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# Perspectives from modern hydrology and hydrochemistry on a lacustrine biodiversity hotspot: Ancient Lake Poso, Central Sulawesi, Indonesia[☆]

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ABSTRACT

The highly biodiverse Lake Poso, located in Central Sulawesi, Indonesia, can be considered one of the least studied ancient lakes in the world. Here, we present a comprehensive analysis of Lake Poso's hydrology and hydrochemistry, shedding light on factors that may have contributed to the exceptional biodiversity. Riverine and lake water chemical compositions indicated a soft water lake and relative major cation and anion abundances of $Ca^{2+} \gg Mg^{2+} > Na^{+} > K^{+}$ and $HCO_3^{-} \gg SO_4^{2-} > Cl^{-}$, primarily a result of the high annual precipitation and chemical weathering of calcareous-siliceous metamorphic bedrock. Lake Poso's nutrient concentrations were low (average DIN/TDP mass ratio of 6.2 and 50.9 for the lake surface water and its tributaries, respectively), indicating that most of the inlets were P-limited and that the lake was likely P-limited as well. Metal pollutants indicated a minor to moderate impact of anthropogenic land use (~32 % of the catchment area). Water isotopic compositions of the different tributaries clearly delineated rivers draining higher elevation catchments with lower $\delta^2H$ and $\delta^{18}O$ from those draining lower elevation catchments with higher $\delta^2H$ and $\delta^{18}O$. Surface lake water isotopic compositions indicated detectable evaporation from the lake leading toward more enriched isotope compositions than the integrated source signal. Overall, the findings suggested that Lake Poso remains relatively resilient to anthropogenic land use and related nutrient and pollutant inputs. However, ongoing alterations to its hydrological balance due to significant changes in land use may drive the lake towards higher trophic levels in the future.

## 1. Introduction

Ancient lakes are unique ecosystems that have existed for more than one glacial-interglacial cycle or >100,000 years, resulting in the evolution of endemic species that are found nowhere else in the world (Cohen, 2012; Wilke et al., 2016). However, these lakes and their biodiversity are threatened by several factors (Hampton et al., 2018), including (1) habitat destruction and fragmentation (e.g., through agricultural development, urbanization, and logging), (2) introduction of invasive species, which may outcompete native species for resources and disrupt the ecosystem balance, (3) climate change including altered water levels (e.g., changes in precipitation and evaporation) and temperature, (4) pollution including the introduction of toxins and fertilizer-derived nutrients, (5) overfishing potentially leading to a

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decline in fish populations and a disruption of the food chain which can have a ripple effect on the entire ecosystem. Overall, the threats to biodiversity in ancient lakes require careful management and conservation efforts to protect these unique and valuable ecosystems. To better assess the threats specific to each ancient lake, accurate information is needed about the current hydrology and hydrochemistry characteristics, land use, input of nutrients and pollutants, fishing practices, and the history of invasive species introductions.

Despite the significant attention given to certain ancient lakes owing to, for example, their mollusk and fish biodiversity (Brooks, 1950) as well as their value for fisheries (Mölsä et al., 2002; Van der Knaap et al., 2014), a considerable number of these lakes have not been adequately investigated. Among these neglected water bodies is ancient Lake Poso in Central Sulawesi, Indonesia. Lake Poso is often referred to as one of Alfred Russell Wallace's original dreamponds, in which one can observe the processes of evolution and natural selection. Indeed, the ancient lakes of Sulawesi, including Lake Poso but also the Malili lake system further to the south, are well-known for their extraordinarily high degrees of floral and faunal endemic biodiversity (Russell et al., 2016; Schubart and Ng, 2008; Vaillant et al., 2011; von Rintelen et al., 2012). To date, studies mostly targeted the faunal biodiversity, their taxonomy and interspecific relationships as well as processes promoting diversification with particular attention on crabs (Schubart and Ng, 2008), shrimps (Cai and Wowor, 2007; Fernandez-Leborans and von Rintelen, 2007; Klotz et al., 2021; von Rintelen et al., 2007), mollusks (Albrecht et al., 2020; Bogan and Bouchet, 1998; Haase and Bouchet, 2006; von Rintelen and Glaubrecht, 2006), and fishes (Parenti and Soeroto, 2004; Serdiati et al., 2020). However, a recent study has suggested that the introduction of non-native fish species had already affected the population size of endemic fish species in Lake Poso (Herder et al., 2022) emphasizing the urgent need for a better assessment of the status quo before further impacts to the entire endemic biodiversity occurs. To date, however, Lake Poso's hydrological and land-use characteristics are poorly documented. Available, very rudimentary, datasets stem from the national inventory of major lakes in Indonesia, which were collected in the early 1990s, indicate oligotrophic conditions (Lehmusluoto and Machbub, 1997). A more recent study has confirmed the earlier oligotrophic state assessment for the lake surface, but total phosphorus (TP) indicated mesotrophic to eutrophic conditions in Lake Poso's outlet, which is heavily populated (Sulawesty et al., 2022).

A detailed assessment of the catchment's hydrology, land use, and hydrochemistry is required to better localize nutrient and pollutant inputs and to characterize Lake Poso's limnology. Such an assessment is also timely and necessary, especially in light of the increase in population growth and associated increases in land use, climate change, and industrial fertilizer use, to provide an important baseline for Lake Poso's natural conditions. Localizing hotspots of anthropogenic pressure and identifying the underlying causes and effects on nutrient and contaminant inputs is important to inform and develop possible future mitigation strategies to conserve its natural trophic state and to protect its unique biodiversity (Greenwood and Eimers, 2023; Kai et al., 2020). Previous studies have shown the importance of hydrological and hydrochemical assessments to not only better understand the water cycle but also to identify the impact of different natural and anthropogenic factors on hydrochemical characteristics (Biswas et al., 2023; Cui et al., 2016; Zhang et al., 2021).

Here we assess the modern hydrology, hydrochemistry, and land use of Lake Poso and its watershed using newly collected river and lake water datasets in combination with satellite image analysis. These data were used to (1) better understand the chemical differences of the major inlets in light of their catchment geology and anthropogenic land use, (2) identify major nutrient and potential pollutant sources, (3) evaluate possible threats through anthropogenic nutrient and pollutant inputs on habitats that harbor species endemic to Lake Poso.

## 2. Study site

Ancient Lake Poso (1°54′49.0″ S, 120°36′40.5″ E) is located at ~485 m above sea level in the province of Central Sulawesi, Indonesia (Fig. 1a, b; Lehmusluoto and Machbub, 1997) and is thought to have formed tectonically ~2 Myr ago (Monnier et al., 1995). It is the third largest (363.63 km$^2$) and third deepest (~400 m) lake in Indonesia (Lehmusluoto and Machbub, 1997). Owing to its depth, Lake Poso is currently well stratified with the thermocline located at ~20 m water depth in November 2022 (Electronic Supplementary Material (ESM) Fig. S1). Geologically, Lake Poso is situated just east of a plate boundary formed by the Eurasian plate to the west and the Pacific plate to the east. Collision of these plates is predominantly accommodated by major strike-slip faults (Hamilton, 1973). The Lake Poso Depression can be considered part of this collision zone (Nugraha et al., 2023) which is also documented by the metamorphic bedrock in its catchment (suture complex; Fig. 1c; Villeneuve et al., 2002) comprising phyllites, micaschists, gneisses, and marbles with minor occurrences of shale and limestone (Fig. 1c).

Climatically, the region around Lake Poso belongs to the humid tropics. Throughout the year, Lake Poso receives ~3,075 mm of precipitation with peak precipitation of ~300 mm/month during the austral autumn (April and May) and comparatively dry conditions (~120 mm/month) during the austral spring (August and September; Hidayat, 2019). Indonesia comprises three dominant rainfall regions, in which the seasonal distribution of rainfall underlies similar mechanisms (Aldrian and Dwi Susanto, 2003). Lake Poso is located in rainfall zone A, which is influenced by western Pacific sea surface temperature (SST) variability and the El Niño Southern Oscillation (ENSO). This is best exemplified by the region's rainfall anomaly with extended droughts during strong El Niño periods characterized by lower western Pacific sea surface temperatures (Hidayat, 2019).

## 3. Material and methods

### 3.1. Hydrology and land-use

Analyses of catchment and hydrological parameters, with a focus on the delineation of individual river catchments, were based on a digital elevation model (DEM) of the Lake Poso region from NASA's Shuttle Radar Topography Mission at 1 arc-second (30 m spatial resolution; downloaded from earthexplorer.usgs.gov). Spatial data analysis was performed in ArcGIS 10.8 using the hydrology toolset to generate the river catchments and flow profiles. Google Earth images were utilized for precise river delineation and ground truthing of the ArcGIS algorithm, especially towards the south of Lake Poso where slope angles are low.

