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| Eutrophication in Lake Utah:  An Applied Study on Existing Lake Data Sets and Prediction of Future Development | SUMMARY  This study is offering options on environmental management measures and predictions of lake development in Lake Utah based on different data sets by various sources, acquired via Lake buoy mesurements May - November 2017 (Utah DWQ HAB Network Utah Division of Water Quality), US climate data and measurements of Phosphate in lake sediments by Brigham Young University (Merrell, 2015).  J. Skalbeck, H. Sander. F. Kügow  March 2018 |

**Eutrophication Development in Lake Utah:**

**An Applied Study on Existing Lake Data Sets and Prediction of Future Development**

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## Introduction

Lake Utah is a shallow freshwater lake of 39 km length and 21 km width with covering an area of about 380 km² with a mean depth of 3.2 m, lake volume 870.000 acre feet (1.07×109 m3) (Jackson and Stevens, 1981). The climate around the lake corresponds to desert climate and is classified as semiarid. 60% of the inflow comes from two rivers, namely Provo River (36%) and Spanish Fork River (24%). Other tributaries include the American Fork River, Current Creek, Dry Creek, Hobble Creek and Mill Race Creek. In addition, a variety of smaller tributaries and hot springs lead into the lake. The only outflow from the lake is the Jordan River (Utah DEQ: Utah Division of Water Quality 2009, PSOMAS). The inflow amounts to a total of about 0.754 km³/a, the outflow about 0.750 km³/a with a mean retention time of about 1.5 years. About 42% of water losses are caused by evaporation leaving the lake slightly salty ​​with 31-190 mg/l Na and 32-273 mg/l Cl, depending on season, water level, and measurement site (Fuhriman, D.K., Merritt, L.B., Woodruff Miller, A. and Stock, H.S., 2017).

Annual phosphorus accumulation is estimated to be 214.1 t/a, based on the annual input (297.6 t/a) and and output (83.5 t/a) values (PSOMAS, 2009). Total phosphorus is a nutrient contributing to plant and algal growth in aquatic systems. Elevated total phosphorus levels enhance algal development along with low dissolved oxygen, elevated pH, and potentially cyanotoxin production by cyanobacteria (blue-green algae). Consequently, harmful algal blooms (HAB) in Lake Utah can occur mostly during the late summer and fall and have been observed in the 1970th (Palmer, 1962; Strong, 1974; Whiting, Brotherson and Rushforth, 1978) and even 1930 (Tanner, 1930; Snow, 1932). Four algal species have been identified so far as responsible for HAB (*Aphanizomon flos-aque, Anabaena spiroides var. Crassa, Ceratium hirundinella, Melosira ganulata var. Crassa;* PSOMAS, 2009; Whiting, Brotherson and Rushforth, 1978). Studies indicate that HAB are checked by natural turbidity in the lake resulting from mineral precipitation rather than nutrient availability (Merritt and Miller 2016).

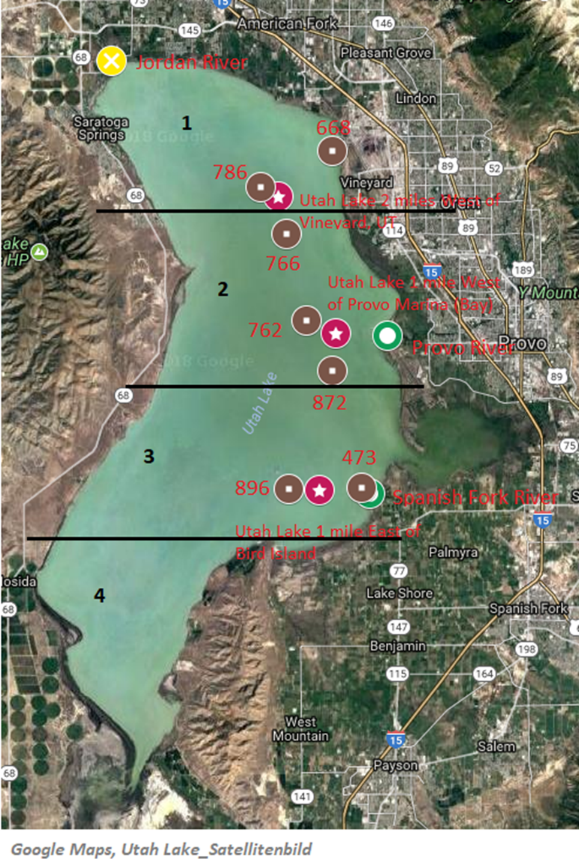


Fig. 1: Lake Utah Buoy Locations (red stars), Total Phosphorus measurement sites near buoys (brown dots), inflow (Provo River and Spanish Fork River, green circles) and outflow (Jordan River (yellow cross)

## Data Set 2017: Buoy Location and Parameter Sets

In 2017 3 buoys were installed measuring lake water quality parameters at lake surface continuously starting at the beginning of May to December in 15 min. increments (Overview Fig. 1), while no parameter measurements from various other depths were taken. Lake Utah Buoy Locations were: One buoy 2 miles W of Vineyard, another buoy 1 mile E of Bird Island and the third buoy 1 mile W of Provo Marina (red stars in Fig. 1).

