ESTABLISHING THE INFLUENCE OF CLIMATE, WATER EXTRACTION AND TECTONICS ON THE WATER LEVEL OF THE PRESPA LAKES (N GREECE)

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Abstract

This paper aims to establish the main factors that control water level fluctuations of the Prespa Lakes, which are a global biodiversity hotspot. The unprecedented fall (~8m) in lake level threatens the biodiversity and water resources of the interconnected Prespa-Ohrid-Drim catchments (covering Greece, Albania and FYROM) as it reduces discharge and increases pollutant concentrations. Causes for this fall are poorly understood: it has been linked to either (i) climate change, (ii) water extraction, or (iii) earthquake-induced changes to underground drainage. There is an urgent need to establish the causes of major lake level changes, especially given future climate change. This key research question is, for the first time, addressed by analysing hydro-meteorological data from all lake-sharing countries, using basic statistical methods and spreadsheet-based calculations. Annual lake level fluctuations are proven to be strongly related to Oct-Apr precipitation; snow-melt fed discharge is an important component of the lake water balance. Water extraction (~$14*10^3m^3$/year, ~0.004% of lake volume) significantly lowers lake level over multiple decades, accounting for ~30% of the observed fall. There is no correlation between earthquake-occurrence and lake level fluctuations. The results support the conclusion that the unprecedented lake level fall is driven by climate and amplified by water extraction.

Keywords: Prespa Lakes, hydrology, climate, extraction, earthquake

Introduction

The Mediterranean stands out globally due to its sensitivity to (future) climate change, with future projections predicting an increase in excessive drought events and declining rainfall [1-5]. Regional freshwater ecosystems are particularly threatened: precipitation decreases, while extreme droughts increase and human impacts intensify (e.g. water extraction, drainage, pollution and dam-building). Many Mediterranean lake-wetland systems have shrunk or disappeared over the past two decades, while river discharges were simultaneously significantly reduced. Protecting the remaining systems is extremely important for supporting global biodiversity and for ensuring sustainable water availability, particularly in the light of future climate scenarios that predict an increase in excessive drought events and declining rainfall [6-9]. This protection should be based on a clear understanding of hydrological system responses to natural and human-induced changes, which is currently lacking in many parts of the Mediterranean.

Figure 1: Greece and the Prespa-Ohrid Lake system

The interconnected Prespa-Ohrid Lake system (Fig. 1) is a global hotspot of biodiversity and endemism [10-12]. This system is threatened by the unprecedented fall in water level (~8m) of Lake Megali Prespa. Studies have linked lake level change to either (i) climate change, (ii) water extraction, or (iii) earthquake-induced changes to underground karst drainage channels [13,14]. However, causes for this fall remain debated as they could not be validated due to institutional and national barriers to data-access. Modelling suggests that the S Balkan will experience rainfall and runoff decreases of ~30% by 2050 [5,9]. Reports suggest that water abstraction in the Prespa catchment, related to irrigation and urban use, will likely increase in the near future [GFA Consulting, Transboundary Prespa Park Project, Part V, Water resources data: 298p; Society for the Protection of Prespa, Agh. Germanos, 2005. *Hereafter*: GFA 2005 report]. This combination of factors may lead to an accelerated water level fall of the Prespa Lakes in the near future. Unfortunately, projections revealing the potential impact of these changes on future lake level are unavailable as lake regime is not understood.

A further drop in lake level may have serious consequences for water resources and biodiversity. Reducing lake volume increases pollutant concentrations and accelerates the on-going eutrophication, which is transmitted throughout the downstream catchment areas. The Prespa Lakes contribute ~25% of the total inflow into Lake Ohrid through underground karst channels; falling lake levels decrease this discharge. In turn, the discharge from Lake Ohrid to the Drim River may decrease. The quality and quantity of water resources in the entire Prespa-Ohrid-Drim catchment – which are of great importance for Greece, Albania and FYROM (e.g. tourism, agriculture, hydro-energy, urban & industrial use) – would therefore be affected by hydrological changes in the Prespa Lakes [12].

This work addresses the urgent need to understand the causes of major lake level changes, in order to provide hydrological impact projections related to future climate change and water abstraction. It presents the first comprehensive analysis of factors driving annual lake regime, based upon hydro-climatic data from all three lake-sharing countries (Greece, Albania and FYROM). Particular attention is paid to lake hydrological responses to climate change, water extraction and episodic earthquake-induced changes to the underground karst drainage system.

Data and Methods

The main long-term meteorological and hydrological records of the Prespa catchment for the period 1951-2004 have been compiled by the Society for the Protection of Prespa from institutions throughout the three lake-sharing countries (Greece, Albania and FYROM). The principal records include: (i) monthly stage level heights of Lake Megali Prespa from the FYR of Macedonia (the only records which are subjected to quality controls - by the Hydrological Institute of Skopje), (ii) monthly rainfall records from seven stations located adjacent to the lakes (~850m; Asamati, Stenje, Nacolec, Gorica, Pustec, Koula and Microlimini), and (iii) monthly evaporation based on a 23-year record with a standard Class A-Pan instrument (Koula station) and extended with the Penman formula to cover the entire 54-year observation period (calibrated for the Koula station). There are no continuous snowfall records and therefore no total precipitation series for 1951-2004. Short snowfall records (10-20 years) are available for some stations that are location at elevations between 850 to 1000m; the surrounding mountains reach up to 2400m. The Brajcinska River (FYROM) has the sole long discharge record (1961-2004) in the Prespa catchment; its catchment occupies less than 10% of the total catchment area. A continuous monthly water extraction record for the entire Prespa catchment has been reconstructed for 1951-2004 using written reports, verbally reported information and indirect extraction estimations from the three lake-sharing countries [GFA 2005 report]. Earthquake occurrence overlapping with the observational records was determined from regional online earthquake catalogues (e.g. http://www.gein.noa.gr/services/cat.html).

