

Mineral Precipitation In Utah Lake And Its Effluent Mixing Zones

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Abstract— While public interest has grown in recent years to rehabilitate Utah Lake's eutrophic condition, restoration efforts imposed on the lake will be most effective when they account for the lake's internal processes. Mineral precipitation within the effluent mixing zones of Utah Lake was investigated through water, precipitate, and sediment analyses, including geochemical modeling and x-ray diffraction. While it may be possible for apatite to form in-situ, calcite is the only major mineral that actively precipitates in Utah Lake. Quantifying the rate of phosphorus coprecipitation with calcite is likely an essential aspect of characterizing total phosphorus cycling in Utah Lake.

Keywords—apatite, calcite, mineral precipitation, phosphorus, PHREEQC, Utah Lake, water quality

I. INTRODUCTION

Despite being a vital natural and economic resource, Utah Lake (located in north-central Utah, USA) has long been considered an impaired water body. For over a century, the lake has been plagued with problems ranging from raw sewage disposal to carp infestation. Multiple wastewater treatment plants and carp removal projects have since been introduced, and while they have improved the lake's overall water quality, Utah Lake has continued to experience elevated levels of total phosphorus (TP) and total dissolved solids up to the present day [1].

With increasing frequency, Utah Lake has received widespread attention for its recurring algal blooms and associated closures [2, 3, 4]. While the general public is often concerned with the blooms' impact on the recreational and aesthetic value of Utah Lake and the outflowing Jordan River, such algal blooms likewise restrict agricultural usage of lake water and hinder the conservation efforts being made for the June Sucker fish species [5, 6, 7]. Algal blooms in Utah Lake are typically triggered by a combination of hot, dry, and calm weather conditions, consequently resulting in lower lake levels, decreased turbidity, increased light penetration, and a warm, aquatic environment ideal for growing algae in the lake's eutrophic waters [2]. Utah Lake's algal blooms are often presumed to be nutrient-limited, and are therefore thought to be exacerbated by incoming wastewater effluent – the lake's most recognizable source of phosphorus [6].

Efforts to limit phosphorus loading to Utah Lake began in the mid-2000s when the Utah Division of Water Quality (DWQ) started the preliminary steps to establish a Total Maximum Daily

Load (TMDL). This initiative included an in-depth study by PSOMAS on the lake's impairment. In their final report, it was concluded that before the TMDL process could move forward, Utah Lake's "individual lake system must be understood to comprehend the internal processes that may influence the cycling of TP and to identify the appropriate mechanisms for limiting TP in [its respective] watershed" [1]. After receiving PSOMAS's final assessment, DWQ chose to suspend Utah Lake's TMDL process in order to allow projects focused on the lake's invasive species to be more adequately addressed [2].

The momentum to advance Utah Lake's TMDL process has since waned, with multiple agencies side-stepping the regulatory procedure entirely in order to introduce alternative remediation methods to the lake. In 2014, the Utah Water Quality Board enacted the Technology-Based Phosphorus Effluent Limit (TBPEL). This policy had particular implications for the wastewater treatment plants surrounding Utah Lake, as all entities releasing discharges to any of Utah's waterways were then required to upgrade their facilities by January 1, 2020 if their discharge(s) had a TP content greater than 1.0 mg L^{-1} [8]. In 2018, a law known as HB0272 was passed allowing the State of Utah to transfer lakebed ownership to external organizations. This action has led to the formation of Lake Restoration Solutions, a company that is now contemplating plans to dredge Utah Lake in an attempt to simultaneously enhance the lake's water quality while building islands for future development [9, 10]. And in 2020, Alpine Technical Services tested a series of copper sulfate treatments on an algae bloom occurring in Lindon Marina, located on the northeastern side of Utah Lake. The procedure improved water clarity inside the marina within a matter of days, and has since been deemed an effective means of providing short-term relief from localized algal blooms [11].

