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Evaluating the Effects of Increased Evaporation on Biogeochemical Processes in Semi-Arid Lakes

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Abstract: Greater evaporation levels tend to increase the concentration of dissolved components in semi-arid lakes; however, changes in concentration cannot serve as indicators of water losses vs. nutrient inputs and transformations. This paper tests whether this separation can be made via analysis of the water and solute balances over ninety days in a hypothetical lake based on information provided in twelve articles written in the recent past. Evaporation rates of 4, 6, 8, and 10 mm per day are assumed for a hypothetical well-mixed lake of a constant surface area equal to one square kilometer and volume equal to two million cubic meters. Constant levels of rainfall and inflow into the lake are also assumed. The chloride ion is considered a conservative indicator, and the solute reactive phosphorous is considered to be controlled by external input, sediment dissolution, and export from the dissolved pool. In the case of 0.5 mg P m^{-2} d^{-1} sediment flux, phosphorus increases from 61.78 to 81.67 µg P L^{-1}. With doubling of the sediment flux, the respective endpoints would be 81.43 and 108.07 µg P L^{-1}. This result is derived from the model assumptions and does not represent any empirical observation for any particular lake. It explains the necessity to consider simultaneously conservative concentration, reactive nutrient dynamics, and water volume. Practical implementation of the approach requires measurements of evaporation and inflow rates, bathymetry, and independent estimates of sediment exchange and retention parameters.

Keywords: Semi-Arid Lakes; Evapoconcentration; Nutrient Balance; Soluble Reactive Phosphorus; Chloride; Sediment Exchange.

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I. Introduction

Chemistry of semi-arid lakes is a function of evaporation losses, catchment input, and interactions between the lake and sediments and ground water. Chemical changes in semi-arid lakes may occur rapidly when evaporation rates exceed replenishment rates. Salinity and water level studies of shallow lakes have revealed that there is variability in salinity and water-level relationships depending on bathymetry and hydrology. Inverse relationship between concentration and volume is thus a limiting case and not a universal case for all lakes (McGrath et al., 2025). In this study, the limiting case is used as a control. A conservative tracer is compared with a reactive phosphorus pool.

The main process by which water is lost is evaporation, whereby nonvolatile dissolved elements remain, so that an increase in the nutrient load may take place even though there has been no proportional increase in the nutrient load. On the other hand, sediment releases, or external loading of nutrients, may cause nutrient load increases, whereas the retention process removes the material into other reservoirs. Work in the Salton Sea illustrates that processes of loading and cycling of nutrients take place together with low flows, high evaporation, and altered conditions of the lake. The key point is that in such a case ecological degradation cannot be explained by evaporation concentration alone in the presence of loading and recycling of nutrients (Hung et al., 2024).

Hydrochemical and isotope studies on Mu Us Desert lakes identify sources of water and solutes, such as groundwater inflow and treated by drainage. This study indicates that under similar climate conditions, lakes with various chemical inputs may exist. Chloride budget needs to define its boundary conditions before interpreting the concentration variations as evaporation (Liu et al., 2025). Isotopic data and trace element concentrations are used in combination in Badain Jaran Desert for studying evaporation, groundwater flow, and geochemical reactions. This kind of evidence promotes the process approach, but it

does not mean that chloride, phosphorus, and redox trace elements have identical behavior. Every component needs its own transport and reaction model (Wang et al., 2026).

Modelling the geochemistry of playa lakes in the Indian Thar Desert looks into evaporation, mineral precipitation, and weathering during brine development. The low salinity chloride cases in this paper deliberately exclude mineral saturation and are not meant to be applied to evaporite brines (Kumar et al., 2024). The focus of the research is on answering the following questions: what is the amount of change in concentration due to water loss alone; how do the sources of phosphorus and phosphorus retention affect this reference; and can nutrient concentration increase while the dissolved nutrient pool is decreasing along an evaporation gradient. The contribution is made in the form of an auditable process comparison and not a fitted empirical equation. A ninety-day dry season experiment is conducted to keep the hydrological boundaries constant while varying evaporation. Two sediment release cases are crossed with four evaporation rates. Chloride and phosphorus concentrations are evaluated using numerical mass budgets and a phosphorus reference.

