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Hydrological processes at Inle Lake (Southern Shan State, Myanmar) inferred from hydrochemical, mineralogical and isotopic data[†]

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ABSTRACT

A one-year hydrochemical and isotopic monitoring was conducted at the Inle Lake, the second largest lake in Myanmar, also considering sediment samples. Lake waters are characterised by low electrical conductivities (236–489 $\mu\text{S}/\text{cm}$), neutral to alkaline pH (7.36–9.26), oxidising Eh (329–457 mV) and Ca–Mg–HCO₃ facies. Stable isotopes indicate that lake waters are only slightly affected by evaporation, are fully flushed yearly and are not stratified. Carbonate equilibria dominate the lake water hydrochemistry. In summer, photosynthetic activity and temperature increase induce calcite precipitation, as testified by its high content in the sediments, up to 97 %, and by its isotopic composition. The short residence time and endogenic calcite precipitation likely prevent the accumulation of contaminants and nutrients in lake waters. This study suggests a high resilience of the system to anthropogenic disturbances and demonstrates the sediment potential for the reconstruction of the environmental evolution in time and for the anthropogenic impact assessment.

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1. Introduction

The Inle Lake is the second largest lake in Myanmar and the most important one, being the main water resource for the Law Pi Ta hydroelectric power plant. The lake is a major tourist attraction upon which many in the local economy rely, a provider of agricultural products, and a habitat for rich biodiversity and traditional culture [1]. It is a vital part of the broader ecosystem and economy of the Shan State, with over 200 villages and more than 120,000 people inhabiting the immediate watershed in the year 2000 [2].

Previous studies report that the Inle Lake is seriously threatened by anthropic activities on the lake sides and in its drainage basin [1–3].

One of the main problems is related to the decrease in the open water surface, estimated to be as much as 32.4 % between 1935 and 2000 [3]. This is due, on one hand,

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to an increase in sedimentation caused by accelerated soil erosion, as a consequence of deforestation in the watershed [2]. On the other hand, shrinkage is due to the expansion of floating gardens. These are manufactured from the dead parts of aquatic and marsh plants, and used as the growing medium for planting fruits, flowers and other vegetables. Once their fertility is exhausted, they are moved to the perimeter of the lake where they settle at the bottom, thus contributing further to its reduction in depth. Direct environmental impacts associated with agriculture activities within the wetlands and margins of the lake include sedimentation, eutrophication and pollution [3].

A second major problem relates to the lake water quality. As in many low-income countries, the population increase, with an exponential growth rate of approximately 2.3 % per year [2], is not paralleled by adequate sanitation infrastructures. This anthropogenic pressure is expected to grow in the future because of the tourism development in the area. In addition, agrochemicals are widely used in floating gardens, especially for tomato cultivation [1], and the unregulated use of pesticides threatens the biological diversity of local flora and fauna [2,4].

Despite its environmental, ecological and economic relevance, and despite the well-known threats to its ecosystem, the Inle Lake has not been fully characterised in its hydrochemical and hydrological behaviour. An assessment of surface water quality, focusing on the definition of the trophic level of the lake, was performed with one water sampling campaign, conducted in November 2004, after the monsoon season [1]. This study concluded that the lake was eutrophic, but underlined the need for more extensive studies due to the rapidly evolving socio-environmental situation.

In this paper we present the result of a comprehensive hydrochemical, isotopic and mineralogical characterisation of water and sediments from the Inle Lake. The objectives are to investigate the seasonal water dynamics, evaluate the processes regulating the hydrochemical contents, define the mineralogical composition of the sediments and assess the vulnerability of the water body to the anthropogenic impacts.

2. Study area

The Inle Lake is situated in Naung Shwe Township, Southern Shan State (20°27'–20°40'N, 96°52'–96°57'E, 870 m a.s.l.; [Figure 1](#)). The lake watershed is characterised by a large, flat valley running N to S, surrounded by mountain ranges. The lake is irregularly shaped, with a present-day average length of 18 km and a width of about 6 km [3]. The main contributor is the Nanlit Stream, with headwaters 16 km N of the inlet to the lake. The river course, while crossing the northern part of the basin, appears to have been rectified and is periodically dredged to facilitate motorboat circulation. At the entrance of the lake, an important fan can be observed from satellite images, extending for more than 1 km S and testifying for the large input of sediments carried by the stream. Several other contributors are present: those flowing from the W, especially the Kalaw Stream, originate large alluvial deltas, whereas the eastern border of the lake is more abrupt due to the proximity of the mountain range. The only lake outlet flows to the S, entering the Thanlwin River [2].