Land-use analysis was based on Landsat image 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) images (downloaded from earthexplore.usgs.gov). Composite Landsat Image bands 1–8 from 14 Nov 2022 were analyzed using the maximum likelihood classification of the image classification tool in ArcGIS 10.8. The classification was done only for differentiating residential and agricultural areas versus densely vegetated areas (mostly natural tropical rainforests). Furthermore, precise classification was done manually by comparing the automatically generated results with the one-meter resolution base map of World Imagery in ArcGIS 10.8.

### 3.2. Hydrochemistry

River water samples were collected from the major inlets including rivers and caves in June 2021. Lake water samples were collected from ~1 m below the lake surface at different locations (Fig. 2a; Table 1). Water samples for anion analysis (60 mL) and for cation and trace element analysis (60 mL) were filtered with a 0.2 μm PES syringe filter, and cation and trace element samples were acidified with $HNO_3$ in the

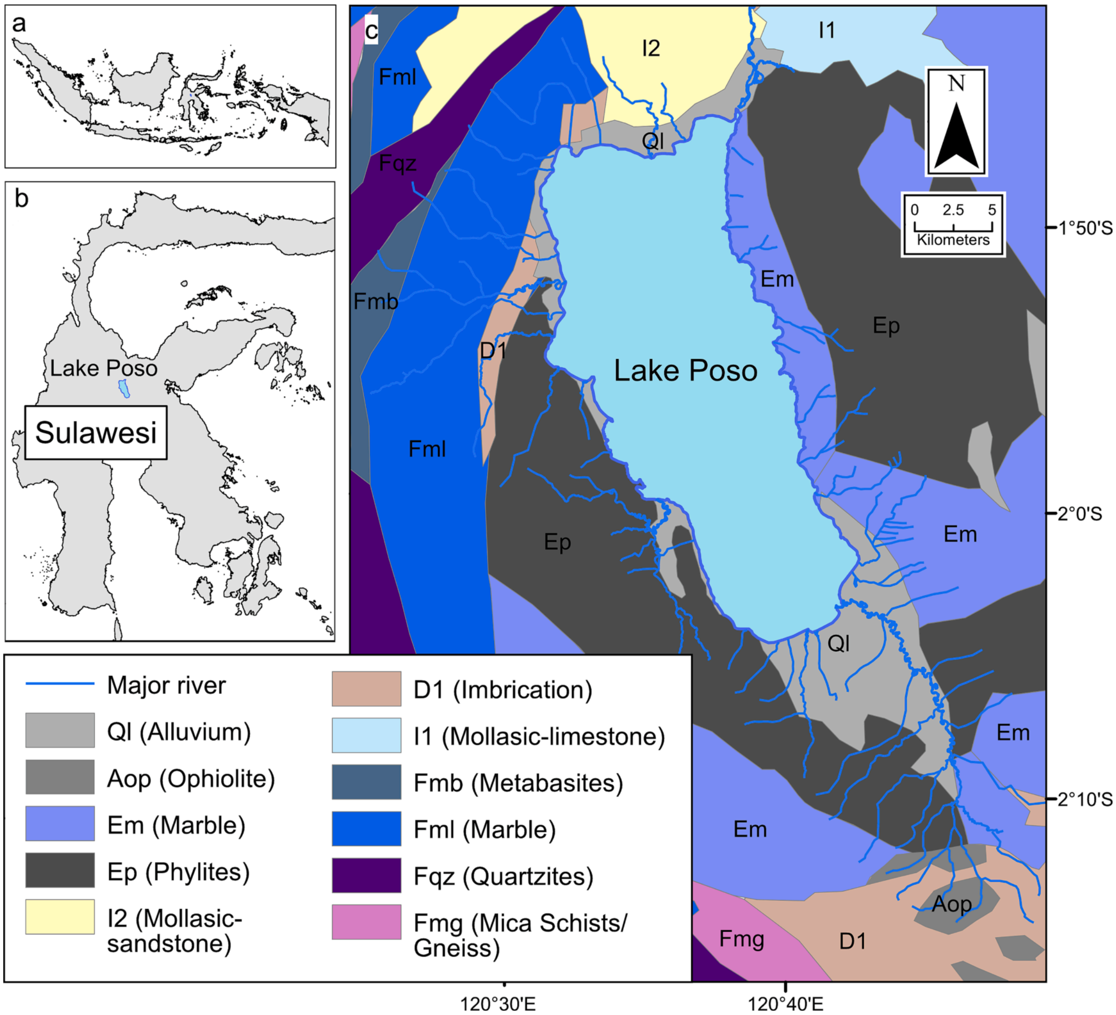


**Fig. 1.** (a) Indonesian Archipelago, (b) Sulawesi and Lake Poso, (c) Geological map of Lake Poso (Villeneuve et al., 2002).

field. Water samples for stable isotope analysis were sampled unfiltered and untreated directly from ~1 m below the lake and river water surfaces. Major ions were measured using a Metrohm Professional IC 850 and Professional Sample Processor 858 at the Institute of Geological Sciences, University of Bern. Samples were diluted with deionized water at a 1:10 ratio before measurements. Measurements were carried out with a Metrosep C4-150/4.0 and Metrosep A Supp7-150–5 columns with conductivity detection for cations and anions, respectively. The calibration ranges were 0.1–10 mg $L^{-1}$ and 0.016–10 mg $L^{-1}$ for cations and anions, respectively with measurement uncertainty around ± 4–10 %. Total dissolved solids (TDS) is a measure of the mineralization of a water body and were calculated from the sum of the total anions and cations. The isotopes ($\delta^2$H and $\delta^{18}$O) were determined by a Picarro L2130-I water isotope analyzer at the Institute of Geological Sciences, University of Bern. Results are expressed as per mill relative to Vienna Standard Mean Ocean Water (VSMOW). The standard deviations were <0.1 ‰ and <1.5 ‰ for $\delta^{18}$O and $\delta^2$H, respectively. Deuterium excess (d-excess) was calculated following the equation $d = \delta^2H - 8 \times \delta^{18}O$ (Dansgaard, 1964). Trace element and total dissolved phosphorus (TDP) compositions were measured using ICP-MS (Agilent 8900 ICP-MS/MS) at EAWAG. Prior to measurement, 6–10 mL of samples were weighed into acid-cleaned Teflon beakers and dried in laminar flow fume hoods supplied with HEPA-filtered air. Subsequently, samples were refluxed overnight with 0.25 mL 14 M $HNO_3$ (sub-boiling distilled) and redried before dissolving in 0.2 M $HNO_3$ + 1 ppb In. Samples were analyzed in duplicate and accuracy was monitored by running SLRS-6 solutions prepared in the same way as the samples, with determined values agreeing with certified or previously published values (Yeghicheyan et al., 2019) within analytical uncertainty (ESM Table S1). Dissolved inorganic nitrogen (DIN), as μg$L^{-1}$ N, was calculated as the sum of inorganic N species determined from the Metrohm Professional IC 850. Arsenic (As) was measured with ICP-MS at the Institute of Geography, University of Bern. Major ions were plotted in a ternary diagram in an Excel template from Stosch (2022). Water column temperature profiles were collected three times between 8 a.m. and 12 p.m. during the sunny and calm weather conditions on November 7$^{th}$, 2022 close to the center of the lake using a CTD48M (Sea & Technology Gmbh) multiparameter probe. All three profiles showed almost identical temperatures. Here we display the measurement taken at 10 a.m (ESM Fig. S1).

## 4. Results

### 4.1. Catchment and hydrology

The catchment area of Lake Poso is 991.74 $km^2$ resulting in a small catchment-to-lake-surface ratio of 2.7. This catchment area comprises 14 % of the area of Poso Regency. Catchment drainage was subdivided into 13 distinct river catchments (Fig. 2a; Table 1) with varying topography and elevation differences of up to ~1,600 m between the upper source areas and the lake surface (Fig. 2a). Low topography catchments are mainly located to the south of the lake and comprise the Pendolo and Tokilo river catchments (Fig. 2b). These two river systems

