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

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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" were used to develop a new index for lake regime characterisation, 'Degree of Lake Wetness' (DLW). DLW is presented as two indexes, 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 lake volume fluctuation patterns around the mean lake volume. These indexes 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 indexes 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.

Keywords: lake hydrology, lake water level, river regime, climate, water balance.

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: Absolute maximum-minimum volume ratio

Bwh: Hot-arid desert climate according to the Köppen climate classification

Cs: Temperate with hot and 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

1. 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 levels are 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 et al., 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 part 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 et al., 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.

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 developed framework 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.

2. Materials and methods

Lake levels were simulated with a water balance equation for volumes of different lake size (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 2.2.2) on water level for lakes with different depth-area-volume relationships. For a general comparison, the river flow from five rivers was scaled to 100×10^6 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.

2.1 River flow and climate data

2.1.1 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 these lakes (any set of lakes with variable size could have been selected).

The case rivers (R1-R5) were selected from five different climate zones 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)’; Peel et al., 2007 represented as C5 climate) (Table 1). The Colorado river regime is regulated due to 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)’ according to the Köppen climate classification method; Peel et al., 2007 represented as C1 climate). 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 and dry summer (Cs)’; Peel et al., 2007 represented as C4 climate). A tributary of the North Platte river (R4), which is located upstream of the Seminoe reservoir in Wyoming State (USA), represented a cold-arid climate (‘cold arid steppe (Bsk)’; Peel et al., 2007 represented as C2 climate). The Godavari river (R5), in the middle of the monsoon zone in India, was used to represent a tropical climate (‘tropical savannah (Aw)’; Peel et al., 2007 represented as C3 climate). Godavari starts from the western state of Maharashtra and, after passing through the state of Andhra Pradesh, discharges into the Bay of Bengal. At 1456 km, it is the second longest river in India (Mikhailov, 2011). These five rivers were of different sizes and had different annual hydrographs (Fig. 2a).

Variations in the amount of inflow could produce non-comparable simulation results, complicating the analysis of climate pattern and flow regime effects. Therefore in order to compare different river regimes, monthly discharge was scaled with a unit flow coefficient (η), defined as:

$$\eta = I' / I \qquad (1)$$

where I' is the flow scaling unit 100 m^3 yr^{-1} (0.10 km^3 per year or 3.1709 m^3/s) and I is the original mean annual flow rate of the river. This scaling (by a factor of 100 m^3 yr^{-1}) is convenient as it allows fast assessment of monthly percentage of annual flow (total annual flow = 100; see also Torabi Haghighi and Kløve, 2013). The scaling is also appropriate considering the lake volumes used (0.024-3 km^3), as it results in residence times of 0.24 to 30 years (see CIR concept explained below). The scaled annual hydrographs obtained using η are shown in Fig. 2b. The Colorado and Kymi displayed a uniform hydrograph during the year, with low monthly fluctuation in annual discharge (standard deviation for scaled discharge (SDSD) 0.98 and 1.52, respectively), so these were classified as rivers with low variation in their intra-annual regime. The Godavari and Platte river hydrographs showed a strong seasonal pattern, with most discharge occurring from July-September (monsoon season) and April-July, respectively. The standard deviation for monthly scaled discharge for these rivers was 4.58 and 4.26, respectively. The Kor river regime also showed a seasonal intra-annual regime, but not as strong as that of the Godavari and Platte rivers, and its scaled annual hydrograph fell somewhere between seasonal and regulated (standard deviation for 40-year scaled monthly inflow data was 3.26) (Fig. 2b). After scaling, the selected rivers represented five different river regimes (R1-R5). It should be noted that the exact location of these rivers (and of lakes L1-L3) is not important, as the intention is only to use the river regimes to provide scenarios for lake level sensitivity simulations. For clarity and comparison, we show the occurrence of different flow regimes (variety in SDSD) in different climate using real examples (Fig. 3 and Appendix B). This shows that the regimes of rivers can be considered partly independently of catchment climate particularly in regulated rivers like Nile river after Aswan dam (Fig 3a), and rivers feed by lakes such as Angara river at Irkustkaya (Fig 3a) or rivers that result after a confluence of two or more rivers with different regimes such as Nile river (confluence of Blue and White Nile) before Aswan Dam (Fig 3b).

2.1.2 Climate data and effective precipitation

The climate in river regions varied in terms of mean effective precipitation depth (P-E) and temporal distribution of mean monthly precipitation within the year (Table 1 and Fig. 4a). As shown in Fig. 4a, the dry period for the Colorado and Kymi rivers is April-September, for Kor and Platte May-October and for Godavari December-May. To generate different water resource system cases (combination of river regime, climate and lake), each river regime (R1-R5) was placed upstream of each lake (L1-L3) in different climates (C1-C5). Monthly climate data for each river basin were used to obtain five series of monthly effective precipitation (P-E) for each climate zone. The wet period (the six consecutive months with the largest cumulative P-E) and the dry period (the other six consecutive months) were adjusted in time to fit the respective climate for each river. The original climate data are shown in Fig. 4a and the time-adjusted data considering the distribution of effective precipitation in Figs. 4b-d. For example, C3 (tropical savannah, Aw) climate data were obtained using as reference the monthly P-E data for the Godavari river (R5), for which the wet period is June-November. Therefore the wet period in other climate data was shifted to coincide with this period (e.g. data for Kymi were shifted forwards 4 months). This resulted in five monthly time series of different P-E, which were used to represent different climates found in tropical basins such as that of the Godavari (Fig. 4d). The effective precipitation values used for the Kymi and Colorado rivers are shown in Fig. 4b and those for the Kor and Platte rivers in Fig. 4c.

A total of 75 different cases were generated, as shown in Appendix A. These 75 cases were categorised in three magnitude models as: Model 1 rivers, with annual discharge (0.100 km^3) greater than lake capacity (we used the geometry of Tammijärvi lake, with 0.024 km^3 volume, L1); model 2 rivers, with smaller discharge than the lake capacity (we used the geometry of Isojärvi lake, with 0.30 km^3 volume, L2); and model 3 rivers, with very small discharge compared with lake capacity (Puula lake with, 3.0 km^3 volume, L3). Each lake was placed in five different climates (C1-C5) to demonstrate the impacts of the climate varying from hot to cold and dry to wet (the combinations of three lakes and five climates produced in total 15 different lake climate and geometry interactions). Moreover, the lake systems were placed at the end of five different river regimes grouped according to their standard division of scaled monthly discharge (SDSD) from 0.98 to 4.58 (giving 75 hydrological systems in total). The lowest SDSD represented river regimes with low variation in monthly flow, e.g. rivers affected by dams or very large lakes, and the highest SDSD represented high seasonal variation in monthly discharge.

2.2. Lake water balance simulation

2.2.1 Lake water balance equation

In order to evaluate the effects of climate pattern, river regime, lake geomorphology and flow rate on lake performance, a virtual water resource system containing a lake fed by a river system was designed (Fig. 5a). A lake water balance simulation code was developed in MATLAB programming based on equation 2:

$$S_{i+1} = S_i + (\Sigma Q_I - \Sigma Q_O)_i \qquad (2)$$

where S_{i+1} is lake water storage on the first day of the next month in the water body, S_i is lake water storage on the first day of the current month in the water body and $(\Sigma Q_I - \Sigma Q_O)_i$ is the difference between inflow and outflow during the current month. ΣQ_I and ΣQ_O can be calculated by equations 3 and 4:

$$\Sigma Q_I = R_I + P_I + G_I \qquad (3)$$

$$\Sigma Q_O = R_O + E_O + G_O \qquad (4)$$

where R_I is lake inflow, P_I is precipitation on the lake, G_I is lake groundwater inflow, R_O is surface water lake outflow, E_O is lake evaporation and G_O is groundwater outflow.

Groundwater and surface water interaction for a lake could include three type of interactions: a) groundwater focused recharge by surface water, b) groundwater discharge to surface water, and c) no net exchange between groundwater and surface water. Each of these main states can contain many different minor states based on the distribution of groundwater states during the month. However, if all these are considered as variables in the balance equation, the number of scenarios to be simulated increases dramatically and interpretation of the results and identification of the effects of climate pattern, river regime or magnitude of flow rate is difficult. Accordingly, the interaction type (c) (no exchange) was assumed for this simulation, i.e. the sum of groundwater and surface water recharging and discharging to the lake was taken to be zero during the year. With this assumption, the monthly balance equation was simplified as shown in equation 5:

$$S_{i+1} = S_i + (I' + \mathbf{1\,e\text{-}6} \times (P - c \times E) \times A - O)_i \qquad (5)$$

$$A = (A_i + A_{i+1}) / 2 \qquad (6)$$

where S_{i+1} (km^3) is water budget in the lake on the first day of the next month, S_i (km^3) is water budget in the lake on the first day of the current month (i^{th} month of simulation), P (mm/month) is rainfall in the current month, E (mm/month) is pan evaporation in the current month, A (km^2) is average lake area in the current month, I'(km^3) is unit river inflow (Eq. 1), O (km^3) is the surface water outflow that occurs after the lake volume (s) is reached to maximum lake capacity and c is a pan coefficient to convert the evaporation from pan to free water body surface. The recommended coefficient for a class A land evaporation pan is 0.7 (Kohler et al., 1955; Webb, 1966). The outflow of the lake (O, km^3) is dependent on the physical conditions at the lake-river connection point at the lake outlet. Since the main purpose of the present work was evaluation of climate and flow regime effects on lake volume response, the lake outlet conditions were kept constant for three lakes. The lake outflow was calculated using the Kymi river rating curve when the lake level reaches the threshold for outflow to occur.