The basin is located in the Shan Plateau, belonging to the Sibumasu block [5], and mainly constituted by Permo–Triassic carbonates [6].

The hydrographic network in Myanmar is strongly conditioned by recent tectonic activity, and particularly by the movement of the eastern Himalayan syntaxis [7]. The

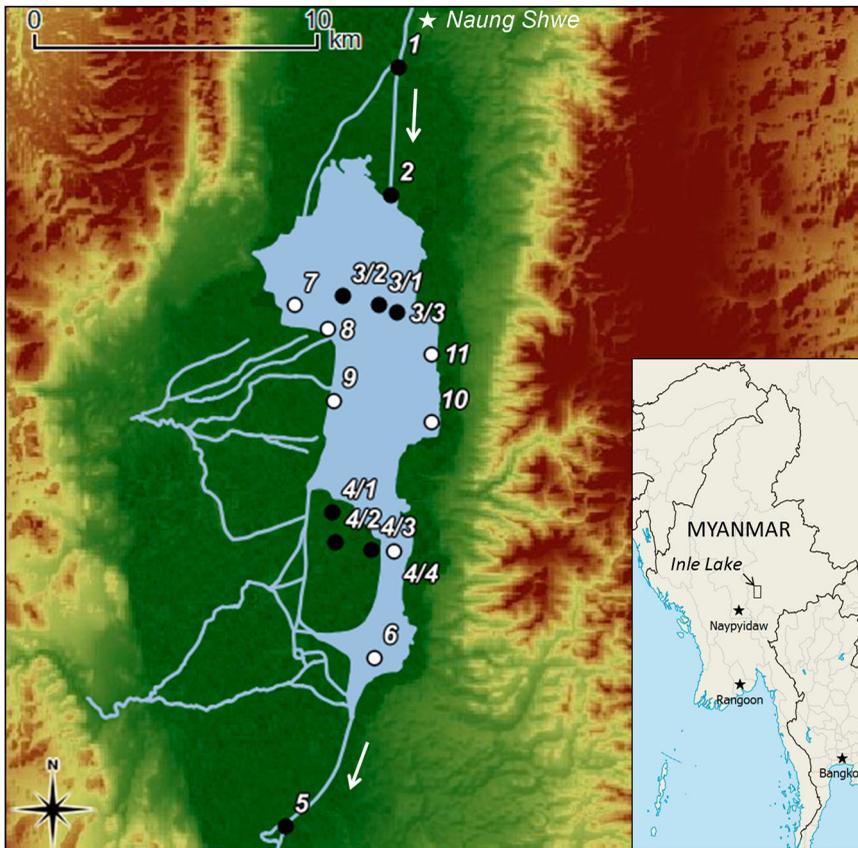


Figure 1. Location of the study area in Myanmar and of the sampling stations: black dots = one-year water sampling and sediments; white dots = March 2014 sampling; white arrows = in and out flow directions; background image = digital elevation model produced using public domain CIAT-CSI SRTM data [8]; Myanmar map produced using public domain data (available from www.natureearthdata.com).

watershed is located about 50 km E of the tectonically active Sagaing fault, a major continental transform fault between India and Sunda plates. Recent neotectonic studies indicate that the Inle Lake watershed develops along a right-lateral strike-slip fault running parallel to the Sagaing fault; the lake itself is bordered on the E side by the Taunggyi normal fault, showing a complex geometry and determining the asymmetrical shape of the basin. Tectonic movements therefore affect the sediment transport and the development of the river deltas [9].

The drainage area and storage capacity of the lake have been estimated at 3,700 km² and 3.5 × 10⁷ m³, respectively, while annual inflow and water residence time are estimated to be 1.1 × 10⁸ m³ a⁻¹ and 0.32 years [2].

The climate in the lake area is humid subtropical (Cwa according to the Köppen-Geiger classification) with three seasons: summer (March, April, May and June), rainy season (July, August, September and October) and winter (November, December, January and February). Approximately 70 % of the annual rainfall occurs in July, August and September: the mean annual rainfall measured in 2000 to 2013 is 984 mm [10], generally occurring on

80 individual days. In these years, no tendency to an increase or decrease in precipitation amount is observed. Mean air temperature near the lake ranges from 16.5 to 25.0 °C [11]. Average daily humidity ranges from 48 % in March to 79 % in the rainy season [12]. The depth of the lake seasonally fluctuates, from about four meters in summer to seven meters in the rainy season [4]. In the last years, and especially in 2010 [13], the lake has experienced dramatic drops in the water level during summer (e.g. during the March 2014 sampling campaign, it did not exceed 2.0 m).