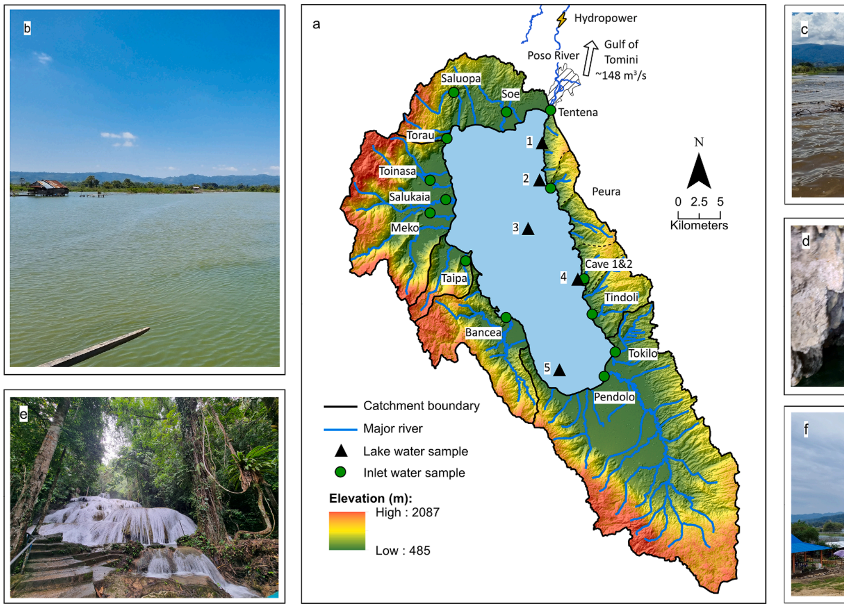


**Fig. 2.** (a) Elevation map of Lake Poso's catchment and sub-catchments (indicated by black lines). Dashed black lines indicate the small sub-catchments of each creek from the east part of the lake. Water sampling locations are indicated by black triangles and green circles, (b) low topography of the Pendolo River, (c) Meko River with high suspended load during sampling, (d) Karst cave spring on the eastern shoreline, (e) Saluopa waterfall on calcareous bedrock, (f) Poso River draining Lake Poso towards the Gulf of Tomini and downstream hydropower stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

drain the largest sub-catchment area, covering 44 % of the entire catchment. Bedrock in these southern catchments is mainly composed of Quaternary alluvium in low-lying areas and calcareous-phyllite at higher elevations but also contains minor occurrences of mafic ophiolitic bedrock outcrops (Fig. 1c). To the west, the Toinasa, Meko, and Salukaia Rivers jointly drain 19 %, the Bancea River drains 11 %, and the Taipa River drains 4 % of the lake's catchment. These rivers mainly drain catchments with marbles and calcareous phyllites (Fig. 1c). The Meko River is known by the locals for its high suspended sediment load, which was also observed during fieldwork in November 2022 (Fig. 2c). Catchments to the east of the lake are generally smaller and drained by small creeks comprising a total drainage area of 11 % of the lake catchment. However, it is unclear how much of the drainage to the east is in addition accommodated by underground karst aquifers given the occurrence of karst cave springs along the eastern shoreline (Fig. 2d). To the north of the lake, Saluopa (Fig. 2e), Torau, and Soe Rivers jointly drain 11.5 % of the catchment with marble being the predominant bedrock type (Fig. 1c). Based on their catchment and hydrological characteristics we will hereafter employ the following grouping of the river catchments: south for Pendolo and Tokilo, west for Salukaia, Toinasa, Meko, Taipa, and Bancea, north for Torau, Saluopa, and Soe, east for Tentena, Peura, and Tindoli (Table 1). The Poso River drains Lake Poso northward into the Gulf of Tomini (Fig. 2f). The average discharge at the outlet is 148 $m^3$ $s^{-1}$ with drainage being controlled since December 2012 through three 65 MW hydropower plants operated by PT. Poso Energy (PT. Poso Energy, 2022; Triyanto et al., 2021). Additionally, four 30 MW and four 50 MW hydropower plants started operating in 2022 which added up the total energy produced from Lake Poso to 515 MW (PT. Poso Energy, 2022; Triyanto et al., 2021).

### 4.2. Land use

The catchment area mainly consists of dense rainforest vegetation (68 %; Fig. 3a) and spatially connected residential and agricultural areas (32 %; Fig. 3a). Differentiation between the tropical rainforest and crop plantations was sometimes difficult in the Landsat 8 imagery, but resulted in only a small error in the assessment of the respective areas covered based on the ground truthing using the World Imagery base map in ArcGIS. This was confirmed by observations made during fieldwork in 2022, which indicated that most crop plantations were located only in easily accessible locations (Fig. 3b). The most common crops planted on the slopes of higher topography terrain include cacao, cloves, durian, and coffee, together yielding ~9,000 tons in annual crop production in the Lake Poso catchment (Fig. 3a; BPS Kabupaten Poso, 2016, 2023). Land use in the lower topography terrain to the south and around the Toinasa and Soe Rivers reflected denser residential areas and agricultural development including rice fields, vegetable gardens, medical plants, and occasional coconut and vanilla (Fig. 3b; BPS Kabupaten Poso, 2016, 2023). The cultivation of rice fields as the predominant agricultural land use in the Poso Regency is promoted by the low topography and major rivers, yielding ~10,000 tons annually. Tentena (to the north) is the largest and most densely populated residential area (Fig. 3c). It is primarily located around the Poso River but is also sprawling along the northern and eastern shoreline (Fig. 3b).

### 4.3. Major ions

Major anion and cation concentrations in water samples are shown in Table 1, ESM Fig. S2, S3, and ESM Table S2. Inlet water samples from Lake Poso showed major anion variability with the following compositions: $HCO_3^-$ (10.4 – 238 mg $L^{-1}$; average: 108 mg $L^{-1}$) ≫ $SO_4^{2-}$ (0.87–5.04 mg $L^{-1}$; average: 1.68 mg $L^{-1}$) > $Cl^-$ (0.13–0.87 mg $L^{-1}$; average: 0.35 mg $L^{-1}$) and the following succession of major cations $Ca^{2+}$ (1.32–67.7 mg $L^{-1}$; average: 30.9 mg $L^{-1}$) ≫ $Mg^{2+}$ (0.47–9.57 mg $L^{-1}$; average: 2.47 mg $L^{-1}$) > $Na^+$ (0.28–4.50 mg $L^{-1}$; average: 1.00 mg $L^{-1}$) > $K^+$ (0.32–1.77 mg $L^{-1}$; average: 0.56 mg $L^{-1}$). Only the Taipa River showed somewhat different characteristics with substantially lower $HCO_3^-$ (10.37 mg $L^{-1}$) and $Ca^{2+}$ (1.32 mg $L^{-1}$) concentrations. On the contrary, five lake surface water samples from different representative sites (Fig. 1b; Table 1) showed little to no variability of lake surface water composition with a similar order of major anion: $HCO_3^-$ (average: 75.1 mg $L^{-1}$) ≫ $SO_4^{2-}$ (average: 1.10 mg $L^{-1}$) > $Cl^-$ (average: 0.27 mg $L^{-1}$) and major cations $Ca^{2+}$ (average: 20. 3 mg $L^{-1}$) ≫ $Mg^{2+}$ (average: 1.81 mg $L^{-1}$) > $Na^+$ (average: 0.69 mg $L^{-1}$) > $K^+$ (average:

**Table 1**
Major anion (mg $L^{-1}$), cation (mg $L^{-1}$), DIN (μg $L^{-1}$), TDP (μg $L^{-1}$), $\delta^{18}O$ (‰), $\delta^{2}H$ (‰), and d-excess (‰) of water samples.

