Present status and future criticalities evidenced by an integrated assessment of water resources quality at catchment scale: the case of Inle Lake (Southern Shan State, Myanmar)

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Abstract – Assessing aquifer dynamics and groundwater interactions with surface waters are prerequisite for the correct management of water resources in the long-term, especially under the increasing pressure of climate change and the growing freshwater demand. This work presents the results of the first integrated assessment in the Inle Lake catchment aimed at understanding the surface and groundwater dynamics and the impact of agriculture and tourism on water quality. Results of an investigation performed in winter 2015, targeting the water chemical and isotopic ($\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$) composition, and soil mineralogy, confirmed that Inle is an alkaline lake, where carbonate equilibria dominate its hydrochemistry. The high resilience of the lake to external perturbations is due to calcite precipitation, that represents an effective mechanism of P removal and, combined to the low residence time of water, prevents the accumulation of nutrients in lake waters. The investigation also permitted the first characterization of groundwater in the region, highlighting the dominance of Mg(Ca)-HCO_3 *facies*. Two deep groundwater circulations could be evidenced: one of high temperature, Na-HCO_3 type (Khaung Daing Hot Spring) and one in equilibrium with the dolomitic rocks of the basement, upwelling along a fault zone oriented N-S in the Northern part of the basin. The latter groundwater contributes to Inle lake by mixing with local recharge in the aquifer and by feeding the network of artificial channels created for reclamation purposes. Evidencing recharge mechanisms of both surface and groundwater makes it possible to highlight the impact of seasonal fluctuations of the water levels, and the associated flooding of some sectors of the catchment, on the Inle Lake agroecosystems and to evaluate possible scenarios for the future sustainable development of the region.

Keywords: Alkaline lake, groundwater-dependent ecosystems, isotopes, cultural eutrophication, groundwater upwelling

1. Introduction

Assessing the interdependence between agroecosystems and water resources is a fundamental step for the sustainable development of any catchment basin. Indeed, not only land and water can not be managed separately, but also, all the interactions among the water cycle with the environmental, economic and social sphere have to be taken into account while planning water resources management actions. This is the basis for the Integrated Water Resources Management (IWRM), that became a mainstream idea after the 1977 United Water Conference in Mar de la Plata (McDonnell, 2008). Even though forty years passed since the first introduction of this concept, water resources worldwide are still severely threatened by anthropogenic (e.g. contamination, depletion, poor planning) and natural (e.g. climate changes) pressures, and the predictions of future trends are not promising either (WWAP, 2017).

The causes are diverse but could be mainly attributed to:

- Growing population and a shift towards more water-dependent economies. Although the agricultural sector is responsible for approximately 70% of the global water abstraction, accelerated urbanization over the coming decades will also contribute to significantly increase the water demand associated to industry, sanitation systems, energy and municipal water supply (WWAP, 2017).
- Lack of sound scientific knowledge, which is generally money and time dependent. Results and possible solutions to environmental problems hence require time to be achieved, while business as usual actions (often associated to population growth, water demand increase and recurrent droughts/extreme events) keep degrading the studied system. As a result, at the end of long-time scientific investigations, things may have worsened, and proposed actions may not be adequate any more.
- Multidisciplinary investigations are often far to address all the interconnected aspects of a studied water issue. Sectorial approaches are still favoured over integrated ones (Foster and Ait-Kadi, 2012) as a result of strong specialization (Daly et al., 2016.) and of the difficulty of practically managing complexity.
- Scarce involvement of water end-users and poor communication of scientific results to the relevant stakeholders. Although public engagement is a pillar of IWRM, its effective implementation in hydrological and hydrogeological investigations is still limited and bottom-up integrated approaches that concretely take into account end-users' needs are still seldom implemented (Re, 2015 and references therein).
- Poor communication of the scientific outcomes outside the academic domain. Ineffective dissemination and interaction with relevant stakeholders often results in management decision taken in isolated form disregarding the direct and indirect effects that action in one component of the system may have on the others.

In addition, the clear identification of the management unit often poses some limitations in terms of responsibilities and stakeholders involvement. To this end, in recent years the catchment has often been recognised as the appropriate organising unit for long-term integrated water resources management (e.g. Ashton, 2000; Ferrier and Jenkins 2010), whether within a country, across state or provincial boundaries within states, or across national borders (Burton, 2003). A catchment, representing an area of land where all of the water that falls in it and drains off of it goes to a common outlet (USGS, 2016), can also be defined as a "multi-functional, topographically-based, dynamic, multiple-scale, socio-biophysical system" (Daly, 2017). This definition highlights both the complexity and integrated dimension of these systems that should include not only the hydrological and hydrogeological components, but also the people living within the area. For this reason, coherently with IWRM, Integrated Catchment Management (ICM) was proposed as an approach recognising "the catchment as the appropriate organising unit for understanding and managing biophysical processes in a context that includes social, economic and political considerations, and guides communities towards an agreed vision of sustainable resource management in their catchment" (Fenemor et al., 2011). In this framework, the activities of various bodies that can affect or influence water resources use and protection must be adequately co-ordinated to ensure that both water and associated land-based resources are "managed in harmony so as to gain the full benefits of multipurpose use" (Ashton, 2000).

Moreover, since the frequency and intensity of water crises worldwide have been, and are still, increasing (WWAP, 2015) it is fundamental to ensure that all the components of the water cycle, including the hidden (and less studied) ones, like groundwater, are adequately addressed in any given environmental assessment.

The latter is still a main problem worldwide and a poor knowledge about (and associated management of) groundwater resources often results in aquifer overexploitation and contamination. Indeed, in the long term, the consequences of poor groundwater management would severely affect human wellbeing both in developed and developing countries, and even in regions where water resources are presently abundant. In fact, the presence of contaminated groundwater can undermine a nation water security in the long run, especially in areas where increasing human pressure (and water withdrawal) are already decreasing the surface water potential. The effects would obviously be more severe in regions where economic resources would be a limiting factor for aquifer exploitation and/or decontamination, and in presence of groundwater-dependent ecosystems.

Myanmar is endowed with abundant water resources which are unevenly spatially and temporally distributed. The monthly distribution of river flows closely follows the pattern of rainfall, which means that about 80 percent flows during the monsoon season (May-October) and 20 percent in the dry season (November-April; FAO, 2016). In the country approximately 89% of the groundwater resources are used for agriculture, 8% for domestic consumption, and 3% is used for industrial purposes (Than and Maung, 2017). However, in regions like the Inle Lake basin (Southern Shan State, Myanmar) population mainly relies on surface water to supply the growing demand for domestic, agricultural, tourism activities and energy production (Thin et al., 2016).

Besides its relevance for the local wellbeing and natural environment, Inle Lake is seriously threatened by anthropic activities on both the lake sides and in its drainage basin. It is in fact affected by a significant decrease of the open water surface, due, on one hand, to an increase in sedimentation caused by accelerated soil erosion (as a consequence of deforestation in the catchment) and on the other to the shrinkage resulting from floating gardens expansion (Sidle et al., 2007). In addition, besides natural climate changes, further pressure will be exerted by the rapid population growth (with a rate of approximately 2.3% per year; Su et al., 2000) and tourist traffic expansion in the region (with 17 new resorts to be built in the catchment area), increasing both the water demand and pollutant loads. The latter are associated to the lack of adequate sanitation facilities, the widespread use of agrochemicals in floating gardens, especially for tomato cultivation (Akaishi et al., 2006), and the unregulated use of pesticides, that threaten the biological diversity of local flora and fauna (Su and Jassby, 2000).

The increasing competition over water use necessarily requires a more holistic and collaborative long-term approach to land and water management. In fact, despite the environmental and ecological relevance of the lake, an integrated and sustainable management of water resources at the catchment scale is hampered by: (i) a scarce knowledge of aquifer characteristics, dynamics and interaction with surface waters, (ii) a limited or absent assessment of the issues faced by local communities exploiting Inle Lake waters, and (iii) a poor involvement of the civil society in environmental management.

A careful assessment of the recharge mechanisms and of the interactions among lake, rivers and groundwater, together with a clear identification of the main sources of water quality degradation and depletion, would represent a sound basis for new management actions required to avoid irreversible lake shrinking, like in the Chad Lake (Gao et al., 2011) or in the Aral Sea (Micklin, 2007).

Recognising that hydrological, soil and biological processes are interlinked and interdependent, this paper aims at contributing to the state of the art by (i) presenting the first groundwater characterization in the Inle Lake catchment, (ii) evaluating the surface-groundwater interaction as a basis for the correct implementation of integrated catchment management in the area, and (iii) assessing how floating agriculture and tourism activities influence the environment and how environmental changes can influence agroecosystems and human wellbeing.

A clear understanding of the water cycle dynamics is prerequisite to the identification of the most effective management actions to minimize both the impact of climate and land use changes on local environment, economy, and society, and the discrepancies between water demand and supply at catchment level. In addition, the paper provides some preliminary information to test the potential of a socio-hydrogeological assessment in the area, following the approach proposed by Re (2015).