While these and other agencies are actively seeking ways to improve the water quality of Utah Lake, the charge given by PSOMAS – to understand Utah Lake prior to treating it [1] – has become more important than ever. In that vein of thought, LimnoTech released a literature review in 2018 that evaluated 37 of the most relevant sources available assessing the water quality of Utah Lake. When discussing the topic of Internal Cycling and Biological Availability of Nutrients, the review states that even though the selected studies "provide some insight into sediment phosphorus characteristics and fluxes... none of the studies quantify actual sediment nutrient flux rates, and no studies were available that quantified the biological

availability of nutrients in lake sediments" [12]. Even though the knowledge gaps identified here are particularly important regarding TP cycling within Utah Lake, endeavoring to address them is no simple matter. In order to begin quantifying sediment nutrient flux rates in Utah Lake, this study (which utilizes material from the thesis written by J. Taggart [13]) sought to identify the key mineral phases that are precipitating in the lake's water column and to determine how those mineral phases could potentially interact with phosphorus in the lake's effluent mixing zones.

II. METHODS & MATERIALS

The analytical methods selected for this study include: 1) geochemical modeling with PHREEQC to model mineral formation in various mixtures of lake-water (LW) and wastewater (WW), and 2) x-ray diffraction to identify the mineral phases present in a precipitate sample as well as in lakebed & tributary sediments from the Powell Slough and Mill Race Creek effluent mixing zones of Utah Lake. See Figure 1 for a depiction of an effluent mixing zone.

A. Water Sample Acquisition and Geochemical Modeling

LW samples were collected from the northern arm of Utah Lake State Park while facing north towards Powell Slough. WW effluent samples were collected from the outflow of the Orem Water Reclamation Facility. The samples collected for geochemical modeling were acquired the same day and in sets of two. The first set of LW & WW samples were taken to Brigham Young University's Environmental Analytical Laboratory to be tested for bicarbonate using the alkalinity method prescribed by Gavlak [14] as well as for elemental detection using iCAP 7400 ICP-OES. The second set of LW & WW samples were taken to Chemtech-Ford Laboratories the same day to be tested for chloride, fluoride, nitrate, and sulfate using the EPA 300.0 ion chromatography method.

B. Geochemical Modeling

In addition to compiling water quality data, the original database for PHREEQC was manually augmented to include kinetic data for 23 additional phosphate minerals [13]. This adjustment made it possible for PHREEQC to predict and account for the possible formation of these phosphate minerals while running geochemical models on the entered water quality data. PHREEQC was additionally programmed to use an incremental mixing model in order to simulate the gradual additions of WW as it flows from its parent tributary into Utah Lake. The resulting geochemical models were then plotted along a mixing line representing a spectrum of mixtures ranging from 0% LW to 100% LW. See Figure 2 for a conceptual depiction of this study's incremental mixing model.

C. Precipitate & Sediment Sample Acquisition

The precipitate sample was collected by conducting an evaporation experiment over the course of 85 days. Using the same LW sampling site mentioned in the above section *Water Sample Acquisition & Geochemical Modeling*, approximately 115 liters of LW water were collected and transferred to an evaporation pool with a height of 30 cm and a diameter of 120 cm. The pool was situated inside a dark, ventilated building in

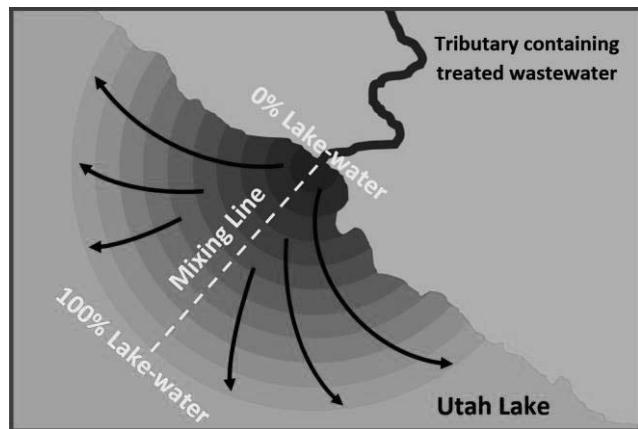


Figure 1. Conceptual representation of an effluent mixing zone and its mixing line, used to mark the dilution of tributary water in the lake. Subsequent figures will be plotted along a mixing line to show how concentrations vary relative to their position within an effluent mixing zone.

order to allow evaporation to occur without the interference of photosynthesizing algae. Roughly 40% of the water was allowed to evaporate, thus coercing mineral precipitation to occur in the remaining water. Upon completion of the experiment, the water was drained, and the settled precipitate was allowed to dry before being collected from the pool

Sediment samples were collected during an airboat excursion to the Powell Slough and Mill Race Creek effluent mixing zones, with each site having 2 samples collected upstream, 1 sample collected at the confluence, and 2 samples collected in the open lake (see [13] for the precise locations). At each sampling site, the top several centimeters of sediment were collected using an Eckman Dredge and were allowed to drain for approximately 30 seconds. The sediment was then stored in a centrifuge tube with the headspace filled with surface water. The opening of each tube was then covered with parafilm with the cap screwed on tight. The samples were then stored at 4°C until analysis could be performed on the samples.