Descriptive statistics were employed to characterise hydro-meteorological records. A single rainfall record was created using the surface integration method (Direct Weighted Averages; Thiessen Polygons [15]). Class-A-Pan evaporations tend to overestimate lake evaporation; therefore a Pan-coefficient of 0.8 was introduced to convert the 54-year Pan- Evaporation series into a Lake-Evaporation series. “Lake Level Stage Height – Lake Volume – Lake Surface Area” tables were created for the upper part of the lake basin (c. 842-852m) using digitised topographic maps and SRTM data. These tables were used to transform bathymetry-dependent Lake stage height changes into Lake volumetric- and surface area changes. Spreadsheet-based calculations were used to analyse the impact of water extraction and groundwater flow changes on lake level. Regression analyses were used to look at the relationship between hydro-meteological parameters and lake volumetric changes.

Catchment hydro-geology and climate

The geological structure of the internally-draining Prespa Basin and its elevation (at 852-844m) above all surrounding catchments assure that there is no inflow of groundwater that originates from outside the basin. The mountains bordering the Prespa catchment to the N and E are composed of Palaeozoic schist and intrusive rocks that are aquicludes. These rocks underlie the entire catchment, including the Mesozoic limestone mountains that border the basin to the W and S. Locally generated groundwater enters Lake Megali Prespa principally from the N and E through small scale, mainly unconfined, gravel aquifers in Pliocene-Quaternary basin-fill sediments that are plastered against the mountains [13, GFA 2005 report]. These aquifers are recharged by precipitation. The lake is only into direct contact with limestone along its Central-SE shore. Here, limestone substrate continues at depth due to down-faulting of the southern part of the horst that separates Lake Megali Prespa from ~150m lower Lake Ohrid to the W [12,14]. There is significant underground karst outflow from this section of Lake Megali Prespa which contains many sinkholes. This water is mainly transferred to springs in the Lake Ohrid basin to the NE, although a minor component is transmitted to the SE Korça Basin [14, GFA 2005 report].

The water level regime of Lake Megali Prespa reflects its complex geological setting and is a function of: (i) fluvial and groundwater input, (ii) direct lake precipitation, (iii) lake surface evaporation, (iv) water extraction, and (v) karst outflow [12,14, GFA 2005 report]. All fluvial and groundwater input is generated within the confines of the steep-rimmed catchment. Therefore, factors (i-iii) should reflect the average climatic conditions of the catchment area. Figure 2 illustrates that the water level of Lake Megali Prespa follows an annual cycle with peak levels in May/June and low levels in Oct/Nov; the inter-annual average variability is ~0.5m. The Brajcinska River is characterised by low discharges during the summer months and the greater part of autumn; discharges increase from November onwards to peak in April/May. Both discharge and lake level cycles are strongly influenced by snow melt in spring. Rainfall peaks in late autumn-winter and summers are relatively dry; the monthly rainfall minus evaporation balance is only positive from October to March. Available records indicate that most snow falls between Dec-Mar. Lake level therefore lags ~5-6 months behind peak precipitation due to transfer delays that are primarily caused by snow-melt. This paper will analyse the data per Oct-Sep (12 month) wet-dry cycle, as is customary for hydrological records in the Mediterranean and for river basins with significant snowfall [16,17].