2. Site description

Inle Lake is the second largest lake in Myanmar and is situated in Nyaung Shwe Township, Taunggyi District, Southern Shan State (20˚27' – 20˚40' N latitude, 96°52' – 96°57' E longitude and an altitude of 890 m a.s.l.; Fig. 1).

The Inle Lake basin has humid subtropical climate with three seasons, hot dry (March–June), rainy (July–October) and winter (November–February). Average daily humidity ranges from 48% in March to 79% in the rainy season (METEOVISTA, 2017). Mean air temperature near the lake ranges from 16.5 to 25˚C. The area experiences strong seasonal wet and dry periods, about 70% of the annual rainfall falling during the months of July, August and September. Thirteen years of recorded precipitation data, from 2000 to 2013, indicate the mean annual rainfall of 984 mm (Tun, 2014), generally occurring on 80 individual days.

The land use pattern in the Inle Lake for 2003 reported about 38% (627 Km^2) of the total area of 1647 Km^2 under open water and only 24% (393 Km^2) used for agriculture (floating gardens), the rest of 38% (627 Km^2) being covered by floating vegetation, settlements and other form of gardening and farming (UN-Habitat, 2013). Floating tomato gardens (a sort of hydroponic cultivation technique, Su and Jassby, 2000) used by the local residents are concentrated mostly in the western part of the lake (Sidle et al., 2007). Concerning the catchment, a survey dated 2010 indicated that agricultural land occupies 42% of the area, forest with sparse canopies 16%, while other forms of land use and water surface areas account for 35%. Forest with dense canopies remains only on 7% of the catchment (MOCEAF, 2014).The lake catchment is characterized by a large, flat valley running north to south, surrounded by mountain ranges averaging about 1200 m a.s.l. The basin is located in the Shan Plateau, belonging to the Sibumasu block (Metcalfe and Aung, 2014), and mainly constituted by Permo-Triassic carbonates (Oo et al., 2002). In Southern Shan State, the stratigraphic sequence is constituted by the Thitsipin limestone formation, and the overlying Nwabandgyi dolomite formation (Oo et al., 2002). The Thitsipin Limestone Formation comprises five main calcareous lithofacies. Some sections of the formation are partially dolomitised and comprise fine grained dolomite. The Thitsipin Limestone Formation passes transitionally upwards into the Nwabangyi Dolomite Formation, further subdivided in four main lithofacies, dominantly dolomitic. Triassic formations tend to be more crystalline and less sandy than the underlying Devonian strata, and contain a greater proportion of calcium carbonate, up to 98%. The sequence of carbonate rocks is thought to be of considerable thickness, with estimates up to 1000 m in the Southern Shan State. No information is presently available on the local geology of the Inle Lake catchment.

The catchment is located about 50 km E of the tectonically active Sagaing fault, a major continental transform fault between India and Sunda plates. The hydrographic network in Myanmar is strongly conditioned by the recent tectonic activity, and particularly the movement of the eastern Himalayan syntaxis

(Robinson et al., 2014). Recent neotectonic studies indicate that the Inle Lake catchment develops along a right-lateral strike-slip fault running parallel to the Sangaing fault; the lake itself is bordered on the east side by the so-called Taunggyi normal fault, showing a complex geometry and determining the asymmetrical shape of the basin (Fig.1). Tectonic movements therefore affect the sediment transport and the development of the river deltas (Wang, 2014). In addition, due to the topography of the catchment, some areas are flooded during the monsoon period in response to the increase in the lake water level. The position and shape of these floodable areas, mostly located to the N and to the W of the present-day open water surface (Fig.1), suggest that in the geological past the entire dark-green area could have been occupied by a swamp, and indeed the northern sector appears as reclaimed land (see also the straight course of the Nanlit stream S of Nyaung Shwe).

Inle Lake, with a present day average length of 18 km and about 6 km width, is recharged by 30 streams, of which 1 form the north, 17 from the east and 12 from the west (Fig. 1). The main contributor, from the north, is the Nanlit stream which flows by the main town of Nyaung Shwe, located about 2 km N of the lake; the western Kalaw and Indein streams form two remarkable birdfoot like deltas (Sidle et al., 2007), whereas the eastern border of the lake is more abrupt due to the proximity of the mountain range. The lake has only one outlet, to the south, entering the Thanlwin River (Su and Jassby, 2000). Inle Lake has been classified as a shallow freshwater lake due to its depth approximately ranging from 4 m to 7 m during hot dry and rainy season, respectively (Butkus and Myint., 2001).

The drainage area and storage capacity of the lake have been estimated at 3,700 km^2 and 3.5×10^7 m^3. Annual inflow water volume is typically 1.13×10^8 m^3 yr^{-1} and water residence time is estimated to be 0.32 years (Su and Jassby, 2000).

In the last years, especially in 2010, the lake has experienced dramatic drops in the water level in summer (Okamoto, 2012), and during the surveys performed in March 2014 and in December 2015 it did not exceed 2.3 m depth (Thin et al., 2016 and this work).

An assessment of surface water quality, focusing on the definition of the trophic level of the lake, was performed by Akaishi et al. (2006) based on one water sampling campaign conducted after the monsoon season. This study concluded that the lake was eutrophic, but underlined the need for more extensive studies due to the rapidly evolving socio-environmental situation. A comprehensive hydrochemical and isotopic characterization of Inle Lake was conducted during one hydrological year, considering both surface and bottom waters to investigate the seasonal water dynamics, evaluate the processes regulating the hydrochemical contents, and assess the vulnerability of the water body to the anthropogenic impacts (Thin et al., 2016). Authors reported that the lake water hydrochemistry was dominated by carbonate equilibria, that lake water was affected by evaporation, although the lake was continuously fed by waters, and that endogenic calcite precipitation, together with the relatively short residence time likely prevented the accumulation of anthropogenic contaminants and nutrients in lake waters. This study indicated a high resilience of the lake to the anthropogenic disturbances in the catchment, but leaved unexplained the reasons of the dramatic drops in the water level, suggesting that further investigation should focus on the anthropogenic impact on the drainage basin (e.g. effects of deforestation and shifting cultivation on rainwater runoff and infiltration) and on the river flow regime (e.g. water abstraction for irrigation). Additional isotopic data for lake and stream waters are reported in the Atlas of isotope hydrology - Asia and the Pacific (IAEA, 2008).

By contrast, no information is presently available in the international literature on the hydrogeology of the Inle Lake catchment nor on groundwater hydrochemical and isotope characteristics.

3. Materials and methods

A sampling campaign was carried out on December 2015 (winter season), collecting surface and bottom lake water from twelve study sites selected based on their position and environmental setting, in agreement with the monitoring plan established by Thin et al. (2015), ensuring a uniform spatial coverage of the lake area and considering all the major rivers' inflows. In addition, river water samples from the western part of the catchment, pond waters from the northern sector and groundwater from the villages near the Inle Lake were also collected (Fig. 2). The selection of the wells was performed in order to cover the whole northern sector, based on the location and accessibility of private wells, since no previous studies were available. In addition, a water sample from the Khaung Daing natural hot spring, sited at the north-western shore of the lake, was also collected. During the sampling campaign, temperature, Electrical Conductivity (EC), pH and Eh were measured in the field with a multi-parameter probe WTW 340i with electrodes, and alkalinity was measured using the HACH Alkalinity Test Kit, Model AL-AP. In the laboratory, all samples were reanalyzed for EC, pH and alkalinity by titration (Gran titration method), whereas the ionic contents were determined by DX-120 ion chromatography at the University of Pavia. Total P content was determined with the Molybdenum blue method (Murphy and Riley, 1962) on an unfiltered sample aliquot previously subject to persulphate microwave digestion to convert all P in othophosphate (Johnes and Heatwaite, 1992). Saturation indices with respect to the main mineral phases were calculated using the Phreeqc software (Parkhurst and Appelo, 1999).

Stable isotopes of the water molecule were determined by Wavelength-Scanned Cavity Ring-Down Spectroscopy (WS-CRDS) at ISO4 in Italy. Results are reported in the usual delta (δ) notation vs V-SMOW, with an uncertainty (2σ) of ±0.2‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$.

Soil samples were collected in the catchment, with the objective to better characterize the unsaturated zone in the lake surroundings. These were mostly shallow soil samples (5-10 cm depth) from the agricultural fields located N of the lake, and full soil profiles from the recently excavated side of the Inle Lake West Corridor Rd (Fig.2c). Samples were dried at room temperature for 2-3 days in order to maintain the crystal structures, weighted, described for their colour using the colour chart, ground to fine powder in an agate mortar and the mineralogical composition was measured by X-Ray Powder Diffraction (XRPD) at the University of Pavia.