The lake volume, area and elevation in different months were obtained from the water balance equation. The model solves the balance equation with a monthly time step. The simulation starts with a fixed water level at month 1 in the lake (full, empty or mean) which defines S_1 and A_1. At the end of month 1 (before month 2), the lake volume S_2 is obtained from the balance equation (Eq. 5). First the area at first day of month 2 is assumed equal with A1 ($A2=A_{1)}$ and S_2 solved using Eq. 5. Then from S_2 a new estimate of A_2 is obtained using the lake area when volume curve is used. If the new A_2 is different from the initial A_2, then the iteration is continued until a convergence criterion of difference less than 0.01 km^2 is obtained (Fig. 5b).

2.2.2 Simulation and comparison of lake responses

The water balance equation can be used to simulate lake water level response to changes in climate and river regime for different sizes of lakes. Here the simulations were carried out for different lake initial conditions, assuming the lake to be full, equilibrium volume and empty of water. The 'full' case represents the general situation for lakes in a cold-wet climate (e.g. in Finland lakes usually show low variations in annual water level Fig. 3d) and the 'empty' case represents the situation in a hot-dry or moderate climate with extreme water use (e.g. in Iran, the Bakhtegan lake downstream of the Kor river shows high fluctuations in water level within years and in some years is dry in October Fig. 3e). By considering these three states, we generated 225 (3 x

75) different water resource systems to be simulated. The response in these lakes to different river and climate forcing was calculated using data from the five rivers with different regimes listed in Table 1.

In order to show the impact of river discharge on lake volumes, we used the concept of capacity inflow ratio (CIR) (Rami Reddy, 2005), which is defined as the ratio of maximum lake capacity to mean annual river flow (Eq. 7):

$$CIR = MLC/MAF \quad (7)$$

where MLC is maximum lake capacity or volume (m^3) and MAF is mean annual river flow (m^3). The lake geometry can be represented as hypsographic (area-volume-depth) curves and maximum lake capacity can be calculated from topography maps and the lake depth-area-volume curve. By selecting 0.10 km^3 as scaled flow, a good variation in CIR from below 1 to 30 was obtained. For open lakes, the CIR can also be interpreted as nominal or theoretical residence time (V/Q), the scaling produced residence times (CIRs) from 0.24-30 years, which are typical for a wide distribution of lakes (Albert et al., 2005).

In order to show the effect of different controlling factors (effective precipitation and river flow) on lake hydrological status (e.g. as a habitat), the DLW index was devised. According to this, lakes can be divided into five wetness categories based on lake volume as a percentage of total volume or nominal volume as: dry (<20%), semi-dry (20-40%); normal (40-60%), semi-wet (60-80%) and wet (>80%). Based on the simulation results or real data on past lake level fluctuations, the length or duration (number of months) of that water level in different zones can be calculated. Using the calculated distribution into different wetness categories, DLW is then calculated as scaled weight average:

$$DLW= (A_1*10+A_2*30+A_3*50+A_4*70+A_5*90- 1000) / 8000 \quad (8)$$

where A_1, A_2, A_3, A_4 and A_5 is the percentage of time which lake is in dry, semi-dry, normal, semi-wet and wet conditions, respectively (duration in months/total record, here 480 months). DLW can vary between 0-1. If the lake experiences more than 80% of maximum capacity in all months of the year (A5=100 and A1-A4=0), DLW is 1 (higher boundary condition for DLW). If the lake experiences less than 20% of maximum capacity in all months of the year (A1=100 and A2-A4=0), DLW is 0 (lower boundary condition for DLW). The values

1000 and 8000 in Eq. 8 are two constants to scale the boundary conditions to 1 and 0 when DLW is calculated. The DLW of a lake can be calculated based on historical lake operation data, estimated by aerial photo or satellite data for a period of years, or simulated based on time series data as mentioned previously. For the present case studies (Table 1), DLW was simulated based on 40 years of data.

The DLW index is here split into two indexes that are a measure of mean and variability around the mean volume (see Fig. 6a and b). DLW_1 can be evaluated as a weighted mean value that indicate lake volume (percentage of total volume based on lake geometry where the volume vary from 0 to maximum physically based volume 1.0, see Fig. 6a). DLW_2 index show how the lake volume fluctuation is distributed between maximum and minimum historical lake volume. Together these indexes show the lake volumetric state and the lake regime pattern. Based on $DLW_{1\ \mathrm{or}\ 2}$, the lakes were classified into five groups, as shown in Table 2. These classes for DWL_1 were based on the concept of open and closed lakes (e.g. Langbein 1961) by adding a refined scale. For DLW_2 the scale is based on the interval where the lake volume is predominantly observed.

In order to show the range of lake volume variations, the maximum-minimum and absolute maximum-minimum ratios can be calculated based on long-term simulation results as:

$MMR=((Max_{volume} - Min_{volume})/Mean_{volume})$ (9)

$AMR=((AMax_{volume} - AMin_{volume})/Mean_{volume})$ (10)

where Max_{volume} is mean annual maximum volume during long-term simulation, Min_{volume} is mean annual minimum volume during long-term simulation, $Mean_{volume}$ is mean volume during long-term simulation, $AMax_{volume}$ is absolute monthly maximum volume during long-term simulation and $AMin_{Volume:}$ is absolute monthly minimum volume during long-term simulation.

Another important parameter that can show lake historical performance is the amount and duration of outflow (NSP). Occasionally, due to a high amount of inflow or low lake capacity, some part of inflow is conveyed out of the lake system. Thus at the end of simulation, the number of months when outflow occurred (NSP) could show how long the lake has been connected to a downstream outlet (NSP >0 indicates ‘open’ lake (lake with outlet, Fig. 3d); NSP = 0 indicates ‘closed’ lake (lake without outlet, Fig. 3e)).

3. Results

The results showed that the lake response to water balance changes is dependent on: i) effective precipitation or climate, ii) size of lake, iii) river regime and iv) initial condition of lake level/capacity. The response time (Fig. 7) for lake level to reach dynamic equilibrium for the three different lake initial conditions (full, medium, empty) depends on the CIR. It took from several months for low CIR to several years for high CIR when the initial volume was full or empty (high and low water level, respectively). For example, the results for three initial conditions for lake model L3 (Puula lake with CIR=30) with the Kymi river inflow regime R2 (R2C1L3, R2C2L3, R2C3L3, R2C4L3 and R2C5L3, Figs. 7a- 7c) showed a long response time of about 20 years for the lake to reach dynamic equilibrium for empty (Fig. 7a) or full (Fig. 7b) initial conditions, respectively. The response time was lower for smaller lake systems, i.e. about five years for a lake with CIR=3.0 (L2), and less than one year for a lake with CIR=0.24 (L1). Fig. 7a could represent an example of an impacted (vanished) lake projected for recreation with 0.10 km^3 flow rate (e.g. as environmental flow allocation). As the diagram shows, the equilibrium volume would be obtained after 20 years in that case. In contrast, Fig. 7b could be considered a natural lake supplied by a river subjected to several constructions (dams), reducing the flow to 0.10 km^3, so it has started to shrink and the final impacted state of the lake would be observed after about 20 years.

The final steady state equilibrium lake volume in different months depends on climate and river regime (Figs. 8, 9). The lake levels fluctuate around an equilibrium volume, as seen in Fig. 8. For example, a lake with high CIR (e.g. L3 Puula) and with a regulated river inflow regime (e.g. R2 Kymi) would have a different volume in different climates, varying between 0.286 km^3 for a hot-arid desert climate (C5) to 3.0 km^3 for a cold-wet climate (C1). For lakes with low CIR, the equilibrium lake volume can be defined as the maximum water capacity of the lake, e.g. for L1 and L2, the major parameter defining the equilibrium volume of the lake is the maximum physical volume, which is 0.30 and 0.024 km^3, respectively. Following a change in CIR or climate pattern, the lake level will find a new equilibrium volume, although as the results in Fig. 7 show, this can take more than 20 years for large lakes.

Lakes in a cold-wet climate have the smallest annual water volume changes (Figs. 8 and 9). The monthly lake volume fluctuation increases when the CIR increases, as seen e.g. from water volume simulations for R3C5 (Fig. 8). The monthly lake volume variation also increases as the flow regime changes from uniform to seasonal, as seen by comparing e.g. cases R1C4, R2C4, R3C4, R4C4 and R5C4 (different river regimes in climate C4). In the uniform flow regime (low fluctuation in monthly discharge, e.g. R1 (Colorado) and R2 (Kymi) with SDSD = 0.96 and 1.52, respectively), the lake monthly variation (R1C2-R1C5 and R2C2-R2C5, Fig. 8) follows the climate pattern (Fig. 4b), while in a highly seasonal flow regime like that of R5 (Godavari) and R4 (Plate) (SDSD = 4.85 and 4.26, respectively), the pattern of monthly distribution of lakes (R5C1-R5C5 and R4C2-R4C5; Fig. 8) is similar to the flow regime pattern (Fig. 2).

The simulation results showed that for lakes with small CIR (L1 and L2 cases), the maximum annual lake volume is quite similar for different climate and inflow regimes (Figs. 9a and b). These lakes reach the maximum water level every year and outflow occurs. The minimum water level in these lakes depends on the flow regime in climates C2- C5 (Bsk, Aw, Cs, and Bwh), except in climate C1 (Dfc) (Figs. 9g and h). For lake L3 with CIR=30, the maximum minimum and mean lake water volumes are mostly dependent on climate and only slightly on river regime (Figs. 9c, f and i). The maximum-minimum (MMR) and absolute maximum-minimum ratio (AMR) in lakes L1-L3 are dependent on climate (have been increased from C1 to C5) and flow regime (have been increased from R1 to R5) (Figs. 9j-l and Tables 3-5). The difference in MMR and AMR increases when the flow regime shows high monthly variation from uniform (R1) to seasonal (R5), as seen in Tables 3-5.