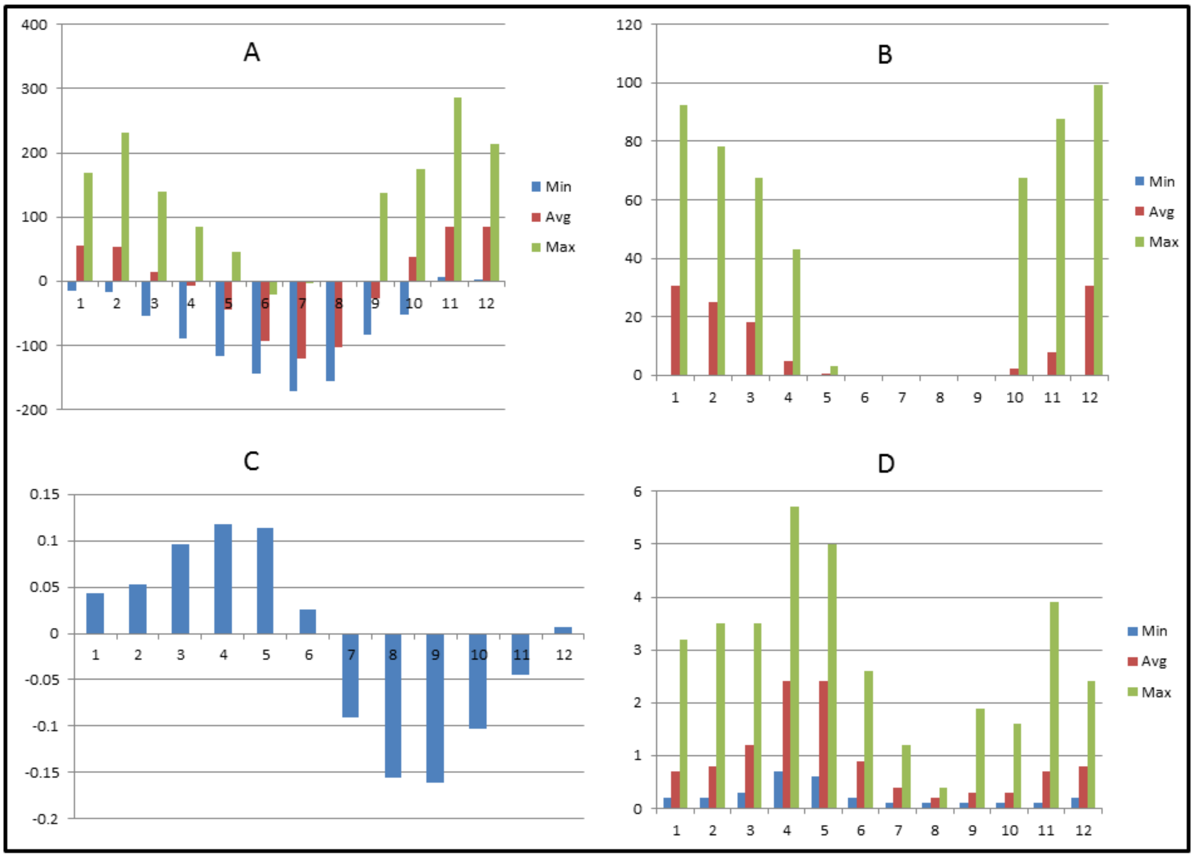

Figure 2: A) Average monthly rainfall *minus* evaporation balance (mm) at lake level 1951-2004, B) Average monthly snowfall (mm) 1966-2002 at Vrondero (Greece; at 1000m), C) Average monthly water level fluctuations (cm) of Lake Megali Prespa (1951-2011), and D) Average monthly runoff Data [m³/s], Brajcinska River, FYROM, 1961-2004

Lake water level and volumetric changes

Monthly lake water level data span the period from 1951 to 2011 (Fig. 3). From 1951 up to 1987, lake levels fluctuated between 852-848m. Lake levels rose almost 3m following the exceptionally wet months from September 1962 to June 1963, and the lake remained high up to the mid-1970s. Lake level fell by ~2.5m from June 1974 to October 1978; over the following years, lake levels recovered and rose by up to 2m. An extraordinary drop of more than 5m affected Lake Megali Prespa between 1987 and 1995 when water level fell to ~844m. Subsequently, lake level rose to ~846m until a strong fall of ~2.2m from June 2000 to September 2002. Hereafter, lake level fluctuated at 843-845m up to September 2011. According to Chavkovski [Hydrology of Lake Prespa, International Symposium, Albania, 1997], lake water levels never fell below 847.5m from 1917 to 1987.

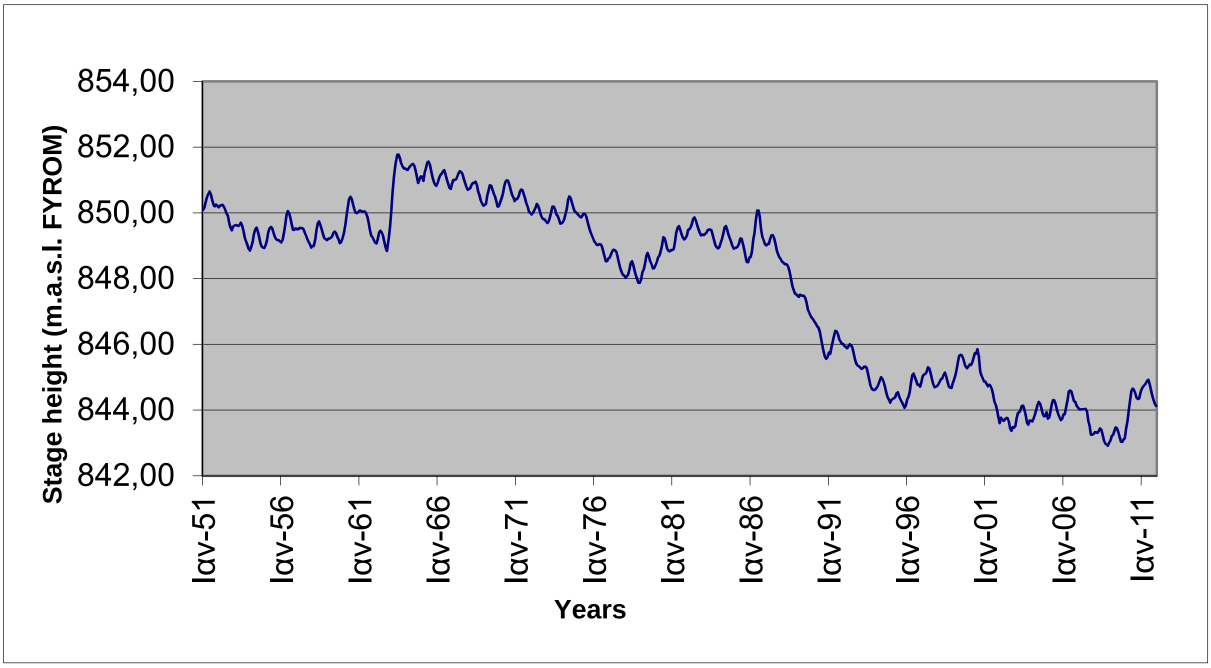

Figure 3: Monthly average water level of Lake Megali Prespa (1951-2011)