Moreover, during the sampling campaign, discussion and confrontation occurred with some well owners involved in the monitoring network and representatives of the agricultural sectors (farmers' association, experimental agricultural stations, and individual farmers). This activity was aimed to (i) retrieve some useful information for a better understanding of the local know-how, (ii) assess the water use and the water users' needs, and (iii) evaluate the feasibility in the future of a full socio-hydrogeological assessment in the area (Re, 2015).

4. Results

Hydrochemical and isotopic results are reported in Tab.1S (Supplementary Materials), together with the statistical summary for each water type.

Lake water results confirm the absence of clear stratification in the water body, as already evidenced by Thin et al. (2016). Indeed, when comparing the composition of surface (Tab. 1S in Supplementary Materials) and bottom waters (Tab. 2S in Supplementary Materials) no significant differences are observed for the main physical and chemical parameters. Therefore, for consistency and comparison with previous studies only surface water samples were considered in the data treatments, except for P analyses.

EC ranges from 328 to 508 µS/cm, the alkaline pH varies between 7.65 and 8.66 (average 8.27). The redox potential is always high, indicating that waters are well oxygenated. The most abundant cations are Ca and Mg, whereas bicarbonate is the most abundant anion.

Groundwater shows a higher variability in pH (5.94–8.66), EC (57-1284 µS/cm) and Eh (128-477 mV, but the Hot Spring (G12) displays a negative value of -106 mV).

The average EC value is lower in the lake water compared with pond and river water. The lake water at the entrance of the Nanlit Stream (L1) displays a higher EC than other study sites in the lake. The average value of Ca and Mg is found to be higher in groundwater compared with lake water. Groundwater G8 has the maximum bicarbonate content whereas the minimum (30 mg/L) is found in G6, which is acidic (pH: 5.94) and with the lowest EC (57 µS/cm).

The Piper diagram (Fig. 1S in Supplementary Material) shows that surface and ground waters are of Mg(Ca)-HCO_3 type, although surface waters present a higher variability in Ca and Mg relative abundances, with respect to groundwater (Tab. 1S in Supplementary Material). The latter is in fact characterized by a more homogeneous composition, with the only exception of the hot spring (G12), showing a relatively high mineralization and a Na-HCO_3 type, and G6, as the least mineralized water sample.

Saturation indices (SI) for the main carbonate phases range between -0.13 and + 0.61 for calcite, between +0.28 and +0.47 for aragonite and between +0.32 and +1.63 for dolomite in lake waters (Tab. 1S in Supplementary Material), and river and pond waters are within the same range. On the other hand, groundwater displays a higher variability, ranging between -3.25 and +0.78, -3.40 and +0.63, -6.58 and +1.89 for calcite, aragonite and dolomite respectively. The hot spring (G12) is strongly undersaturated for all mineral phases.

The $\delta^{18}O$ and $\delta^{2}H$ determined in all water samples range from -7.76 to -2.86‰ and from -53.5 to -26.3‰, respectively. Groundwater isotopic composition is generally more depleted than Inle Lake waters.

The crystalline material within the soils, as determined by X-rays powder diffraction, consists of various minerals. The results of mineralogical analyses in soil samples are described in Tab. 3S (Supplementary Material). In the bulk soils, the most abundant mineral is quartz, ranging between 24 and 73%, followed by kaolinite (0-45%). Other less abundant, mineral phases are: mica/illite (0-27%), interstratified minerals (0-25%), calcite (0-20%), hematite (0-29%), smectite (0-31%) and anatase (0-5%). Soils sampled in the northern part of the catchment (S1, S2, S3) are more abundant in calcite and clay minerals. By contrasts the soil profiles (S4 and S5) display a higher percentage of quartz. In particular, the mineral distribution of quartz, kaolinite and clay minerals in soil profile S4, located in the north-west part of the lake, shows a variability with depth that reflects the weathering sequence typical of tropical red soils.

5. Discussion

5.1 Surface Waters

Data of the 2015 campaign confirm the results of previous studies (Akaishi et al., 2006; Thin et al., 2016), indicating that Inle is an alkaline lake, where carbonate equilibria dominate the lake water hydrochemistry. High HCO_3 contents are a consequence of the dissolution of carbonates rocks in the catchment area and of biological activity in the lake. A good agreement is found with the results of Thin et al. (2016) as shown in Fig. 3a, where lake samples, as well as most surface water samples, generally fall on a 1:1 line of HCO_3^- vs Ca+Mg. Significant deviations from this trend are recorded for the Nanlit Stream (R1), the Kalaw Stream (R2), lake water collected at the entrance of the Nanlit Stream (L1) and Pond 2 (P2), all showing a higher bicarbonate content (Tab. 1S in Supplementary Material). As far as the ratio of Ca to Mg, all surface waters fall on a -1:-1 line. Thin et al. (2016) already observed that, in lake water, the Ca/Mg ratio had a seasonal evolution, with samples collected during the rainy season dominated by Ca, and winter (but especially summer) samples showing an increase in the Mg content paralleled by a decrease in Ca, roughly aligning along a -1 slope. Based on hydrochemical and isotopic evidence, they attributed the Mg increase in the warmer months to evaporation of the water body, and the Ca decrease to endogenic calcite precipitation, triggered by photosynthetic activity and temperature increase. Most of lake water samples, as well as river and pond waters appear supersaturated (SI>0) with respect to the main carbonate phases (calcite, aragonite and dolomite), indicating that the precipitation of these minerals could potentially occur (Reddy and Hoch, 2012).

During photosynthesis, phytoplankton and macrophytes subtract CO_2 from the water, displacing carbonate equilibria and causing an increase in pH (Otsuki and Wetzel, 1974). Alkaline conditions favour calcite precipitation, which removes dissolved ions from the solution. This could be the reason why lake water displays a lower EC than R1, R2 and P2, with the exception of L1, obviously influenced by the Nanlit Stream (Tab. 1S in Supplementary Material). However, during the 2015 sampling campaign, pH values were not as high as those measured in March 2014 (Thin et al., 2016), therefore the inverse correlation that they found between pH and EC is not significant for the 2015 data.

Lake waters are subject to evaporation, as evidenced in Fig. 4, where samples fall on a regression line of equation:

$$\delta^2H=5.49\ \delta^{18}O - 10.384\ (n=12;\ R^2 = 0.965)$$

The slope of the regression line (5.49) is higher than that calculated for the March 2014 campaign (4.26; Thin et al., 2016), indicating evaporation under relatively higher humidity conditions (about 75%), in agreement with the sampling season (mid-winter) (Clark and Fritz, 1997). The more depleted values (L1, L4) fall close to the regression line for Yangon precipitation data and are located at the inflows of the main rivers, whereas the more enriched values (L8, L7) are located towards the lake centre.

River waters R2 and R3 fall on the Yangon precipitation line and are in agreement with the isotopic compositions of lake waters collected during the rainy seasons (Thin et al., 2016). The Thanlwin River (R4), collecting the outflow of the lake, is closer to the mean lake water isotopic composition, that is partially affected by evaporation. Finally, the two ponds as well as the Nanlit Stream (R1) are also enriched but to a lower extent (Fig. 4). These results for surface waters are comparable to those reported by IAEA (2008).

Assuming that the lake is fed only by river water (R1, R2 and R3), with mean isotopic composition of -6.28‰ and -44.4‰ in $\delta^{18}O$ and $\delta\ ^2H$, respectively, and considering that the difference with the most enriched lake water (L8) is only 3.42‰ in $\delta^{18}O$ and 18.1‰ in $\delta\ ^2H$, this could indicate that the fraction of lake water lost by evaporation is low (around 15%) and/or that the lake is continuously fed with water.

Thin et al. (2016) used the isotopic composition of lake waters to trace the seasonal water dynamics. They demonstrated that during monsoon the lake water is fully flushed by inflow waters (and therefore the residence time is shorter than one year), and that the lake is not stratified since the isotopic composition of surface and bottom waters is similar. In addition, they suggested that the water movement in the lake was from N to S, in through-flow conditions. A $\delta^{18}O$ interpolation map was also elaborated for the 2015 campaign, using as additional information the isotopic composition of river and pond waters (Fig. 2S in Supplementary Material). The water inflow from the western rivers (R2 and R3) is clearly evidenced in the map, as well as the contribution from the Nanlit Stream, the latter being more enriched than the previously mentioned inflows. As already stated, the effect of evaporation is mostly visible at the centre of the lake.

The influence of evaporation on the seasonal increase in Mg contents and on calcite precipitation was traced by Thin et al. (2016) using the isotopic composition of lake waters but, due to the limited evaporative enrichment measured during the 2015 campaign, no significant correlations of $\delta^{18}O$ with the Mg or Ca contents in lake waters could be observed.