3. Materials and methods

A one-year hydrochemical and isotopic monitoring was conducted, collecting surface water samples from five study sites (Figure 1), selected based on their position and environmental setting (Table 1 in the Supplemental Material (SM)) [14]. Sampling campaigns were performed in August, September and October 2013 (rainy season), in November and February 2014 (winter), and in May 2014 (summer). A more detailed water sampling campaign was carried out in March 2014 (summer), increasing the number of sampling stations (Figure 1) and collecting both surface and bottom water. Only during this last campaign, water depth, surface temperature, pH, electrical conductivity (EC) and alkalinity were measured in the field. Finally, a water sample from the Khaung Daing natural hot spring located near the lake was also collected. All samples were stored in the dark and in the refrigerator prior to the analysis. During the March 2014 sampling campaign, a few drops of chloroform were added to a separate aliquot of water in order to stop the biological activity. The comparison of the results obtained on the two different aliquots did not show significant differences in the ionic contents.

In the laboratory, all water samples were (re)analysed for pH, EC and alkalinity (by titration). Major ion contents were determined by ion chromatography at the University of Pavia. Analysis reliability was estimated from electro-neutrality balances: charge balance errors were generally within $\pm 6\%$, and all samples out of range ($>\pm 10\%$, [15]) were excluded from the data interpretation phase.

Stable isotopes of the water molecule were determined by wavelength-scanned cavity ring-down spectroscopy at ISO4 in Italy. Results are reported in the usual delta (δ) notation versus Vienna Standard Mean Ocean Water (VSMOW), with uncertainties (2σ) of $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 1\text{‰}$ for $\delta^2\text{H}$. Water samples from the March 2014 campaign were also analysed for $\delta^{13}\text{C}_{\text{DIC}}$ using the gas evolution technique [16]. Results are expressed in ‰ versus Vienna Pee Dee Belemnite (VPDB), with an analytical uncertainty of $\pm 0.2\text{‰}$.

Nine sediment cores were collected in October 2013 by inserting a metallic tube of 5 cm diameter into the lake bottom. Only the deepest portions of the sediment cores, corresponding to a depth of about 100 cm from the sediment–water interface, depending on the location, could be recovered and were retained for mineralogical analyses. Sediment samples were dried at room temperature for 2–3 days. Major shells were eliminated by manual picking, and the sediment was ground to fine powder in an agate mortar. The mineralogical composition of sediment samples was measured by X-ray powder diffraction at the University of Pavia. Five sediment samples, selected based on their calcite content, were analysed for the isotopic composition of carbonates ($\delta^{13}\text{C}_{\text{CaCO}_3}$ and $\delta^{18}\text{O}_{\text{CaCO}_3}$) at ISO4 in Italy, using the procedure described in [17], with results expressed with the usual δ (‰) notation versus VPDB [18].

4. Results

4.1. Hydrochemistry

Results of the water chemical analyses are reported in Table 2 (one-year monitoring) and Table 3 (March 2014 campaign) in the SM. Lake waters are characterised by relatively low EC values (EC range 236–489 $\mu\text{S}/\text{cm}$, with higher values in the summer season), neutral to alkaline pH (range 7.36–9.26) and oxidising conditions (range 329–457 mV). The more abundant cations are Ca^{2+} and Mg^{2+} , followed by Na^+ and K^+ , whereas bicarbonate is by far the most abundant anion, followed by Cl^- , SO_4^{2-} and NO_3^- . The hot spring water is sensibly different, showing the highest conductivity (773 $\mu\text{S}/\text{cm}$) and a $\text{Na}-\text{HCO}_3$ facies. A Piper plot reporting the seasonal variation in water chemistry is shown in Figure A (in SM).