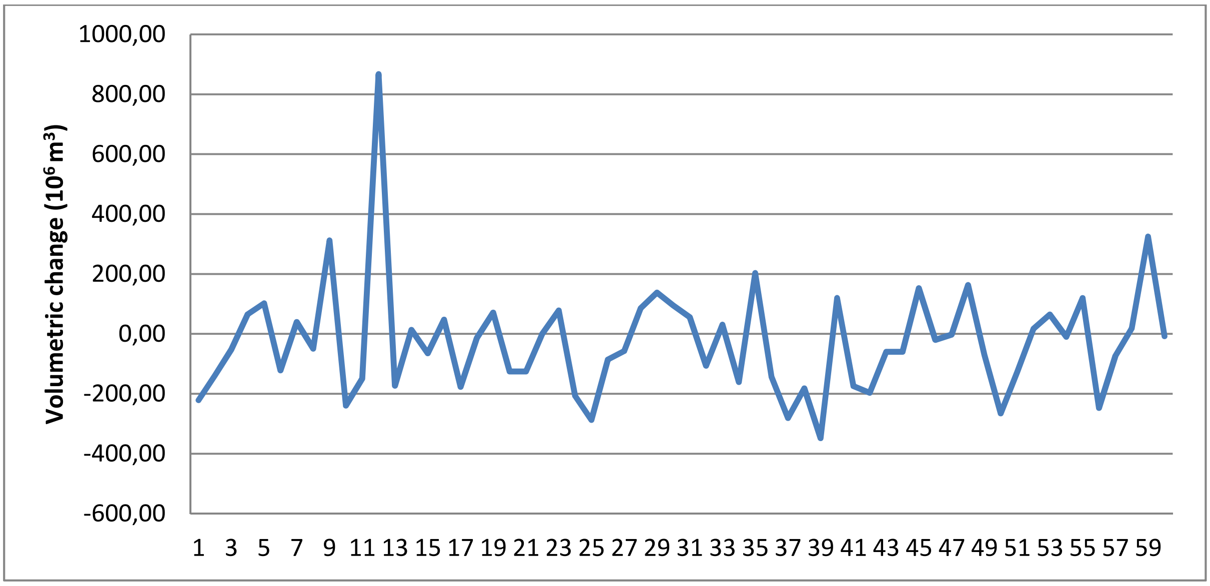

Figure 4: Annual volumetric change of Lake Megali Prespa (October: 1951-2011)

Lake level changes at different absolute stage heights cannot be compared as water volumes involved vary due to the bathymetry of the lake. This paper therefore converts stage height variations into lake volumetric differences that are independent of the bathymetry. Annual changes in lake volume (Oct year 2 *minus* Oct year 1) were calculated using stage-volume-surface tables (Fig. 4). Prior to 1976, the volume/surface areas of Lakes Mikri and Megali Prespa are combined as the lakes moved approximately in tandem. Since 1976, Lake Mikri Prespa is perched above Lake Megali Prespa as the latter's water level fell below the base of the weir (build in 1969) in the channel connecting the two lakes [GFA 2005 Report]. Therefore, only the volume/surface area of Lake Megali Prespa is used after 1976.

Extraction and lake volumetric change

The impact of lake- and groundwater extraction on the level of Lake Megali Prespa was calculated in a spreadsheet. Annual extracted water volume from 1951 until 2004 was added to the observed lake volumetric changes per hydrological year, thus creating an annual lake volumetric change series *in absence* of extraction. The extracted volumes were also converted into stage height differences, using the stage-volume-surface area tables, to create an annual lake stage height record *in absence* of extraction. However, higher lake levels in absence of extraction would have incurred a higher total annual evaporation as the lake surface area would have been greater. Therefore, the difference between the lake surface areas at the measured and recreated stage height was computed. The extra evaporation over the difference in lake surface area was then calculated using the hydro-annual lake evaporation series and subtracted from the recreated annual lake volumetric change records. Thus the final reconstructed record shows annual lake volumetric- and stage height change *in absence* of extraction and *corrected* for extra evaporation that would have been incurred under higher lake levels. These reconstructions may slightly over-estimate lake level, as higher lake levels lead to higher hydraulic pressure and may access sinkholes located higher up the shoreline.