5.2 Groundwater

As shown by Fig. 1S (Supplementary Material), groundwater is of Mg(Ca)-HCO_3 type (with the exception of G6 and of the Hot Spring G12), but the ratios between these constituents and the processes regulating the composition are different from those of surface waters. Fig. 5a shows that the bicarbonate content is much higher than the sum of Ca and Mg, while in surface waters it was similar, and that the ratio of Mg to Ca is approximately 1, whereas in surface waters samples plotted on a -1:-1 line (Fig. 3b). In addition, all cations are linearly and significantly correlated with the Cl content (Fig. 5c, d and e), suggesting a common mineralization process for groundwater, whereas such correlations do not exist in surface waters. These correlations in groundwater are calculated excluding G12 because of its high temperature and Na-HCO_3 type, both parameters suggesting a longer and deeper water circuit within a fault zone in a region characterized by an elevated geothermal gradient (Sacchi et al., 2017). Also G6 was excluded from the correlations since its very low EC, acidic pH and low dissolved constituents suggest that it could represent a lens of meteoric waters stored in an aquifer with a low content of soluble minerals (in agreement with well depth, Tab. 1S in Supplementary Material). Indeed, this sample was collected close to the western margin of the Inle Lake basin. The soil profile (S4) located nearby shows the presence of a low amount of calcite (20%) only in the top soil, while, with depth, quartz and clay minerals increase up to 58% and 45% respectively.

Concerning stable isotopes in groundwater (Fig. 5f), the more depleted values (< -7‰ in $\delta^{18}O$, including G12) fall on the regression line for precipitation collected in Yangon (YMWL), whereas more enriched water deviates approaching the mean isotopic composition of surface waters.

When trying to interpret groundwater composition, combining the information provided by hydrochemistry and stable isotopes, and knowing the processes that regulate the composition of surface waters, some inconsistences appear:

1) groundwater has a higher content of Ca and Mg than surface waters, although the latter are already saturated with most carbonate minerals (Tab. 1S in Supplementary Material). In addition, a higher bicarbonate to (Ca+Mg) ratio suggests another source of dissolved CO_2 generating alkalinity, that is not present in surface waters;

2) despite the higher mineral content, groundwater shows a more depleted isotopic composition than surface waters (Fig.5f). Therefore, evaporation of surface waters prior to infiltration or transpiration are not at the origin of groundwater mineralization;
3) the most mineralized sample (G8) cannot derive from evaporative concentration of groundwater with more depleted isotopic compositions and lower mineral contents (e.g. G9, G10). Indeed, a mass balance calculation based on the Mg content (assumed to be conservative in this system) indicates that the initial water should have evaporated to about 50% to provide the final concentration of G8, but, if this was the case, the final isotopic composition would be more enriched than what observed (Clark and Fritz, 1997);
4) the Ca/Mg ratio of about 1 suggests that the dissolution of dolomite could be at the origin of mineralization. Nevertheless, this mineral is poorly soluble at ambient temperature (Appelo and Postma, 2005) and was not detected in the soils or in lake sediments (Thin, 2015; Thin et al., 2016; Sacchi et al., 2017);
5) despite the overall homogeneous composition of groundwater (Fig. 1S in Supplementary Material), samples are characterized by a high local variability (e.g. the neighbouring wells G8 and G9). Although these differences could be attributed to the well depths, no clear correlation is established between this parameter and the overall mineralization (e.g. G8 is the shallowest while G9 is the deepest, although mineralization is higher in the former well). The spatial heterogeneity of groundwater compositions is not in accordance with the supposed homogeneity of an alluvial aquifer.

All this contrasting information can be combined in a consistent picture if we consider that the sample G8 may represent another water type, circulating at depth in the dolomite bedrock. Although not detected in the basin, dolomite is present to the NW of the study area and constitutes the outcrops along the roadside from Heho to Shwenyaung (Thin, 2015). This deep water may upwell along one of the faults associated to the genesis of the Inle Lake catchment. Indeed, when looking at the location map of Fig. 2b, sample G8 is positioned at the centre of the basin, and the two other samples that could receive a higher contribution of this groundwater type (based on their isotopic composition, G2 and G3) are aligned with G8 in the N-S direction.

According to Hem (1989), mature groundwater in carbonate sedimentary terranes often has a high Mg/Ca ratio, since the conditions for direct precipitation of dolomite from solution are not commonly found in normal groundwater, and the precipitate formed may be almost pure calcite. In our case, the conservative behaviour of all major ions including Ca (Fig. 5c, d and e), and the groundwater saturation with respect to calcite suggest that the progressive dissolution of carbonate species cannot account for the observed variability in groundwater compositions. Rather, the dilution of mineralized water, equilibrated with dolomite, with variable proportions of fresh recharge by local precipitation should be considered.

5.3 Surface and ground waters interactions

The relationships between surface and ground waters can be traced using hydrochemistry coupled to isotopic compositions.

Considering that the isotopic composition of groundwater samples falling on the YMWL (Fig. 5f) and lake water samples during the rainy season (Fig. 4; Thin et al., 2016) are comparable, the main recharge of the aquifer in the Northern part of the catchment is constituted by local precipitation water. The extent of floodable areas may therefore play a crucial role in favouring infiltration, since the surrounding areas are characterized by a low permeability unsaturated zone, as deduced by the soil type and mineralogy (Tab. 3S in Supplementary Material), and by the presence of accelerated erosion processes (Htwe et al., 2015).

Groundwater may then contribute to Inle Lake through underground flow but, more noticeably, feeds the dense network of natural and artificial canals that are constructed for land reclamation purposes. This continuous feeding of groundwater to the lake is also sustained by the emergence of deep groundwater circulating in the fractured bedrock, that partially mixes with groundwater in the aquifer, but also enters the main lake inflow R1, P2, and eventually the lake itself. This is clearly evidenced by the higher bicarbonate content with respect to (Ca+Mg) displayed by these surface water samples (Fig. 3a) consistent with the hydrochemical characteristics of groundwater. Also R2, flowing form the W, may receive a contribution of waters circulating in the dolomite bedrock, in agreement with its location at the foothills of the range (Fig. 1).

The input of groundwater rich in Mg to the lake may be responsible for the variable Ca and Mg contents displayed by lake waters, generally characterised by an inverse relationship (Fig. 3b; Thin et al., 2016). While the Mg content seasonally increases due to evaporation, the Ca content decreases because of calcite precipitation, therefore explaining the relationship between the two cations. The Mg/Ca ratio and TDS often correlate positively over a wide range of salinity among lakes and wetlands, and this is attributed to evaporative concentration of lake water and calcite formation (Shapley at al., 2010). Nevertheless, the two processes (evaporation and calcite precipitation) do not give automatically a linear -1:-1 relationship such as that observed. In our case, since Ca and Mg are in a 1:1 relationship in groundwater feeding the lake, inflow water would precipitate calcite and remove Ca, causing a proportional increase in Mg. Alternatively, Mg may also be trapped during carbonate precipitation, but could be released from endogenic carbonates during transformations occurring in the sediment (e.g. the formation of authigenic calcite) (Sinclair, 2011). Whatever the reason for the seasonal increase in Mg, the sum of (Ca+Mg) in lake waters is constant.

The above described processes regulating both surface and groundwater hydrochemistry are summarized in Fig. 6.

5.4. Environmental awareness and emerging criticalities

Given to the lack of literature on aquifer dynamics and recharge mechanisms, the discussion and confrontation with the well owners involved in the sampling campaign and some representatives of the agricultural sector proved to be fundamental to retrieve additional information to support the hydrogeochemical assessment, and to embed the local know-how on the lake status and evolution in the analysis. This also permitted to gain further insights on the human-lake interactions. In particular, the following emerged:

- The periodic flooding of the northern sector during the rainy season (Fig. 1) is appreciated by local farmers as it enhances the moisture content in soils and also increases the soil fertility, although floods are often perceived as a limiting factor for crop diversification (as only rice cultivation is possible under certain conditions) and as vectors of pests (e.g. snails).
- At present, water scarcity is not perceived as an issues in the region, but this is in contrast with the clear evidence that the water level in the Inle lake is declining, and that soil erosion processes occur in the northern sector of the basin, increasing sedimentation and creating difficulties in transport along rivers and in canals. Inle Lake still represent the main freshwater source for both domestic and agricultural activities in the

region (although the latter are also occasionally supplied by irrigation channel water, subject to no specific fees).

- Water quality is not perceived as an issue in the area, although end-users are aware of the potential presence of contaminants, proven by the widespread use of bottled waters. In certain parts of the catchment both surface and ground water are visibly ferruginous: some well owners declared having been advised not to use them for drinking purposes, and oxygenation is generally a common practice in most of the households. In addition, the large consumption of bottled water is resorting the local community to reuse and recycle plastics, although plastic pollution is being perceived as a problem. In fact, some farmers reported the presence of a high level of suspended materials (mainly plastics garbage) in the irrigation channel, that requires the construction of some physical barriers to prevent their entrance in the fields.