4.2. Stable isotopes

Water stable isotopes range from -8.23 to -0.76 ‰ VSMOW in $\delta^{18}\text{O}$ and from -63.6 to -18.1 ‰ VSMOW in $\delta^2\text{H}$. In the rainy season, the isotopic compositions align parallel to the global meteoric water line, but with a lower d -excess (Figure 2), and close to the isotopic composition of precipitation in Yangon [19]. The isotopic composition of the hot spring agrees with the mean composition of waters from the rainy season (Figure 2), indicating that, despite its high temperature (70 °C, [20]), it is not strongly modified by water–

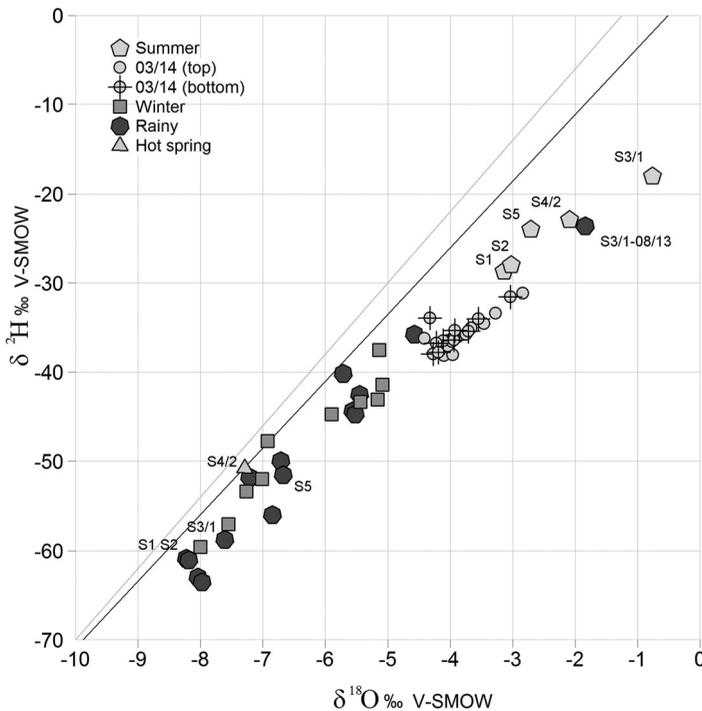


Figure 2. Seasonal variation of the isotopic composition of lake waters. The composition of the Khaung Daing hot spring water is also shown. Grey line: global meteoric water line. Black line: regression line for Yangon precipitation data [19].

rock interaction processes and could be representative of the isotopic composition of groundwater in the area.

The isotopic composition of dissolved inorganic carbonates ($\delta^{13}\text{C}_{\text{DIC}}$) ranges from -7.98 to -1.86 ‰ VPDB with the most depleted values characterising inflow water and the most enriched values recorded in open lake water (Table 3 in SM). The $\delta^{13}\text{C}_{\text{DIC}}$ of the hot spring water with the highest bicarbonate content is the most enriched one ($+1.85$ ‰).

Calcite from sediment cores ranges from -1.34 to 4.67 ‰ VPDB for $\delta^{13}\text{C}_{\text{CaCO}_3}$ and from -9.13 to -6.67 ‰ VPDB for $\delta^{18}\text{O}_{\text{CaCO}_3}$ (Table 4 in SM).

4.3. Mineralogy

In the bulk sediment, the most abundant mineral is calcite (range from 48 to 97 %), followed by quartz (0 to 27 %) (Table 4 in SM). Other less abundant, sporadically present, mineral phases are: mica/illite (0–12 %), kaolinite (0–14 %), aragonite (0–12 %) and hematite (0–11 %). The clay fraction is mostly composed by kaolinite with lower mica/illite and chlorite, and traces of smectite. Figure B (in SM) shows the mineral distribution in the sediment cores. Calcite is not evenly distributed in the lake area: samples collected at or near the inflow (sites 1 and 2) and at the outflow (site 5) show an abundance of about 50 %, generally increasing with depth, whereas within the lake calcite rises up to more than 90 %.