D. X-ray Diffraction

Assuming the precipitate was composed primarily of calcite, the precipitate sample was prepared for x-ray diffraction by being soaked in 2 mL of acetone while being ground into powder, and was then subsequently allowed to dry for 15 minutes.

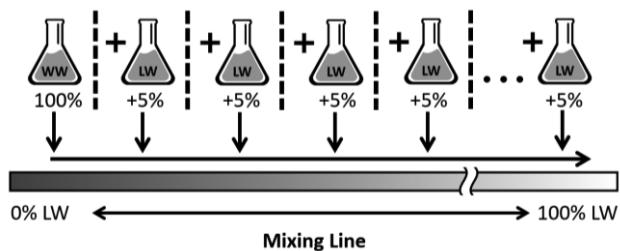
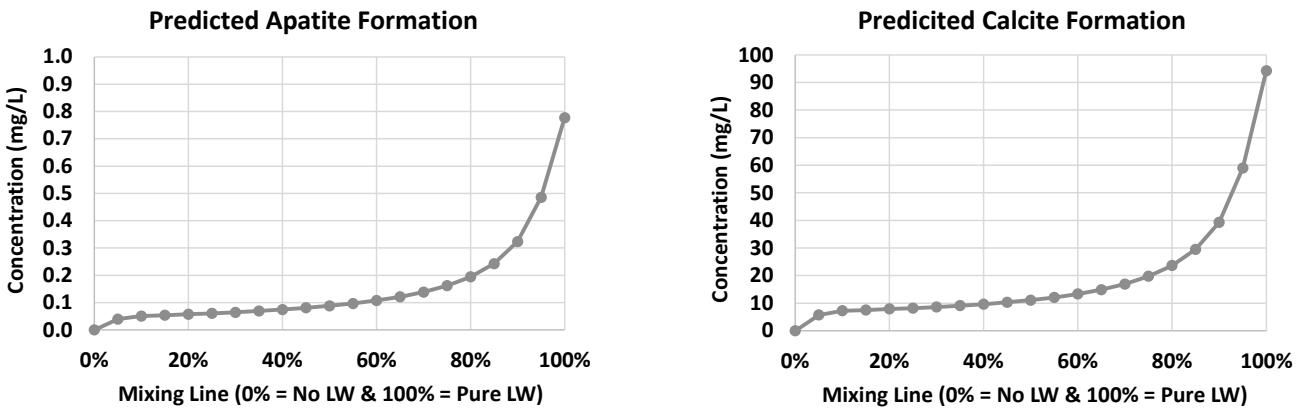


Figure 2. Conceptual representation of the incremental mixing model created in PHREEQC for this study. The model begins with a sample of 100% WW and has LW added to it in 5% increments (by mass) until the WW solution has become infinitely diluted with LW.



Figures 3 & 4. Geochemical modeling results for the potential formation of apatite and calcite within Utah Lake's effluent mixing zones. Note the difference in scale between the y-axes. While the formation patterns appear similar between apatite and calcite, the resulting concentrations for calcite are approximately two orders of magnitude greater than that of apatite.

On the other hand, because the sediment samples were expected to contain clay minerals, the wet sediments were allowed to dry in a drying oven for three days at no warmer than 50°C to keep the clay minerals from becoming unstable. Once dry, each sediment sample was sealed within a container with aluminum oxide pestles and 2 mL of methanol to suspend the sediment without causing the clay to swell. The containers were then sealed and shaken by a heavy-duty vibrator for 2 minutes to grind the sediment into powder. The sediments were then allowed to be dried again in a drying oven at 50°C for three days. Once dry, the sediments were then placed inside small bottles along with a plastic pestle and about 1 mL of hexane. The bottles were next shaken in a heavy-duty shaker for 20 minutes to randomly orient the clay particles, and the sediment samples were then allowed to dry overnight in a drying oven,

The dry precipitate and sediment samples were then placed into loading trays for examination using Rigaku MiniFlex 600 XRD. The diffraction patterns produced for each sample were next uploaded into PDXL2 and analyzed for potential mineral candidates until the calculated diffraction pattern matched the measured pattern and the associated weighted-profile R values (R_{wp}) were less than 10%.