In addition, the confrontation with farmers and local populations during field activities suggested that cultural eutrophication may represent in the future a serious problem. Indeed, while in pristine areas the primary source of nutrients to surface water bodies comes from soil erosion, urban settlements and intensive agriculture can provide an additional load of nutrients impacting on surface and ground water quality. As a consequence, the nutrients’ concentrations were determined to evidence the present status and define possible criticalities.

The statistical summary for nitrate and total P concentrations is reported in Tab.1S (Supplementary Material). Nitrates are generally very low and mostly in the range expected for natural unpolluted waters (Edmunds and Shand, 2008), never exceeding the limit set for drinking water purposes. Also the P content was found rather low, although relatively high concentrations are observed in some groundwater samples (G9, G12).

Akaishi et al. (2006) conducted a first survey on the P concentration in lake waters, and concluded that the lake was eutrophic. This conclusion was re-discussed by Thin et al., 2016, based on the definition of the chemical processes governing hydrochemistry and the short residence time of water in the lake. A precise classification of the tropic state of Inle lake waters is out of the scope of this work and should be based on more detailed investigation on the different P and N forms together with other relevant parameters (e.g. Secchi depth, chlorophyll etc., see EPA, 2000). Nevertheless, as we analysed the total P content and nitrate concentrations in surface and groundwater, we calculated the N:P ratios that, according to different authors (e.g. Elser et al., 1990), may be indicative to determine the limiting nutrient. This molar ratio varies between 45.5 and 948 in surface waters, and between 7.67 and 334 in groundwater. Considering that we used dissolved nitrate rather than total N, the ratios should be even higher. The lowest value, approaching the Redfield ratio (Redfield, 1934) is displayed by G9 that shows the highest (and anomalous) P content. Therefore, the low amount of P and the high N:P ratio for all surface and groundwater samples suggest that P could be the limiting nutrient for this freshwater ecosystem. Nevertheless, some concern is raised when looking at the spatial distribution of P in surface waters (Fig. 7). Three hotspots are identified, one corresponding to R1 (Nanlit Stream) and two located in the floating gardens area. The latter has already been the focus of attention because of the large amounts of pesticides used in tomato cultivation (Butkus and Myint, 2001) and the elevated P contents detected in lake sediments (Thin, 2015; Thin et al., 2017).

The reason of such low P concentration detected in the catchment could be that both surface and groundwater are generally saturated with calcite, and its precipitation is an effective process sequestering P in a mineral form and making it unavailable for the development of organic matter (Koshel et al., 1983).

Indeed, when plotting the calcite SI versus the P concentration (Fig. 8), a significant negative correlation is observed for surface waters ($R^2 = 0.2521$; n= 29; p<0.01); the correlation is even higher ($R^2 = 0.4406$; n=39) for all waters, if we exclude G9 for its anomalous content and G6 as the most freshwater sample. This internal mechanism of P removal, combined to the low water residence time, likely prevents the accumulation of nutrients in lake waters. Nevertheless, when establishing the nutrient budgets at the catchment scale, the presence of P in groundwater should be accounted for, as it may represent a possible source for surface waters.

The findings of this work permitted to build a conceptual model of water dynamics in the catchment. The periodic flooding of the northern sector during the rainy season (Fig. 1 and Fig. 9) contributes to the creation of a storage of surface water in the ground which is particularly valuable for the implementation of agricultural activities. Due to photosynthetic activity and the shallow depth of the water during flood periods, recharge water likely reaches saturation with calcite, that precipitates as indicated by the mineralogical analyses of soil samples (S1, S2 and S3, Tab. 3S in Supplementary Material), enhancing their fertility by ameliorating the soil texture and pH. Therefore, future agricultural development plans must also take into account the positive effects of flooding on soils and aquifer-lake dynamics to avoid irreversible environmental damages and the associated negative externalities on local population wellbeing. In this framework, a new guiding philosophy at regional and national level that can balance the need for economic growth and ensures water resources protection in the long-term will be fundamental. In fact, if the decrease of surface water will continue at present rates, not only this will become a limiting factor for crop production and domestic use, but could also force the local population to increase groundwater exploitation with a positive feedback mechanism on lake water levels and associated eutrophication (Fig. 10). In addition, the construction of future accommodation establishments and resorts should be accompanied by the implementation of adequate wastewater treatment systems in order to maintain the current nutrient concentrations, and of water saving technologies (e.g. rainwater harvesting, and treated wastewater reuse for irrigation) to minimize the impact on the lake ecosystem.

6. Conclusions

Results of the first integrated assessment of surface-ground water interactions and recharge mechanisms in the Inle Lake catchment permitted to:

- Confirm previous studies that affirmed that Inle is an alkaline lake, where carbonate equilibria dominate the lake water hydrochemistry, characterized by a high resilience.
- Assess groundwater quality and origin in the region, highlighting the dominance of Mg(Ca)-HCO_3 *facies*, in the aquifer, with the exception of the Khaung Daing Hot Spring showing a relatively high mineralization and a Na-HCO_3 type.
- Evidence groundwater contribution to Inle Lake recharge through both underground flow and by feeding the dense network of natural and artificial canals that are constructed for land reclamation purposes. Recharge is also sustained by the upwelling of deep groundwater circulating in the fractured bedrock, that partially mixes with groundwater in the aquifer, but also enters the main lake inflow (L1), and eventually the lake itself.

These scientific findings also permitted to define the first conceptual model of the water dynamics in the catchment (Fig. 9), evidencing the seasonal fluctuations of the water levels and the associated recharge mechanisms of both surface and groundwater, while contributing to the literature on alkaline lakes and on groundwater dependent ecosystems.

Research findings highlighted how a scarce awareness of potential water quantity issues, combined with the increasing demand due to agricultural development, population growth and tourism activities in the long-term, may negatively affect aquifer-lake interactions. Therefore, action should be taken to avoid irreversible lake shrinking, as already happened in many lakes worldwide. This would represent not only a serious environmental loss of a natural heritage, but also a potential driver of social instability at regional and national level, if the rural population was to abandon the lake area to migrate towards cities. As a consequence, future research developments involve improving the groundwater knowledge and performing a full socio-hydrogeological assessment (Re, 2015), in order to better understand aquifer dynamics while contributing to involve individual citizens, landowners and government agencies, in a participatory process targeted to natural resources conservation and sustainable development.

Acknowledgements

The mobility towards Myanmar was supported by the Erasmus+ programme, KA107 International Credit Mobility, Outgoing Teaching Mobility Grants 2015-2017 managed by the University of Pavia. The University of Pavia also supported the work of Viviana Re through the "*Fondo Ricerca & Giovani*" funding scheme. Authors wish to sincerely thank Mrs. Mya Mya, Professor (Rtd.), Yezin Agricultural University, Myanmar for her help through the sampling campaign and Dr. Enrico Allais of ISO4 for the construction of the smart sampling devices used for water collection. We would like to thank the colleagues of the Department of Geology of the University of Mandalay for their critical review of the conceptual model presented in the manuscript. We greatly appreciated the valuable comments and useful suggestions for improving our research in the Inle Lake area provided by an anonymous reviewer.