5. Discussion

5.1. Hydrochemical processes

The lake water composition is regulated by carbonate dissolution and precipitation. This is clearly observed in Figure 3(a), where samples all plot on a 1:1 relationship between $\text{Ca}^{2+} + \text{Mg}^{2+}$ and HCO_3^- contents, in meq/L. This relationship is not displayed by the hot spring water, which is of Na– HCO_3 type (Figure A in SM). It is interesting to note that the Ca/Mg ratio is not constant, and varies in the different seasons (Figure 3(b)). Samples collected during the rainy season are dominated by Ca, whereas in winter and especially in summer, the Mg content increases parallel to the decrease in Ca, roughly aligning along a slope of -1 . This suggests that calcite precipitation occurs in the warmer months. Saturation indices (SI) for the main carbonate species could only be calculated for the March 2014 campaign, as for the others we miss the field water temperature (Table 3 in SM) [21]. SI ranged between -0.20 and $+1.19$ for calcite, between -0.39 and $+2.25$ for dolomite, and between -0.28 and 1.02 for magnesite. Supersaturation indicates that the precipitation of these minerals could potentially occur [22], triggered by photosynthetic activity and evaporation of the water body [23].

The role of photosynthetic activity can be evidenced by pH values, which were measured in the field during the March 2014 campaign. Inflow waters (sites 1 and 2) are characterised by pH values below 8.2 and relatively higher EC values. During photosynthesis, phytoplankton and macrophytes subtract CO_2 from the water displacing carbonate equilibria and causing an increase in pH up to >9 in open lake waters [24]. Such an alkaline pH favours calcite precipitation, which removes dissolved ions from the solution as