Microscale studies of Hongjian Lake demonstrate different phosphorus mobility characteristics and phosphorus dynamics depending on the sediment microhabitat and sulfur cycle. The adsorption study proves an additional threat of phosphorus mobility with increasing danger due to the salinization process. This justifies the necessity of considering different source potentials of sediments without using any actual quantifiable values in this specific case (Guo et al., 2025). Investigation of the model of phosphorus reduction from Brazil's semi-arid reservoirs takes both hydrological inputs and adaptation of removal rates into account. The principal conclusion from this research is that nutrient accounting should consider water balance and reaction rates (Lima et al., 2025). Drying and rewetting studies of the sediments of Nansi Lake consider the dynamics of organic phosphorus and the amount of dissolved organic matter. It turns out, as stated by their conclusions, that past experience of drying can change phosphorus mobilization rather than increase the concentration of some unchanged water pool. In these specific ninety days experiment, there is no rewetting, hence no ability to predict the release due to the drought (Zhang et al., 2024). Another study on drawdown zones investigates the release of phosphorus under inundation and drying cycles and emphasizes the importance of organic matter, oxygen, and redox processes. These processes make it possible to differentiate source terms from mere concentration, but the current sediment flux is prescribed and not predicted (Yang et al., 2026).

Pangong Tso sediments' experiments focus on the impact of the salinity factor on nitrogen cycle transformations. They prove why a conservative-ion reaction is not enough to serve as a full indicator of nutrient cycling since the processes of nitrification and denitrification have biological components that depend on the environment in their own way. The nitrogen compounds and losses of gaseous nitrogen are not considered in the current quantitative model (Chang et al., 2025). The reconstruction of the changes in nitrogen and phosphorus content in the sediments of multiple lakes in China shows that these elements could have divergent dynamics and human activity is important together with climate (Ji et al., 2024)

. Studies have been conducted on the interplay between volume, water quality, and the reaction of benthic macroinvertebrates in tropical semi-arid reservoirs. This research gives the ecological background for assessing the chemistry of drawdown, but at the same time demonstrates that the change in concentrations does not necessarily indicate a straightforward biological effect. None of algal bloom, oxygen level, or biodiversity effect can be expected in this case (Medeiros et al., 2025).

II. Materials and Methods

2.1 Evidence Base and Scenario Boundaries

Twelve primary research papers published between 2024-2026 with a specific focus on semi-arid lakes, evaporation, salinity, phosphorus, sediment exchange and nutrient cycling were chosen through targeted searches. Bibliographic metadata, publishers' records and institutional records of research were searched on 10 November 2026. The selection below offers process context but neither is a systematic review nor a

pooled estimate of model coefficient values. It assumes a hypothetical continuously flooded lake of constant surface area A = 1.0 × 10^6 m^2 and constant volume V_0 = 2.0 × 10^6 m^3. Mean depth will thus be 2.0 m initially. Rainfall R is constant at 1 mm d^{-1} and non-rainfall water inflow Q_i at 1000 m^3 d^{-1}. There is no liquid outflow or seepage losses and no reduction in shoreline area. Evaporation E is assumed at 4, 6, 8 and 10 mm d^{-1} for ninety days. All the values used are assumed and not observations, regional climatology or future projections. Constant area is an approximation of a lake that does not shrink much under drawdown. Temperature-dependent reactions are independent of the forced changes in evaporation: the model does not increase sediment fluxes automatically when E increases.

2.2 Water Balance and Conservative Chloride

Given that E and R are measured in units of mm/day, the scale factor of 10^{-3} results in the water flux per day being obtained in cubic meters. The net water loss term "b" as well as the total volume of water "V" at any time t are given by equation 1.

$$b = A(E - R)10^{-3} - Q_i; \quad V(t) = V_0 - bt \tag{1}$$

The initial chloride concentration is 100 mg L^{-1}, which corresponds to an inventory M_c of 200,000 kg.

It is assumed that rainfall and inflows are chloride free, that chloride is not volatile, and that there is no precipitation or adsorption of chloride. The response function in mg L^{-1} according to equation 2 is:

$$dM_c/dt = 0; \quad C_c(t) = 10^3 M_c/V(t) \tag{2}$$

This is a conservative tracer model. A natural lake receiving an input from saline groundwater or undergoing loss of dissolved salts from seepage into soil would need additional terms. The chloride concentration is not changed into salinity or conductivity because the values of salinity and conductivity depend on ion composition.

2.3 Soluble Reactive Phosphorus Balance

The second parameter is the phosphorus concentration of the water column C_p, measured in µg P L^{-1}. The water column phosphorus inventory M_p is equal to 100 kg, that is equivalent to 50 µg P L^{-1}. The phosphorus input L is set at 0.20 kg P d^{-1}. The sediment flux J is set at 0.5 or 1.0 mg P m^{-2} d^{-1}, which corresponds to 0.50 or 1.00 kg P d^{-1} for the entire modeled lake. These two flux values are sensitivity parameters, not measurements or fits to salinity.

$$dM_p/dt = L + 10^{-6}JA - vA[M_p/V(t)] \tag{3}$$

$$C_p(t) = 10^6 M_p(t)/V(t). \tag{4}$$

Effective removal velocity v equals 0.010 m d^{-1}. This is the net transfer out of the dissolved reactive state as a result of uptake, sorption and retention process. Soluble phosphate does not sediment as an isolated solute but its removal is represented by the velocity of the process caused by biological activity or particulate matter. The material transferred from M_p is accounted for as a retained pool and not destroyed and assumed to be buried forever in equation 4. The sedimentary source is sustained in the simulation by an undefined sediment reservoir for ninety days. It does not change during the process. Temperature, oxidation/reduction state, pH, resuspension, and mineral deposition remain outside the source equation.