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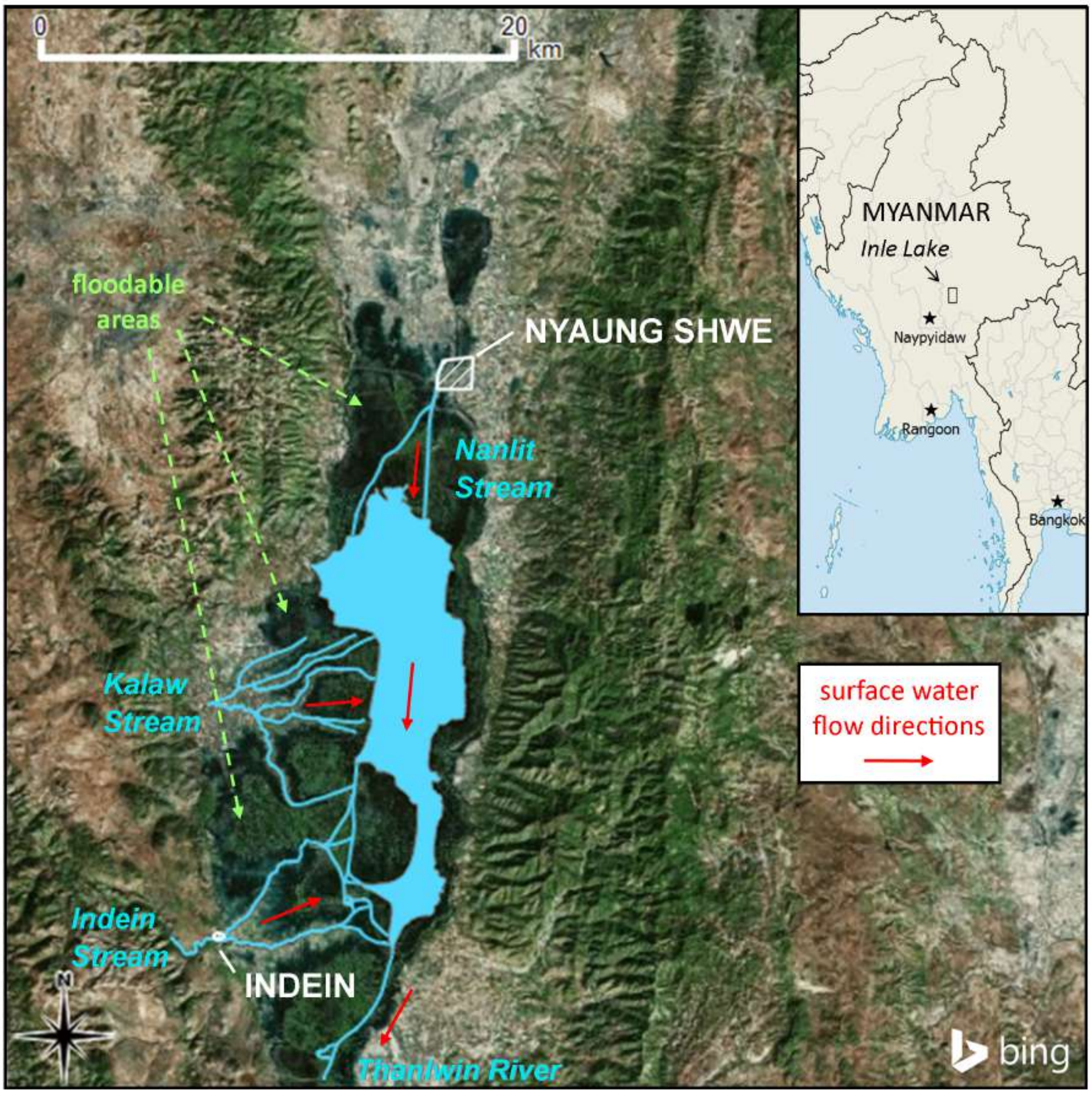

Figure 1. Location of the Inle Lake catchment.

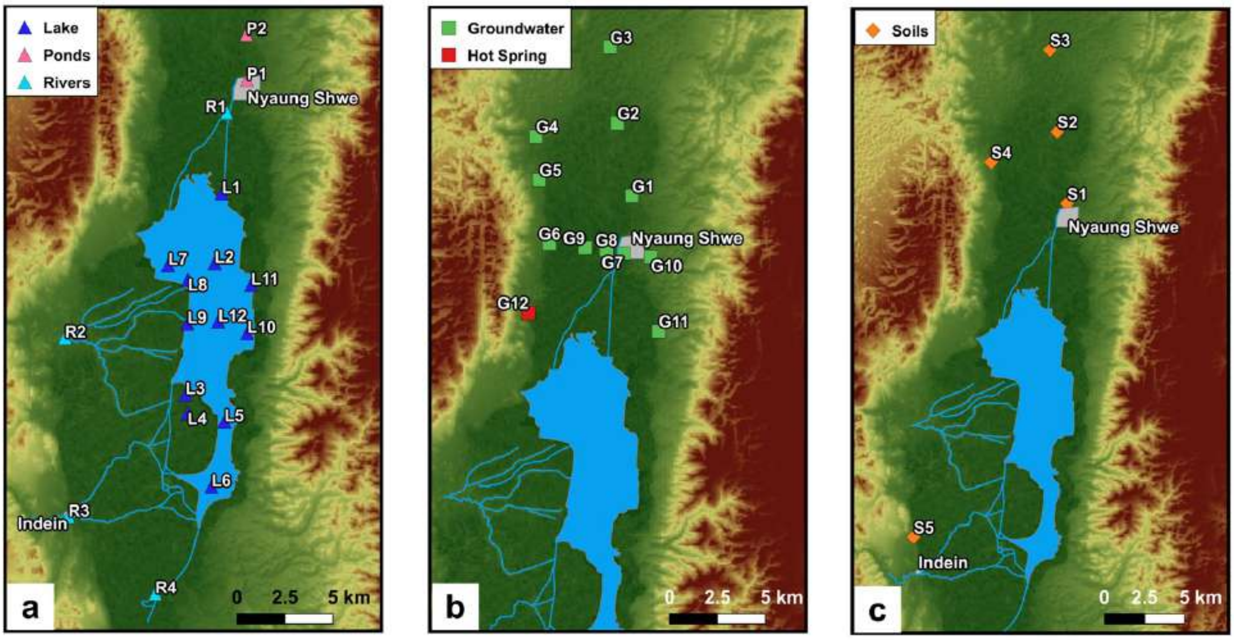

Figure 2. Location of the sampled sites; (a) surface waters; (b) groundwater; (c) soil samples.

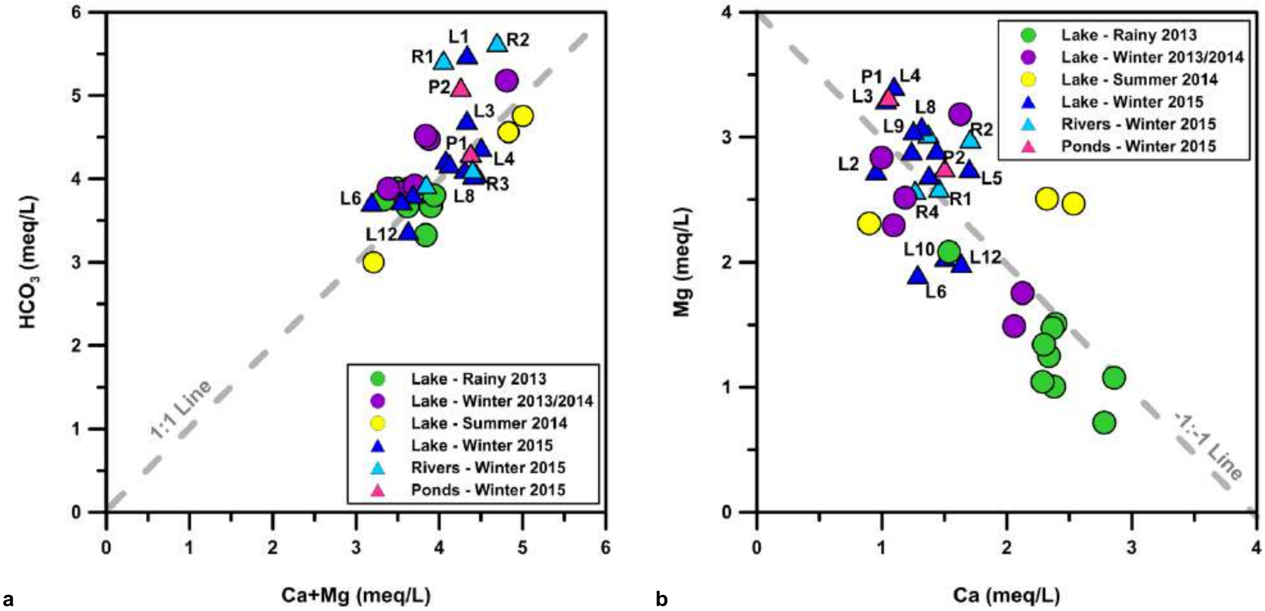

Figure 3. Surface water seasonal variations of (a) HCO_3 versus Ca+Mg; and (b) Mg versus Ca. Data for 2013-2014 from Thin et al., 2016.

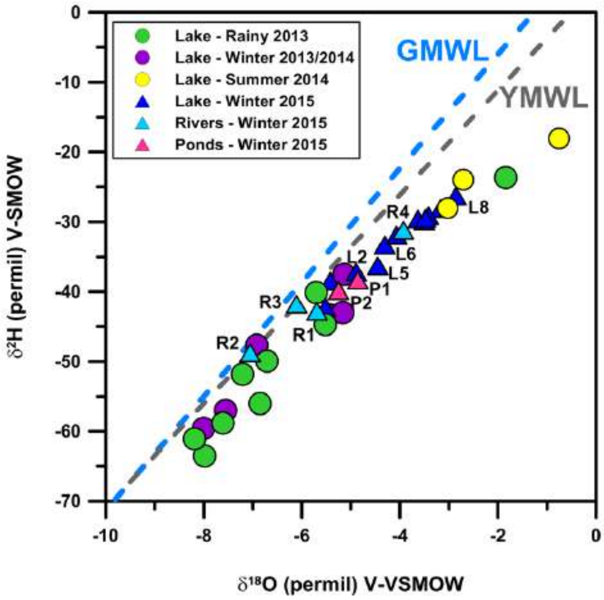

Figure 4. Seasonal variations of isotopic composition of surface waters. Data for 2013-2014 from Thin et al., 2016. GMWL: Global Meteoric Water Line ($\delta^2H = \delta^{18}O*8.17 + 10.35$; Rozanski et al., 1993); YMWL: regression line for Yangon precipitation data (IAEA/WMO, 2015).