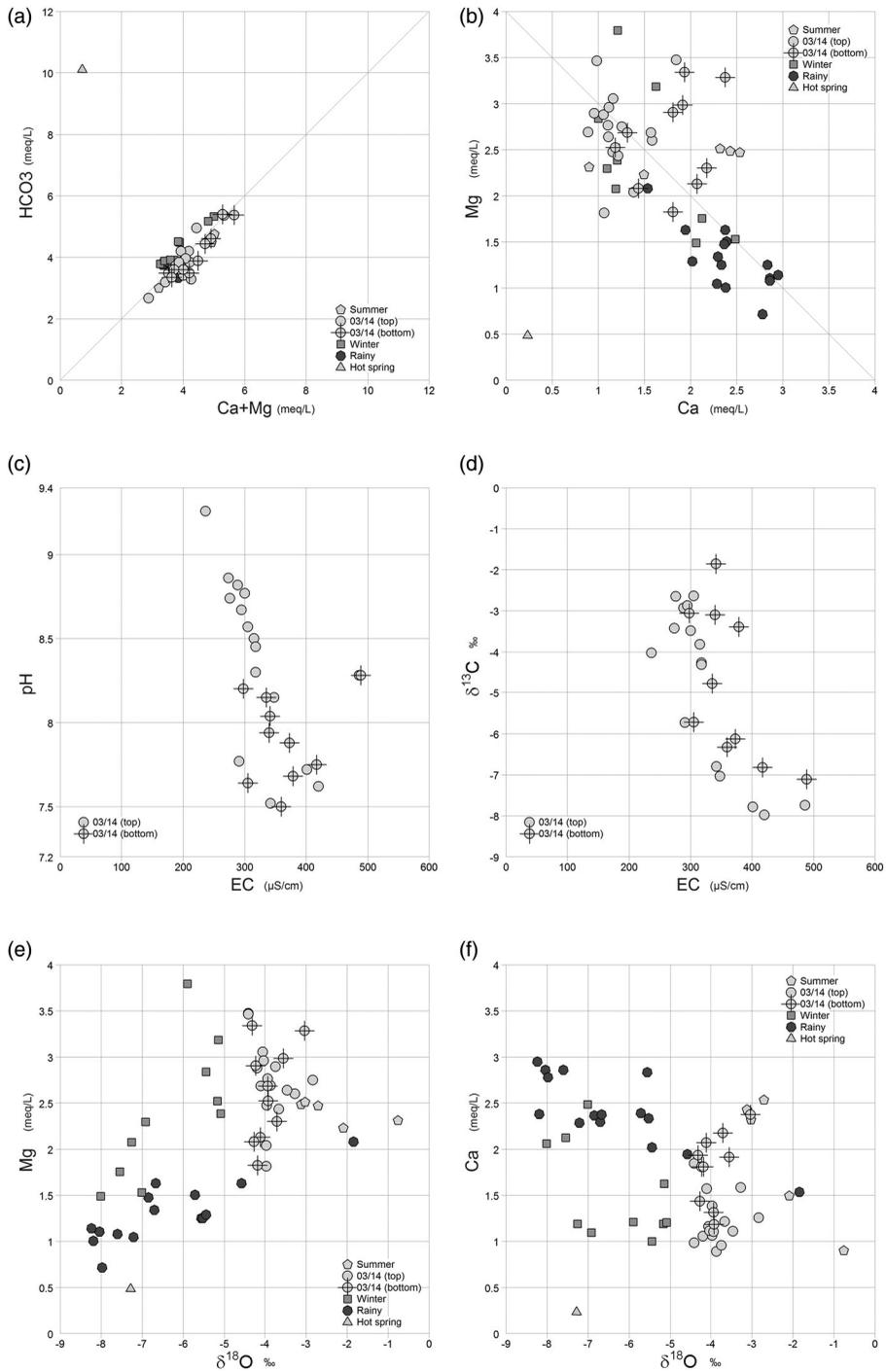


Figure 3. Relationships between (a) Ca + Mg and HCO₃ content in lake waters; (b) Ca and Mg in lake waters; (c) EC and pH measured in March 2014; (d) EC and δ¹³C_{DIC} measured in March 2014; (e) δ¹⁸O and Mg in lake waters; and (f) δ¹⁸O and Ca in lake waters.

evidenced by the inverse correlation existing between pH and EC (Figure 3(c)). In addition, inflow waters are characterised by depleted $\delta^{13}\text{C}_{\text{DIC}}$, around -7‰ , indicating a contribution from the dissolution of soil CO_2 in areas dominated by C4 vegetation [25]. In open lake waters, the photosynthetic activity by preferential uptake of ^{12}C to form the organic matter induces an enrichment in $\delta^{13}\text{C}_{\text{DIC}}$ [26], as shown by the inverse correlation observed with EC (Figure 3(d)). This process is widely recognised in the literature, although comparative studies on different lakes have evidenced that many other factors may influence $\delta^{13}\text{C}_{\text{DIC}}$ in its absolute value [27,28].

Lake waters are subject to evaporation as it will be discussed in detail later, and the influence of evaporation on calcite precipitation can be traced using the isotopic composition of lake waters (e.g. $\delta^{18}\text{O}$). This shows a significant positive correlation with the Mg content in lake waters ($n = 56$; $R^2 = 0.3687$; $p < 0.001$; Figure 3(e)) and negative correlation with the Ca content ($(n = 56$; $R^2 = 0.2491$; $p < 0.01$; Figure 3(f)), although the correlations appear to vary in the different campaigns. This suggests that, while the Mg content seasonally increases with evaporation, the Ca content decreases because of calcite precipitation, thus explaining the relationship between the two cations shown in Figure 3(b). 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 [29]. Nevertheless, it should be noted that the two evolutions do not give automatically a linear relationship and that Mg may also be trapped during carbonate precipitation. Alternatively, one could consider the Mg release from endogenic carbonates during transformations occurring in the sediment (e.g. the formation of authigenic calcite) [30].

Although limited in number and possibly not fully representative, sediment samples may provide an additional confirmation of carbonate precipitation from open lake waters. Indeed, the calcite content determined on samples collected at sites 3 and 4 is high, ranging between 79 and 97 % (Table 4, Figure C, both in SM). Nevertheless, detrital calcite is also likely present in the sediments, especially in those sampled at the inflow sites (1 and 2), showing a calcite content of 40–50 %. Using the $\delta^{13}\text{C}$ fractionation factor between CaCO_3 and DIC at 25 °C (equal to 0.91, [31]), and the isotopic composition of DIC in March 2014 (about -3.5‰ , Figure 3(d)), the isotopic composition of newly precipitated calcite should be around -2.5‰ . Besides, assuming that the isotopic composition of the hot spring water is in equilibrium with the carbonates of the surrounding rocks and considering its temperature and the relative fractionation factors [20], the isotopic composition of detrital calcite could be around $+4.60\text{‰}$. Both these calculated $\delta^{13}\text{C}_{\text{CaCO}_3}$ values are compatible with the isotopic compositions measured in the sediments (Table 4). Therefore, even if based on few preliminary data, the more depleted values of $\delta^{13}\text{C}_{\text{CaCO}_3}$ measured in the sediments could correspond to endogenic calcite precipitated from open lake waters [28], whereas enriched values could correspond to detrital calcite [32].

Finally, further evidence is provided by the isotopic composition of $\delta^{18}\text{O}_{\text{CaCO}_3}$. This shows a significant positive correlation with the calcite content of the sediments ($n = 5$; $R^2 = 0.8221$; $p < 0.05$). Using the $\delta^{18}\text{O}$ fractionation factor between CaCO_3 and water at 25 °C [33], and the mean isotopic composition of lake waters measured in March 2014 (-3.88‰), the isotopic composition of endogenic calcite should be around -6‰ versus VPDB. This value is in good agreement with that measured in the sediments containing the higher calcite percentage.

