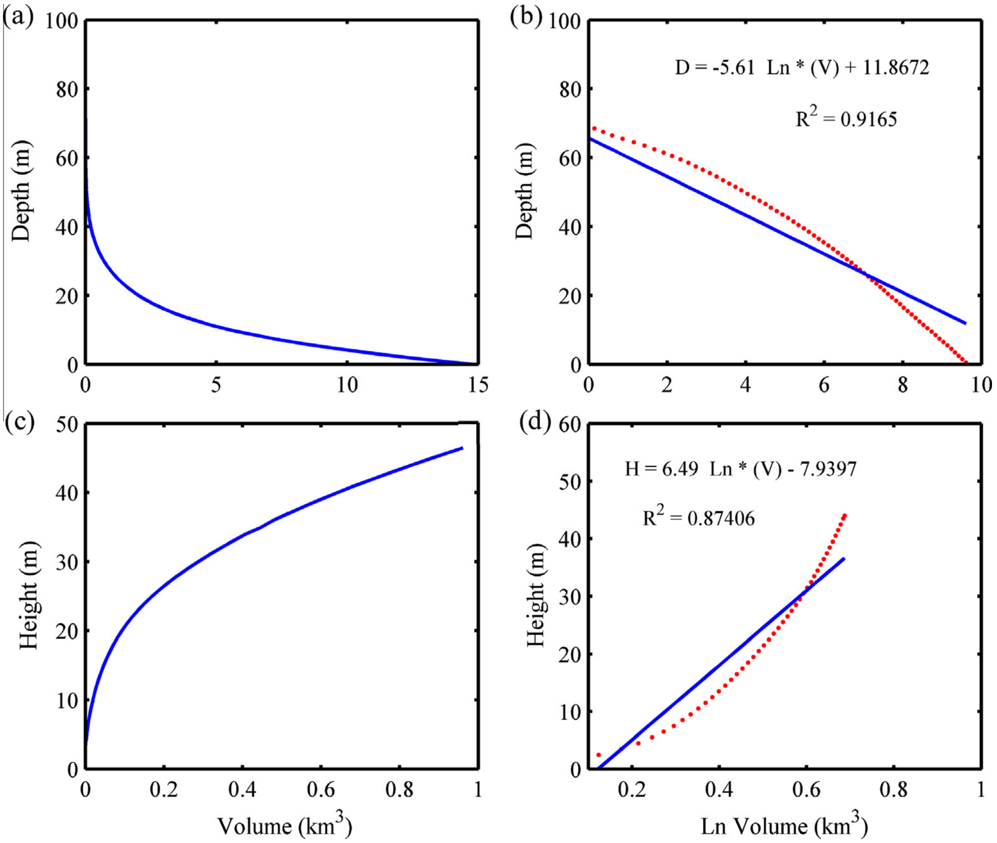

Fig. 1. Example of depth and height volume curves used in calculation of lake geometry index (LGI): (a) normal hypsometric curve for a natural lake (Saimaa, Finland), (b) converted hypsometric curve after log conversion for volume (Saimaa, Finland), (c) normal hypsometric curve for a man-made reservoir (Doroudzan reservoir, Iran), (d) converted hypsometric curve after log conversion for volume (Doroudzan reservoir, Iran).