The lake level change indicator developed here, DLW, is sensitive to changes in lake hydrology, climate and river regime. DLW_1 provides general results where lakes are compared and DLW_2 provides an indicator to show past historical stages. For lakes with CIR=30, DLW_1 is 0.00 (‘Closed predominantly dry lake’), 0.25 (‘Closed temporarily dry lake’), 0.72 (‘Open temporarily wet lake’), 0.75 ‘Open temporarily wet lake’) and 1 (‘Open predominantly wet lake’) for the climates C5- C1 (Bwh, Cs, Aw, Bsk and Dfc respectively). Using DLW_2, lake systems with CIR=30 are classified as lake with ‘predominantly near maximum observed volume for a cold-wet climate with continuous discharge surplus. For other climates and river regimes they are classified as lake with ‘predominantly around average observed volume (Table 3). With DLW_2, lake systems with CIR=3 are classified as lake with ‘predominantly near maximum observed volume ’ for all river regimes in C1 climate and most other cases except for rivers R3 and R4 in C5 climate and river R5 in other climates, which are classified as lake with ‘predominantly above average observed volume (Table 4). With DLW_2, lake systems with CIR=0.24 are classified as ‘predominantly near maximum observed volume’ for all cases except river R5 in all climates C2-C5 (Bsk, Aw, Cs, and Bwh) which is classified as lake with ‘predominantly above average observed volume (Table 5).

Given a certain climate and flow regime, the lake type (as open or closed) is controlled by the CIR. Lakes in a cold-wet climate are always open (have an outlet), but for lakes in other climates this depends on CIR. The duration of outflow (NSP) shows that lakes with high CIR in a cold-wet climate have outflow in 98-100% of the simulated months (480 months), whereas in other climates the lakes with high CIR are closed lakes. Smaller lake systems with CIR=3.00 discharge water most of the time when the river regime is regulated and have a uniform flow regime (see 8 first rows in Table 4). For medium-size lakes with uniform flow in a temperate or hot arid climate (R2C4L2 and R2C5L2), the lakes are occasionally closed, as NSP is less than 480 months. For seasonal river regimes (R3-R5), the NSP is lower than for uniform regimes. The smallest lake (CIR=0.24) has the highest NSP (Tables 3-5).

4. Discussion

4.1 Validity of the selected framework

The main innovation with the selected framework is to enable wide analysis of how various lakes behave and respond to external pressures. In order to do so, river flow and lake volumes are scaled for a more general comparison. This scaling does not influence the lake level change patterns, but has an influence on absolute values which are not so relevant when different types of lakes are compared. The approach developed can be seen as a sensitivity study for lakes in different climate zones and having different hydrologic gradients e.g. form dry to wet conditions. To our knowledge, no such analysis has been made previously, as this type of data would be difficult to obtain for the large range of cases presented.

The flow regimes used are based on real data from representative rivers. The rationale for combining various flow regimes for various climates is justified by Fig. 3, which demonstrates that different regimes occur in different climates (see also appendix B). A seasonal regime is observed in cold climate which is controlled by seasonal snowmelt (R4 with SDSD: 4.26 for Platte river in USA or Beatton river with SDSD: 3.7 in Canada), and warm climate controlled by seasonal rainfall or monsoon (R5 with SDSD: 4.85 for Godavari river in India, Atbara river in Sudan with SDSD: 5.58) (Fig. 3 and appendix B). A uniform flow regime can be found where a large lake control the outflow such as for cold climate (R2 Kymi river in Finland, with SDSD: 1.52, Angara river in Russia with SDSD: 0.29) and for warm climate (R1 Colorado river below Hoover dam in USA, with SDSD: 0.98, Nile river below Aswan dam in Egypt, with SDSD: 0.73). Also, one of the main reason for variety in flow regimes in different climate is that about 59% of the world's rivers are regulated (Nilsson et al., 2005), resulting in major changes in river regime. The impact of changes in natural regimes on water volume can be seen in Fig. 8 by comparing the regulated river case to other flow regimes. This type of analysis is useful for assessment of seasonal variations in river flow. Impacts of short-term regulation (e.g. daily or hourly) cannot be deduced, as monthly data were used. However, monthly data are much more available than higher resolution data and in many cases regulation is also based on monthly consideration of water inflow and demand. While large river systems produce a less dynamic monthly hydrograph than smaller river systems, the selected rivers provide a sufficient variation pattern in river regimes (from regulated to seasonal) that is needed to study impacts of river regimes on lakes.

The variation in climate was represented here as a variation in effective precipitation, which is a measure of water availability. The method is most suitable for evaluating the sensitivity of lakes to changes in water availability (inflow) caused by e.g. irrigation or climate variability or shift (e.g. Deser et al., 2012). The impact of anthropogenically induced climate warming on hydrology is normally smaller than the changes discussed here and occurs over longer time periods. For several river basins, the main effect of climate warming on river flow or water availability will be changes in snow melt. Such specific changes are reviewed by e.g. Barnett et al. (2005) and beyond the scope of the present study.

The approach used relies on scientifically based assumptions regarding e.g. the representativeness of selected lake sizes, flow regimes and climate, and also on the possibility of combining these independently. The lake hydraulic characteristic represented by the CIR parameter is similar to mean hydraulic residence time, which is commonly used e.g. in the Vollenwieder (1976) model. Due to this scaling, the simulated results for lakes are independent of lake capacity and flow magnitude and both independent parameters are gathered as one parameter in CIR. The range of lakes studied covered typical lake sizes with residence times ranging from less than a year to 30 years. The analysis excluded very large lakes with low inflow compared with their volume (high CIR; e.g. Caspian Sea, Lake Baikal). In order to place emphasis on the impact of flow regimes, 100 m^3 yr^{-1} (or 3.17 m^3 s^{-1}) was used as scaling ratio thereby removing the effects of magnitude in river flows in the five river models used (R1-5). Also, the scaling ratio was selected, considering the selected lake volumes which range from 24 to 3000 MCM, in order to produce sensible CIRs representing typical range of lake "residence times" ranging from 0.24 to 30 $years^{-1}$.

4.2 Water level model validity

The selected water level model applies the water balance equation, where the outflow is considered as a residual term. This concept is widely used and well-validated for many lakes in different climates, hydrological conditions and regulation regimes (e.g. Niedda et al., 2014; Muvundja et al., 2014; Troin et al., 2012; Yihdego and Webb, 2012; Demlie et al., 2007; Kebede et al., 2006). An alternative approach is to employ the storage-outflow method, which is commonly used in reservoir routing in open lakes where inflow dominates the water balance (e.g. Chow, 1988). However, the water balance equation includes evaporation in a more direct way as lake evaporation is estimated, which is relevant especially for closed lakes where evaporation is a large component of the water balance (e.g. Langbein, 1961; Wood and Sanford, 1990; Sanford and Wood, 1991).

The monthly modelling neglects the small time lags (hourly or daily) between inflow and outflow hydrographs. However, using a monthly time step is a common approach in water balance simulations (e.g. Muvundja et al., 2014; Yihdego and Webb, 2012; Becht and Harper, 2002) and can be considered sufficiently accurate for the purpose. The use of a more dynamic approach where outflow depends on water levels would require specific knowledge on outlet configurations. For more specific simulations for a special case with known outlet configuration, a dynamic approach would be more appropriate.

4.3 Sensitivity of lakes to climate and river regimes

The simulations showed that lake equilibrium volume is mainly controlled either by climate or by CIR (lake hydraulic properties). For large CIR, the steady state lake level (equilibrium lake volume) depends on climate and to some extent also river regime. For example, a lake with high CIR and with a regulated river inflow regime has a different equilibrium volume in different climates, varying between 0.286 km^3 for a hot-arid desert climate to 3.0 km^3 for a cold-wet climate. Following a change in inflow (CIR) or climate pattern, the lake level will find a new equilibrium volume, although as the results in Fig. 7 show, this can take more than 20 years for large lakes. These results can be used in climate change studies to estimate expected response times, which may be long, following the impacts of land use and climate change. For lakes with low CIR, the equilibrium volume can be defined as the maximum water capacity of the lakes and could found from hypsometric characteristics of lake. As seen in Figs.8 and 9, for smallest lakes with CIR=0.24 the maximum calculated volume is 0.024 km^3 (equal with maximum volume based on hypsometric curve Fig. 1a), while for lake with CIR=3 it fluctuates around 0.30 km^3 (equal with maximum volume based on hypsometric curve Fig. 1b).

The sensitivity of lakes to climate and river regimes also depends on timing of runoff and evaporation. In most hydrological conditions, runoff is low when effective precipitation is low (ET is high), except for mountainous regions with considerable snowmelt during summer. This can be seen from the flow regime and climate pattern of R3 (Kor river) and R4 (Platte river) (Figs. 2 and 4). In a cold-dry climate as in Platte (Wyoming, USA), runoff peaks in summer months due to snowmelt in the mountains. The combination of high runoff and high evaporation make mountain lakes less sensitive to water level variations caused by summer drought, e.g. as seen in Fig. 9f where the average lake volumes are decreasing when the flow regime changes from regulated to seasonal. However, for R4 the lake volume increases instead of decreases (in comparison with R3) which is due to snowmelt occurring at the same time as ET maximum.