2.4 Numerical Solution and Reference Comparisons

The integration of equation 3 was done using the fourth-order Runge-Kutta method at a step size of 0.10 days. The accuracy of the results obtained was verified using the step size of half and the closed-form solution. Letting $r = vA/b, z = V(t)/V_0$, and $s = L + 10^{-6}J$. A gives equation 5 where r ≠ 1.

$$M_p(t) = M_p(0)z^r + [sV(t)/\{b(r - 1)\}][1 - z^{r-1}] \tag{5}$$

In the equation for phosphorus passive reference, the only part considered is the first 100 kg without any addition and removal and thus $C_{\mathrm{p}}, passive = 10^6 \times 100/V(t)$. It does not include water concentration loss effects and is not a measurement treatment alternative. Inventory at last and transfer cumulative to retention are used for diagnostic budget purposes, and chloride and C_p are the two measured responses. Removal velocities of 0.005 and 0.020 m d^{-1} have been used with E = 10 mm d^{-1} and J = 0.5 mg P m^{-2} d^{-1}. Such comparisons indicate parameter sensitivity rather than statistical uncertainty. Budgets for scenario results have been compared to initial mass plus additions minus accumulated retention. The numerical and analytical phosphorus inventories matched each other within less than 10^{-8} kg. There is no empirical sample size, confidence level, or significance test for the deterministic results.

III. Results

3.1 Evaporation Gradient and Endpoint Concentrations

The values for ninety-day endpoints are illustrated in table 1. There is a final volume reduction from 1.82 million m^3 to 1.28 million m^3 when there is an E = 4mm d^{-1} and E = 10 mm d^{-1}, respectively. There are reductions of 9% and 36% from the original volume, respectively. The reductions are net water balance reductions and lower than evaporation.

Table 1: Synthetic Day-Ninety Chloride and Phosphorus Concentrations Under four Evaporation Rates

Evaporation (mm d^{-1})	**Final volume (10^6 m^3)**	**Chloride (mg L^{-1})**	**SRP at J = 0.5 (µg P L^{-1})**	**SRP at J = 1.0 (µg P L^{-1})**
4	1.82	109.89	61.78	81.43
6	1.64	121.95	67.16	88.62
8	1.46	136.99	73.66	97.31
10	1.28	156.25	81.67	108.07

Chloride concentration increases from 100 mg L^{-1} to 109.89, 121.95, 136.99, and 156.25 mg L^{-1}, respectively, as E increases. Chloride's final stock always amounts to 200,000 kg for all cases. The greatest increase in chloride concentration, which is 56.25% greater than the initial concentration, is fully attributable to water loss within the set conservative conditions. SRP concentration at J = 0.5 increases from 61.78 to 81.67 µg P L^{-1}, while SRP concentration at J = 1.0 increases from 81.43 to 108.07 µg P L^{-1} as E increases. A doubling of the sediment flux leads to an increase in nutrient concentration without any change in chloride concentration or water volume. The end states identify eight reactive models and four common chloride models. They do not constitute independent field replicates. The differences between them are a direct result of the equations and cannot be referred to as statistically significant treatment effects.

3.2 Conservative Concentration and Reactive Modification

Figure 1 contrasts the two metrics in different scales. The panel for the chloride ion exhibits the conservative concentration gradient. The phosphorus panel contrasts the sediment source assumptions with passive transport of the phosphorus inventory. All three phosphorus curves increase with evaporation, but their spacing defines the contribution of the assumptions.

Passive phosphorus is from 54.95 to 78.13 µg P L^{-1}. With the reduced sediment flux, modelled SRP surpasses the referenced SRP by 6.84 µg P L^{-1} for E = 4 and 3.55 µg P L^{-1} for E = 10 mm d^{-1}. The reduced excess in higher evaporation is attributed to increased dependence on concentration in transfer into the retained pool and not on decreased prescribed sediment source. Inventory diagnostic is an indicator of the differentiation. For J = 0.5, water-column phosphorus decreases along the evaporation gradient from 112.45 to 104.54 kg despite the increase in concentration. The accumulation of transfer out of the dissolved pool is from 50.55 to 58.46 kg.