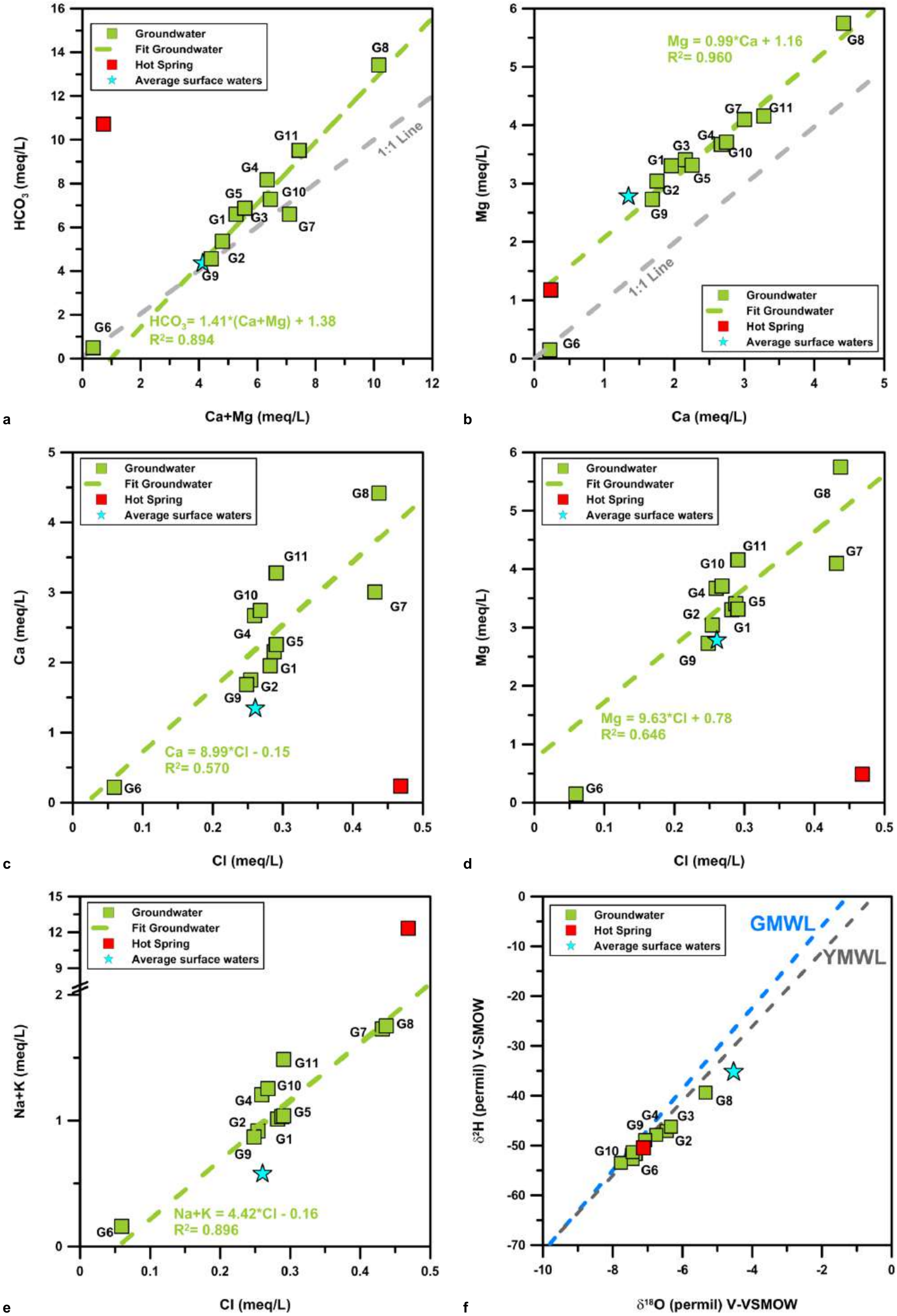
a
HCO3 (meq/L)
Ca+Mg (meq/L)
Groundwater
Fit Groundwater
Hot Spring
Average surface waters
HCO3= 1.41*(Ca+Mg) + 1.38
R²= 0.894
1:1 Line
G1 G2 G3 G4 G5 G6 G7 G8 G9 G10 G11
b
Mg (meq/L)
Ca (meq/L)
Mg = 0.99*Ca + 1.16
R²= 0.960
1:1 Line
c
Ca (meq/L)
Cl (meq/L)
Ca = 8.99*Cl - 0.15
R²= 0.570
d
Mg (meq/L)
Cl (meq/L)
Mg = 9.63*Cl + 0.78
R²= 0.646
e
Na+K (meq/L)
Cl (meq/L)
Na+K = 4.42*Cl - 0.16
R²= 0.896
f
δ²H (permil) V-SMOW
δ¹⁸O (permil) V-VSMOW
GMWL
YMWL

Figure 5. Groundwater composition: (a) HCO_3 versus Ca+Mg; (b) Mg versus Ca; (c) Ca versus Cl; (d) Mg versus Cl; (e) Na+K versus Cl. Dashed line = 1:1 line, Fit Groundwater line calculated without G6 and G12. (f) Isotopic composition of groundwater. GMWL: Global Meteoric Water Line ($\delta^2H = \delta^{18}O *8.17 + 10.35$; Rozanski et al., 1993); YMWL: regression line for Yangon precipitation data (IAEA/WMO, 2015).

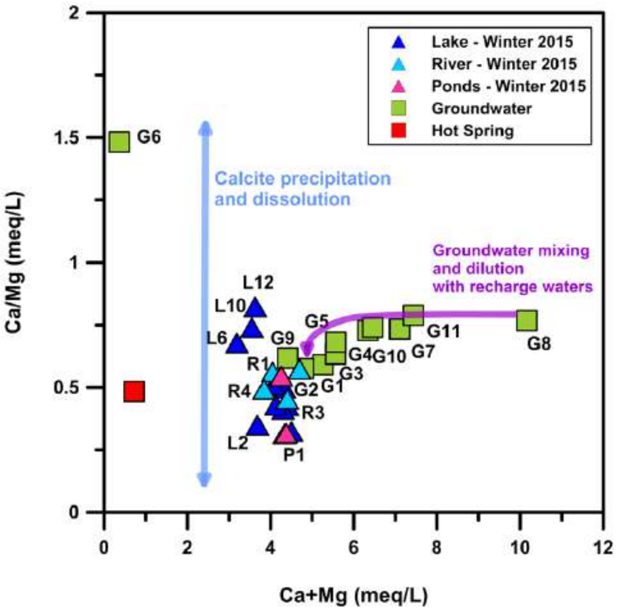

Figure 6. Ca/Mg versus Ca+Mg. Arrows correspond to the trends of calcite precipitation and dissolution (light blue arrow) and groundwater mixing and dilution with recharge water (purple arrow), and have no mathematical meaning.

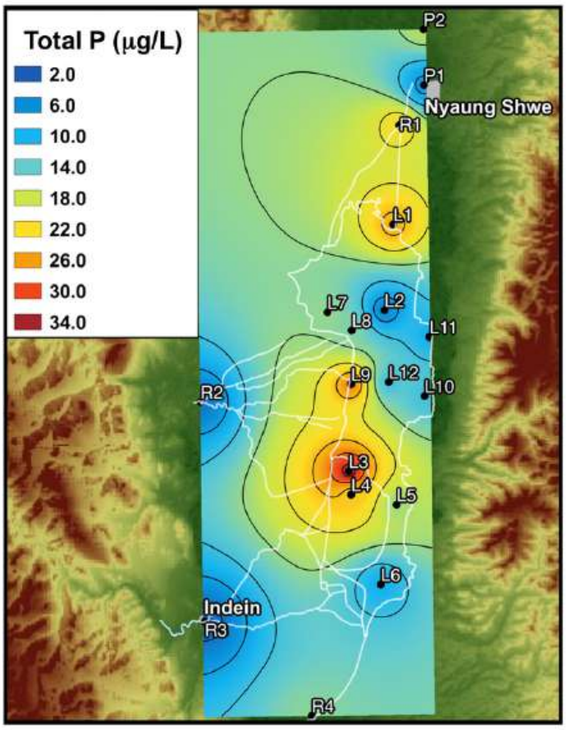

Figure 7. Spatial distribution of P concentrations in surface waters.