For lakes in a cold and wet climate (C1), the difference between maximum and minimum water levels is small. Thus in normal condition the water level in these lakes stay at the maximum level and changes in river flow regime will not have a major effect on lake levels. Lakes in a warm climate are sensitive to changes in water quantities. As the water use in these regions is under high pressure for agriculture and hydropower, lake level changes have already occurred. Further water level changes can be expected for lakes with high CIR, whereas lakes with low CIR may experience only very slight changes, despite intensive water use and regulation. The method developed here could be used on a regional scale to map lakes that are sensitive to water extraction and changes in land use.

4.4 DLW as an index for lake environmental flow management

The DLW index developed here could be used as a simple index to describe lake hydrological regime. DLW represents a statistical characteristic of the lake based on lake volume past times series and classifies it. DLW_1 is suitable for lake classification as closed or open. DLW_2 index is useful to show whether the lake level is predominantly near the observed maximum or minimum observed volume, as it is scaled to historical fluctuations in the lake. The index DLW_1 is a measure of the average filling percentage determined by a scaled weighted average based on five interval groups as (0-20 with midpoint as 10), (20-40 with midpoint as 30), (40-60 with midpoint as 50), (60-80 with midpoint as 70), (V>80 with midpoint as 90) that are scaled using two constant coefficients (1000 and 8000 to achieve a scale from 0 to 1.0). The use of average filling percentage as an alternative index could be justified, but in some cases for lakes with outflow the maximum level is not always defined from historical records and a filling percentage above 100% can result (if the lake floods above past historical levels). In the past, water level fluctuation within years and between years has been considered a key factor in lake and wetland management (Coops et al., 2003; Paillisson and Marion, 2011). However, using water level data alone does not summarise lake status. The major merit advantage of the DLW index is that it helps to quantify lake response to changes in different components of the water balance equation. Use of the DLW index could help decision makers to better understand how lake hydrology changes due to different water allocation scenarios. DLW can be used to quantify climate change effects and the impacts of hydraulic structures on lake regimes. For example, it can be calculated in two main periods before and after dam construction and the results can be used for quantifying the impact of the dam on a water body. DLW can be used in allocation of environmental flows to lakes and wetlands as an index to calculate the lake status after impact due to dam construction.

5. Conclusions

This work examined the effect of changes in different effective parameters on lake hydrological regimes. Three lakes with different hydrological characteristics (CIR, i.e. volume/inflow) were placed at the end of virtual water resources systems incorporating different scaled river regimes such as seasonal and regulated. They were then subjected to five different climates (hot-arid, moderate, tropical, cold-arid and cold-wet). At high CIR (large lake compared with inflow), the lake regime mostly depended on climate pattern. With decreasing CIR the effect of climate pattern decreased and the effect of flow regime increased. This explains why certain lakes suffer from a water level decline, whereas other lakes have a stable water level. A new parameter, Degree of Lake Wetness (DLW), was developed for explaining the lake regime. DLW_1 is a measure of the lake filling percentage and DLW_2 of the lake regime (it show what is the predominant lake volume). Based on DLW_1 index, lakes can be classified into five main groups between the end-points 'open' and 'closed' as: 'closed predominantly dry', 'closed temporarily dry', 'closed intermittent', 'open temporarily wet' and 'open predominantly wet'. Using DLW_2, the regime variation could be classified from predominantly near minimum observed volume to predominantly near maximum observed volume. Quantifying lake state in natural flow regimes using the DLW parameter could help assess the effect of any change in flow regime or flow rate due to e.g. hydraulic constructions. Here DLW was calculated for the different case studies in order to classify the lake in different climate and river flow regimes. In future work, DLW can be calculated based on climate conditions in different periods and the results can be compared to show the effect of variations in river regime or climate change on lake systems.

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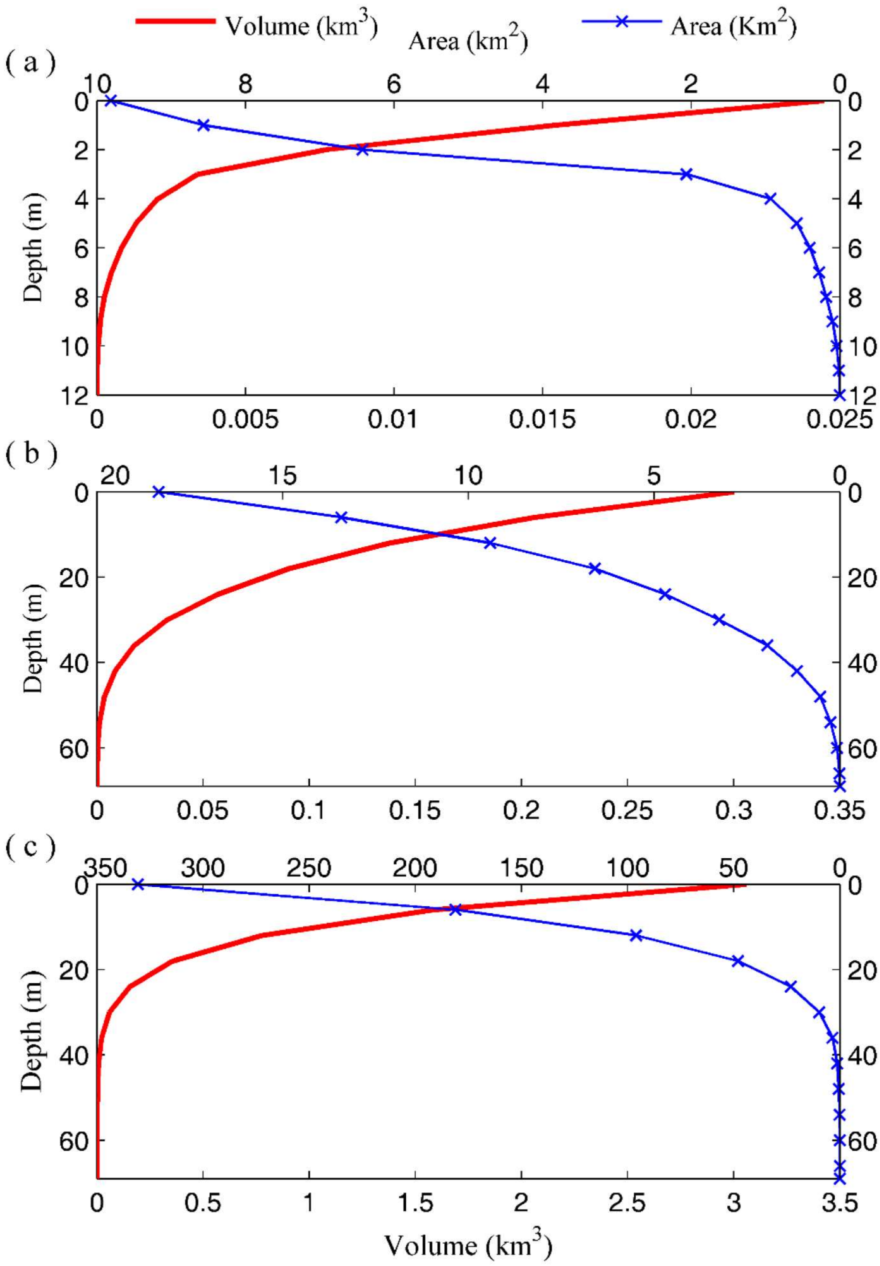

Fig. 1. Depth-area-volume curves for lakes: a) Tammijärvi (L1), b) Isojärvi (L2) and c) Puula (L3) in Finland (http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp).

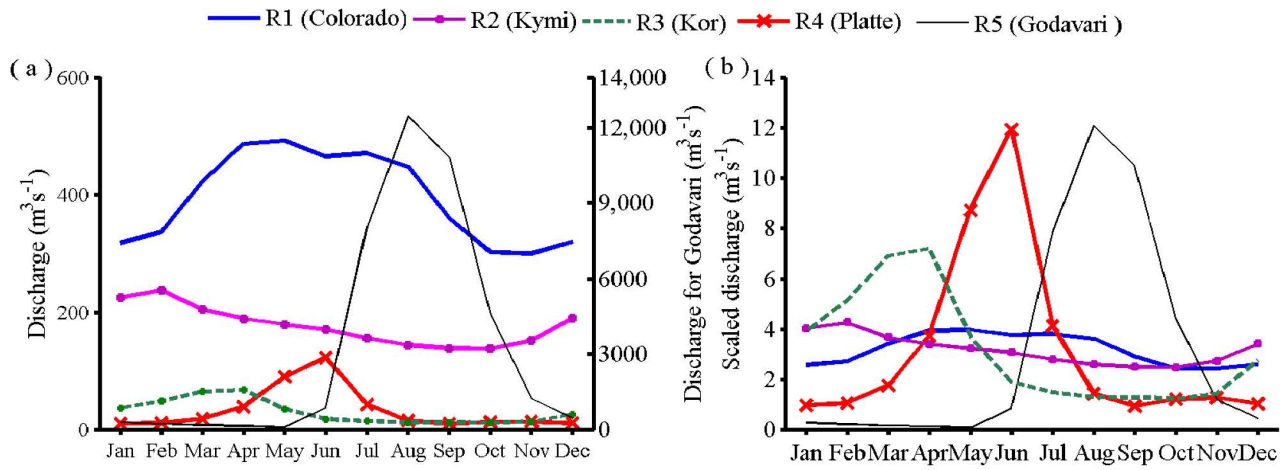

Fig. 2. Hydrological regime for different case studies with a) observed discharge and b) scaled discharge.

