Phosphorus Sorption in Utah Lake: Why Concentrations Remain Stable Despite Inputs and Volume Changes

A Briefing for Policy Makers and Water Resource Managers

Background

Utah Lake is a large (380 km^2), shallow (average depth ~3 meters), and well-mixed freshwater lake in central Utah. It receives water from multiple tributaries and discharges through a single outlet, the Jordan River. Despite its shallow nature and variable inflows, the lake exhibits **remarkably stable levels of phosphorus (P)** in the water column, which contrasts with expectations from conventional mass balance models.

Since phosphorus (P) is a primary driver of harmful algal blooms (HABs), understanding the mechanisms that control its concentration is critical for developing effective nutrient management policies.

Stable Phosphorus Concentrations Over Decades

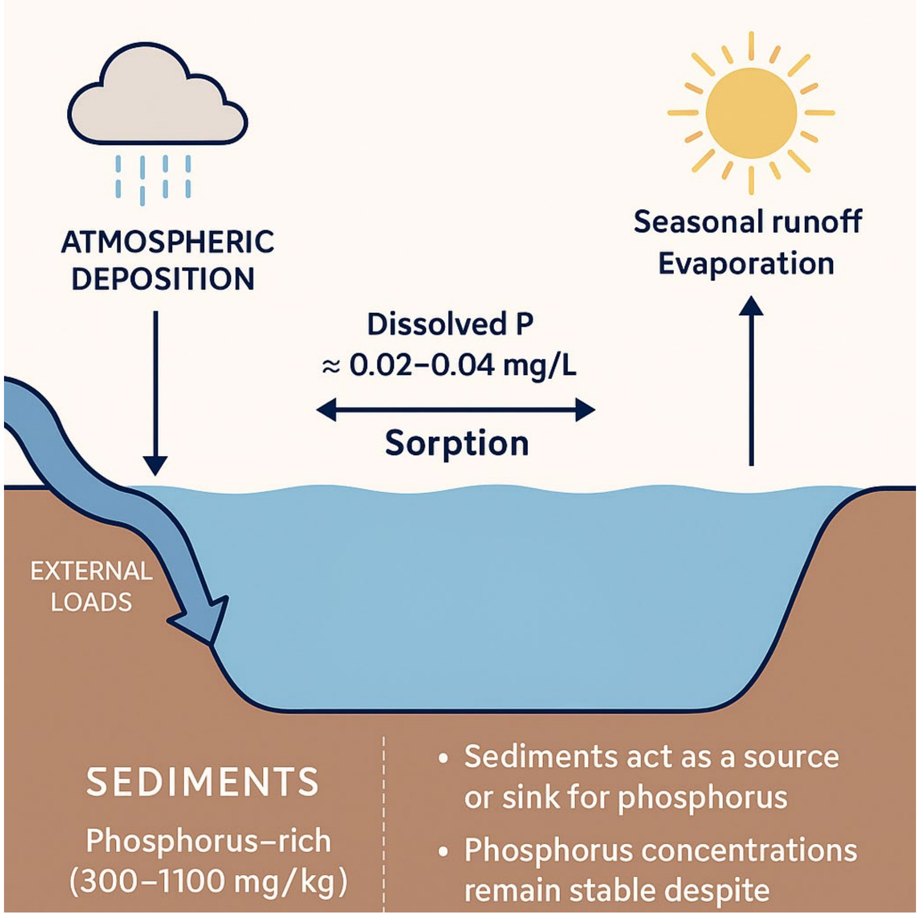
Analysis of long-term data (1989–2023) from State sources shows that water column DP concentrations have remained consistently between **0.02 and 0.04 mg/L**, with most values near **0.03 mg/L**, regardless of wide fluctuations in lake volume. Volume can vary by a factor of 2 or more annually due to spring runoff and summer evaporation, but DP concentrations don't change.

Why this matters: Traditional models would predict dilution in wet years and concentration in the late summer (or dry years). The data show otherwise, suggesting another mechanism governs phosphorus concentrations.