| Location | Lat | Long | Bicarbonate ($HCO_3^-$) | Sulfate ($SO_4^{2-}$) | Chloride ($Cl^-$) | Calcium ($Ca^{2+}$) | Magnesium ($Mg^{2+}$) | Sodium ($Na^+$) | Potassium ($K^{2+}$) | Total Dissolved Solids | DIN | TDP | DIN/TDP | $\delta^2H$ | $\delta^{18}O$ | d-excess |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mg $L^{-1}$ | | | | | | | | μg $L^{-1}$ | | | ‰ | | |
| **SOUTH** | | | | | | | | | | | | | | | | |
| Pendolo | −2.055 | 120.698 | 99.46 | 1.09 | 0.3 | 26.59 | 2.84 | 0.59 | 0.41 | 131.3 | 119.95 | 2.33 | 51.41 | −57.55 | −8.72 | 12.21 |
| Tokilo | −2.029 | 120.709 | 122.03 | 1.83 | 0.33 | 36.1 | 1.8 | 0.74 | 0.42 | 163.2 | 45.86 | 1.30 | 35.41 | −52.12 | −7.64 | 9.03 |
| **WEST** | | | | | | | | | | | | | | | | |
| Meko | −1.879 | 120.512 | 52.47 | 0.87 | 0.13 | 14.79 | 1.35 | 0.49 | 0.32 | 70.4 | 40.21 | 7.05 | 5.71 | −63.04 | −9.59 | 13.66 |
| Salukaia | −1.865 | 120.529 | 129.97 | 3.19 | 0.25 | 37.44 | 2.68 | 0.63 | 0.37 | 174.5 | 75 | 4.68 | 16.03 | −56.76 | −8.99 | 15.17 |
| Toinasa | −1.844 | 120.512 | 124.47 | 3.08 | 0.24 | 35.84 | 2.72 | 0.65 | 0.38 | 167.4 | 167.84 | 3.22 | 52.19 | −57.98 | −9.15 | 15.18 |
| Bancea | −1.992 | 120.593 | 73.83 | 1.08 | 0.27 | 20.01 | 1.8 | 0.68 | 0.48 | 98.2 | 14.01 | 0.89 | 15.67 | −45.47 | −6.46 | 6.2 |
| Taipa | −1.931 | 120.55 | 10.37 | 1.1 | 0.3 | 1.32 | 0.47 | 0.84 | 0.53 | 14.9 | 48.79 | 4.17 | 11.70 | −55.14 | −8.72 | 14.63 |
| **NORTH** | | | | | | | | | | | | | | | | |
| Torau | −1.799 | 120.53 | 156.81 | 1.11 | 0.33 | 53.8 | 1.4 | 0.28 | 0.34 | 214.1 | 295.03 | 0.80 | 370.64 | −56.47 | −8.93 | 14.96 |
| Saluopa | −1.75 | 120.538 | 179.39 | 1 | 0.35 | 54.24 | 2.71 | 0.43 | 0.32 | 238.4 | 280.79 | 2.87 | 97.94 | −56.60 | −8.91 | 14.66 |
| Soe | −1.771 | 120.594 | 237.97 | 5.04 | 0.8 | 67.68 | 9.57 | 4.5 | 1.77 | 327.3 | 131.02 | 4.41 | 29.72 | −54.28 | −8.44 | 13.24 |
| **EAST** | | | | | | | | | | | | | | | | |
| Tindoli | −1.988 | 120.685 | 68.34 | 1.22 | 0.31 | 18.4 | 1.64 | 0.73 | 0.47 | 91.1 | 12.65 | 2.61 | 4.86 | −48.74 | −7.05 | 7.66 |
| Peura | −1.853 | 120.641 | 57.36 | 0.9 | 0.87 | 13.46 | 1.5 | 2.22 | 1.08 | 77.4 | 28.92 | 32.53 | 0.89 | −57.64 | −8.62 | 11.35 |
| Tentena | −1.769 | 120.641 | 75.66 | 1.09 | 0.29 | 20.35 | 1.82 | 0.7 | 0.51 | 100.4 | 4.74 | 1.80 | 2.64 | −45.65 | −6.64 | 7.47 |
| Cave 1 | −1.952 | 120.676 | 98.85 | 1.22 | 0.26 | 27.46 | 2.2 | 0.75 | 0.51 | 131.2 | 23.95 | 2.50 | 9.58 | −48.16 | −7.00 | 7.81 |
| Cave 2 | −1.95 | 120.676 | 126.31 | 1.38 | 0.25 | 35.72 | 2.65 | 0.8 | 0.54 | 167.7 | 45.86 | 0.77 | 59.33 | −50.88 | −7.54 | 9.44 |
| **LAKE** | | | | | | | | | | | | | | | | |
| Lake 1 | −1.805 | 120.632 | 75.05 | 1.08 | 0.28 | 20.24 | 1.81 | 0.7 | 0.48 | 99.6 | 8.13 | 1.57 | 5.19 | −46.74 | −6.75 | 7.23 |
| Lake 2 | −1.846 | 120.629 | 75.05 | 1.2 | 0.26 | 20.33 | 1.81 | 0.69 | 0.48 | 99.8 | 10.17 | 0.86 | 11.89 | −46.62 | −6.78 | 7.61 |
| Lake 3 | −1.898 | 120.617 | 75.05 | 1.07 | 0.26 | 20.49 | 1.82 | 0.68 | 0.47 | 99.8 | 10.39 | 3.20 | 3.25 | −47.28 | −6.85 | 7.52 |
| Lake 4 | −1.951 | 120.671 | 75.05 | 1.09 | 0.26 | 20.35 | 1.81 | 0.69 | 0.47 | 99.7 | 7 | 2.62 | 2.68 | −45.66 | −6.63 | 7.39 |
| Lake 5 | −2.049 | 120.65 | 75.05 | 1.08 | 0.27 | 20.31 | 1.82 | 0.68 | 0.47 | 99.7 | 7.45 | 0.93 | 7.98 | −47.07 | −6.83 | 7.6 |

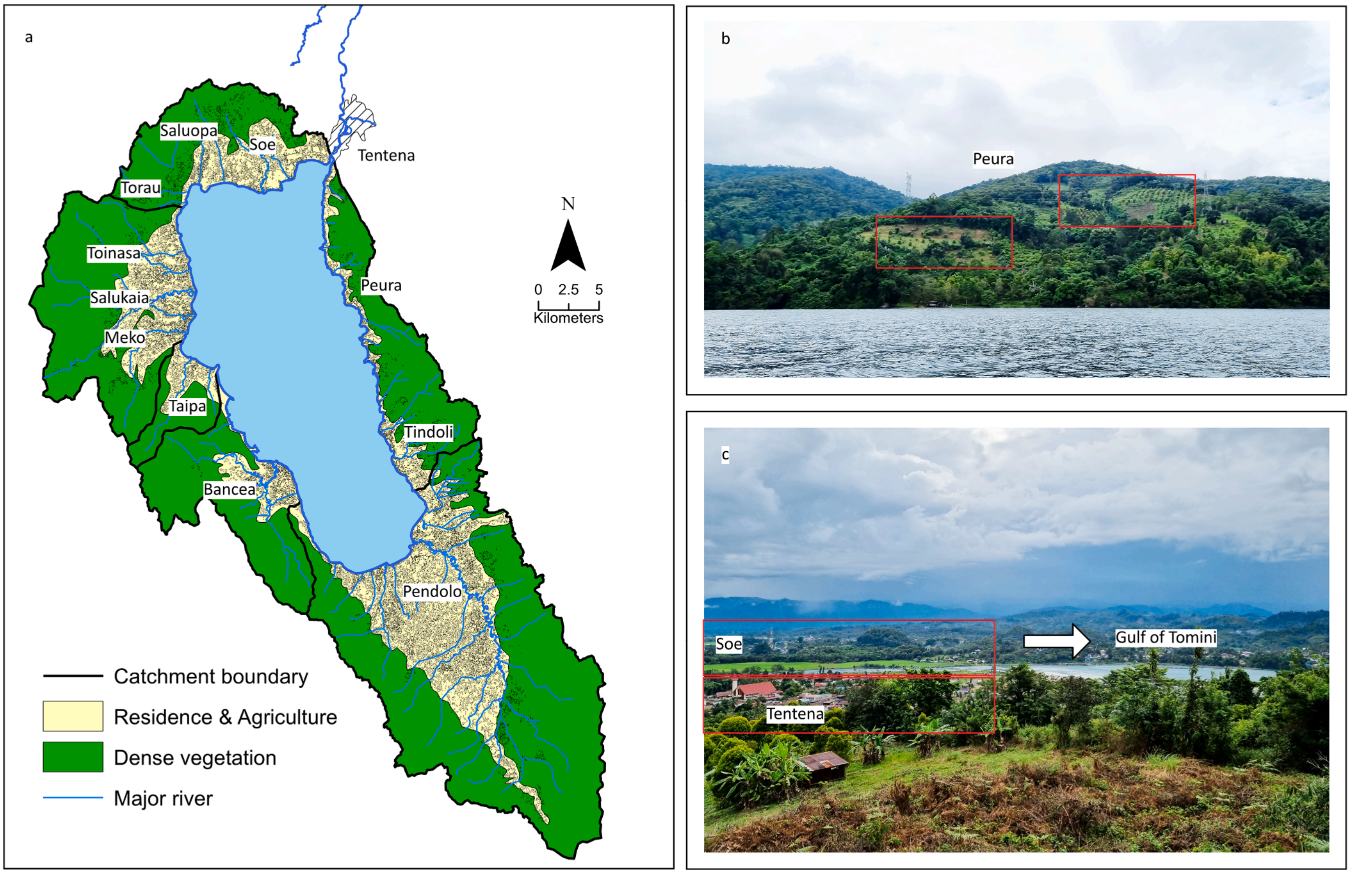


**Fig. 3.** (a) Land-use map of Lake Poso's catchment. Light yellow shading indicates where residence and agricultural land use is highest. Polygons outside the yellow-shaded areas indicate more localized and lower-impact land-use areas, (b) Crop plantations interspersed with rainforest in the hilly terrain surrounding the village of Peura on the eastern shoreline, (c) Residential area and neighboring agricultural areas with rice fields close to the Soe River in the flat landscape on Poso's northern shoreline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.48 mg L$^{-1}$) successions.

In Lake Poso and its watershed, TDS varied from 14.9 mg L$^{-1}$ in the Taipa River to 327 mg L$^{-1}$ in the Soe River yielding averages of 100 mg L$^{-1}$ and 144 mg L$^{-1}$ of the lake surface and inlet water, respectively (Fig. 4a). This average TDS is considered a low endmember and below the TDS value of most of the world's large rivers (Gaillardet et al., 1999).