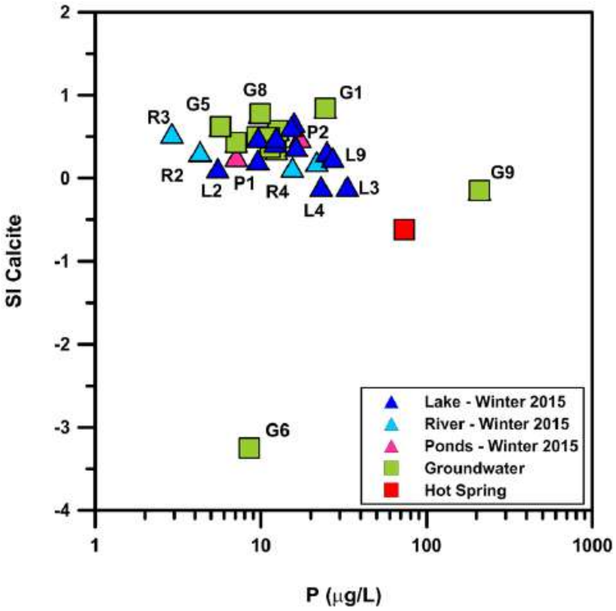

Figure 8. Plot of Saturation Index of calcite versus total P concentrations.

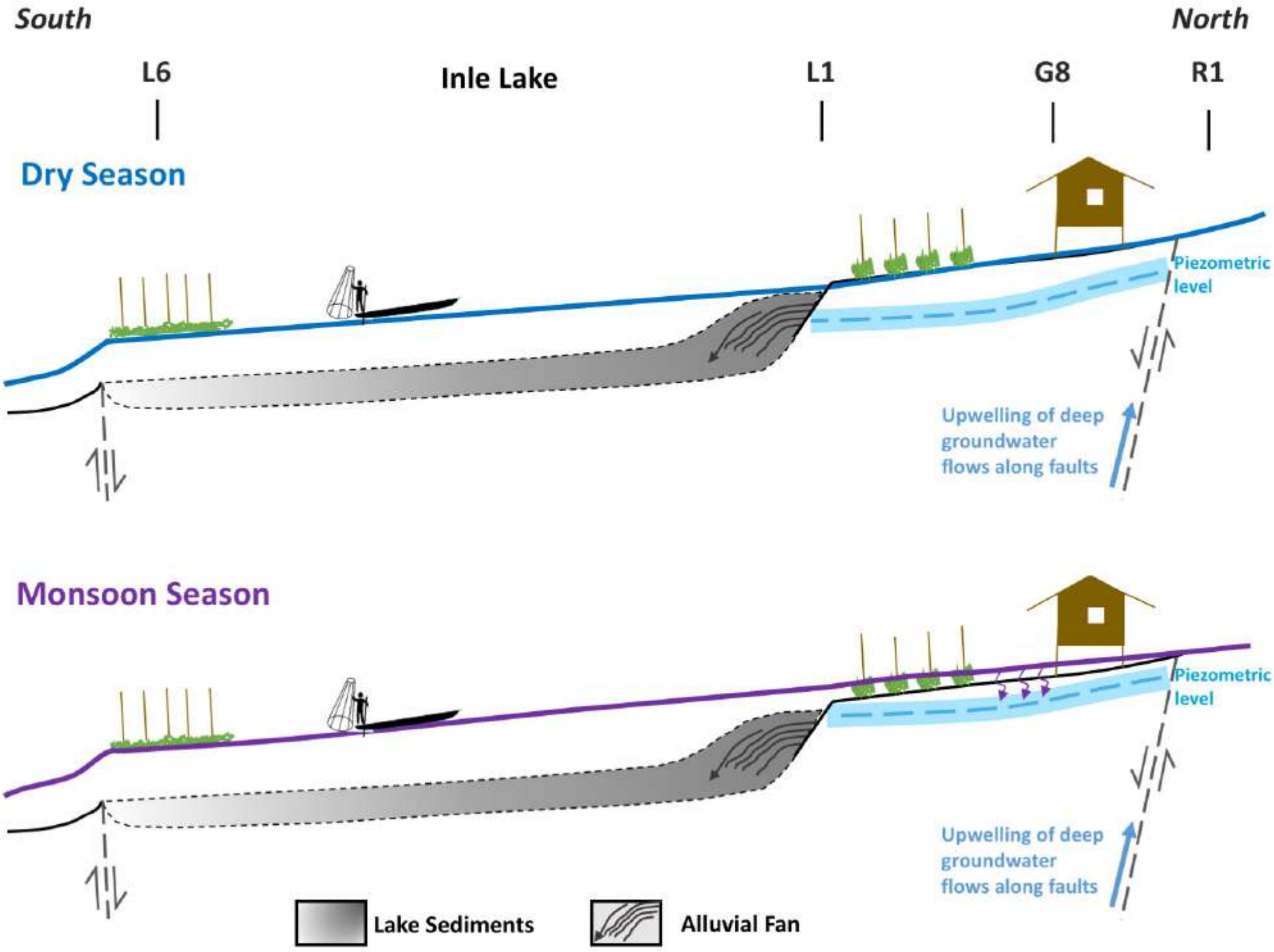

Figure 9. Conceptual model of the water dynamics in the Inle Lake catchment.

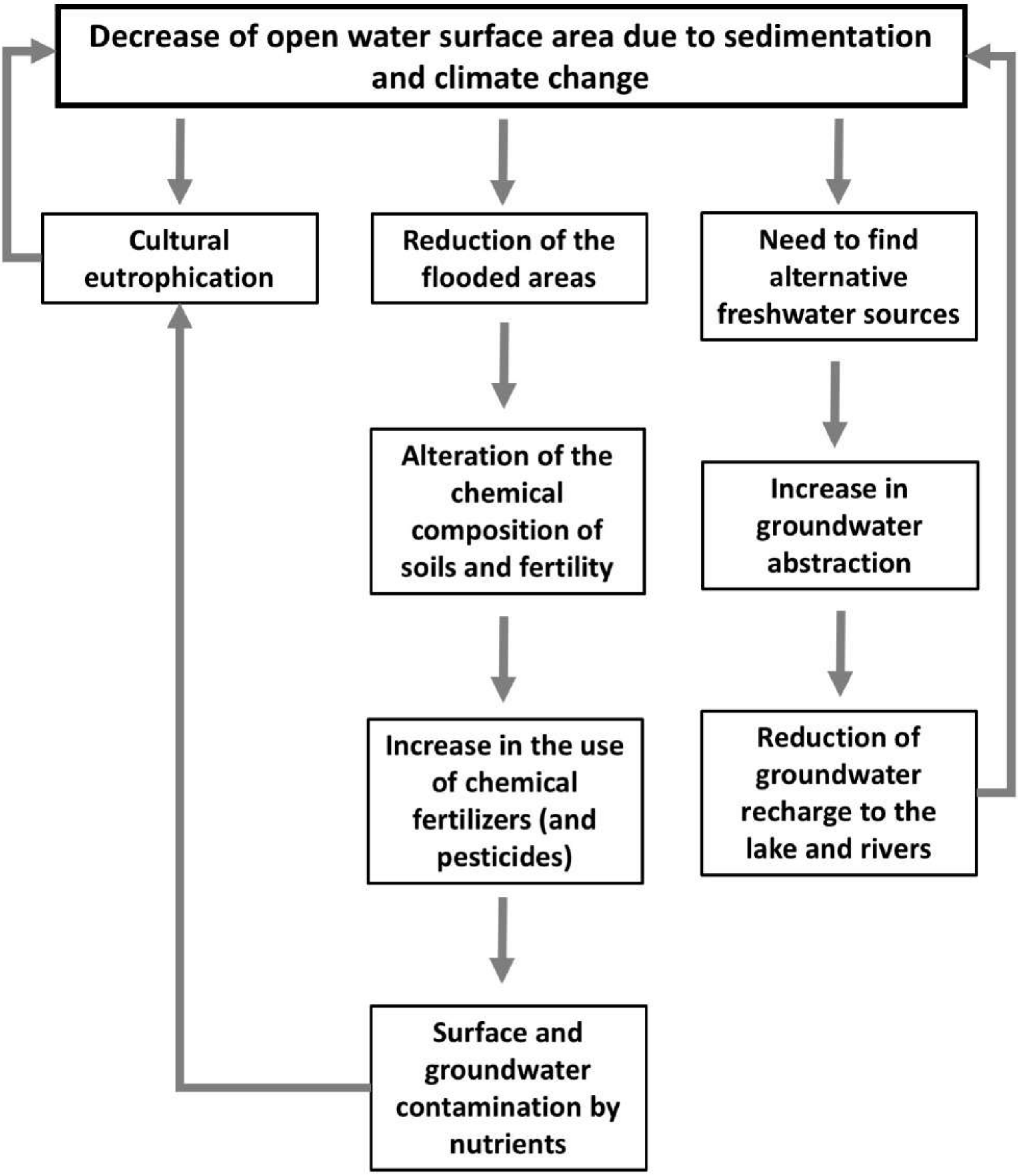

Figure 10. Possible scenarios and positive feedback mechanisms associated to the continuous decrease of open water surface at Inle Lake.