Can lake sensitivity to desiccation be predicted from lake geometry?

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Abstract

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 to 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.

Keywords. Lake water balance, lake response time, environmental flow, water level fluctuation.

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 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 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 resulted in five different lake systems with different geometries, providing cases L1, L2.1, L2.2, L3.1, L3.1 and L3.2 (Table 1, more detail explain later in section 2.2.2.2).

2.2.2.1 Characteristics of the Kor river and Lake Bakhtegan

Lakes Bakhtegan and Tashk are shallow terminal closed lakes (wetlands) located at the end of the Kor river basin in southern Iran that are suffering from lake level decline (Torabi Haghighi and Kløve, 2015a). During periods of considerable rainfall excess, they form a single lake (total area 1280 km^2). In most years, however, the lakes are separated by bar salt flats due to low water level. These two lakes are hereafter called Lake Bakhtegan (best known by this name). The maximum volume of this combined lake has been estimated to be about 1.592 km^3 (Teimouri et al., 2011). Hypsometric curves of the lake were developed based on lake area at different depths using ETM+ images (Teimouri et al., 2011). The Polkhan gauging station is the closest station to Lake Bakhtegan lake with reliable data (Torabi Haghighi and Kløve, 2015a). A 30-year period (1976-2005) of monthly natural flow data from this station was used as natural flow and monthly climate (evaporation and rainfall) data from Jahan-Abad meteorological station (the closest to the lake) were used for WLF simulations (Fig. 4, see section 2.3 for details).

2.2.2.2 Extrapolated cases L1, L2.1, L2.2, L3.1 and L3.2

The volume of Lake Bakhtegan and the Chahnime IV and Doroudzan reservoirs is 1.53, 0.88 and 0.96 km^3, respectively, and the area is 1280, 98.8 and 54 km^2, respectively (Fig. 3). To have comparable conditions in geometry of cases, the depth-area and depth-volume curves were scaled (developed) by extrapolating the curves from the Chahnime IV and Doroudzan reservoirs. This extrapolation resulted in lakes with the same maximum volume as Lake Bakhtegan (1.53 km^3), producing cases L2.1 and L3.1 for Chahnime IV and Doroudzan, respectively. The Lake Bakhtegan hypsometric curve was kept unchanged as the reference case, L1. Cases L2.2 and L3.2 were generated by extrapolating the area of the Chahnime IV and Doroudzan reservoirs to be the same as that of Lake Bakhtegan (about 1280 km^2).

2.3 Water balance equation

The water balance was simulated for cases L1, L2.1, L2.2, L3.1 and L3.2. The water balance equation used was:

$$V_{i+1} = V_i + (\Delta V_{(i,i+1)})_i \quad (1)$$

$$\Delta V_{(i,i+1)} = (RI + GI + (P - c \times E) \times A - RO + GO)_{\mathbf{i}} \quad (2)$$

where i indicate current month and i+1 indicate the next month, V_{i+1} is lake volume on the first day of the next month in the lake, V_i is lake volume on the first day of the current month in the lake (i^{th} month of simulation), $\Delta V_{(i,i+1)}$ is monthly change in volume during current month (difference between volume of the lake trough current month (i) and next month (i+1)), P is rainfall, E is pan evaporation, A is average lake area, RI and GI are river and groundwater inflow, GO is groundwater outflow, RO is surface water outflow that occurs after the lake capacity has reached a certain threshold and c is the pan coefficient for converting pan evaporation to lake evaporation. The recommended coefficient for class A land evaporation pans is 0.7 (Kohler et al., 1955; Webb, 1966). For the purposes of this study, groundwater discharge and recharge were assumed to be equal (GI = GO).

The simulation resulted in lake systems that were open or closed. When the water level simulation gave a water level lower than the maximum volume, no outflow occurred and the lake was classified as a closed lake. At higher water levels than the maximum volume, outflow was produced and the lake was classified as an open lake (Torabi Haghighi and Kløve, 2015b; Szesztay, 1974; Langbein, 1961). Since the shape of the lake outlet might have an impact on lake WLF, outlet shape was assumed to be identical for all three lakes used in the simulation processes. The dynamic outflow of the lakes was computed assuming an ogee spillway. The rating curve of the Doroudzan reservoir spillway was used in the simulations to calculate the outflow.

Model efficiency was evaluated using the Nash-Sutcliffe model efficiency coefficient (Eq. 3).

$$E = 1 - \frac{\sum_1^N (V_{obs} - V_{sim})^2}{\sum_1^N (V_{obs} - V_{ave})^2} \qquad (3)$$

where V_{obs} is observed volume of reservoir or lake, V_{sim} is simulated volume of reservoir or lake, V_{ave} is average volume of reservoir or lake and N is number of months in the simulation. Since water level fluctuation data for Lake Bakhtegan were not available, the water balance simulation model developed was validated using the observed inflow, outflow and water level of the Doroudzan reservoir. The water level in that reservoir has been recorded continuously by a digital limnograph. The WLF for the Doroudzan reservoir was simulated using rainfall (Fig. 5a), pan evaporation (Fig. 5b), effective rainfall (Fig. 5c), observed inflow data (Fig. 5d), observed volume (Fig. 5e) and the real outflow from the main outlet for drinking water (pipeline) and irrigation during the five-year period October 1986-September 1990. This five-year period was selected as it had the longest series of reliable continuous data available. The model used was validated for Doroudzan reservoir data, showing good agreement between observed (Fig. 5e) and modelled WL (Nash-Sutcliffe efficiency coefficient 0.78).

Using the validated model, the WLF of lakes was simulated by defining eight different scenarios of lake inflow. The first scenario (Q1) was the natural flow in Polkhan gauging station (observed monthly flow data 1976-2005) and the other seven scenarios (Q2-Q8) represented 75%, 50%, 25%, 15%, 10%, 5% and 2.5% of the natural flow regime time series (observed monthly flow data 1976-2005, see Fig. 4a for mean monthly value for each). Each flow scenario in combination with climate conditions (precipitation and evaporation) contributed in the simulation process, and therefore each simulation belongs to a hydro-climatic condition which represents a hydro-climatic index (HCI1-HCI8, HCI explained in section 2.4).

2.4 Simulation of lake equilibrium state and response to changes in flow

The simulations were run in two different parts. First, the dynamic equilibrium state of each lake for different inflow scenarios (Q1-Q8) was calculated by the simulation water balance equation, where initial lake volume was set as V_0 (any initial volume). The simulation uses a monthly time step repeated with different V_0 to find the equilibrium state. The simulation is carried out until the mean lake volume in the first month is equal or close to assumed V_0 (Abs (V_0- V_1) $< \varepsilon$, where $\varepsilon = 0.1$ million cubic metres was assumed here as the dynamic equilibrium state reached; (Fig. 6a). This gave eight lake equilibrium states (S1-S8) for the eight different inflow scenarios used (Q1-Q8, Fig. 3a), where S1-S8 represent long-term mean monthly distribution of lake fluctuation (volume, area and water level) for Q1-Q8.

In the second part, simulations were performed to find the response time of each lake to reach a new equilibrium state when the flow changed. For each lake equilibrium state (S1-S8, see Fig. 6b), the eight different inflow scenarios (time series of Q1-Q8) were used in the water balance simulation to find response times for each inflow scenario to reach its corresponding new equilibrium state (e.g. corresponding equilibrium state for Q2 is S2, when the initial condition is S5, the response time for changing from S5 to S2 state would be calculated, Fig. 6b and Table 2). Simulation of lake water level variations was carried out for given climate data (Kor river basin data). If the lake reached the relevant state (S1-S8) during the first 30 years of simulation (Q1-Q8), the response time was obtained from simulation results; otherwise the simulation was continued with assumed repetition of the same 30-year time series data. For example, if due to past lake hydro-climatic conditions (Qx) the lake equilibrium state is placed at Sx, while due to some change (climate or anthropogenic) the hydro-climatic condition changes to Qy, from the first part of the simulation we know the equilibrium state for Qy condition is Sy and the goal of the second part is to find the response time for changing lake equilibrium state from Sx to Sy due to stable Qy condition in the long term. Eight different scenarios of inflow were combined with different lake conditions. Based on the initial lake condition and flow scenarios the lake are characterized by three states: DWL- decline water level, EWL- equilibrium water level and RWL- recreated water level (Table 2).