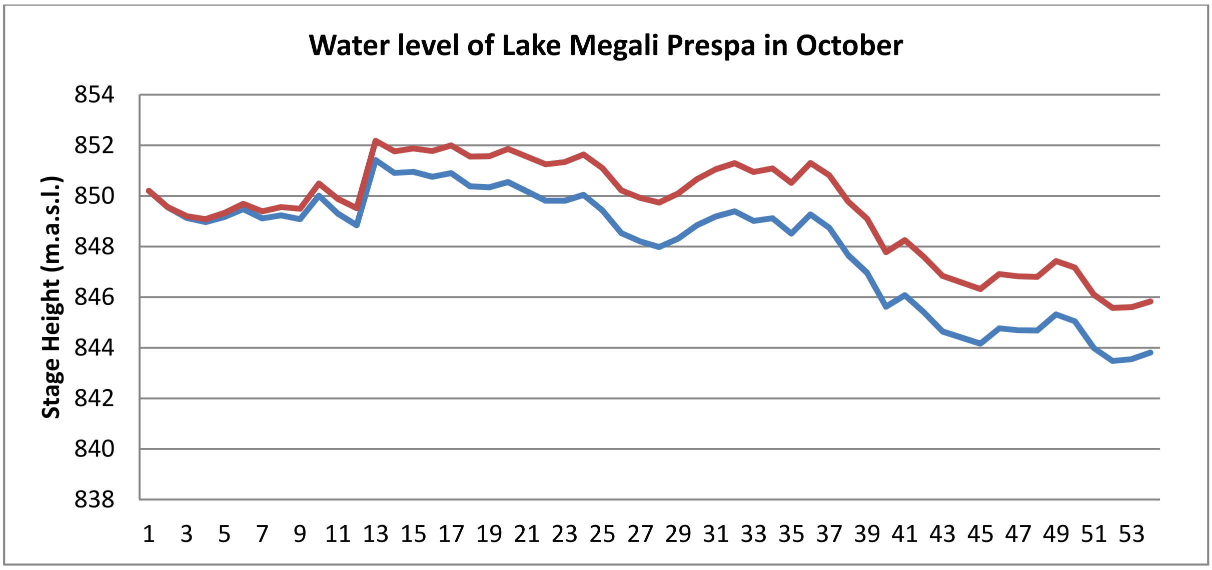

Figure 5: Reconstructed (*upper line; no extraction*) vs observed (*lower line*) stage height of Lake Megali Prespa in October (1951-2004)

Figure 5 shows that water extraction exerts a significant, cumulative, impact on lake level on (multi-)decadal timescales *although* annual differences between observed and reconstructed lake volumetric changes are very small due to the modest extraction rates (~0.004-0.003% of total lake volume per year). Extraction rates have been variable in the past, but since the end of the direct communication of Lakes Mikri- and Megali Prespa, annual extraction has likely not exceeded ~14 $10^3 m^3$ per hydrological year [12,14, GFA 2005 Report]. Even if actual extraction numbers can be debated, this modelling exercise clearly shows the slow, cumulative, impact of water withdrawal on lake level. The extraction-induced incremental fall in lake stage only ends when lake surface area reduction has led to a decrease in lake evaporation that is equivalent to the amount of water extracted. The maximum diversion of about 2.2m between the actual and modelled lake level record is attained

45 years after the start of extraction in 1951. Hereafter the actual and modelled lake levels start to converge; this probably reflects the decrease in abstraction after 1976.

Theoretical calculations support the above analysis. Without extraction, average lake level would have been ~850.6m from 1951 to 1987 (Fig. 5). A stage height of 850.6m corresponds to a lake surface area of 277.8 km^2 (Lake Megali Prespa). The annual water volume lost due to evaporation over this lake surface area is: 0.832m *277.8 km^2 = 231.1 $10^6 m^3$. Water extraction can only be compensated for by an equivalent decrease in lake evaporation caused by a reduction in lake surface area. Thus, 14 $10^6 m^3$ (annual water extraction) is subtracted from 231.1 $10^6 m^3$ to obtain a value of 217.1 $10^6 m^3$ for the required lake surface evaporation to stabilise lake level. Dividing 217.1 $10^6 m^3$ by 0.832m gives a lake surface area of 260.9 km^2 at a lake stage height of ~845.4m. This calculation assumes that average hydro-climatic conditions stay stable over time. However, average lake level may have been 846.5m from 1995 to 2004, in absence of extraction (Fig. 5). An average lake level at 846.5m corresponds to a lake surface area of 266.1 km^2 (Lake Megali Prespa), and an annual loss of water volume due to lake evaporation of 0.832m *266.1 km^2 = 221.4 $10^6 m^3$. If we subtract 14 $10^6 m^3$ (annual water extraction) from 221.4 $10^6 m^3$ we obtain a value of 207.4 $10^6 m^3$ for evaporation to stabilise lake level. Dividing 207.4 $10^6 m^3$ by 0.832m gives a surface area of 249.3 km^2 at a lake stage height of ~844.5m. The calculations show that lake level falls are highly dependent on the bathymetry of the lake.

Groundwater and earthquake-induced changes to karst outflow rates

Groundwater flows in the Prespa catchment are poorly known. Small-scale, unconfined, gravel aquifers in the Resen plain (N) and alluvial fans (E) contribute 4-7 $10^6 m^3$ annually to the lake (GFA 2005 Report). Precipitation changes will affect their discharge rate as they are recharged by precipitation. Since 1976 Lake Mikri Prespa has been perched above Lake Megali Prespa, which has created a significant groundwater flow through the alluvial isthmus. Falling levels of Lake Megali Prespa increase the hydraulic gradient and thus this groundwater discharge; some studies put this discharge to Lake Megali Prespa as high as 20 $10^6 m^3$ per year since 1995 [18]. The most reliable groundwater *outflow* estimates of 334.3-384.7 $10^6 m^3$ per year are based on spring discharge data in the Ohrid basin where up to 50% of the total spring discharge (estimated at 21.2-24.4 $m^3 s^{-1}$) is assumed to derive from the Prespa Lakes [2]. However, actual outflow rates may be higher as groundwater flow estimates to the Korça basin are not available. Outflow rates are considered relatively stable, but estimates of annual groundwater fluxes based on Lake Water Balances vary wildly: 10 $10^6 m^3$ (inflow) - 428.9 $10^6 m^3$ (outflow) [GFA 2005 Report], to 49 $10^6 m^3$ (inflow) - 313-245 $10^6 m^3$ (outflow) [12] and 63 $10^6 m^3$ (inflow) - 282 $10^6 m^3$ (outflow) [Popov et al. Sustainable management of the international waters – Prespa Lake, NATO report, Ohrid, March 2010].