### 4.4. Major nutrients

Dissolved inorganic nitrogen (DIN) concentrations in inlet water samples varied from 4.74 to 295 μg L$^{-1}$ with an average of 89.0 μg L$^{-1}$ (Table 1; Fig. 4b). Total dissolved phosphorus (TDP) concentrations varied from 0.77 to 32.5 μg L$^{-1}$ with an average of 4.08 μg L$^{-1}$ (Table 1; Fig. 4c). DIN averaged 8.6 μg L$^{-1}$ and TDP averaged 3.2 μg L$^{-1}$ in the lake surface water including all measurements from the different sites (Fig. 2a; Table 1). The average major nutrient concentrations were therefore low overall in Lake Poso and its tributaries suggesting lake-wide surface water oligotrophy. Based on the DIN/TDP classification (Bergström, 2010; Guildford and Hecky, 2000; Ptacnik et al., 2010), the lake DIN/TDP (mass ratio) of 6.2 suggests that Lake Poso was tending slightly towards being a P-limited system. Its tributaries were predominantly P-limited with an average DIN/TDP (mass ratio) of 50.9. The

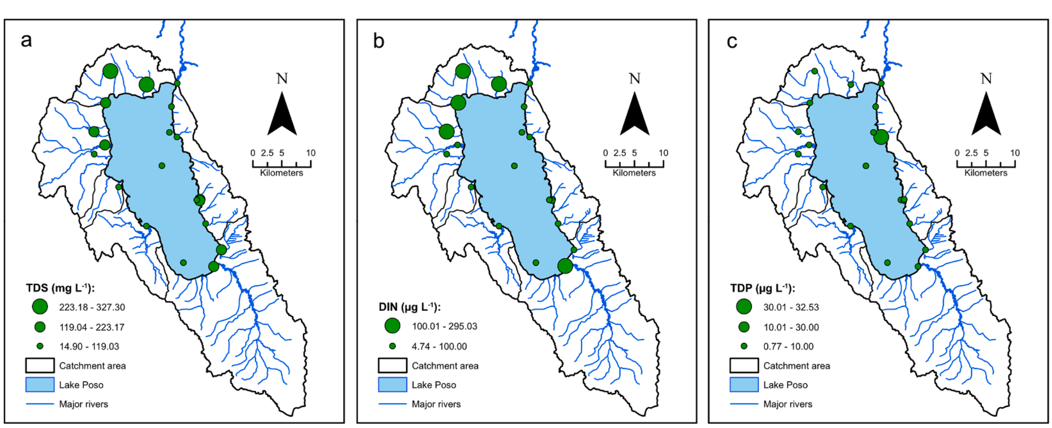


**Fig. 4.** (a) TDS (mg L$^{-1}$), (b) DIN (μg L$^{-1}$), (c) TDP (μg L$^{-1}$) of water samples from Lake Poso.

only exception was close to where the Peura River enters the lake. Here, TDP concentrations of 32.5 μg $L^{-1}$ and a DIN/TDP of 0.9 suggested local eutrophication and sufficient P according to the classification introduced in Carlson and Simpson (1996).

### 4.5. Stable water isotopes

$\delta^2H$ of the river and lake waters varied from −63.04 ‰ to −45.6 ‰ with an average of −52.0 ‰ (Table 1; Fig. 5a). $\delta^{18}O$ varied from −9.59 ‰ to −6.46 ‰ with an average of −7.81 ‰ (Table 1; Fig. 5b). The d-excess varied from 6.2 ‰ to 15.2 ‰ (Table 1; Fig. 5c). Both isotopes varied within the range of rainfall isotopic compositions measured between March 2013 to March 2015 at Lake Towuti ~80 km to the south of Lake Poso (Konecky et al., 2016). The variability of water isotope compositions can be classified into two clusters. The higher values for $\delta^2H$ (-52.1 ‰ to −45.5 ‰), $\delta^{18}O$ (-7.65 ‰ to −6.46 ‰), and lower values for d-excess (6.2 ‰ to 9.44 ‰) were indicative of water samples originating from the lake as well as from the rivers to the east, south, and the Bancea River. The rivers Peura and Pendolo represented exceptions from this general pattern in the east and south of the lake with lower water isotope composition values as shown in Fig. 5a, b. To the contrary, water samples collected from the rivers to the west and north exhibited more depleted isotope compositions which varied from −63.0 ‰ to −54.3 ‰, from −9.58 ‰ to −8.44 ‰ for $\delta^2H$ and $\delta^{18}O$, respectively, and higher d-excess varying from 11.4 ‰ to 15.2 ‰ (Fig. 5).

## 5. Discussion

### 5.1. Hydrochemistry of Lake Poso and its tributaries

River water hydrochemistry is a commonly used source tracer primarily controlled by catchment lithology. In this way, rivers can be characterized by their specific dissolved load patterns (Gurung et al., 2018; Li et al., 2020; Zhang et al., 2021; Zheng et al., 2022) using, for example, the Piper diagram (Piper, 1944; Stosch, 2022; Fig. 6). The samples from Lake Poso and its catchment almost exclusively fall into the calcium-, bicarbonate-, calcium-magnesium bicarbonate water type in the Piper classification (Fig. 6). The only exception is the sample from the Taipa River which had slightly higher relative $Mg^{2+}$ and $Na^+ + K^{2+}$ concentrations and therefore falls into the "no dominant cation" category (Fig. 6a). We note that this site had generally low absolute concentrations of major ions (especially Ca, Mg, and alkalinity), and therefore analytical uncertainty may comprise a larger component of the measured value, which would subsequently influence this site's position on the Piper diagram. This higher relative uncertainty due to low absolute concentrations is also reflected in the high difference in ion balance (–13 %; ESM Table S2). However, the low $Ca^{2+}$, $Mg^{2+}$, and $HCO_3^-$ in the Taipa River, along with $Na^+$, $K^+$, and $Cl^-$ comparable to or larger than the other river sites, would still result in the Taipa River diverging from the other sites in the Piper classification, as observed (Fig. 6).

Although the dissolved element load of rivers in most systems primarily depends on chemical weathering and dissolution rates of the respective catchment lithologies (Cohen, 2003), evaporation and precipitation can exert important additional controls on the total element loads and the characteristic hydrochemistry. To disentangle chemical weathering from climate-related parameters such as evaporation and precipitation, TDS was placed in relationship with $Na^+/(Na^+ + Ca^{2+})$ in the Gibbs diagram (Fig. 7). Samples from Lake Poso and its catchment are all clearly characterized by a predominance of bedrock chemical weathering and dissolution in controlling their TDS. This is in line with the correlation between the predominately calcareous bedrock lithologies and major ion compositions primarily comprising carbonate endmembers in the inlets. The only exception is the Taipa River with the lowest TDS in the entire Poso catchment, which is likely a result of its confined catchment and high topography catchment (Gibbs, 1970; Fig. 7). The low TDS in the Taipa River also results in higher relative uncertainty and can explain the higher apparent relative ion imbalance at this site.

Weathering of different bedrock lithologies can lead to complex dissolved ion composition and hydrochemical characteristics. Here we employed the major cation ratios of Ca/Na vs. Mg/Na (Gaillardet et al., 1999; Fig. 8) to better discriminate the bedrock source of the major ions plotted in the Piper diagram. This ion proportion analysis confirms that the dissolved loads were originating primarily from carbonate dissolution albeit with a notable contribution from silicate weathering. This catchment-wide uniform pattern in ion composition ($R^2 = 0.99$) thereby reflects the lithological composition with abundant calcareous-siliceous metasediments (Fig. 1c). The carbonate signature is particularly pronounced in the Saluopa, Torau, and Soe rivers with dissolved $Ca^{2+}$ concentrations of up to ~60 mg $L^{-1}$ (Table 1; Fig. 8b). To the contrary, the Taipa River shows a major ion composition hinging more towards dissolved loads originating from silicate weathering (Fig. 8a) and with overall low total cation concentrations (Fig. 8b). This is likely related to Taipa's small, steep, and confined catchment with shorter water residence times and is consistent with the more weathering-resistant siliceous phyllite-dominated bedrock lithology of the catchment.