2.5 Potential lake area (A_{pot}) index

The potential lake area (A_{pot}) concept was developed based on the water balance equation. In a closed lake case, the maximum area (A_{max}) forms when inflow volume is equal to the net evaporative volume A×(P-E). This is the potential area of the lake (A_{pot}) and depends on the hydro-climate conditions (inflow, precipitation, evaporation, groundwater outflows). When the lake basin (depression) is such that the lake spills water before A_{pot} is reached, then the maximum area is smaller than A_{pot} and the lake is open. To define this threshold (condition for open or closed), we developed the following classification approach:

The hydro-climatological index (HCI) and potential lake area (A_{pot}) were used to classify lakes as open or closed systems (Table 3), using Eq. 4 and Eq. 5.

$$HCI = \frac{V_{inflow}+GW_{exchange}}{(P-E)} \quad (4)$$

$$A_{pot} = \mathrm{Abs}\ (HCI) \quad (5)$$

where HCI [L^2] is lake hydro-climatological index, V_{inflow} [L^3] is mean long-term annual volume inflow to the lake, $GW_{exchange}$ [L^3] is annual volume of groundwater exchange (positive or negative), P [L^1] is annual precipitation, E [L^1] is annual evaporation from the lake surface and A_{pot} [L^2] is potential lake area. Based on the HCI and A_{pot} results from Eqs. 4 and 5, the lakes were classified into Types I-IV as shown in Table 3.

3 Results and discussions

3.1 Classification of lakes and man-made reservoirs

The results showed that the newly developed LGI index for natural lakes varies from 0.52 to 7.47 (for Ruoko and Lohjanjärvi lakes) and for man-made reservoirs from 2.04 (Dehghan Taibad) to 51.15 for Shahid Abbaspour dam (height 190 m, maximum volume 3.1 km^3 and maximum area 54.77 km^2 , a reservoir which was constructed in a narrow valley with steep sides).To further develop a classification from the observed large variation in LGI, the natural lakes and man-made reservoirs were divided into five groups based on their LGI values as: 0.5-2.5 (group 1), 2.5-4.5 (group 2), 4.5-6.5 (group 3), 6.5-8.5 (group 4), and LGI >8.5 (group 5) (Fig. 7a). Most natural lakes (about 58%) in the data used in this study were placed in LGI group 1 and most man-made reservoirs (about 38%) in LGI group 5 (Figs. 7 b, c). Generally, lakes located in deep valleys (depressions) with steep sides has a high LGI and contrary shallow lakes in a flat terrain have a low LGI. The LGI approach presented is somewhat similar to the approach used for evaluating the effect of sedimentation on the area-volume-height curve of reservoirs (USBR, 1987).

LGI is a lake index that captures different types of lake systems with respect to variations in depth, area and volume. Compared with previous indices such as residence time, LGI provides additional information as it accounts for depth and area relationships, which are important especially for lakes in regions with high potential evaporation. Depth of the lake itself is another important characteristic of lakes. The different LGI values for the lakes and reservoirs studied were 0.75 for Lake Bakhtegan (L1) (representing group 1), 2.75 for the Chahnime IV reservoir (L2.1 and L2.2) (representing group 2) and 6.5 for the Doroudzan reservoir (L3.1 and L3.2) (representing group 3). The area-volume-depth curves used represent the most common groups 1-3, which cover more than 90% of the natural lakes in the database (Fig. 7b).

3.2. Sensitivity analysis of lakes

Water balance simulations showed that the lake equilibrium state for different inflow scenarios varied for different lake systems or LGIs (Fig. 8). For some cases an equilibrium state was reached showing a constant area in different months (e.g. scenarios Q1-Q3 in lake L2.1 and scenarios Q1-Q4 in lake L3.1; Fig. 8). This was due to positive monthly change in volume ($\Delta V_{(i,i+1)} > 0$), resulting in overflow, which kept the water level almost constant (open lake). These types of lakes are found in regions with precipitation excess, e.g. in northern temperate regions or around the equator, or when the lake is connected to a river with significant inflow. These lakes have a fairly stable water level and for practical reasons can be considered to be in equilibrium. In contrast, for some cases in the simulation process the maximum area was not reached for the given hydro-climatic conditions (e.g. all inflow scenarios in case L1; Fig. 8). Lakes with large maximum capacity and area in hot, arid regions (high evaporation and low precipitation) are closed lakes. These lakes can be in dynamic equilibrium, showing a high monthly fluctuation around a long-term mean. In an intermediate case between closed and open lake types, some lakes have the characteristic of being closed in some part of the year (dry period) and open in others (wet period) (e.g. scenarios Q3 and Q4 in case L2.1; Fig. 8). These types of systems can be found in regions with a strongly seasonal climate (e.g. monsoon climate).

The results showed that for closed lakes, mean area (annual basis) is constant for different LGIs (L1, L2.2 and L3.2) for each hydro-climate condition when the lake is in an equilibrium state (Fig. 9 a2). This occurs as water inflow (Q and P) are equal to outflow (E). For open lakes, the area is equal to the maximum physical area of the lake (A_{max}) (scenarios Q1-Q6 for L2.1 and L3.1; Fig. 9 a1). The open lake can change to a closed lake if changes occur in its hydro-climatic condition (as can be seen in Fig. 8, L3.1 for Q1-Q6 is open, while Q7-Q8is closed for Q7-Q8).

While the area depends only on hydro-climatic condition for closed lakes, the other two geometric characteristics of lakes (volume and depth) depend on the geometry (LGI) and hydro-climatology. For lakes with higher LGI, the water level changes more as the natural flow reduces (Fig. 9c). For example, in scenario Q8 the water level drawdown increased from -4, -19 and -25 for lakes L1, L2.1 and L2.2, respectively (Fig. 9 c1). Average lake volume is higher for lakes with higher LGI (Fig. 9 b1 and b2). With high LGI, the volume of evaporation is low (lake area/volume ratio is small), resulting in smaller water losses from the reservoir and therefore allowing a larger volume. The effect of precipitation and evaporation on lake response depends mainly on lake area, as the net flux is (P-E)×Area. When the LGI index is low, the lake is most sensitive to climate change. In previous studies, we examined the lake sensitivity to changes in climate and river regime (Torabi Haghighi and Kløve, 2015b). In present study, we examined the role of lake geometry in similar sensitivity analysis.

3.3 Open versus closed lake classifications and responses

The results of the analysis showed that the lake with the lowest LGI (L1: LGI=0.75) behaved as a closed lake in all flow scenarios, as lake volume never reached the outlet threshold at which runoff occurs (Fig. 8). This was also apparent from the long-term mean volume, area and water level of the lakes (Figs. 9 a1, b1 c1), as the mean volume was less than 1.54 km^3 (maximum capacity of Lake Bakhtaran (L1) and average water level were 0.5-3.0 m lower than maximum water level in different scenarios (Fig. 9 c). In L2.1 (LGI= 2.75), lake volume passed the lake threshold (1.528 km^3) in the first four flow scenarios (Q1-Q4), and the lake behaved as an open lake, while in other scenarios (Q5-Q8) the lake behaved as a closed lake (Fig. 8). The third lake (L3.1, LGI=6.5) responded as a closed lake in the last two flow scenarios (Q7 and Q8) and as an open lake in the other flow conditions (Q1-

Q6) (Figs. 8 and 9). The lake cases L2.2 and L3.2 behaved as closed lakes in all flow scenarios in which the lake water levels did not pass the threshold water level (Figs. 8 and 9).

Closed lakes have previously been considered to occur mostly in semi-arid and arid climate conditions (Langbein, 1961). However, as shown here for three lake cases, lake performance (open or closed) is a consequence of the superimposition of lake geometry and water balance components, and not only the climate. The results from this study indicate that lake geometry has an effect in partitioning lakes into open or closed systems.

The difference between potential lake area (A_{pot}) and long-term mean area of closed lakes (obtained from water balance simulation) was less than 5% (cases L1, L2.2 and L3.2; Fig. 10). For open lakes, the mean long-term area was significantly lower than A_{pot} (cases L2.2 and L3.2; Fig. 10). Thus, while hydro-climatology of lake plays an important role in classifying lakes as open or closed, comparison A_{pot} with A_{max} could be used as a supplementary index for lake classification, as mentioned in Table 3 for lake Types II and III. The A_{pot} index can be used for lake classification or to define the current dynamics of lake state (lake in disappearing process, growing process or in equilibrium), as we explain later.