Phosphorus-Rich Sediments from Geologic Sources

Utah Lake's sediments are **naturally rich in phosphorus**, originating from geologic formations such as the Phosphoria and Park City formations. Measured P sediment concentrations range from **300 to 1100 mg/kg**, with about **40% of that P available for interaction** with the water column.

The same phosphorus signature appears in soils and sediments upstream in the watershed, indicating this is a **geologic regional, not anthropogenic**, feature.



Sorption Dominates Phosphorus Dynamics

Sorption is a reversible process in which phosphorus attaches to or detaches from sediment particles. This natural buffering keeps water column P concentrations near equilibrium.

Utah Lake's physical characteristics enhance sorption:

- **Shallow depth and wind exposure** mix sediments into the water column.
- **Invasive carp** stir up bottom sediments through feeding.
- **High suspended solids** (~1000 mg/L) and shallow Secchi depths (~tens of cm or less) indicate constant sediment-water interaction.

Utah Lake K_D Values

The **K_d value**, or *distribution coefficient*, is the ratio of sediment concentration to water concentration. A high K_d means phosphorus tends to **stick to sediments** (strong sorption), while a low K_d means more phosphorus stays in the water, but the ratio stays relatively constant, so if P is taken from the water, it is released from the sediment to maintain the concentration ratio (K_d). Conversely, if there is an increase in water column concentrations from increased loads, this P moves to the sediment to maintain the concentration ratio (K_d).

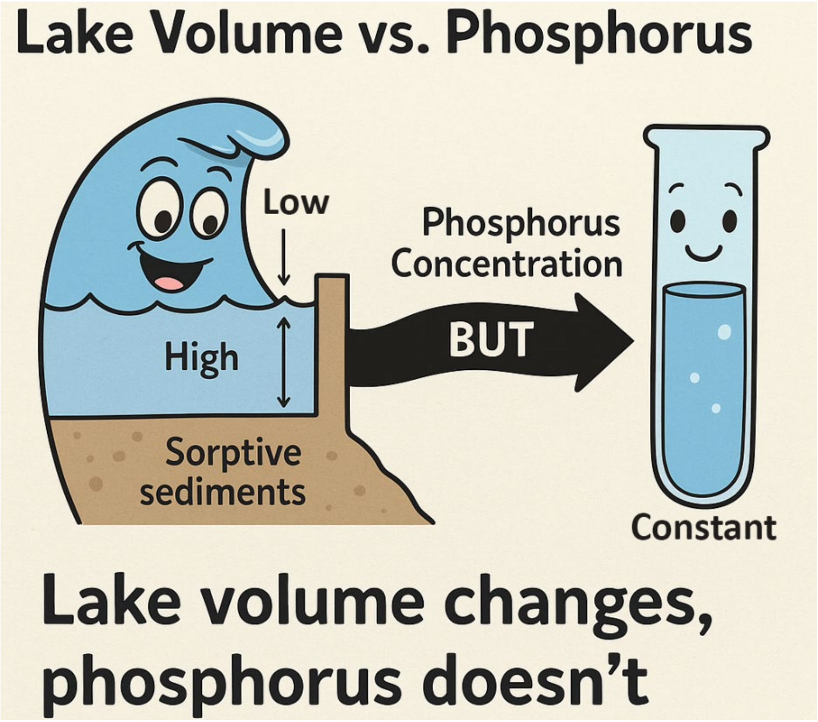
In Utah Lake, experiments show K_d values range from **hundreds to over 1000**, depending on conditions. These high values indicate that **most dissolved phosphorus quickly binds to sediment**, which helps explain why phosphorus concentrations in the water remain stable—even when external phosphorus inputs or lake volumes change.

A Sorption-Controlled System

Sorption refers to phosphorus attaching to or releasing from sediment particles depending on the surrounding water chemistry. Utah Lake's shallow depth (~3 meters), constant sediment mixing (due to wind and carp activity), and phosphorus-rich sediments create conditions where sorption controls P levels in the water column. This means **the lake "buffers" itself**, maintaining equilibrium regardless of inflow variations.