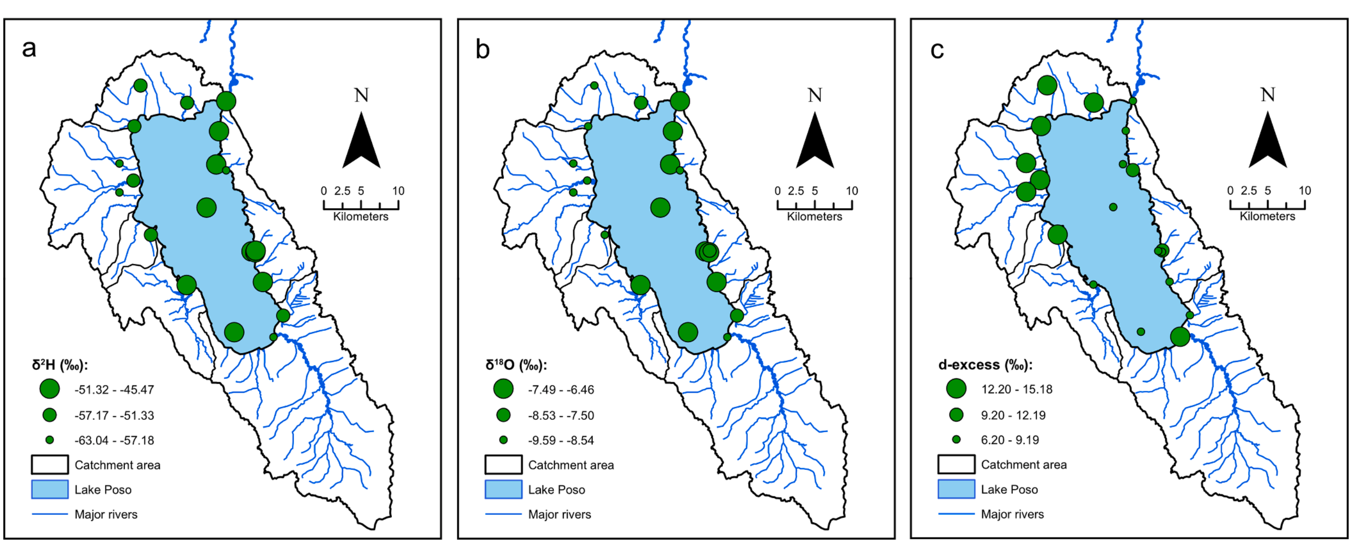


**Fig. 5.** (a) $\delta^2H$ (‰), (b) $\delta^{18}O$ (‰), (c) d-excess (‰) of water samples from Lake Poso.

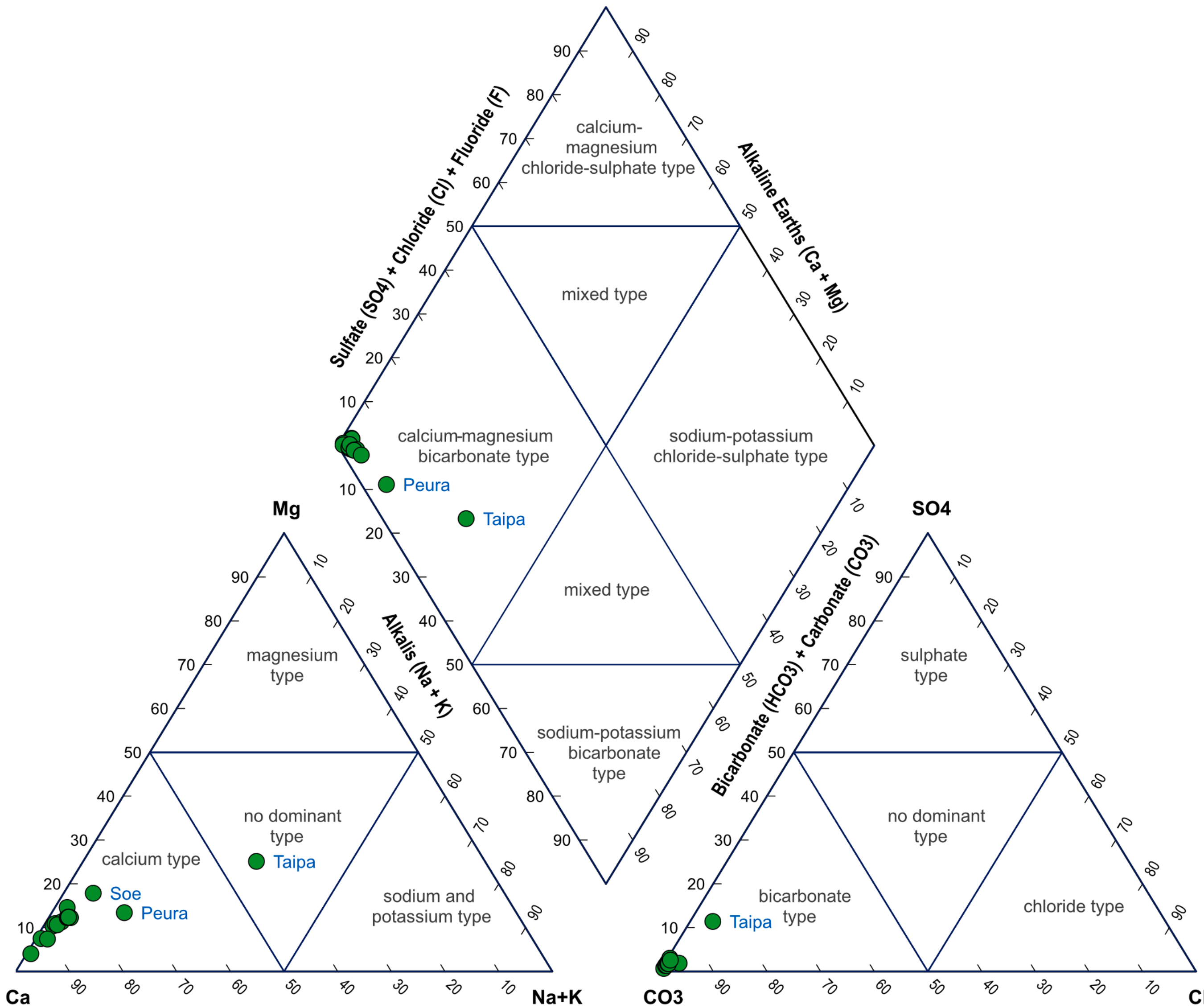


**Fig. 6.** Piper diagram: ternary diagram of (a) major cation, (b) anion, (c) projected diamond diagram of ions of water samples from Lake Poso.

### *5.2. Isotopic constraints on hydrology*

Given the various sub-catchment areas, elevations, and distances to the source, there are distinct differences in the hydrological balance and meteoric water isotopic composition between the different sub-catchments of Lake Poso. Owing to the river water sampling locations close to the inlets into Lake Poso, water samples do not exclusively represent rainfall isotopic compositions of the different catchments. Evaporation during transport may have altered isotope compositions from the original rainfall compositions. To disentangle the different catchment-specific processes controlling water isotope compositions, we utilize the linear relationship between $\delta^2H$ and $\delta^{18}O$ (Li et al., 2020; Skrzypek et al., 2015; Timsic and Patterson, 2014; Zheng et al., 2022) and comparison with the global meteoric water line (GMWL; $\delta^2H = 8 \times \delta^{18}O + 10$; Craig, 1961; Fig. 9) and the nearest precipitation isotopic composition data, from Lake Towuti, as local meteoric water line (LMWL: $\delta^2H = 7.9 \times \delta^{18}O + 11$; Konecky et al., 2016; Fig. 9). The Lake Poso catchment water isotope data show linear relationships albeit with slopes deviating quite substantially from the GMWL and LMWL. Both the average lake and inlet water lines show $m = 7$ and 4.9 slopes, respectively (Fig. 9). These values are lower than the GMWL ($m = 8$; Fig. 9) and LMWL ($m = 7.9$; Fig. 9) and therefore indicate evaporative enrichment in the heavy isotopes as is also apparent in other lakes from the humid tropics (Vystavna et al., 2021). Apart from the inlet and lake water average values an apparent division of isotopic compositions with the lowest $\delta^2H$ and $\delta^{18}O$ values in the western and northern rivers and the Pendolo River compared to the remainder of the inlets is another striking feature of Lake Poso's hydrology. This is likely due to the orographic effect being most pronounced to the NW, W, and SW of the lake where steep slopes prevail and mountain ranges exceed altitudes of 2000 m a.s.l. (Fig. 2a; Dansgaard, 1964). The division of these western hydrological inputs from the remainder of the lake is also apparent in the d-excess with values >10 ‰ indicating water sourced from high-elevation catchments and lower values (<10 ‰) those from lower-elevation catchments. Owing to the small catchment size and assuming that all of the precipitation across the Poso catchment originates from the same oceanic source, higher d-excess could be indicative of a higher contribution of moisture recycling in high-elevation catchments (Cropper et al., 2021; Froehlich et al., 2008).