Lakes with positive effective rainfall (P-E) and positive inflow (V_{inflow} + $GW_{exchange}$) are obviously open lakes (Type I in Table 3). This type of lake is typical in wet-cold climates such as Fennoscandinavia, Canada and northern parts of the Russian Federation (Torabi Haghighi and Kløve, 2015b), e.g. Great Slave Lake between the Peace and McKenzie rivers in Canada, Lake Baikal, the source of the Angara river in Yenisei basin in Russia, and Lake Oulujärvi, a major source of the Oulujoki river in Finland. In these regions, the numerator and denominator of friction in Eq. 2 both have a positive sign. This type of lake is open or reaches open state with a lag depending on lake geomorphology and hydro-climatic conditions (Torabi Haghighi and Kløve, 2015b). In contrast, Type IV lakes are ephemeral lakes, e.g. wetlands found at the interface between surface water and groundwater (Naughton et al., 2012). This type of lake appears after heavy rainfall or flood season, but can disappear due to high rates of evaporation or groundwater seepage, e.g. Lake Hamoun in Iran (Rashki et al., 2013) or turloughs (karstic lakes) in Ireland (Naughton et al., 2012).

Certain lakes are open or closed (Types II and III in Table 3) depending on the hydro-climatology index (HCI, here different Q), A_{pot} (defined as maximum area of a lake depending on water balance) and A_{max} (maximum physical area of a lake). This is well illustrated in the simulation results, where lakes L2.1 and L3.1 at a distance from the A_{pot} line in Fig. 10 behaved as open lakes, while other scenarios lying closer to the A_{pot} line behaved as closed lakes.

Thus A_{pot} is an effective index to evaluate the current status of lakes. In general, depending on the current lake water level and water balance components, three dynamic patterns can occur: i) The lake is in equilibrium (e.g. see lake volume fluctuations in Figs. 11 panels a1-a8 after 2 years or panel c8 after 40 years or the green box conditions in Fig. 6b), ii) the lake is growing (e.g. see Fig. 12c1 or the blue box conditions in Fig. 6b) or iii) the lake is shrinking (e.g. see Fig. 12c8 or the red box conditions in Fig. 6b). Smaller A_{pot} values, calculated from present hydro-climatology data, than the current surface area of lakes indicate shrinking conditions. Thus, the A_{pot} index can easily be used to predict future lake condition under changing climate or land use patterns. In addition, A_{pot} can effectively be used to evaluate the success of environmental flow allocations by substituting the amount of allocated flow for lakes. Hence, the lake equilibrium area after flow allocation can be estimated and compared with expected area.

3.4 Response time to flow alterations and LGI

Lake response time to flow alterations is the time needed for the lake to find new equilibrium conditions (Torabi Haghighi and Kløve, 2015b). In the present study, the lake with low LGI (L1, LGI=0.75) showed a quick response time to the new altered condition. For arbitrary initial condition of lake status (S1-S8), the lake reached its new equilibrium level in less than 2 years (Figs. 11 and 12 a1-a8). Thus, a lake that has undergone a 97.5% reduction in inflow (Q8 scenario) could be restored back to normal in less than two years if sufficient environmental flow is allocated to the lake (Fig. 12a1). As an example, this finding could be applied to the closed Lake Bakhtegan, which has low LGI. If at a certain future time Lake Bakhtegan undergoes a change to worst condition and recreating the lake is required, restoration can be completed within a short period of time. For the other two lakes, with LGI = 2.75 and 6.5, the response time depended on i) the initial condition of the lake at the start of simulations, ii) the magnitude of flow alteration, and iii) whether the lake was open or closed. In the closed lake system, the response time for lakes L2.1 and L3.1 varied from 20 to 200 years (Fig. 12 b1-8) and 75-400 years (Fig. 12 c1-8) years, respectively. However, in the open lake system, for an inflow scenario of Q1-Q4 in Lake L2.1 and Q1-Q5 in Lake L3.1, the response time varied between 2-20 years (Fig. 11 b1-b4 and c1-c5). As mentioned previously, lake equilibrium condition can be affected by any change in water balance equation components. Thus, one of the important benefits of using the framework presented in this study is to determine the expected time required for the lake to reach new equilibrium status.

The results show that many closed lakes will need a considerable time, even centuries, to recover from lake level decline or desiccation due to changes in inflow caused e.g. irrigation or climate change. Moreover, lakes with low LGI are more sensitive than lakes with high LGI to such desiccation for equal maximum volume or area under same hydro-climate conditions. When the hydro-climate condition from HCL1 was changed to HCL8, the response time to lake complete desiccation (drying of the lake) was less than 1, 80 and 360 years for L1, L2.2 and L2.3 respectively (Fig3 12 a8, b8 and c8).

3.5 Novelty of indexes LGI and A_{pot}

The benefit of the developed indexes LGI and A_{pot} is that they are based on important characteristics of lakes. LGI is sensitive to lake geometry (volume-depth curve) of lake. Lakes with large LGI values are less vulnerable to changes in inflow and climate change. The index A_{pot} is an indicator of water access and it can also be used to show if a lake is hydrologically closed or open, especially in arid regions. As A_{pot} shows water access, it is sensitive to changes in inflow caused by water regulation or climate change. By simulating different cases, we showed that lake responses to different environmental flow scenarios can be predicted by LGI and A_{pot} indexes. The indexes clearly show the sensitive of lakes for desiccation and response time to alteration in flow or climate. We recommend that these indexes are used in environmental flow assessment to assess impact of flow regulation and climate change. The new indexes are physically sound, easy to calculate and capture the complexity of reality as demonstrated for a large number of lakes. To our knowledge, this is the first time the term lake geometry has been used to assess lake sensitivity to inflow changes. Previously most of environmental flow assessment (over 207 different methods were reported by Tharme 2003) were developed based on hydrological, water quality, ecological condition or habitat condition and most of them were developed for rivers (Torabi Haghighi and Kløve, 2015a). Compared to past methods, the newly developed indexes will clearly provide additional information for lakes. Also, they are useful in assessment at larger scales to compare and group different systems as they are dimensionless.

4 Conclusions

Understanding different drivers behind lake responses to climate variability and water use changes is useful for better management of water resources. For water management, the novel contribution of this study was to clarify the role of lake geometry in lake responses under different hydro-climatic changes. The novelty of this work is the development of two new indices, LGI and A_{pot}, for lake water resource management purposes. The indexes help to predict expected time for lake desiccation and our results clearly indicate that the response time for lakes after impacts on water budget depends on lake geometry. The results show that shallow terminal lakes are sensitive to lake changes in inflow, but differences are also seen between this type of lakes depending on LGI and the inflow regime. Thus when considering e.g. environmental flow allocations, lake geometry must be considered to find an optimum solution. Both indices can be used for effective lake categorisation for management and rehabilitation purposes. Moreover, the framework presented can be used to define the response time for a desired lake state, as A_{pot} indicates whether the current state of a lake is stable, shrinking or expanding.