Observed lake level fluctuations cannot easily be explained by earthquake-triggered changes in the karst outflow rates as some studies have suggested [e.g. 13]. Theoretically, karst outflow decreases when water level falls: the hydraulic pressure diminishes and karst sinkholes are progressively exposed above the water line [2,12]. This mechanism, however, does not explain the abrupt water level falls which would need a significant *increase* in outflow rate to explain them. Lake fluctuations may be trigged by earthquakes that either block or unblock underground karst drainage channels, thus causing sudden variations in the outflow rate. However, there are no major earthquakes (>4 on the Richter scale) on record that coincide with any of the key lake level changes. Minor earthquakes (3-4 on the Richter scale) did frequently occur in the region throughout the entire observation period (1951-2004), but are not concentrated at any specific period that coincides with major lake level change [e.g. 19].

A water balance modelling exercise [GFA 2005 Report] of lake level fluctuations from 1951-2004 showed that groundwater outflow needed to be kept virtually constant in order to keep the model stable (for this specific model: 13.6 $m^3 s^{-1}$ or 428.9 $10^6 m^3$ / year). However, the outflow needed to be decreased, or the inflow increased, for two periods: (i) Oct 1978 – Sep 1986 (8 years: 600 $10^6 m^3$ total reduction in outflow, or extra inflow) and (ii) Oct 1989 – Sep 1996 (7 years: 500 $10^6 m^3$ total reduction in outflow, or extra inflow). Extra inflow into the lake cannot be linked to an increase in precipitation or discharge, or to a decrease in evaporation. Noteworthy is that the modelled periods of temporary increased inflow follow significant water level falls that started in 1974 and 1987, respectively. These falls themselves may have *directly caused* groundwater inflow increases through the drawdown of the groundwater table in the alluvial sediments bordering the lake to the N and E. This explanation fits the timing of modelled inflow increases and explains the periodic nature of it: once the groundwater stores emptied, the inflow rates returned to normal. If the fall in lake level had caused a significant *reduction in outflow*, then modelled outflow rates would have stayed reduced – and not return to normal - as lake level remained at record-low levels after 1987.

Precipitation influence on lake level variability

The relationship between climate and lake level has been assessed through regression analyses that used available catchment-specific parameters (i.e. lake volumetric change, fluvial discharge, rainfall and evaporation). Long precipitation series do not exist due to the lack of snowfall data. The regression analyses implicitly assume that there is a linear relationship between rainfall at lake level and (i) rainfall in the mountains, as well as (ii) catchment snowfall. However, these relationships may change over time and thus affect correlations. The best correlations are found with climate data that are limited to the Prespa catchment, as local climates and trajectories of climate change are different in adjacent basins (e.g. Prespa and Ohrid [14]). Furthermore, the correlation of lake level with precipitation and discharge parameters on a monthly basis is poor, as is common in geologically complex Mediterranean lakes that experience significant summer evaporation and snow-melt input [20]. However, the annual variation in lake level shows good correlation with hydro-meteorological parameters.

There are good correlations between the cumulative seven month (Oct-Apr) rainfall *minus* evaporation balance and hydro-yearly lake volumetric changes over the 54-year period between 1951 and 2004. When annual volumetric changes are adjusted for extraction, the R^2 is 0.87 (Fig. 6). Correlations improve marginally (R^2 of 0.90) when annual lake volumetric changes are also corrected for the hypothetical groundwater inflow that may have followed strong lake level falls (Fig. 7). This outcome supports the extra groundwater inflow hypothesis during two periods: 1978-1986 (606 $10^6 m^3$ extra inflow) and 1989-1996 (505 $10^6 m^3$ extra inflow).