5.2. Hydrological processes

In the rainy season and in winter, lake water samples plot on a line parallel to that of precipitation collected in Yangon, but with a lower deuterium excess (Figure 2). At the end of winter, but mostly during summer, with rising temperatures, evaporation affects both inflow and lake waters. The slope of the regression line calculated for the May 2014

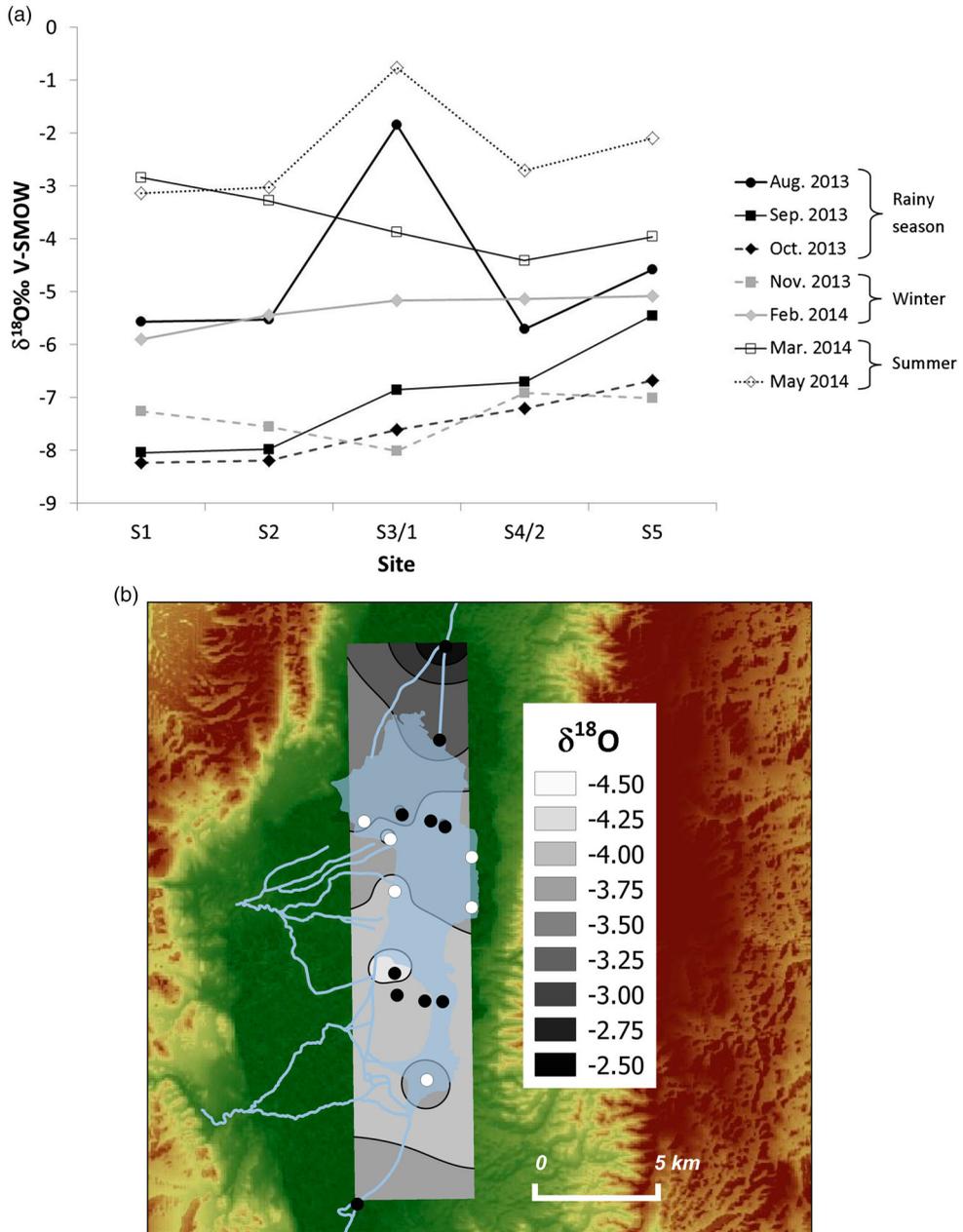


Figure 4. (a) Seasonal evolution of $\delta^{18}\text{O}$ from N to S and (b) interpolation map of the $\delta^{18}\text{O}$ values through the lake (March 2014 campaign).