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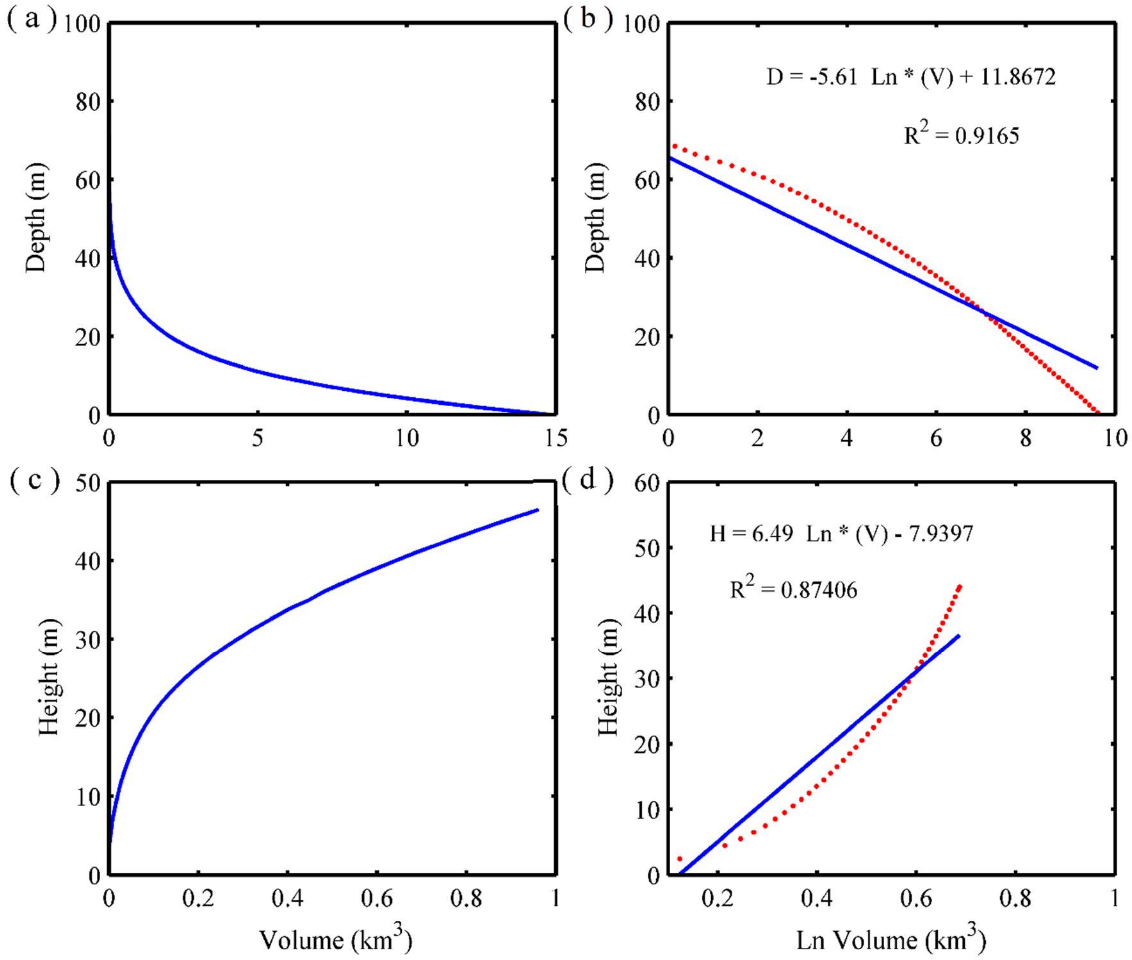

Figure 1. Example of depth and height volume curves used in calculation of lake geometry index (LGI): a) normal hypsometric curve for a natural lake (Saimaa, Finland), b) converted hypsometric curve after log conversion for volume (Saimaa, Finland), c) normal hypsometric curve for a man-made reservoir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

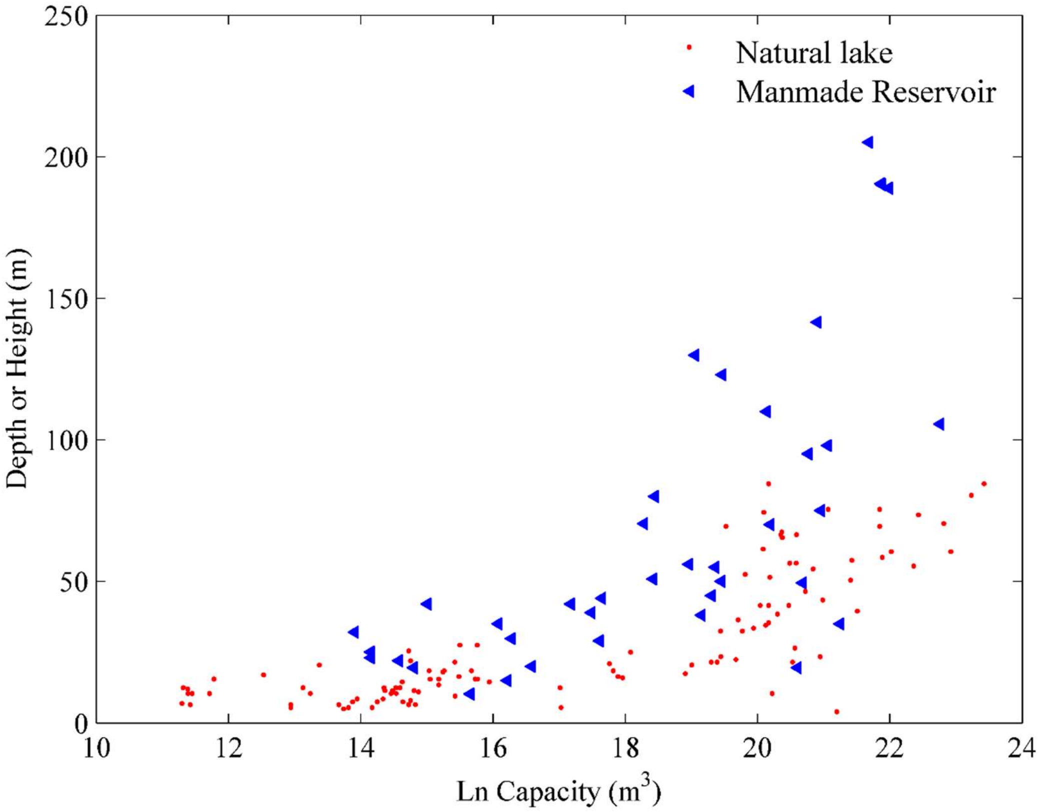

Figure 2. Variation in volume as a function of depth of natural lakes or man-made reservoirs for lake and reservoir data from cases listed in Appendix 1.

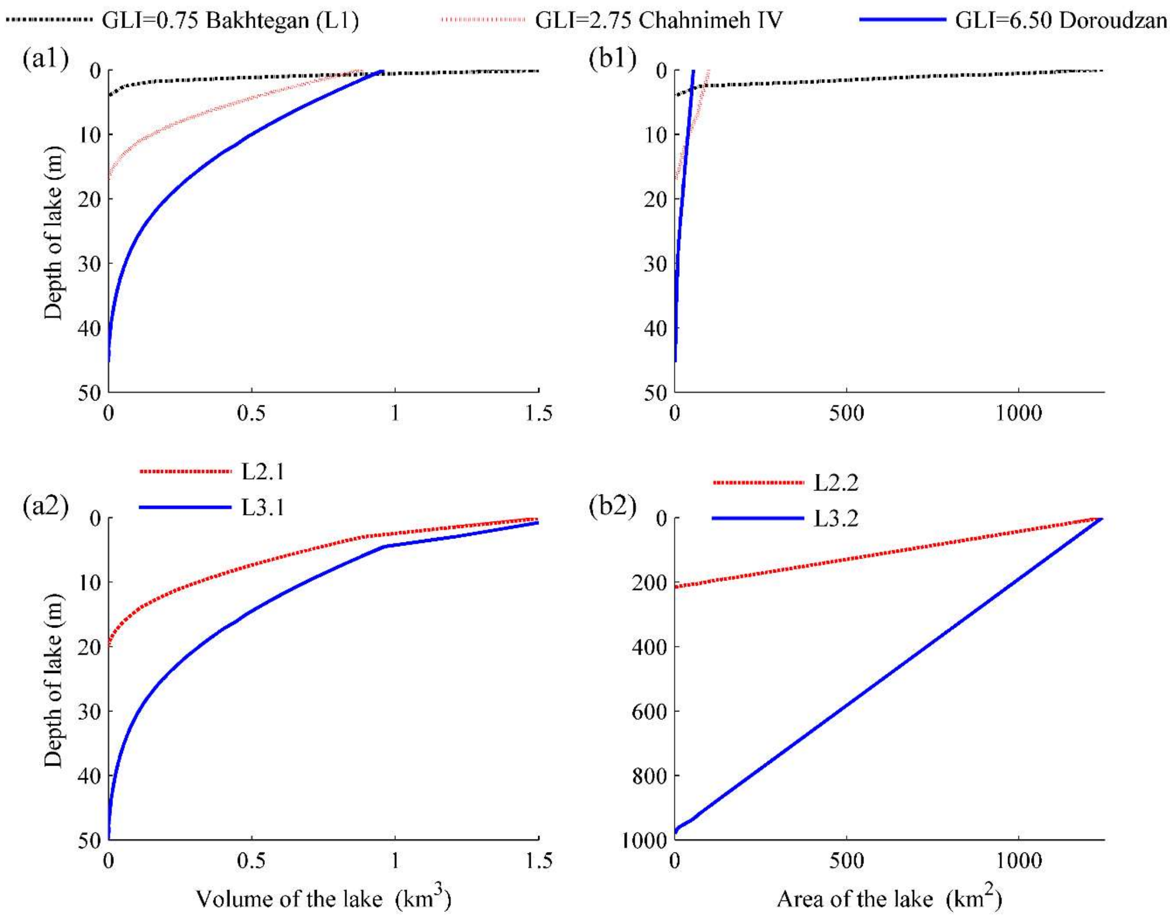

Figure 3. Hypsometric curves for case studies: a1) original volume-depth curve, b1) original area-depth curve, a2) extended volume-depth curve for cases L2.1 and L3.1, and b2) extended area-depth curve for cases L2.2 and L3.2.