Modeling shows that reducing external P sources—even eliminating wastewater treatment plant discharges—would produce only minimal changes in water column P concentrations.

- Sorption buffering is so strong that altering P concentrations requires **extreme interventions,** depending on the assumed K_d value:
  - To increase water column P by 0.005 mg/L (from 0.030 to 0.035 mg/L), it would take **346 to 714 metric tons** of added P.
  - To decrease it by the same amount, the lake would need to be **flushed with clean water 13–27 times**—an impossible scenario.
  - The range depends on the assumed K_d value, with the lower numbers related to a K_d of 100.
- Sorption experiments confirm that sediment P is actively involved in short-term exchange processes. For example, **kinetic studies** show different rates of phosphorus retention depending on sediment type.
- **Internal Cycling Is Active and Complex** Monthly changes in internal P mass often exceed external load estimates. The sediments act both as a **source and a sink**, depending on short-term fluctuations like inflow and evaporation. These dynamics are consistent with sorption-dominated behavior rather than simple input-output models.



Laboratory Experimental Work

Recent experimental work on Utah Lake sediments has quantified phosphorus sorption dynamics using *distribution coefficients* (K_d).

A high K_d indicates strong phosphorus retention by sediments. For instance:

- At pH 8.5 (typical for Utah Lake), K_d values exceed **100–800**.
- **Anoxic or anaerobic sediment conditions** mobilize iron (Fe)-bound phosphorus. Fe(III) compounds dissolve, releasing Fe-bound P into pore water, which can then re-adsorb as conditions shift or reprecipitate with carbonates. This enhances short-term sorption fluxes and makes Fe a key player in phosphorus cycling.

Implication: These high Kd values confirm that sediments act as a powerful buffer, maintaining equilibrium and resisting external perturbations in phosphorus loads. This supports the conclusion that Utah Lake is **sorption-dominated**, and reducing external loads may have little impact on water P concentrations.

Policy Implications for Utah Lake Management

❗ Load Reductions Alone May Be Ineffective

Conventional strategies focus on reducing external inputs, such as wastewater treatment plant (WWTP) discharges. However, evidence indicates that **even total removal of WWTP P contributions** would have **minimal impact** on in-lake concentrations due to the dominant internal cycling through sorption.

✅ Focus on Internal Dynamics

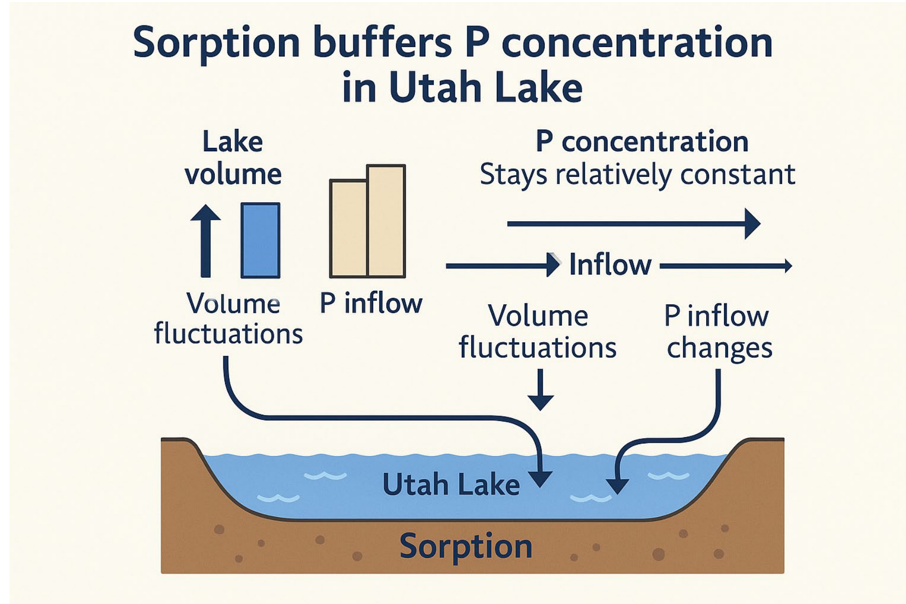
Resource management should:

- Prioritize sediment stabilization (e.g., carp removal, vegetation restoration).
- Monitor short-term mass changes and sediment-water interactions.
- Invest in understanding redox dynamics, organic matter behavior, and carbonate precipitation—factors that control sorption efficiency.