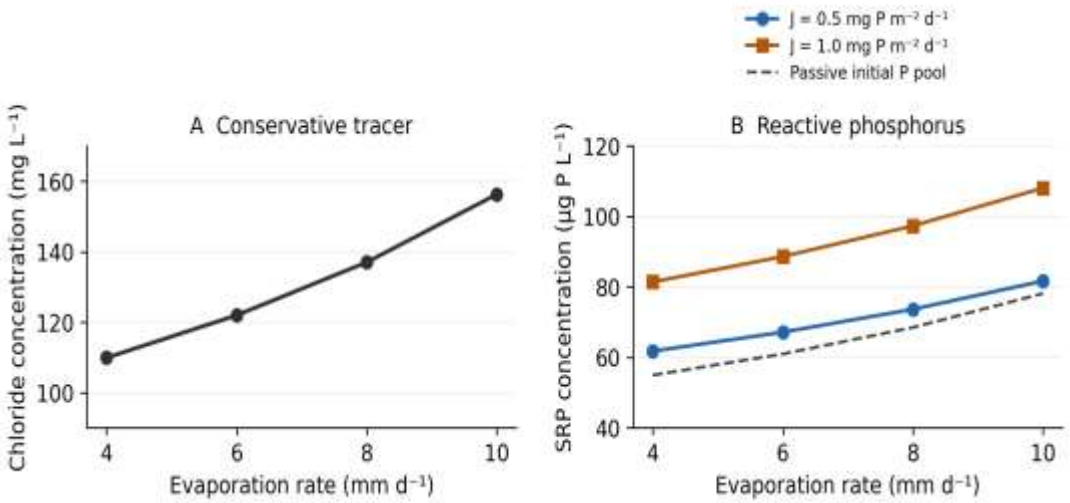


Figure 1. Day-ninety model concentrations across the evaporation gradient. Panel A conservative chloride. Panel B soluble reactive phosphorus at two prescribed sediment fluxes and passive concentration of the initial phosphorus pool. Points represent deterministic scenarios; connecting lines do not estimate a regional climate-response curve.

3.3 Sensitivity to Retention Strength

Where E equals 10, and J equals 0.5, changing the velocity value between 0.005 – 0.020 m d-1 changes the SRP value from 101.62 to 54.07 mg P L-1; the important value here is 81.67 mg P L-1. The concentration of chloride is consistently 156.25 mg L-1. It is clear that the reactive interpretation depends on retention despite the constant signal for water loss.

IV. Discussion

The crucial point is that high concentration does not mean increased nutrient content. Evaporation leads to high concentrations of both simulated substances; phosphorus cycle involves sources and storage. For a fixed input, an increase in evaporation leads to increase in SRP concentration and decrease in phosphorus amount in all cases because the removal is determined by the concentration. This is an example of a conditional effect of process, not a general response of semi-arid lakes to evaporation. This is crucial for interpretation of the field data. Hydrochemical studies draw attention to diversity of sources of lake water and geochemical processes, sedimentological studies in desert lakes to diversity of nutrient mobility. It is evident from such studies that one should measure the water budget and sediment fluxes, and not to think that each increase in concentration is caused by evaporation. Choice of a conservative tracer is possible only when the sources and sinks are taken into account (Liu et al., 2025; Wang et al., 2026; Guo et al., 2025).

Both sediment fluxes have been intentionally kept independent from evaporation. The fact that this happens doesn't mean any proof of salt release and redox feedback effects. Wet/dry sediment studies can give us information on such phenomena; nevertheless, the representation of such phenomenon will require information on exposure, pore water composition, and subsequent release upon rewetting. The same way, retained phosphorus may become available at a later stage, and the concept of the model implies that retention is different from burial (Zhang et al., 2024; Yang et al., 2026). The application of the model to a field situation will require estimates of the evaporation, precipitation, flows, water level, bathymetry, and concentrations of chloride and reactive phosphorus. Total Phosphorus, nitrogen, oxygen, and biological measurements will assist in interpreting findings beyond just the two-screening metrics. Calibrations of models using regional conditions should be done (Lima et al., 2025; Chang et al., 2025; Medeiros et al., 2025). Assumptions include a fixed area, perfect mixing, steady flows of sources into the wetland, no export

from the wetland through the aquifer, no saturation of minerals, feedbacks from oxygen, and dependence on temperature kinetics. Ninety days does not take into account sediment depletion as well as re-wetting following a drought. Testing of two rates of removal is not an uncertainty analysis.

V. Conclusion

A paired conservative and reactive mass balance differentiates between direct Evapoconcentration and source/retention of nutrients. For the synthetic ninety-day evaporation gradient, chloride increases from 109.89 to 156.25 mg L^{-1}, whereas SRP for the low sediment flux increases from 61.78 to 81.67 μg P L^{-1}. Due to the increase in sediment transport, SRP also increases substantially; however, the total dissolved P mass budget could decrease across the evaporation gradient despite increasing concentrations of P. This is seen in the results obtained through the use of the model. To apply the above findings in semi-arid environments, one needs to define the hydrologic boundary, sediment transport, and retention rates.

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