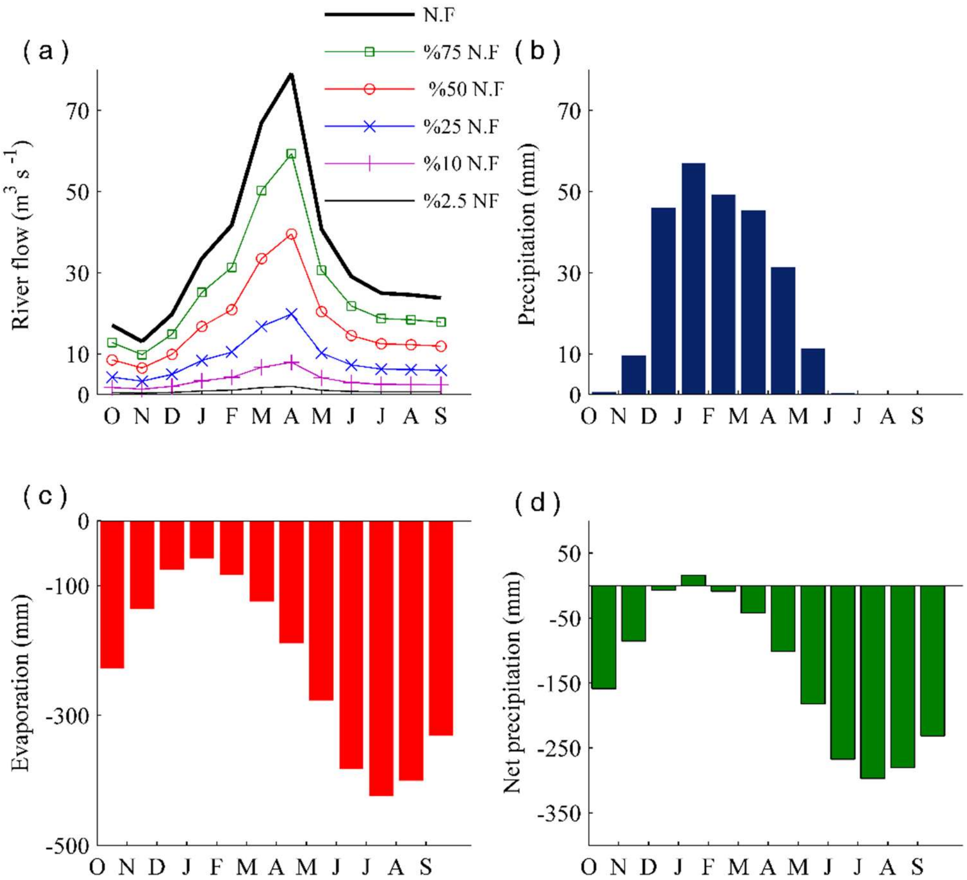

Figure 4. Mean monthly (1976-2005): a) natural flow rate (Q1) and some flow reduction scenarios at Polkhan gauging station (Q2-Q8), b) precipitation at Jahan-Abad climatological station, c) evaporation at Jahan-Abad climatological station, and d) net precipitation in Lake Bakhtegan.

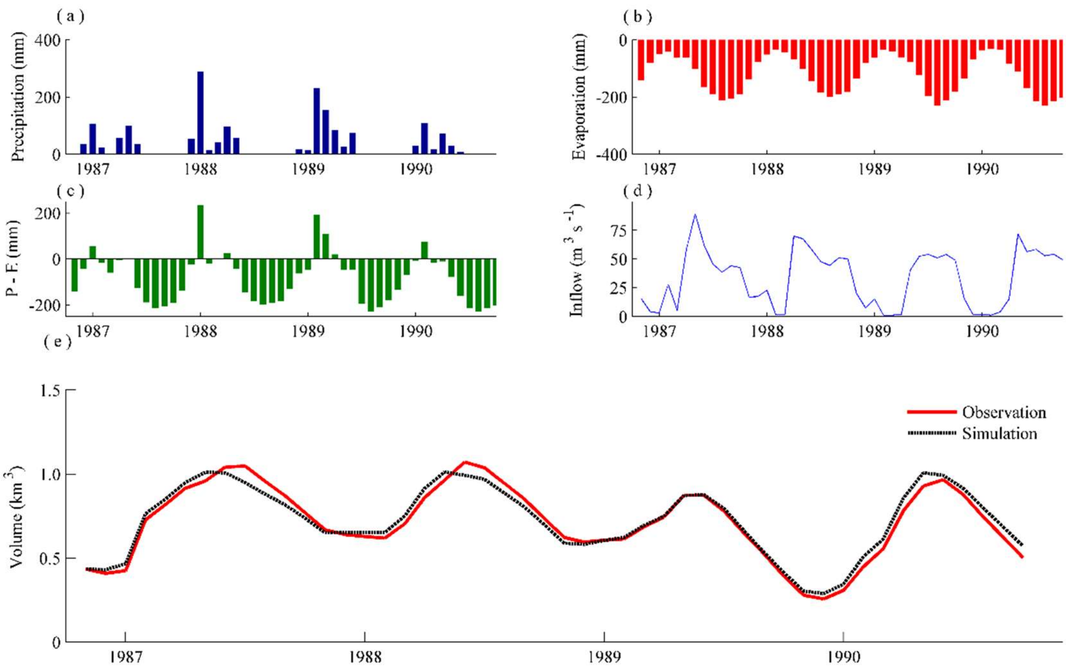

Figure 5. Data used for simulation of Doroudzan reservoir to validate the simulation model (Oct. 1986-Sept. 1990): a) precipitation, b) evaporation from pan, c) effective precipitation, d) inflow, and e) simulated and observed reservoir volume using monthly water balance equation (Oct. 1986- Sept. 1990).