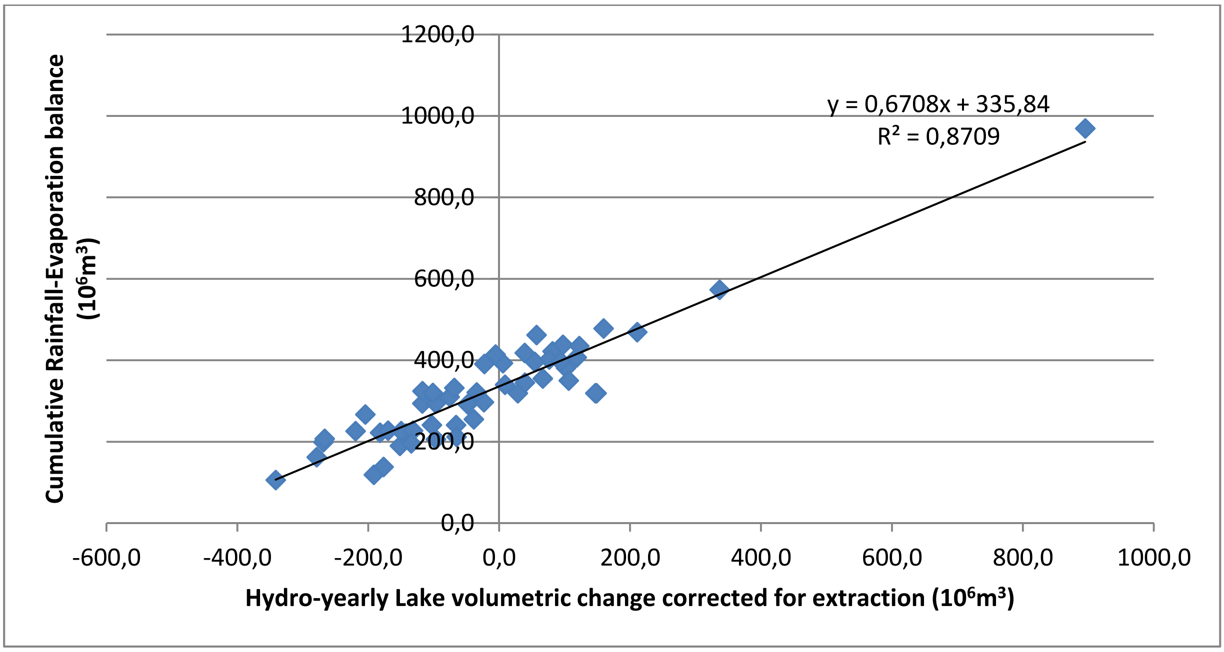

Figure 6: Annual lake volumetric change of Lake Megali Prespa (corrected for extraction) versus the cumulative 7-month rainfall *minus* evaporation balance (October to April)

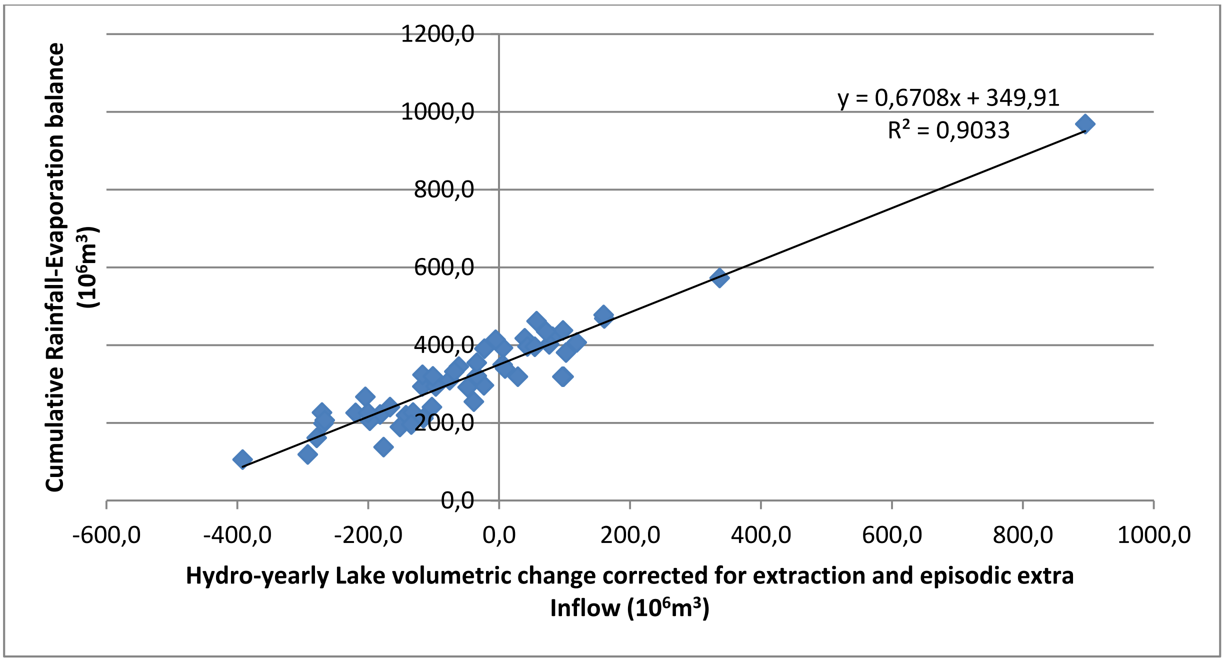

Figure 7: Annual lake volumetric change of Lake Megali Prespa (corrected for extraction *and* extra groundwater inflow) versus the cumulative 7-month rainfall *minus* evaporation balance (October to April)

Regression analyses between hydro-yearly lake volumetric changes and Brajcinska River (FYROM) Discharge have an R^2 of 0.74 although its catchment occupies less than 10% of the total Prespa Basin (Fig. 8). Discharge is strongly influenced by snowfall and peaks during spring snow-melt, causing lake water levels to peak in May-June. The good correlation suggests that runoff, and indirectly snowfall, exerts a significant influence on lake level fluctuations. The analyses strongly imply that annual lake level change is strongly determined by the total precipitation in the months from October to April; during these months the rainfall *minus* evaporation balance of is on average positive. When more months are included in the regression analyses, the R^2 decreases. This suggests that evaporation and rainfall from May to September do not significantly affect annual lake level change.