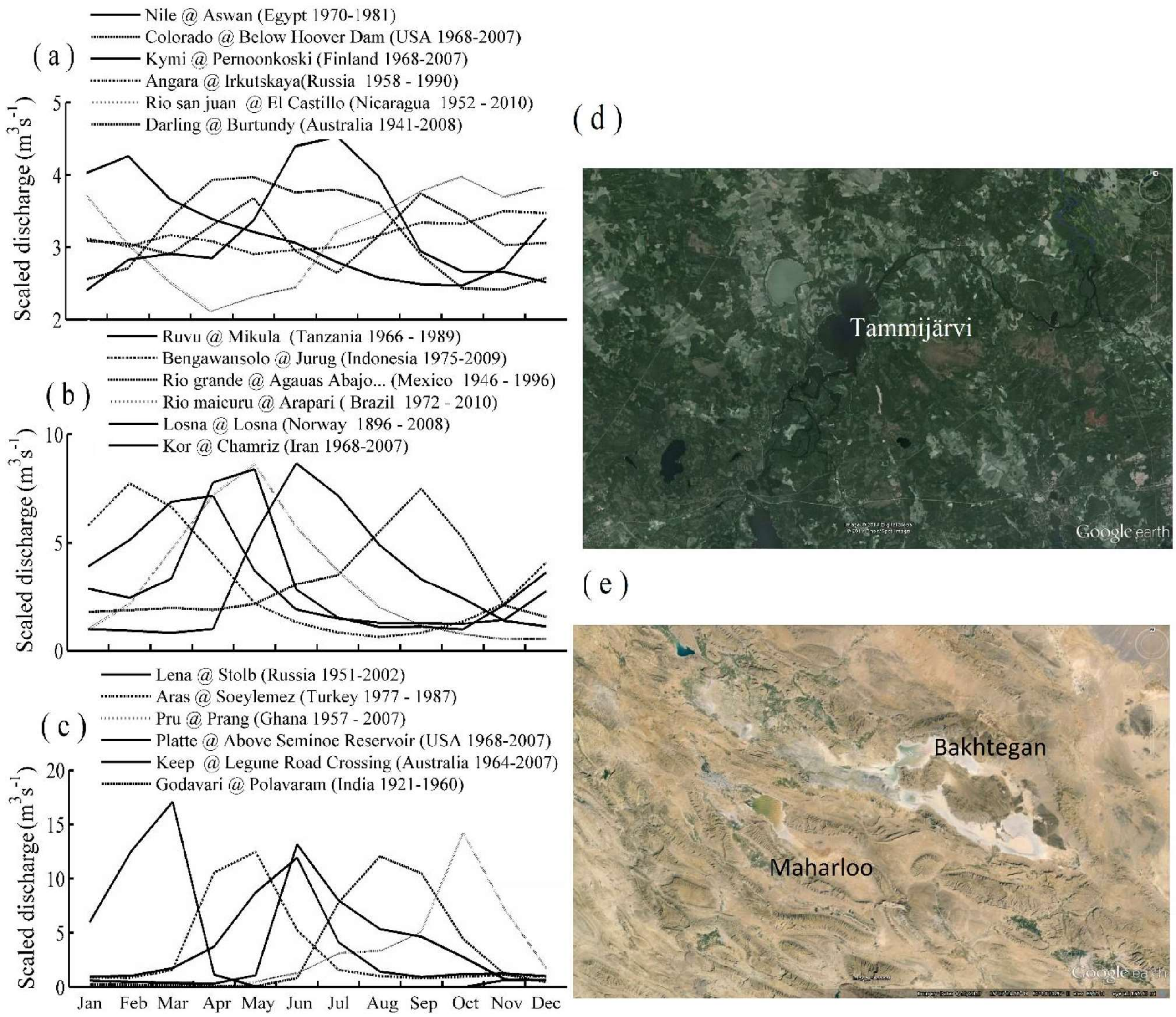

Fig. 3. Example of lake and river flow regimes in different climate1: a) Rivers with uniform flow (similar with R1 (Colorado) and R2 (Kymi) rivers), b) river regimes between strong seasonal and uniform flow (similar with

R3 (Kor) river) and c) rivers showing a strong seasonal regime (similar with R5 (Godavari) and R4 (Platte) rivers), d) an open Lakes in a cold-wet climate (Lake Tammijärvi, Finland) and e) two closed lakes in a dry climate (e.g. Bakhtegan and Mahrloo in southern Iran). River data from http://www.sage.wisc.edu/riverdata/ and source of images: Tammijärvi: 60°34'54"N and 26°32' 29"E 4/10/2113, Bakhtegan lake: 29°33'56.72"N and 53°32'24.76"E 4/10/2113, Google Earth.

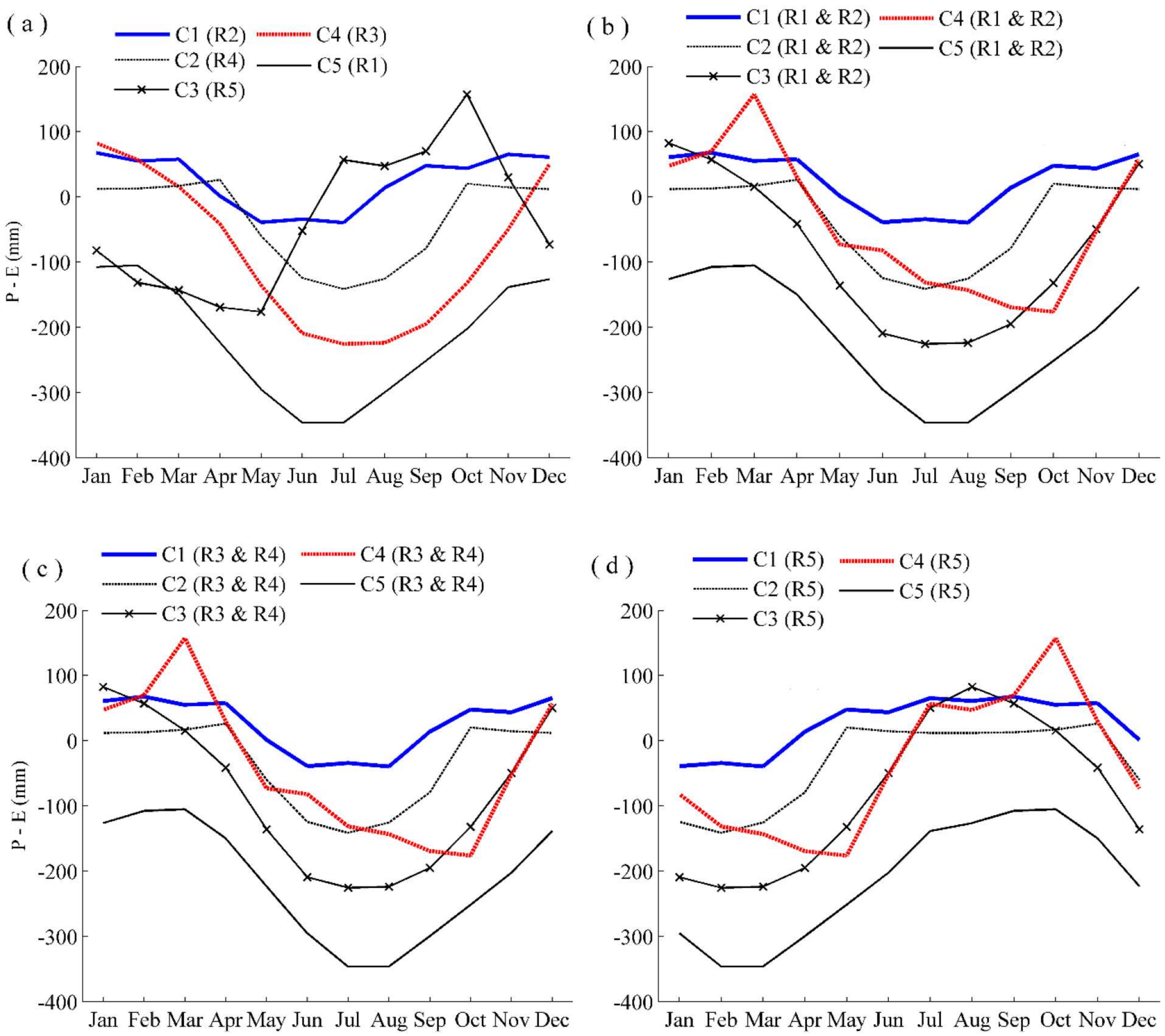

Fig. 4. Climate data for different river systems: a) Original climate for different rivers, b) climate pattern data used for the Godavari river regime cases, c) climate pattern data used for the Platte and Kor river regimes cases and d) climate pattern data used for the Kymi and Colorado river regimes cases. The climate classes are Bwh: hot-arid desert, Bsk: cold arid steppe, Dfc: cold without dry season, Aw: tropical savannah and Cs: temperate with hot and dry summer.