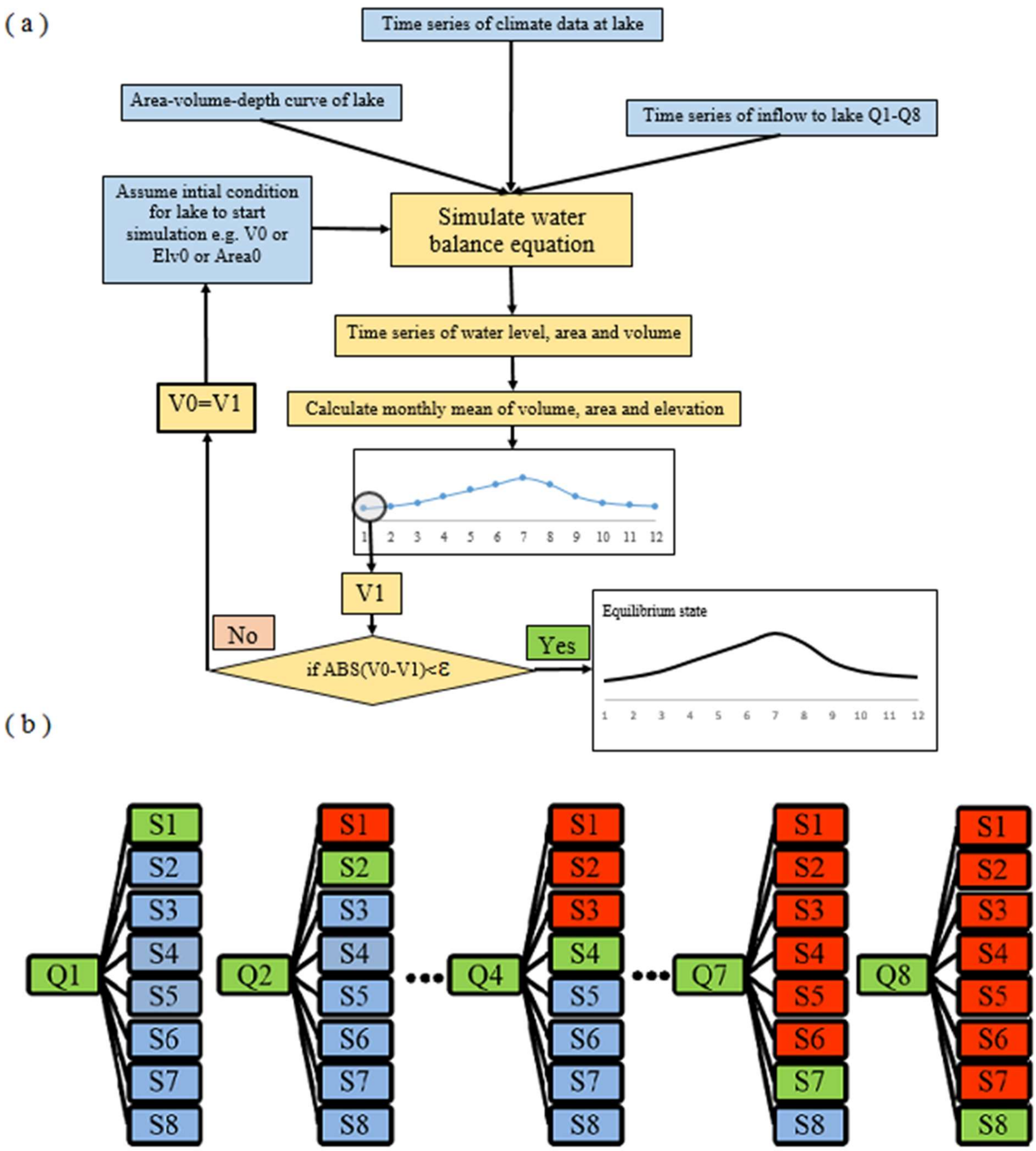

Figure 6. Water balance simulation process: a) flowchart for simulation and finding dynamic equlibrium state, and b) schematic for second part of simulation, combining different flow scenarios (Q1-Q8) with different lake equilibrium levels (S1-S8).

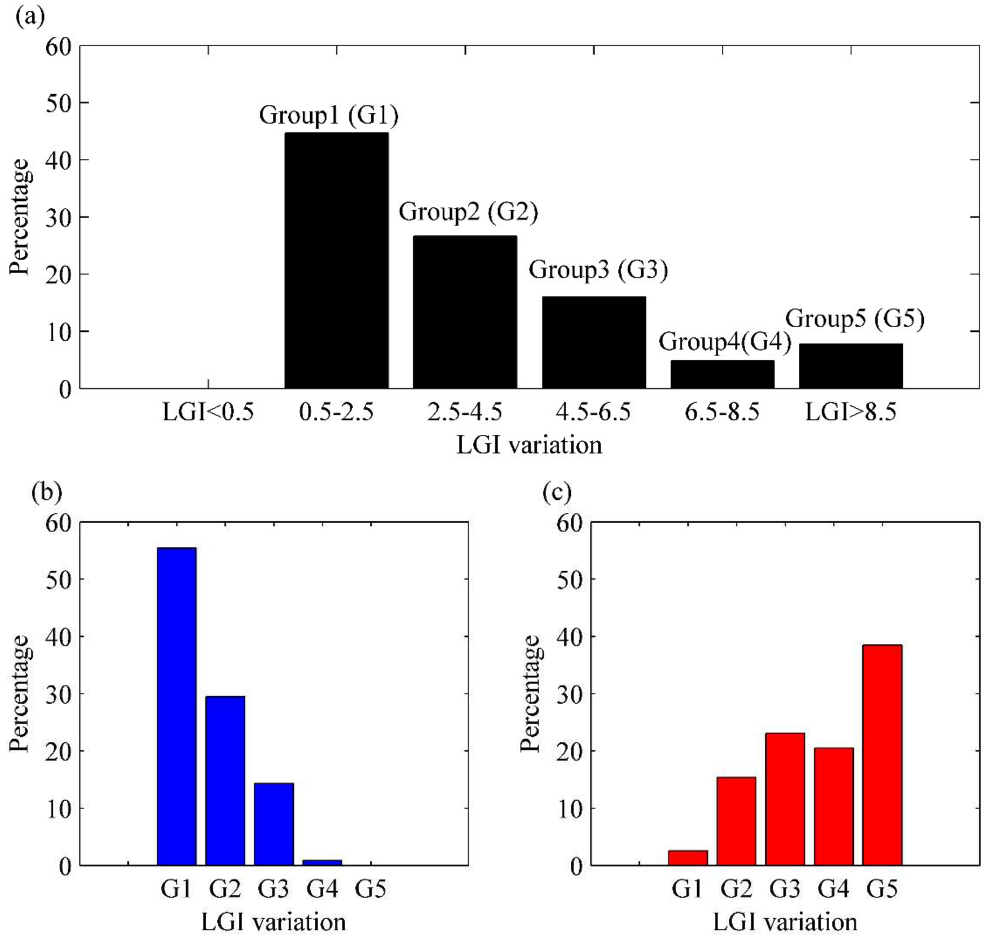

Figure 7. Frequency of lakes and man-made reservoirs in different LGI groups: a) all data, b) natural lakes, and c) man-made reservoirs.

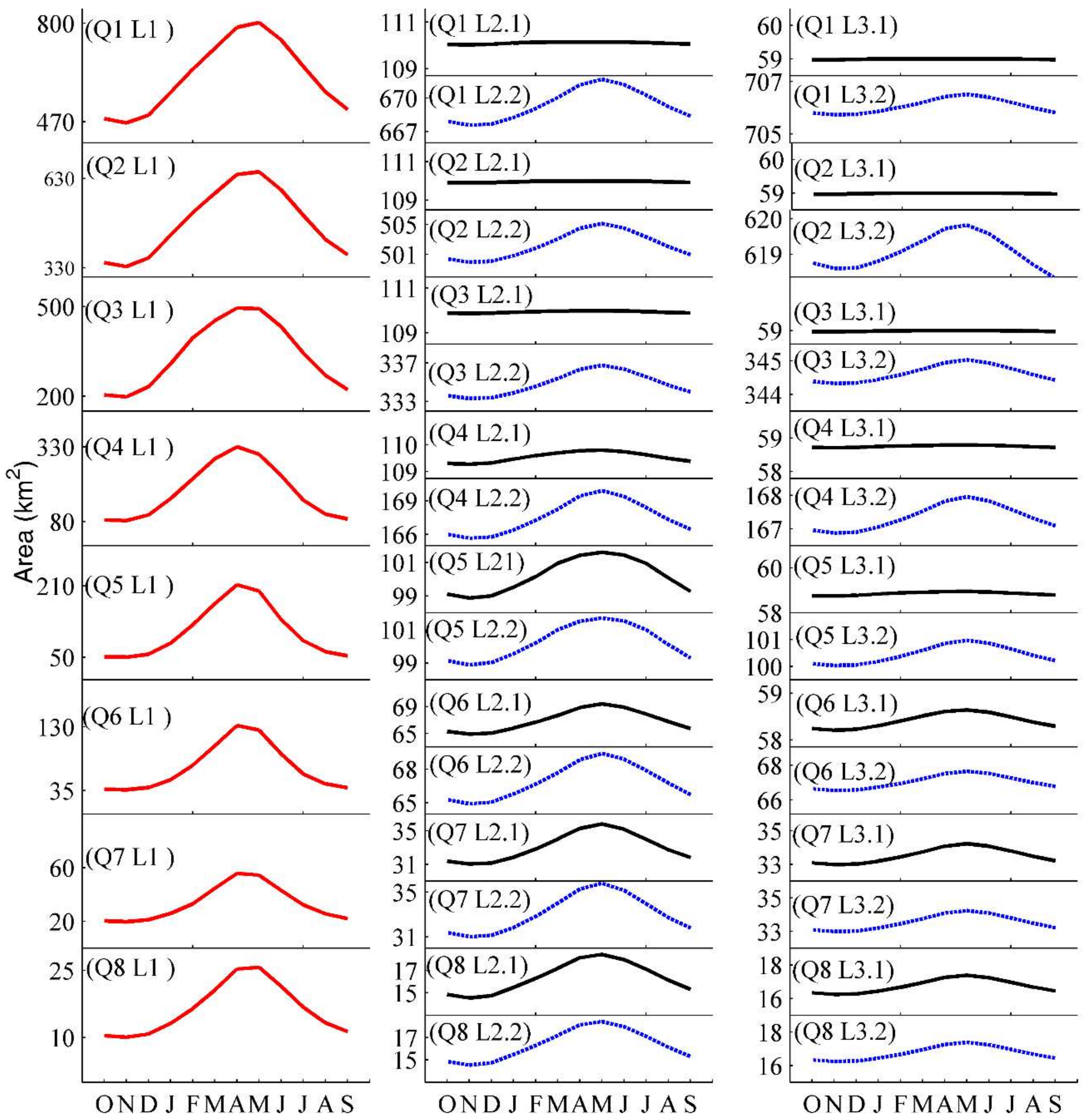

Figure 8. Monthly equilibrium state of lake area in different cases [(notation Qx Ly, where x indicates the inflow scenario (Q1- Q8) corresponding to HCI1-HCI8, and y indicates the lake cases (L1, L2.1, L2.2, L3.1 and L3.2)].