The variability of the isotopic composition provides insight into the hydrological dynamics across the sub-catchments and how these affect the lake water isotopic composition. Considering the larger catchment sizes and associated higher discharge rates in catchments draining these rivers with lighter isotope compositions it can be assumed that heavier

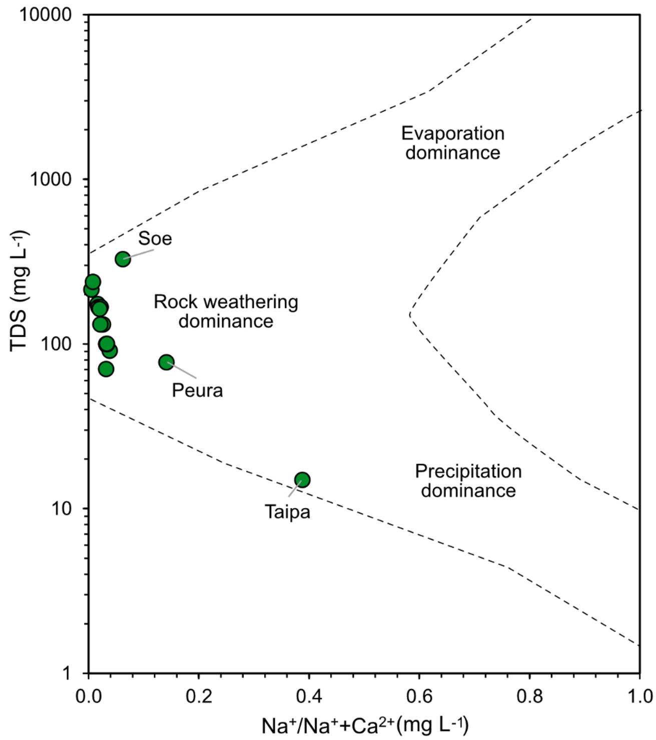


**Fig. 7.** Gibbs diagram, $Na^+/Na^+$+$Ca^{2+}$ (mg $L^{-1}$) vs TDS (mg $L^{-1}$) of the water samples.

lake water isotope compositions are the result of substantial evaporation from the lake surface. However, when calculating the hydrological budget of Lake Poso using the total catchment and lake area (1,355.37 $km^2$), annual precipitation (~3,075 mm), and surface outflow through the Poso River (148 $m^3$ $s^{-1}$), it was not possible to get close to an estimation of the evaporative loss. Instead, the budget requires an additional ~ 45 $m^3s^{-1}$ of hydrological inputs to balance the output quoted for the outflow. This deficit could possibly be explained by an underestimation of precipitation across the catchment in which precipitation may increase with elevation, additional input through subaquatic springs, and/or an overestimation of the outflow rate. Future studies involving flow rate measurements of the major rivers, subaquatic springs, and the outlet are required to provide more accurate estimates of the total inputs and outputs and to calculate a meaningful hydrological budget.

*5.3. Anthropogenic impacts on Lake Poso*

Anthropogenic land use, including urbanization and agriculture are known factors that can alter the trophic state of aquatic settings. Excess nutrient input from untreated wastewater, as well as fertilizer and manure runoff from agricultural and livestock areas, are considered the main factors for anthropogenic eutrophication (Smith and Schindler, 2009). Within the Lake Poso catchment, around 32 % is currently occupied by residential and agricultural areas. A population survey from 2023 suggests that ~60,000 people are living in the districts surrounding the lake with an annual population growth rate of ~1.2 % (BPS Kabupaten Poso, 2023). However, the administrative district border does not precisely match the catchment of Lake Poso, meaning that the population living within the Poso catchment is probably lower. The majority of the population resides in Tentena where most of the wastewater is drained into the Poso River, and consequently, most of the wastewater from this part of the population does not impact the lake. Nonetheless, the wastewater produced by the population living in the residential areas in the catchment enters the waterbodies untreated, either through surface runoff or drainage pipes. Another potential source of nutrients to the lake is fertilizer usage in agricultural areas. There is no quantitative assessment of fertilizer use in the Poso catchment to date but according to local sources, commercial fertilizers are commonly regarded as too costly by the local population and relatively unnecessary due to the relatively high nutrient contents and productivity of freshly converted tropical forest soils. Consequently, industrial fertilizers are currently not widely applied to increase crop yield in the Poso catchment despite increasing fertilizer consumption in Indonesia (Ludemann et al., 2022).

Notwithstanding widespread anthropogenic land use and the absence of wastewater treatment and other environmental measures, inlet and lake water nutrient values are low and indicative of oligotrophic surface water conditions across most of the catchment and lake. Somewhat elevated DIN concentrations (>100 μg $L^{-1}$; Fig. 4b) were measured in samples from inlets surrounded by residential and agricultural areas, i.e., Torau, Saluopa, Toinasa, Soe, and Pendolo rivers. While these values are still within the range of oligotrophy, the distinctly higher concentrations indicate the presence of point sources in areas with substantial anthropogenic land use. Besides DIN as a trophic indicator, Peura River showed a higher TDP concentration (32 μg $L^{-1}$) indicating local eutrophic conditions which are likely the result of wastewater input from the village of Peura, possibly in combination with additional nutrient input from exposed soils in agricultural areas on the steep catchment slopes (Fig. 3a, b). Conversely, due to their different catchment sizes, runoff volume, and morphologies, each inlet also contributes differently (Table 1). The Peura River only drains 8.4 $km^2$ which is equal to 0.85 % of the total catchment (Fig. 2a) making its

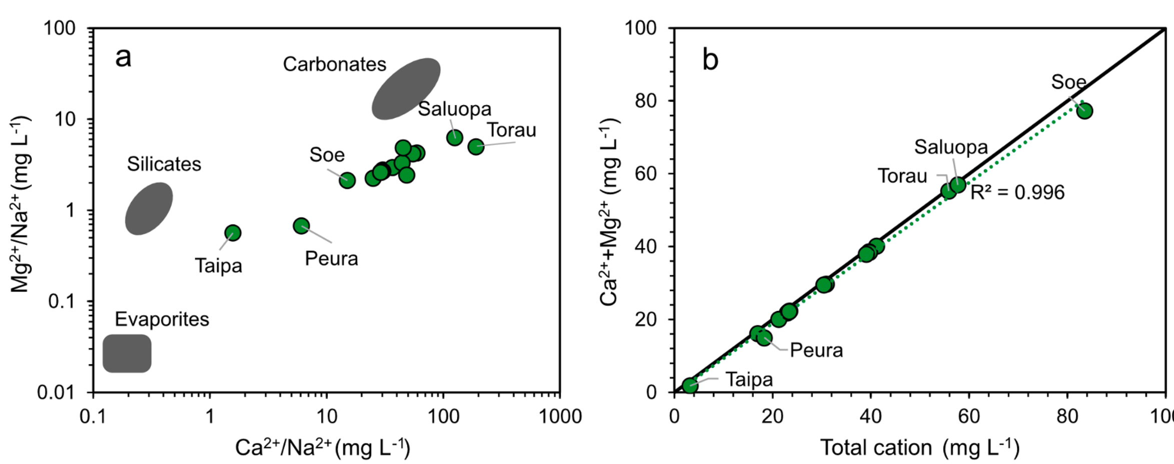


**Fig. 8.** (a) Ca/Na vs Mg/Na biplot distinguishing bedrock lithologies of river catchments of Lake Poso, (b) total cation vs $Ca^{2+}$ + $Mg^{2+}$ biplot.

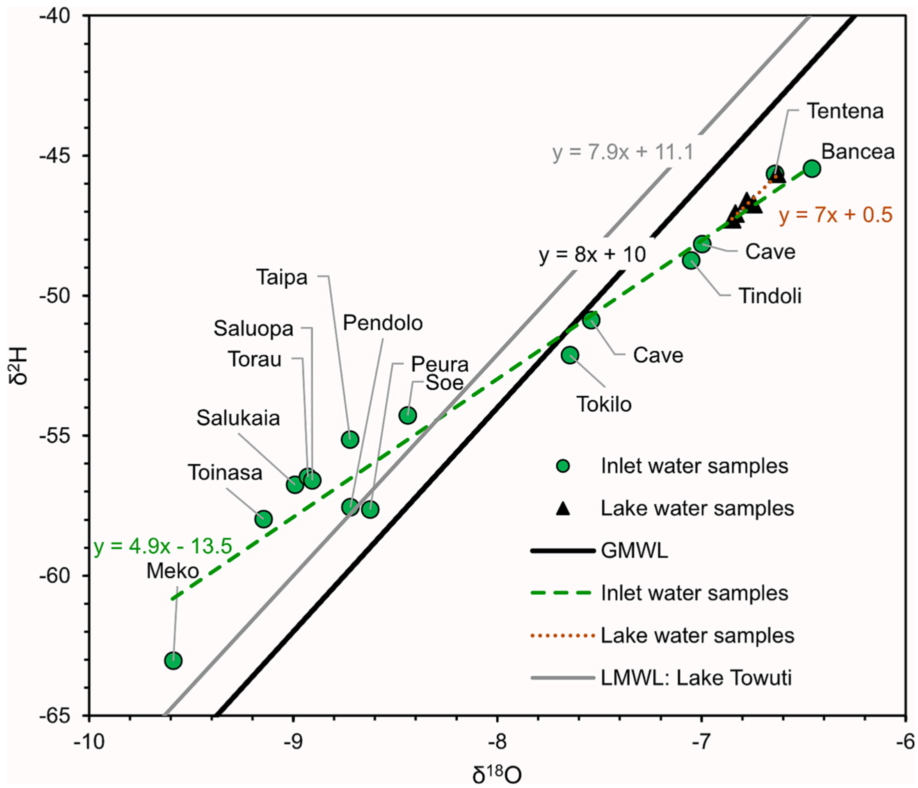


**Fig. 9.** $\delta^2H$ (‰) vs $\delta^{18}O$ (‰) of water samples from Lake Poso. Black triangles represent lake water samples. Green dots represent inlet water samples. The brown dashed line indicates the lake water line whereas the green dashed line indicates the inlet water line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relative contribution to the hydrological budget and nutrient input to the lake rather small. The higher nutrient inputs at Peura are therefore only considered as having a local effect.