samples is 4.26 indicating evaporation under low humidity conditions [25]. Nevertheless, in this sampling campaign, the difference between the more enriched and the more depleted compositions is only 2.37 ‰ in $\delta^{18}\text{O}$. This limited evaporative enrichment is due, on one hand, to river waters feeding the lake already affected by evaporation (Figure 2). On the other hand, it could indicate that the fraction of lake water lost by evaporation is low (around 10 %) and/or that the lake is continuously fed with water. Also, assuming that the isotopic composition of the hot spring water is representative of that of groundwater, there is little evidence of a significant contribution of the latter to the lake, since the evaporation line does not originate from that composition [25].

The seasonal evolution of the $\delta^{18}\text{O}$ from sites 1–5 (i.e. from N to S) is shown in Figure 4. At the end of summer, site 3/1 at the centre of the lake displays the most enriched isotopic value which is maintained also at the onset of the rainy season (Figure 2); at the end of the rainy season, site 3/1 displays a composition in $\delta^{18}\text{O}$ more similar to that of the inflow river (site 1), whereas more enriched waters characterise the southern portion of the lake. In February, at the end of winter, the isotopic composition is rather homogeneous, but in March, the inflow water is more ^{18}O enriched with respect to water collected at site 4/2, towards the S of the lake. A $\delta^{18}\text{O}$ interpolation map was elaborated for the latter campaign (Figure 4(b)), which suggests a water movement in through-flow conditions from N to S. This seasonal behaviour also indicates that, during monsoon, the lake water is fully flushed by the inflow water, and therefore the residence time is shorter than one year.

Finally, the comparison between the isotopic composition of top and bottom waters collected in March 2014 shows a good correspondence between deuterium values and only a slight enrichment in ^{18}O displayed by top waters, likely due to evaporation (Figure C in SM). Therefore, lake water is not stratified. This observation is also in agreement with the presence of an oxic environment even in bottom waters, as indicated by positive Eh values (Table 3 in SM) and by the presence of hematite in the sediments (Figure B in SM) [23].

All these findings testify for a highly dynamic system, where water coming from the rivers continuously feeds the lake, even during summer, therefore maintaining through-flow conditions. The short residence time is also in agreement with the previously estimated residence time, as low as 0.32 years.

6. Conclusion

Hydrochemical results indicate that carbonate equilibria dominate the lake water hydrochemistry. In summer, the intense photosynthetic activity, coupled to an increase in temperature, induces endogenic calcite precipitation, as testified by the high calcite content detected in the sediments sampled in the centre of the lake. Lake water is affected by evaporation, but the isotopic evaporative enrichment is minor, suggesting that the lake is continuously fed by waters. These waters also provide dissolved constituents (e.g. Ca and Mg), where Ca is removed by calcite precipitation. Therefore, endogenic calcite precipitation is an active mechanism that could significantly contribute to sedimentation.

Isotopes of the water molecule indicate a residence time shorter than one year and the absence of lake water stratification, which is also in agreement with the presence, even in bottom waters, of oxic conditions. The relatively short residence time and calcite precipitation likely prevent the accumulation of anthropogenic contaminants and nutrients in

lake waters (e.g. calcite precipitation is an effective process sequestering P into the sediments and making it unavailable for the development of organic matter) [34].

This general picture of the Inle Lake hydrodynamic and hydrochemical behaviour suggests a high resilience of the system to the anthropogenic disturbances in the watershed, but leaves unexplained the reasons of the dramatic drops in the lake water level experienced in recent years. Precipitation data collected since 2000, also compared to those provided by Sidle et al. [3] for the previous decade, fail to evidence modifications in the precipitation amount or in the number of rainy days. Since the lake appears to continuously be fed mainly by inflowing rivers, investigation should focus on the anthropogenic impact on the drainage basin (e.g. effects of deforestation and shifting cultivation on rain-water runoff and infiltration) and on the river flow regime (e.g. water abstraction for irrigation).

Finally, the study demonstrates the sediment potential to contain information allowing for the reconstruction of the environmental evolution in time and to assess the anthropogenic impact on this valuable ecosystem.

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