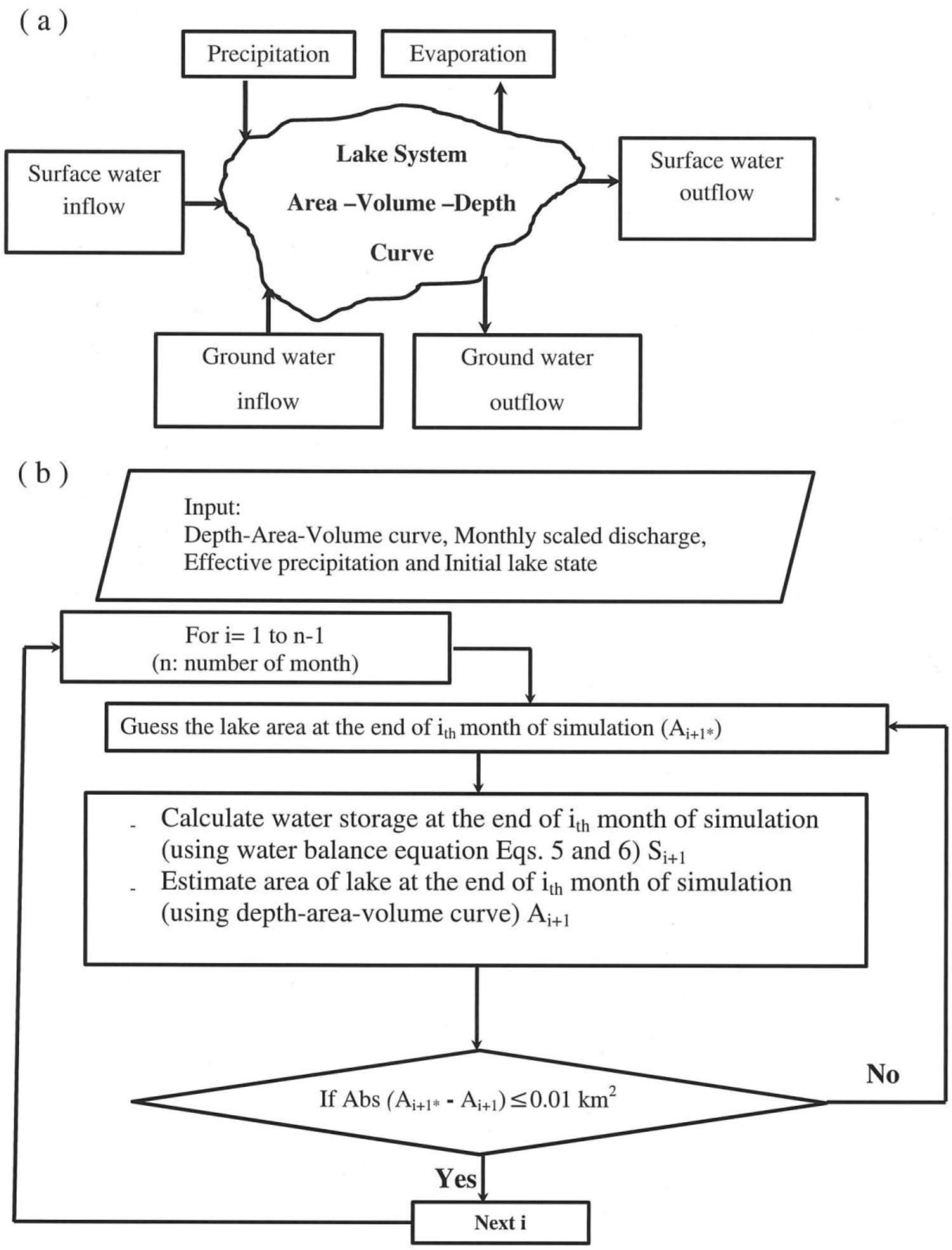

Fig. 5. Flow chart for a) lake system and b) lake level calculations.

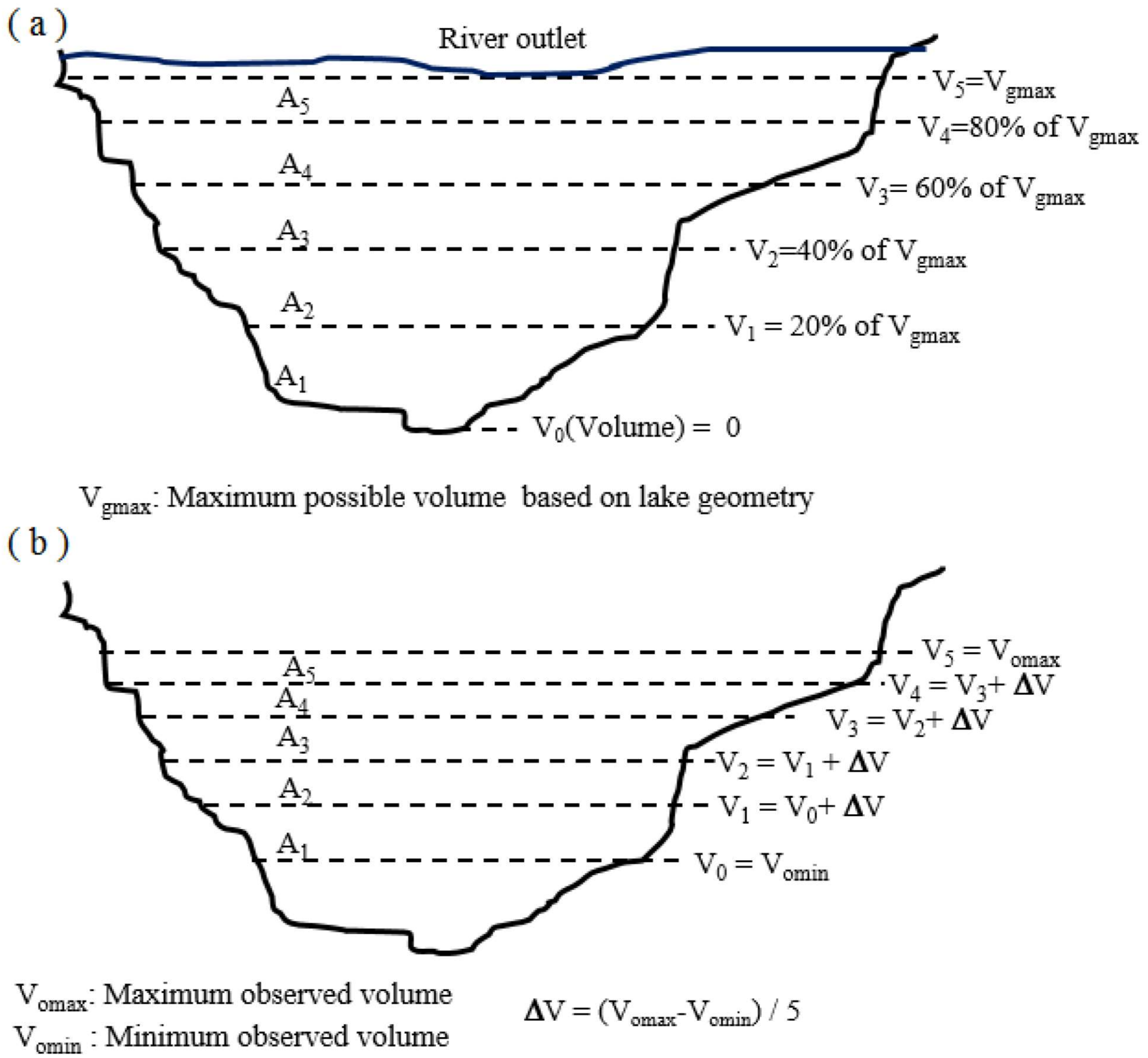

Fig. 6. Graphical demonstrate of DWL concept: a) DWL_1, b) DWL_2, A_1-A_5: number of months which lake volume between V_0-V_1, V_1-V_2, V_2-V_3, V_3-V_4, V_4-V_5 respectively.