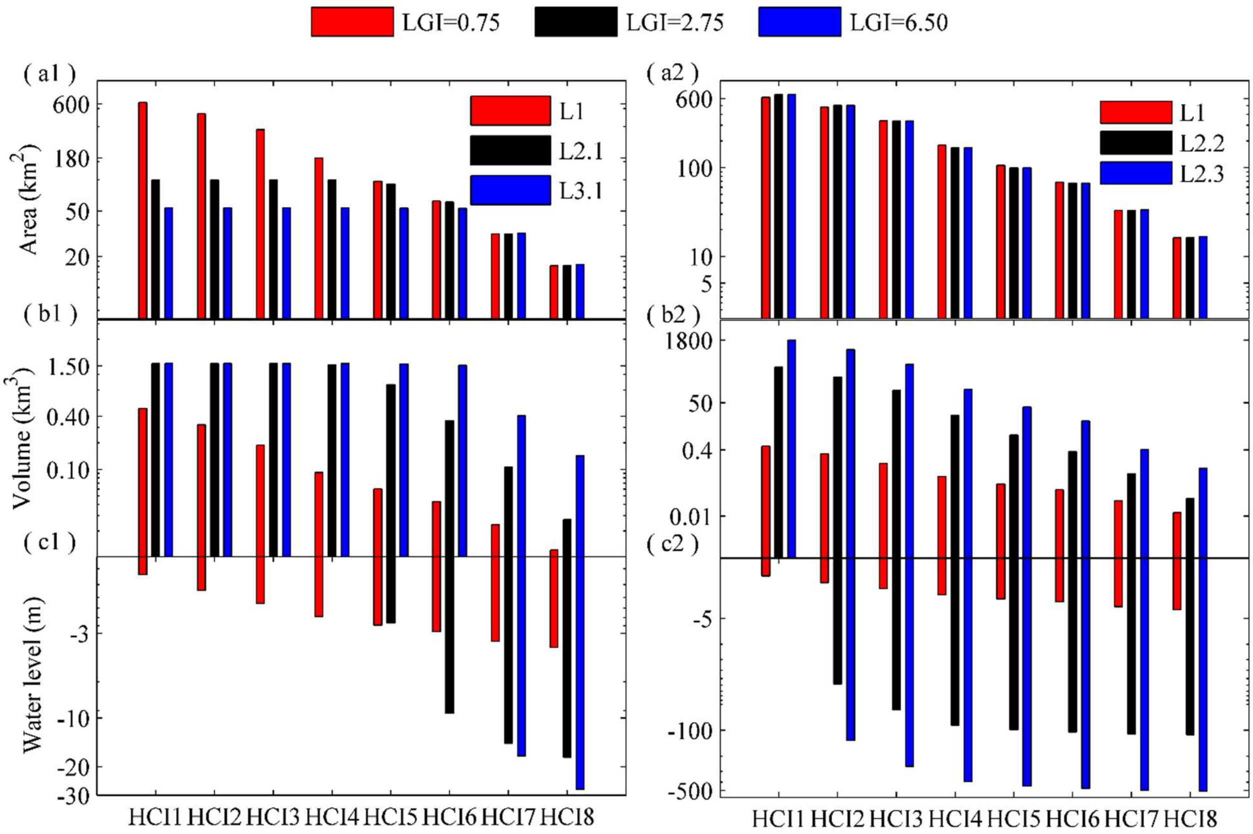

Figure 9. Long-term mean a) area, b) volume and c) water level (a1-c1 for cases L1, L2.1 and L3.1 and a2-c2 for cases L1, L2.2 and 3.2).

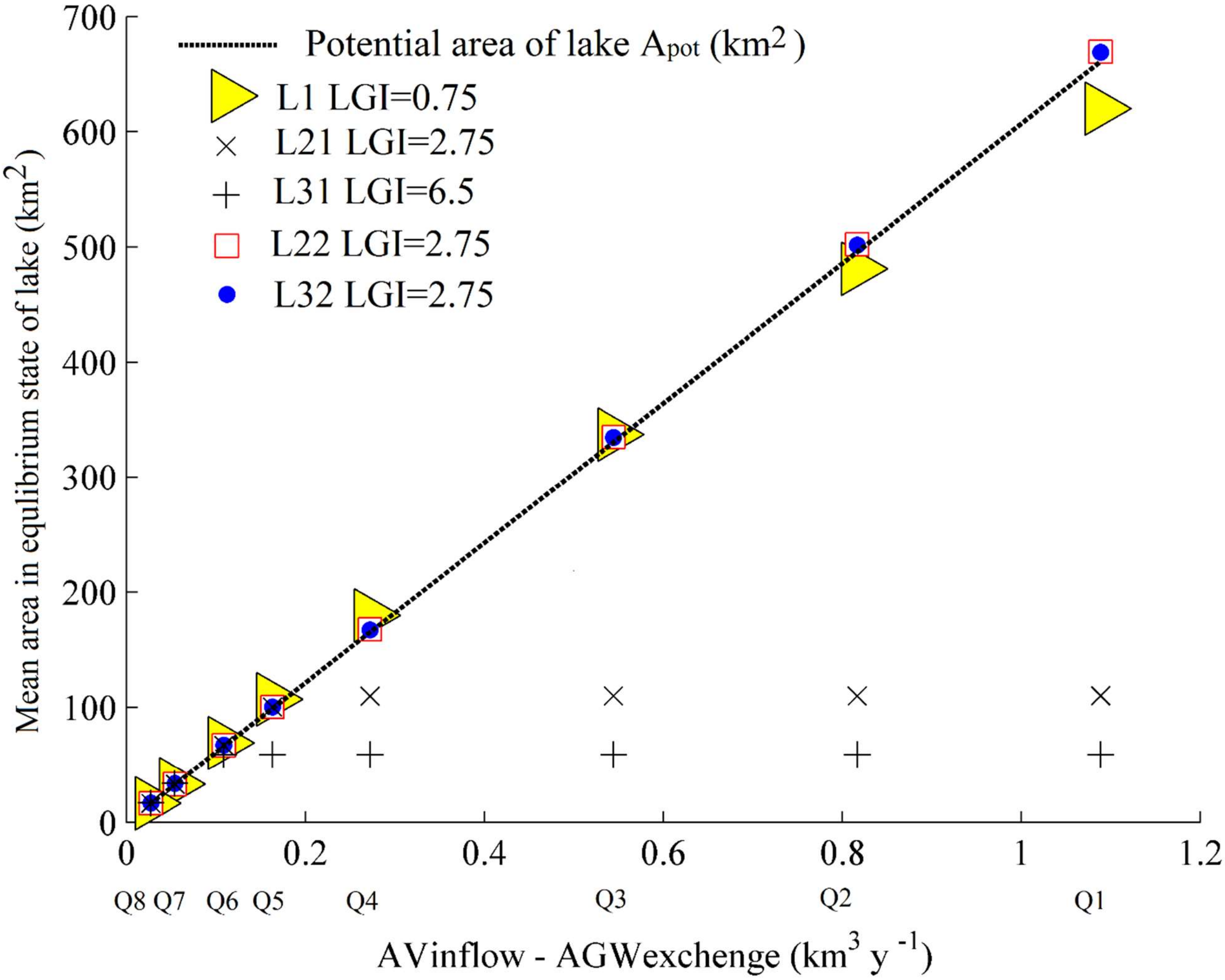

Figure 10. Potential lake area (A_{pot}) line and position of the mean simulated lake area for different inflow scenarios (Q1-Q8). The simulated area below the A_{pot} line shows an open lake system, while the lakes on the A_{pot} line are closed lakes.