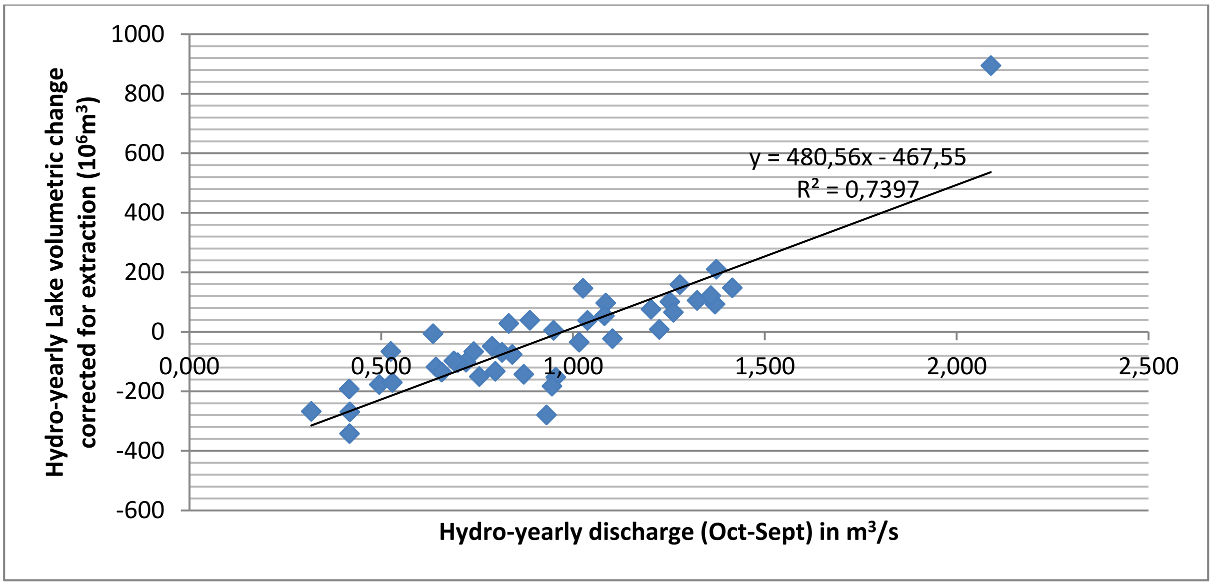

Figure 8 Hydro-yearly Brajcinska River (FYROM) discharge (Oct-Sept) vs annual lake volumetric change of Lake Megali Prespa (corrected for extraction)

Discussion and conclusions

This work proves for the first time that inter-annual water level variability of the Prespa Lakes is dominated by late-autumn to early-spring precipitation. Linear regression analyses show that annual lake level change (from Oct to Oct) is strongly related to rainfall and snowfall during the first seven months (Oct-Apr) of the hydrological year (Oct-Sep). There is a very good correlation between the cumulative seven month rainfall *minus* evaporation balance and hydro-yearly lake volumetric change between 1951 and 2004 (R^2 of 0.90). This suggests a link between lake level and the North Atlantic Oscillation, which is known to strongly influence Mediterranean winter precipitation [21].

There is no correlation between earthquake-occurrence over the observation period (1951-2004) and lake level fluctuations. Furthermore, years that are characterised by strong lake level rises (1962-‘63) and declines (1974-’78 and 1987-‘95) are near the regression line. This strongly suggests that precipitation and precipitation-fed groundwater/fluvial discharge control these major lake level movements. If these movements were related to episodic, earthquake-induced, karst channel changes, then there would be a much poorer correlation. Finally, the major rise in lake level (1962-1963) matches a wet event that is recognised throughout Greece, while significant falls (1974-1978 and 1987-1995) correspond with major Mediterranean-wide droughts [7, 22]. Other lakes in the S Balkans (e.g. Lake Skardar, Lake Ohrid and Lake Dorjan) also show falling water levels during these drought periods [GFA 2005 Report]. Given this regional synchronisation, it appears unlikely that there is a local tectonic control on the observed major water level fluctuations of the Prespa Lakes. Given these different lines of evidence, it is considered highly unlikely that inter-annual lake level fluctuations are driven by earthquake-induced changes to underground karst drainage channels.

Multi-decadal lake level trends are strongly influenced, and water level falls amplified, by water extraction in the Prespa catchment. The amount of lake level lowering after 1987 is for ~30% determined by extraction. Even minor water extraction has a progressive and serious impact on lake level, with a lag-time of multiple decades. Annual water extraction of 14 $10^6 m^3$ at a lake level of 850.6m would lead to a cumulative fall of ~5.2m, to a lake level of ~845.4m. However, the same extraction at a lake level of 846.5m would incur a cumulative fall of ~2m, to a lake level of ~844.5m. Lake level lowering due to extraction ends when lake-surface area shrinkage has led to a decrease in lake-surface evaporation that is equivalent to the amount of extraction; the total amount of lake level lowering is a function of the bathymetry. Water extraction does not influence the pattern or timing of lake level fluctuations. However, the gradual adjustment of lake level takes multiple decades under stable extraction rates and is strongly dependent on the bathymetry.

This research will help steer adaptation and mitigation strategies by informing on lake response under different climate change and extraction scenarios. Lake protection is a cost effective and sustainable solution for supporting global biodiversity and for providing essential ecosystem services that benefit the regional socio-economy.

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