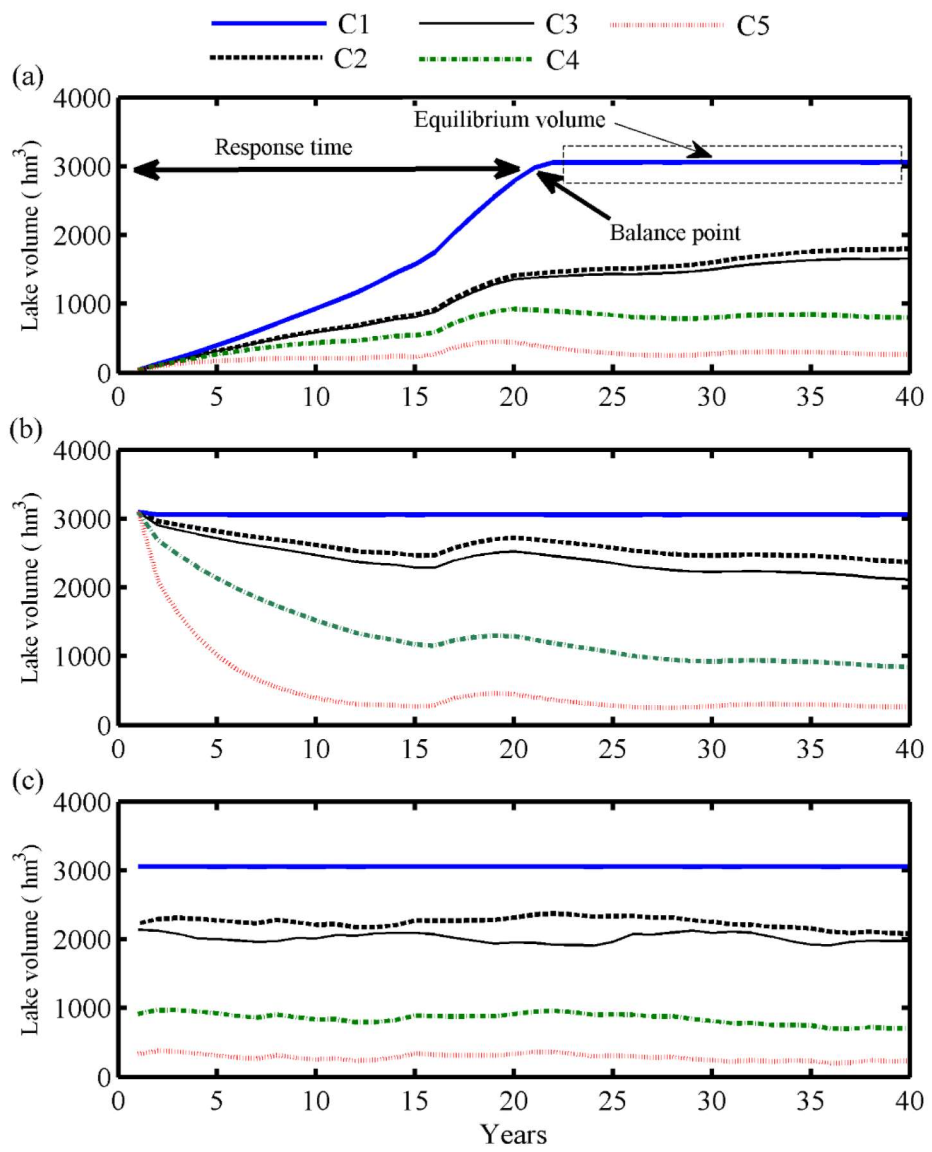

Fig. 7. Lake volume fluctuation for Lake L3 (CIR=30) with River R2 (Regulated river system Kymi regime) in different climates. a) Rising state (volume at start point is empty), b) falling state (volume at start point is full) and c) stable state (volume at start point is intermediate). C1: Cold without dry season (Dfc), C2: cold-arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, and dry summer (Cs) and C5: hot-arid desert (Bwh).

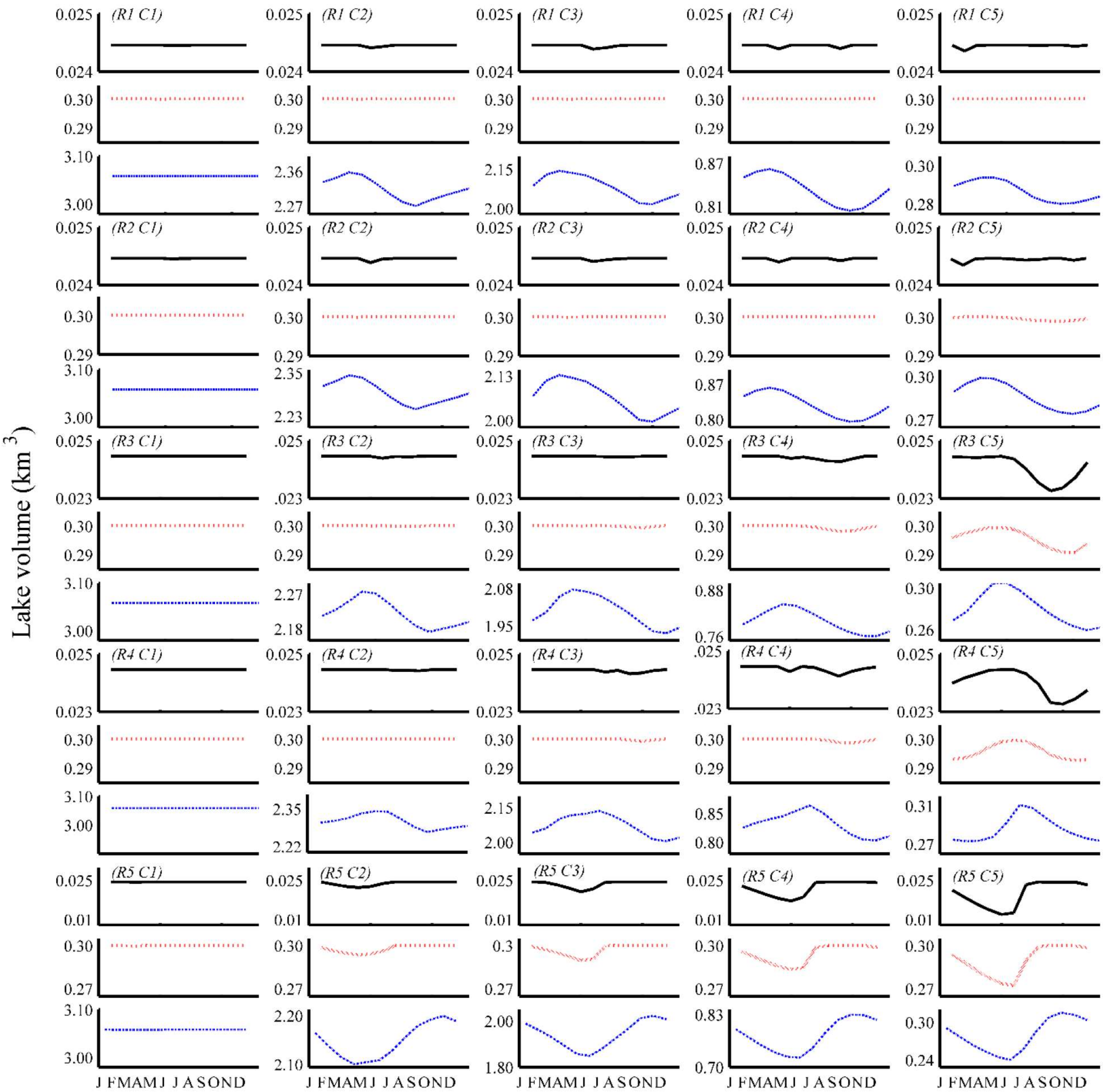

Fig. 8. Long-term monthly average volume (40 years) for different lake systems based on third initial condition, black solid line: lake L1 CIR=0.24, red dashed line: lake L2 CIR=3, blue dotted line: CIR=30. R1: Colorado river regime, R2: Kymi river regime, R3: Platte river regime, R4: Kor river regime, R5: Godavari river regime, C1: cold without dry season (Dfc), C2: cold-arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, and dry summer (Cs) and C5: hot-arid desert (Bwh).

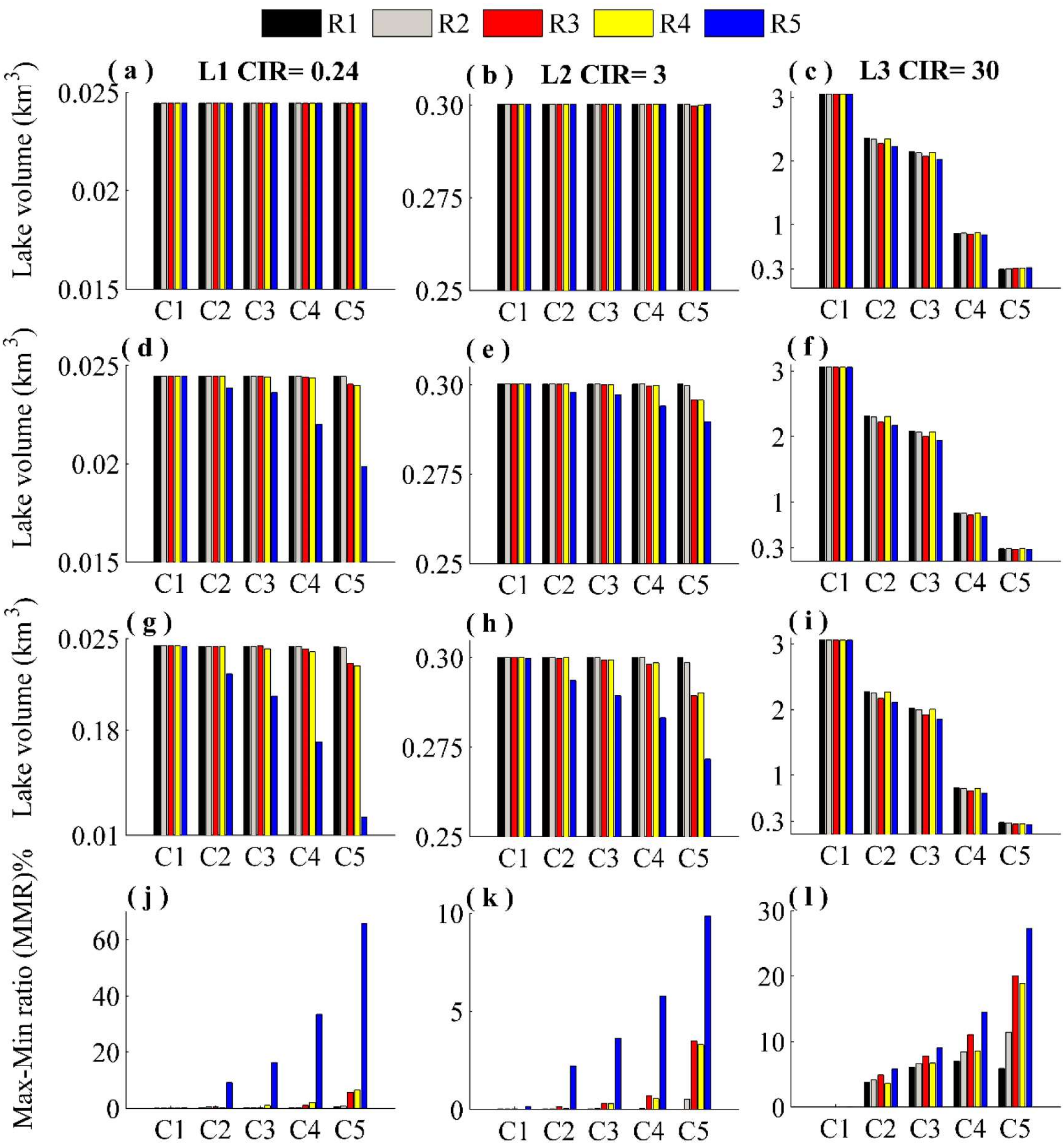

Fig. 9. Summary of simulation results for different lake systems. a-c) Mean monthly maximum lake volume, d-f) mean monthly lake volume, g-i) mean monthly minimum lake volume and j-l) max-min ratio (MMR), R1: Colorado river regime, R2: Kymi river regime, R3: Platte river regime, R4: Kor river regime, R5: Godavari river regime, C1: cold without dry season (Dfc), C2: cold-arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot, and dry summer (Cs) and C5: hot-arid desert (Bwh).