Water entering Lake Poso as well as its lake water were highly diluted in terms of their ion concentrations with a TDS of ~140 mg $L^{-1}$. The overall low TDS concentrations also result in overall low toxic heavy metal concentrations in the rivers and lake waters (ESM Fig. S4; Table S2). Maximum concentrations for As (0.81 μg $L^{-1}$), Cr (1.14 μg $L^{-1}$), copper (0.61 μg $L^{-1}$), Zn (1.21 μg $L^{-1}$), and Pb (0.17 μg $L^{-1}$) were well below the toxicity threshold for drinking water (World Health Organization, 2017) though some of the measured As, Cr, and Pb concentrations were slightly above average global river concentrations, (Gaillardet et al., 2014). The Soe River stood out in terms of As concentrations and also contained the highest concentrations of Ba, K, Na, Mo, Sr, U, and V in the Poso catchment (ESM Fig. S5). Zinc was only notably elevated in the Peura River (ESM Fig. S5). Elevated toxic metal concentrations in these rivers are likely a result of their densely populated catchments. Likewise, deviations towards higher ion concentrations (>200 mg $L^{-1}$) were only observed for rivers draining more densely populated areas, particularly for the rivers Torau, Saluopa, and Soe. We suggest that higher TDS concentrations in these rivers are primarily due to increased evaporation in artificial channels and flooded rice fields with some minor contribution from the dissolution of the calcareous bedrock in the catchments of these rivers. On the contrary, TDS concentrations were not notably elevated in the southern Pendolo River, which also drains a catchment that is affected by anthropogenic land use. The Pendolo River only contained notably elevated Cr, Ni, and Co concentrations (ESM Fig. S5) which are likely originating from the weathering of the ophiolitic rocks in the upper southern part of the Pendolo catchment (Fig. 1c). The overall lower impact of land use in the Pendolo catchment on river hydrochemistry can probably best be explained by the overall larger catchment size and related higher runoff volumes.

Relative to other catchments feeding Lake Poso, the Peura River had elevated dissolved Fe and Mn, as well as As, P, Co, and Mo concentrations. Arsenic, P, Co, and Mo are known to be scavenged onto particulate Fe and Mn oxide phases (Hongve, 1997; Koschinsky and Hein, 2003; ). This observed coincident enrichment suggests sampling may have coincided with the reductive dissolution of oxide phases in soils, releasing Fe, Mn, and the adsorbed species (e.g., Bennett and Dudas, 2003; Smith et al., 2021). Another possibility is that there may be a transport of colloidal oxide particles with associated adsorbed elements (e.g., Kretzschmar and Schafer, 2005; Hartland et al., 2015). The Meko River contained the highest concentrations of many trace elements (Al, Cd, Ce, Co, Cr, Cu, Fe, Ni, Nd, Pb, Ti, V) with some of these elements being only poorly soluble. Owing to the brownish color of the Meko River water and the high suspended sediment load, we suggest these elevated element concentrations are the result of increased soil and humic substance mobilization. Possibly, these elements are transported in the form of chelates which are formed in tropical catchment soils and stabilized in river water by humic substances (e.g., Kretzschmar and Schafer, 2005; Pédrot et al., 2008). The Taipa River showed slightly higher Fe, Co, Cu, and Zn concentrations which are indicative of weathering solutes in this phyllite-dominated catchment.

### *5.4. Potential impacts of hydrology and hydrochemistry on biodiversity in Lake Poso*

The chemical, lithological, and topographic characteristics of the river catchments and the resulting specific TDS concentrations and predominance of carbonate ions in the river and lake waters may also function as a determinant for general ion-depleted and nutrient-poor local aquatic habitat characteristics. The diversity seen in terms of dissolved loads is also apparent in water isotope composition albeit with a much clearer pattern. Drainage of higher elevation rainforest and steep terrain may result in an increased flux of suspended sediment and organic matter loads as was also observed for some of the rivers draining the catchments along the western shoreline. High suspended sediment loads in these rivers and at the river mouths paired with elevated runoff generated by larger and higher elevation catchments may create an effective natural barrier for littoral species. Such a barrier effect, or better the lack thereof, may partly explain the spread of non-native species along the eastern shoreline (Herder et al., 2022) where rivers tend to be smaller with lower runoff and suspension loads. Additional studies also taking into account a more detailed biodiversity assessment of littoral species along Lake Posos shoreline are necessary to explore the effect of larger rivers as active barriers. Effects of land use are notable but still considered low given that 68 % of the catchment area was occupied by natural rainforest. This was also documented in the overall nutrient concentrations with DIN concentrations varying between 4.74–295 μg $L^{-1}$ and TDP concentrations varying between 0.77–32.5 μg $L^{-1}$ (Table 1; Fig. 4b, c). These values are similar or in the case of N could potentially be even below TN values measured in Lake Poso in 1992 by Lehmusluoto and Machbub (1997) which note that concentrations varied between 0.24–1.09 mg $L^{-1}$ N and TP concentrations remained below the detection limit of 0.04 mg $L^{-1}$ P. These factors along with low metal pollutant concentrations imply that anthropogenic impact on Lake Poso in terms of nutrient and pollutant inputs remained relatively constant and low over the past 30 years. This suggests that the notable impact of current land use in Lake Poso's catchment to date is restricted to a few point localities, for example, the Peura River but trophic state changes towards higher trophic states are not yet detectable on a lake-wide scale. This is in stark contrast to the impact on littoral biota caused by the introduction of non-native species (Herder et al., 2022).

## 6. Conclusion

Analyses of hydrochemical and hydrological parameters in Lake Poso and its tributaries have provided valuable insights into the lake's water composition and the influence of various factors on its ecosystem. The waters of Lake Poso were relatively dilute (low TDS), with a predominance of carbonate ions such as calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), and bicarbonate ($HCO_3^-$). This composition is primarily attributed to the weathering and dissolution of calcareous and calcareous-siliceous bedrock lithologies within the lake's catchment area. Furthermore, the isotope compositions of the water exhibited distinct patterns, allowing differentiation between high (lower $\delta^2$H and $\delta^{18}$O) and low-elevation (higher $\delta^2$H and $\delta^{18}$O) catchments, best explained by the orographic effect. In addition, higher d-excess values in rivers draining higher-elevation catchments indicated that these catchments may receive precipitation that is affected more strongly by moisture recycling. Relatively high $\delta^2$H and $\delta^{18}$O values, similar to the isotopic composition of waters originating from the smaller, low-elevation catchments suggest that lake water isotopic compositions are not only the result of the mixing of the different sources but in addition, are affected by evaporation. Analyses of land use in the Lake Poso catchment revealed that 32 % of the catchment area consists of a mix of residential and agricultural areas, primarily located in the low topography landscapes close to the lake shore. Croplands were mainly established on accessible slopes, whereas steeper slopes and higher-elevation regions remained covered by tropical rainforests. Rivers passing through more developed agricultural and residential areas are only moderately affected by anthropogenic influences to date. Clear anthropogenic imprints in terms of elevated TDS are seen in smaller rivers passing through rice fields to the north of Lake Poso. Elevated nutrient concentrations were only observed in the small Peura River to the east of the lake. The Soe River (particularly As) and the Peura River (particularly Zn) contained somewhat elevated toxic trace element concentrations. The remaining rivers showed very little to no signs of traceable anthropogenic impacts. Additionally, slightly elevated major and trace elements in some of the rivers are a result of the catchment geology as well as weathering and erosion processes and are thereby interpreted as being geogenically controlled. Comparison with previous assessments of Lake Poso's nutrient loading reveals that nutrient concentrations remained low and unchanged over the last 30 years. Overall, the hydrochemical, hydrological, and land use data presented here imply that anthropogenic land use so far has little or only moderate impacts on the local scale on Lake Poso's trophic state and hydrochemistry. This study, therefore, provides an important reference point for future conservation and monitoring efforts. It also indicates that, to date, the impacts of land use on the lake's ecosystem likely remain below the threshold for concern in terms of its impact on aquatic trophic state and pollutant loading. However, continued vigilance regarding land use and its effect on nutrient and pollutant inputs but more importantly in controlling the spread of non-native species, is necessary to ensure the long-term preservation of this exceptional biodiversity hotspot.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2023.102254.

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