III. RESULTS

A. Geochemical Modeling

Of the 23 phosphate minerals added to the PHREEQC database, only the apatite minerals ($\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$) were predicted to precipitate within the effluent mixing zones of Utah Lake. Even so, the model shows that only one form of apatite is able to form at a given time. In addition to apatite, the carbonate mineral calcite (CaCO_3) is the only other mineral that is predicted to precipitate in Utah Lake's effluent mixing zones.

The incremental mixing model programmed into PHREEQC predicts minimal formation of both apatite and calcite in undiluted WW, but the ability for the two minerals to precipitate gradually increases as LW is allowed to be mixed with WW. As WW becomes more and more heavily diluted with LW, the formation of the two minerals increases

dramatically. The precipitation of apatite and calcite appear to be most suitable in 100% LW, producing a maximum of about 1 mg L⁻¹ of apatite and 94 mg L⁻¹ of calcite – assuming that the necessary chemical reactions are carried to completion. See Figures 3 & 4 for a graphical representation of these results.

B. X-ray Diffraction

As was expected, fewer minerals were detected in the precipitate sample than in the sediment samples. In regards to the precipitate sample, the weight percentages for its mineral content are as follows: calcite at 56.0%, quartz at 13.6%, muscovite at 12.7%, albite at 8.2%, apatite at 6.6%, and gypsum at 2.9%.

Although the sediment samples from the effluent mixing zones of Powell Slough and Mill Race Creek are fairly similar in their mineralogy, the mass percentages of their mineral content varied enough to require them to be reported separately. The average weight percentages for the Powell Slough sediments are as follows: quartz at 39.4%, carbonates at 20.7% (predominantly consisting of calcite at 14.2%), feldspars at 19.9%, clays at 12.1%, apatite at 2.5%, ankeriteite at 2.0%, hornblende at 1.4%, pyrite at 1.1%, and goethite at 0.6%.

	Albite	Apatite	Calcite	Muscovite	Quartz	Other
PS-1	11.0%	2.7%	23.0%	9.0%	32.0%	22.3%
PS-2	18.0%	2.8%	25.0%	7.0%	16.0%	31.2%
PS-3	13.0%	0.0%	12.0%	9.0%	47.0%	19.0%
PS-4	17.0%	5.2%	4.7%	1.7%	53.0%	18.4%
PS-5	10.4%	2.0%	6.3%	4.8%	49.0%	27.5%
MR-1	9.5%	1.1%	33.0%	7.0%	31.0%	18.4%
MR-2	12.0%	2.7%	45.0%	0.8%	20.0%	19.5%
MR-3	2.0%	7.0%	43.0%	4.0%	9.0%	35.0%
MR-4	10.0%	2.4%	34.0%	18.0%	19.0%	16.6%
MR-5	20.0%	3.2%	4.7%	0.7%	53.0%	18.4%
Precipitate	8.2%	6.6%	56.0%	12.7%	13.6%	2.9%

Trace Mineral
Assemblage

Major Mineral
Assemblage

Table 1. Summary of x-ray diffraction results for this study's precipitate and sediment samples.

The average weight percentages for the Mill Race Creek sediments are as follows: carbonates at 38.4% (predominantly consisting of calcite at 21.9%), quartz at 26.4%, feldspars at 13.9%, clays at 12.0%, hornblende at 3.6%, apatite at 3.3%, ankerite at 0.9%, goethite at 0.8%, and pyrite at 0.5%. See Table 1 for a summary of this study's x-ray diffraction results.

IV. DISCUSSION

In regards to mineral precipitation, the most significant part of Utah Lake's effluent mixing zones is the open lake itself, where incoming WW effluent has become completely diluted with LW. Both of the minerals predicted by the PHREEQC model to precipitate in Utah Lake – apatite and calcite – are known to interact with phosphorus. As a phosphate mineral, apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$) incorporates phosphorus into its mineral structure as it forms. While calcite is not a phosphate mineral, it is still capable of adsorbing or, more importantly, coprecipitating phosphorus provided that it has nucleation sites available. Due to the elevated pH levels of Utah Lake, the apatite and calcite found within the lake are unlikely to dissolve, and are thus capable of sequestering phosphorus in a way that renders it biologically unavailable [15].