Table 1. Characteristics of the five rivers and five climate classifications used in simulations.

	River									Climate	
						Mean				Class	
	Name	Country	Available Data years	Gauge Stations	system	Inflow m^3s^{-1}	Prec. mm	Evap. mm	Temp. °C	Köppen	
R1	Colorado [a]	USA	1934-2011	Below Hoover Dam	Regulated	392.6	155.4	3919	23.0	Bwh	C5
R2	Kymi [b]	Finland	1900-2010	Pernoonkoski	Regulated	176.8	667	521	3.0	Dfc	C1
R3	Kor [c]	Iran	1968-2011	Chamriz	Seasonal	29.5	550	2150	17.7	Cs	C3
R4	Platte [a]	USA	1939-2011	Ab. Seminoe Res.	Seasonal	32.5	230	919	5.8	Bsk	C2
R5	Godavari [e]	India	1900-1975	Polavaram	Seasonal	3271	1087	2216	28.7	Aw	C4

[a] River data from http://waterdata.usgs.gov/nwis/monthly/; climate data from Climatography of the United States No. 20. [b] River and climate data from http://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp.http://www.wrcc.dri.edu/htmlfiles/westevap.final.html. [c] River and climate data from Fars regional water authority . [d] River data from http://www.sage.wisc.edu/riverdata/; climate data from http://www.tropmet.res.in.

Table 2. Lake classification based on Degree of Lake Wetness (DLW).

Lake group	**DLW Range**	**Lake index**	
		DLW_1	DLW_2 (lake volume predominantly)
I	$0 \leq DLW < 0.2$	Closed predominantly dry lake	Close to Minimum observed volume
II	$0.2 \leq DLW < 0.4$	Closed temporarily dry lake	Below average observed volume
III	$0.4 \leq DLW < 0.6$	Closed intermittent lake	Around Average observed volume
IV	$0.6 \leq DLW < 0.8$	Open temporarily wet lake	Above Average observed volume
V	$0.8 \leq DLW < 1$	Open predominantly wet lake	Near Maximum observed volume

Table 3. Summary of simulation results for lake L3 (CIR=30) in different river regimes and climates.

Case	DLW1	DLW2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L3	1	1	480	3059	3059	3059	3059	3059	0.00	0.00
R1C2L3	0.80	0.56	0	2314	2562	2042	2358	2270	0.04	0.22
R1C3L3	0.73	0.56	0	2082	2367	1767	2144	2017	0.06	0.29
R1C4L3	0.25	0.51	0	833	1038	667	863	804	0.07	0.45
R1C5L3	0.00	0.43	0	287	397	218	296	279	0.06	0.62
R2C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R2C2L3	0.75	0.57	0	2295	2468	2049	2345	2250	0.04	0.18
R2C3L3	0.74	0.56	0	2067	2304	1776	2134	1996	0.07	0.26
R2C4L3	0.25	0.54	0	829	989	661	865	795	0.08	0.40
R2C5L3	0.00	0.49	0	286	413	184	303	271	0.11	0.80
R3C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R3C2L3	0.75	0.46	0	2220	2411	2074	2279	2170	0.05	0.15
R3C3L3	0.75	0.50	0	2002	2204	1818	2078	1922	0.08	0.19
R3C4L3	0.25	0.46	0	800	997	658	846	757	0.11	0.42
R3C5L3	0.00	0.49	0	281	437	174	307	251	0.20	0.94
R4C1L3	1.00	1.00	480	3059	3059	3059	3059	3059	0.00	0.00
R4C2L3	0.77	0.55	0	2307	2534	2041	2350	2267	0.04	0.21
R4C3L3	0.74	0.56	0	2073	2325	1752	2141	2002	0.07	0.28
R4C4L3	0.25	0.52	0	832	1042	647	869	797	0.09	0.48
R4C5L3	0.00	0.52	0	285	440	167	314	260	0.19	0.95
R5C1L3	1.00	0.99	475	3058	3059	3022	3059	3058	0.00	0.01
R5C2L3	0.75	0.47	0	2168	2385	2029	2234	2108	0.06	0.16
R5C3L3	0.73	0.52	0	1942	2172	1772	2024	1849	0.09	0.21
R5C4L3	0.25	0.49	0	782	1014	644	838	724	0.15	0.47
R5C5L3	0.00	0.47	0	280	454	196	317	241	0.27	0.92

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime and R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot and dry summer and C5: hot-arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean of maximum and minimum of volume during 40-year simulation, Ave.: Average volume during 40-year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40-year simulation, MMR: Maximum-minimum ratio, AMR: Absolut Maximum-minimum ratio.

Table 4. Summary of simulation results for lake L2 (CIR=3) in different river regimes and climates.

Case	DLW1	DLW2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C2L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C3L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C4L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R1C5L2	1.00	1.00	480	300	300	299	300	300	0.00	0.00
R2C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C2L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C3L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R2C4L2	1.00	0.92	473	300	300	299	300	300	0.00	0.00
R2C5L2	1.00	0.89	412	300	300	290	300	299	0.01	0.03
R3C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R3C2L2	1.00	0.93	448	300	300	296	300	300	0.00	0.01
R3C3L2	1.00	0.92	429	300	300	295	300	299	0.00	0.02
R3C4L2	1.00	0.86	383	300	300	290	300	298	0.01	0.03
R3C5L2	1.00	0.69	227	296	300	269	300	289	0.03	0.11
R4C1L2	1.00	1.00	480	300	300	300	300	300	0.00	0.00
R4C2L2	1.00	0.92	475	300	300	298	300	300	0.00	0.01
R4C3L2	1.00	0.92	437	300	300	295	300	299	0.00	0.02
R4C4L2	1.00	0.88	404	300	300	291	300	299	0.01	0.03
R4C5L2	1.00	0.64	200	296	300	265	300	290	0.03	0.12
R5C1L2	1.00	0.89	390	300	300	299	300	300	0.00	0.00
R5C2L2	1.00	0.64	245	298	300	293	300	294	0.02	0.03
R5C3L2	1.00	0.72	239	297	300	288	300	289	0.04	0.04
R5C4L2	1.00	0.64	192	294	300	281	300	283	0.06	0.06
R5C5L2	1.00	0.64	161	290	300	266	300	272	0.10	0.12

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime and R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot and dry summer and C5: hot-arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean of maximum and minimum of volume during 40-year simulation, Ave.: Average volume during 40-year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40-year simulation, MMR: Maximum-minimum ratio, AMR: Absolut Maximum-minimum ratio.

Table 5. Summary of simulation results for lake L1 (CIR=0.24) in different river regimes and climates.

Case	DLW1	DLW2	NSP	Ave	A.Max	A.Min	Max	Min	MMR	AMR
R1C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C2L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R1C3L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C4L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R1C5L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R2C2L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C3L1	1.00	1.00	480	24	24	24	24	24	0.00	0.01
R2C4L1	1.00	0.89	480	24	24	24	24	24	0.00	0.01
R2C5L1	1.00	0.93	476	24	24	23	24	24	0.01	0.05
R3C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R3C2L1	1.00	0.94	477	24	24	24	24	24	0.00	0.02
R3C3L1	1.00	0.94	477	24	24	24	24	24	0.00	0.04
R3C4L1	1.00	0.94	458	24	24	21	24	24	0.01	0.15
R3C5L1	1.00	0.86	388	24	24	17	24	23	0.06	0.30
R4C1L1	1.00	1.00	480	24	24	24	24	24	0.00	0.00
R4C2L1	1.00	0.98	476	24	24	23	24	24	0.00	0.07
R4C3L1	1.00	0.93	454	24	24	22	24	24	0.01	0.10
R4C4L1	1.00	0.91	447	24	24	20	24	24	0.02	0.18
R4C5L1	1.00	0.84	382	24	24	16	24	23	0.06	0.35
R5C1L1	1.00	0.96	456	24	24	24	24	24	0.00	0.02
R5C2L1	1.00	0.72	295	24	24	21	24	22	0.09	0.16
R5C3L1	1.00	0.78	321	24	24	19	24	21	0.16	0.25
R5C4L1	0.93	0.67	216	22	24	16	24	17	0.33	0.39
R5C5L1	0.84	0.65	184	20	24	10	24	11	0.66	0.75

R1: Colorado river regime, R2: Kymi river regime, R3: Kor river regime, R4: Platte river regime and R5: Godavari river regime. C1: cold without dry season (Dfc), C2: cold arid steppe (Bsk), C3: tropical savannah (Aw), C4: temperate with hot and dry summer and C5: hot-arid desert (Bwh). DLW_1: Degree of lake wetness based on lake geometry, DLW_2: Degree of lake wetness based on lake history, NSP: Number of months in which water spill occurred, Max and Min: Mean of maximum and minimum of volume during 40-year simulation, Ave.: Average volume during 40-year simulation, A.Max and A.Min.: Absolute maximum and minimum volume during 40-year simulation, MMR: Maximum-minimum ratio, AMR: Absolut Maximum-minimum ratio.