Conclusions

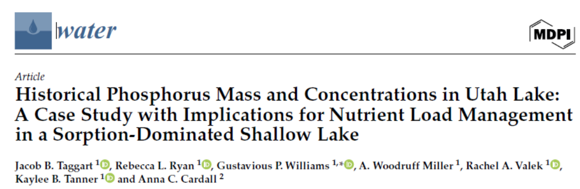
Utah Lake's phosphorus behavior is governed not by external loading but by **internal, geochemically driven processes.** Sorption acts as a dynamic buffer that maintains steady-state phosphorus concentrations, making the system **resistant to rapid change** even with dramatic shifts in input or volume.

As a result, effective restoration of Utah Lake will require **innovative, sediment-focused solutions** rather than conventional nutrient load reduction policies.



Primary Sources

- Taggart et al. (2024). *Historical Phosphorus Mass and Concentrations in Utah Lake*. Water 16(933).
- Jarvis (2023). *Phosphorus Sorption and Kinetics Across the Sediment-Water Interface of Utah Lake*. Thesis, BYU ScholarsArchive.
- Aremu (2023) *Investigating the Geochemical Trends at the Sediment-Water Interface of the Shallow and Eutrophic Utah Lake* Thesis, BYU ScholarsArchive.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Article

Historical Phosphorus Mass and Concentrations in Utah Lake: A Case Study with Implications for Nutrient Load Management in a Sorption-Dominated Shallow Lake

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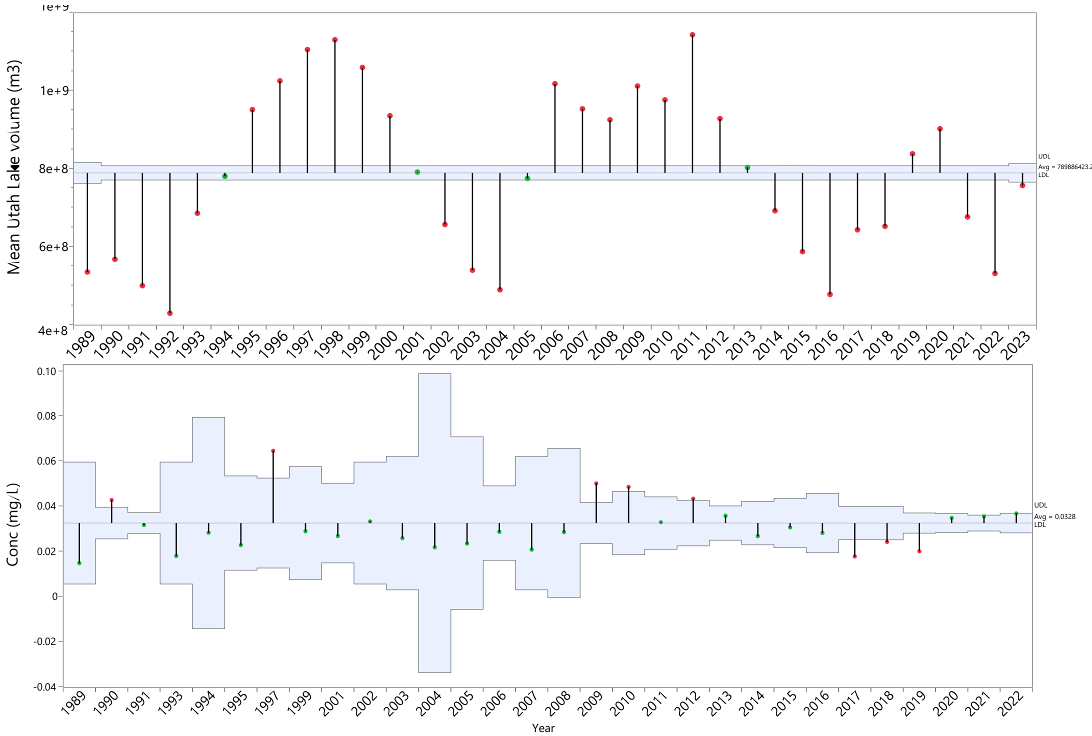