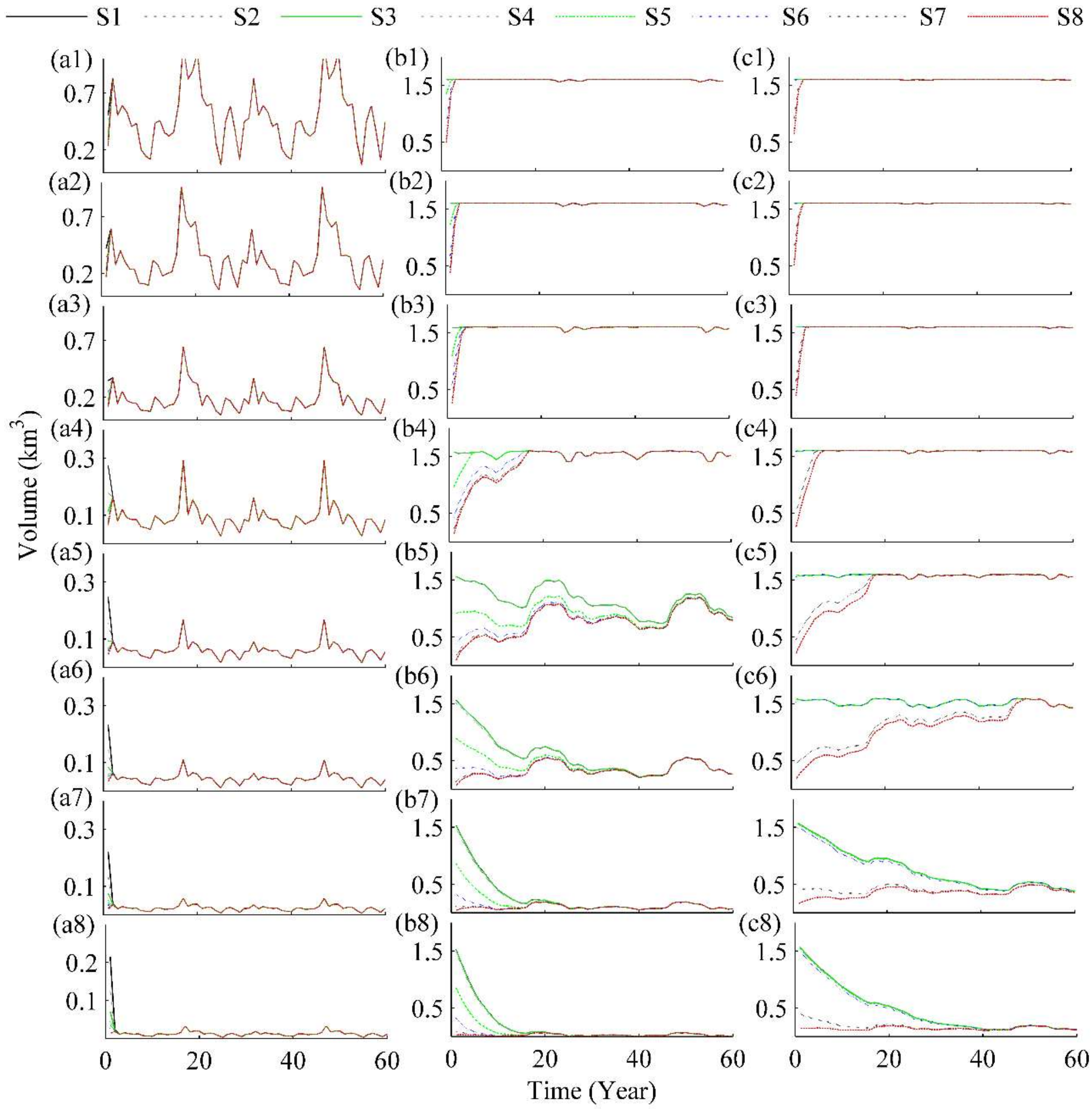

Figure 11. Response time to reach a new dynamic equilibrium state in lakes with equal maximum volume (1.53 km^3) for lakes L1 (a1-a8), L2.2 (b1-b8) and L3.2 (c1-c8) for different inflow scenarios (Q1-Q8) and initial conditions (S1-S8).

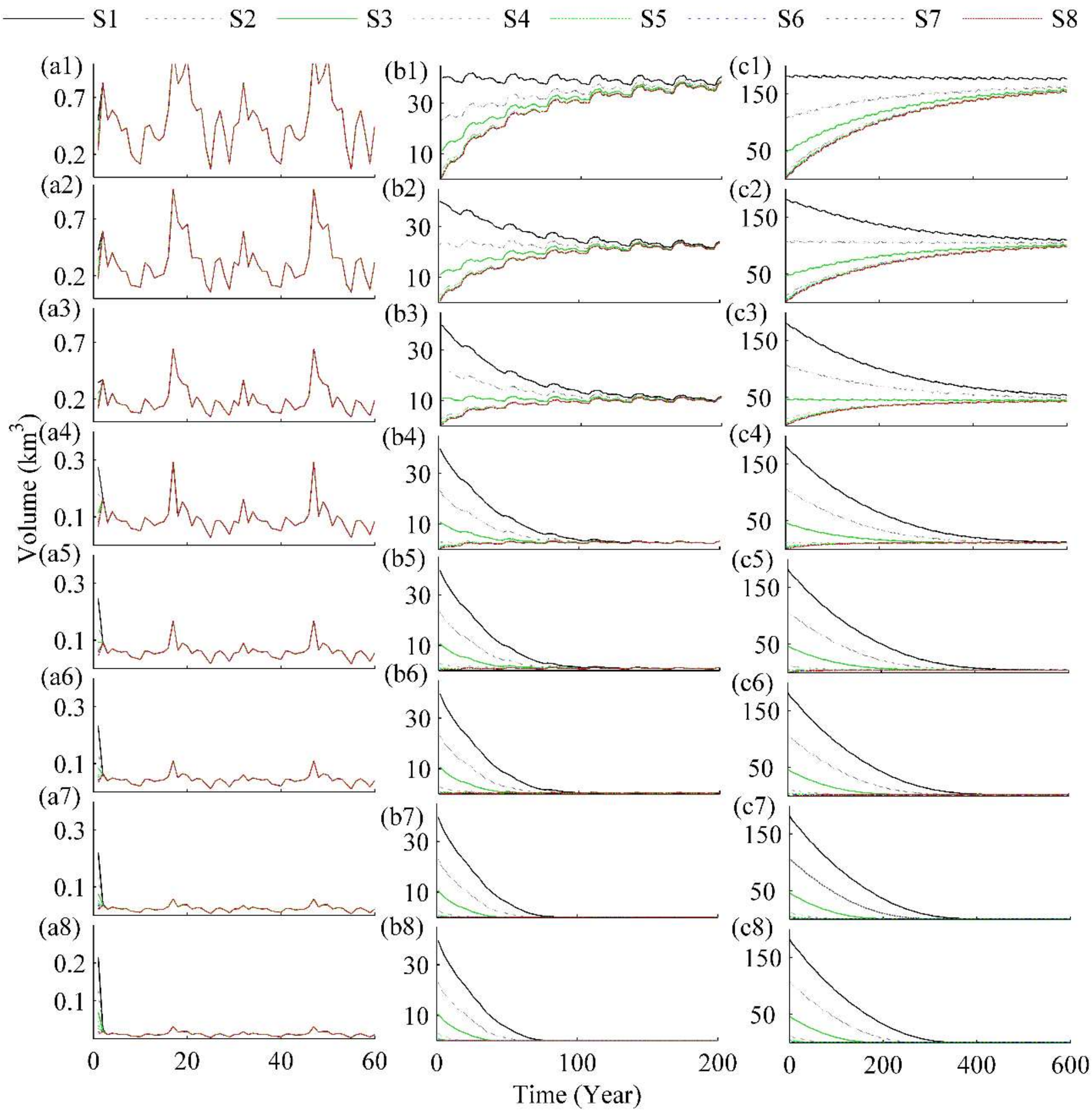

Figure 12. Response time to reach a new dynamic equilibrium state in lakes with different LGI and equal maximum area (1200 km^2) for lakes L1 (a1-a8), L2.2 (b1-b8) and L3.2 (c1-c8) for different inflow scenarios (Q1-Q8) and initial conditions (S1-S8).