While the geochemical models from this study assert that apatite is capable of forming in Utah Lake, it is important to note that apatite formation is a slow process and that it does not directly precipitate within the water column. Sedimentary apatite is instead created when phosphate forms a surface complex with calcite via coprecipitation and is then repeatedly transformed into several intermediate phases, usually through dissolution and reprecipitation, before apatite is finally produced [16, 17].

Under geochemically saturated conditions, calcite precipitation can occur rapidly once initial seed crystals have been formed, thus creating nucleation sites upon which further calcite mineralization can be propagated [18]. A corresponding increase in pH can likewise increase calcite insolubility. Calcite precipitation, however, can be hindered or even inhibited when its nucleation sites become overwhelmed by an overabundance of dissolved phosphorus or organic matter. Barriers such as these often require laboratory experiments to introduce calcite seed crystals in order to induce calcite precipitation [19].

In regards to this study's precipitate sample, x-ray diffraction detected several mineral phases in addition to apatite and calcite. Instead of this being an indicator that these other minerals precipitated along with apatite and calcite, this observation is most likely the result of collecting suspended solids with the precipitate as a consequence of using unfiltered LW for the experiment. The weight percentages for apatite and calcite were higher than the average weight percentages found in the sediment samples, suggesting that some amount of precipitation (or formation in regards to apatite) may have occurred for those minerals. It is fairly possible, however, that a portion of the apatite and calcite measured in the precipitate sample came from the existing suspended solids, and so the actual amount of precipitation that occurred cannot be measured from this sample.

With the exception of one sediment sample (PS-3 at the Powell Slough confluence with Utah Lake), x-ray diffraction detected apatite in all of this study's sediment samples. There

were no noticeable trends between the weight percent of apatite and the location associated with each sample. Calcite was found ubiquitously throughout the sediment samples, with higher weight percentages found within the tributary sediments and in Provo Bay. A comparative study of the mineral content of Utah Lake's sediments observed that the lakebed sediments are generally dominated by calcium carbonate as well [20]. In contrast, the sediments collected near shore for this study were found to be quartz-dominated. This occurrence, however, is likely just a local phenomenon caused by vigorous wave action and is commonly observed in the sands near the shorelines and the mouths of Utah Lake's major tributaries [21].

While the apatite and calcite minerals found in the lakebed sediments of Utah Lake could very well have been transported from throughout the watershed, the geochemical model from this study suggests that calcite and apatite could also have been formed in-situ. Calcite has been confirmed to actively precipitate in Utah Lake, with estimates of approximately 300 mg L⁻¹ forming in the lake each year during the mid-1900s [22]. Precipitation of calcite, therefore, provides an opportunity for phosphorus coprecipitation to occur, thus initiating the first stages of apatite formation within Utah Lake.

V. CONCLUSION & RECOMMENDED RESEARCH

A. Conclusion

Effluent mixing zones form a transitional boundary where tributaries containing wastewater intermix with their receiving water-body. In Utah Lake, mineral precipitation is best facilitated when incoming wastewater has become completely diluted with lake-water. Calcite is the only major mineral that forms and precipitates in Utah Lake. In-situ formation of apatite in Utah Lake is possible, but most likely occurs in trace quantities.

Precipitation of calcite and consequential coprecipitation of phosphorus with calcite could potentially be the only inorganic sedimentation mechanism capable of permanently rendering phosphorus biologically unavailable to the algae in Utah Lake. Although it is unclear how much of the calcite in Utah Lake is the result of precipitation within the lake itself, the prevalence of lakebed calcite in conjunction with active calcite precipitation and elevated levels of total phosphorus within the lake suggests that phosphorus coprecipitation with calcite could serve as an important, natural mechanism for removing phosphorus from Utah Lake.

B. Recommended Research

In line with Limnotech's recommendation to quantify actual sediment nutrient flux rates within Utah Lake [12], the rate at which in-lake calcite coprecipitates and adsorbs phosphorus should be measured. Care should be taken to differentiate the two mechanisms as adsorbed phosphorus is generally considered more bioavailable than coprecipitated phosphorus. Determining the rate of in-situ apatite formation would be a helpful addition to understanding sediment nutrient flux rates. The behavior of redox-sensitive minerals should likewise be investigated as they have been shown to play an important role in the sediment nutrient fluxes of Utah Lake [15].

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