*These charts show how Utah Lake's annual mean water volumes (top) and annual mean phosphorus (P) concentrations (bottom) behave over time. The **horizontal line** represents the long-term average across all years, and the **colored band** indicates statistical uncertainty in estimating the annual mean. This uncertainty is **larger in years with fewer measurements** and **smaller in years with more data**. Each **dot** represents the average for a single year. If the dot falls **outside the shaded area**, the annual value is **statistically significantly different** from the long-term average, if it is inside the blue band, we cannot say it is different from the long-term mean at a statistically significant level.*

Understanding ANOM (Analysis of Means)

- These charts use a statistical method called **Analysis of Means (ANOM)** to help compare values from individual years against the long-term average. Here's how to interpret them:
- **Center Line**: The horizontal line in the middle of the plot represents the **long-term average** (or "grand mean") for all years combined.
- **Blue Shaded Band**: This is the **confidence range** (bounded by the **Upper Decision Limit (UDL)** and **Lower Decision Limit (LDL)**). It shows the range of annual values that are **not significantly different** from the long-term average.
- **Dots**: Each dot is the **average value for a specific year** (e.g., lake volume or phosphorus concentration).
- **Vertical Lines**: These lines connect the annual average value to the long-term average value for comparison.

What It Tells Us

- If a dot falls **inside the blue shaded band**, that year's average is **not statistically different** from the long-term average.
- If a dot falls outside **the shaded area**, the difference **is statistically significant**—that year was meaningfully higher or lower than normal.
- The **width of the blue band** changes depending on how much data were collected in that year: **narrower bands** mean more confidence, while **wider bands** (usually in years with less data) mean more uncertainty.

This method helps us clearly see trends—such as how Utah Lake volumes often differ significantly from the long-term average, while phosphorus concentrations remain stable, reinforcing that sediment interactions dominate phosphorus behavior.

Stable Phosphorus Concentrations

In the **top panel**, we see that in most years, the lake volume differs significantly from the long-term average—sometimes by hundreds of millions of cubic meters. In contrast, the **bottom panel** reveals that dissolved phosphorus (DP) concentrations are **rarely statistically different** from the long-term average. Even when DP differences are statistically significant, the magnitude of variation is small as the point is just outside the band.

Annual Utah Lake volume (top) varies substantially due to climatic wet–dry cycles and seasonal hydrology, yet dissolved phosphorus (DP) concentrations (bottom) remain remarkably stable. Given the lake's hydrology: we would expect phosphorus concentrations to **decrease in wet years** due to dilution and **increase dry years** due to concentration if external loads remain relatively constant. Similarly, we would expect **lower concentrations in spring** (when runoff fills the lake and dilutes the phosphorous) and **higher concentrations in late summer** (when ~50% of the volume evaporates and concentrates the phosphorous). But the data do not follow this expected pattern. Instead, phosphorus concentration remains stable, providing strong evidence that **sorption processes with phosphorus-rich sediments buffer the lake** against seasonal and long-term hydrologic changes and that changes in external P-loads have minimal impact on water concentrations.

The data show that DP concentrations stay consistent year-round and year-to-year, indicating that **sorption processes with phosphorus-rich sediments dominate lake chemistry**, buffering the water column against external fluctuations.

Sources

Figures from Taggart et al. (2024). *Historical Phosphorus Mass and Concentrations in Utah Lake*. Water 16(933).
All data from the State of Utah AQWMS database.