Buoys were measuring water temperature (°C), turbidity (NTU), conductivity (µS/cm), oxygen saturation (%) and pH as general parameters and Chlorophyll a (RFU, µg/L) and BGA Phycocyanin (RFU, µg/L) as Parameters of algal development and cyanobacterial occurrence.

In addition, Total Phosphorus content in sediments near the buoy sites were derived from another Study (Merrel, 2015).

Daily air temperature (as min and max temperatures, °C) and preciptiation data (mm/d) were derived from US Climate Data for Provo 2017 and moreover back until 1948 for Salt Lake City (SLC).

## Data Set 2017: Air and Water Temperatures

Daily air temperatures (Provo weather station, Utah County, Local Climatological Data Set from NOAA National Centers for Environmental Information, formerly National Climatic Data Center) as well as precipitation events and Relative Humidity data (daily mean) from May to Dec 2017 are shown in Fig 2a,b. Fig 3a-c displays water surface temperatures from the three measurement sites. Note, that water surface temperatures follow air temperature conditions fairly closely. Water temperature data of the three buoy sites behave uniformly independent from measurement station within the lake.

*Fig. 2a,b: a. Upper Panel: Air Temperatures daily high/low (°C) and Precipitation events (mm/d) [single values], b. Lower Panel: Relative Humidity (%) [daily mean, n=24], May - Nov 2017 (Local Climatological Data Set from NOAA National Centers for Environmental Information, Provo Station, Utah County)*

*FIg. 3a: Water Temperatures (°C) May – Nov 2017, Buoy 2 miles W of Vineyard (x̅ ±SEM; n=96/d)*

*FIg. 3b: Water Temperatures (°C) May – Nov 2017, Buoy 1 mile E of Bird Island (x̅ ±SEM; n=96/d)*

*FIg. 3c: Water Temperatures (°C) May – Nov 2017, Buoy 1 mile W of Provo Marina (x̅ ±SEM; n=96/d)*

As to be expected, water temperatures follow high (R²=0.8355, y = 0,6967x - 1,0117) and low (R² = 0.8429, y = 0,896x + 7,9953) air temperatures over the time period observed, while water temperature and relative humidity are not related (R²=0.3187) (Fig. 3d).

*FIg. 3d,e: Linear Regression of d. high and low air temperatures (daily values, Local Climatological Data Set from NOAA National Centers for Environmental Information, Provo Station, Utah County) versus water temperatures (°C) from Buoy 1 mile W of Provo Marina (x̅ ±SEM; n=96/d) [left panel] as well as e. water temperatures versus relative humidity (%, daily mean, Local Climatological Data Set from NOAA National Centers for Environmental Information, Provo Station, Utah County) [right panel] during a time period of May – Nov 2017.*

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## Data Set 2017: General parameters Turbidity, Conductivity, oxygen saturatuion and pH

Daily Surface measurements of conductivity, turbidity, oxygen saturation (%) for the three measurements sites (Fig. 4 a-c) again showed a fairly uniform behaviour of those parameters throughhout the lake, when the three measurement sites are compared. Please note, that only the data sets from the bouy 2 miles of Vineyard are complete, the buoy 1 mile E of Bird Island did not perform in Midjune tot he beginning od Jule and the buoy 1 mile W of Provo Marina stpped sending valid data after November 5th.

While pH remains at 8-9 over the measuring period, conductivity is showing changeable behaviour until the end of June, then rises steadily until the end oft he measurement period. Turbidity values are changeable from May to Midjune and again from Midseptember until the end oft he measurement phase, while oxygen saturation values are fairly stable between 80-90% from May to Midjune and then again from Midseptember tot he end oft he measurement period, while exhibiting values from 70-120% in midsummer.

*FIg. 4 a: pH, Conductivity (µS/cm), turbidity (NTU), oxygen saturation (%) May – Nov 2017, Buoy 2 miles W of Vineyard (x̅ ±SEM; n=96/d)*

*Fig. 4 b: pH, Conductivity (µS/cm), turbidity (NTU), oxygen saturation (%) May – Nov 2017, Buoy 1 mile E of Bird Island (x̅ ±SEM; n=96/d; grey=probe malfunction)*

*FIg. 4c: pH, Conductivity (µS/cm), turbidity (NTU), oxygen saturation (%) May – Nov 2017, Buoy 1 mile W of Provo Marina (x̅ ±SEM; n=96/d; grey=probe malfunction)*

## Data Set 2017: Phosphate Accumulation within Lake Sediments

In Lake Utah annual phosphorus accumulation is estimated to be 214.1 t/a, based on the annual input (297.6 t/a) and and output (83.5 t/a) values (PSOMAS, 2009). Phosphorus release from sediments is dependent on several intertwined factors such as sediment resuspension, temperature, pH, Fe and Ca concentrations, redox potential and microbial processes.

In 2015 a study (Merrel, P.D., 2015) on lake sediments (n=56 samples, 0-10 cm) showed an average Total Phosphorus content of 710 ppm (Range 306 - 1710 ppm) within lake sediments with varying distribution throughout the lake and higher values at the Provo and Orem areas. Phosphate values near the buoy mesuring sites were 766-786 ppm near Buoy 2 miles W of Vineyard, 762-872 ppm near Buoy 1 mile E of Bird Island and 896 ppm near buoy 1 mile W of Provo Marina (see Fig.1).

## Data Set 2017: Algal development parameters Chlorophyll a and Phycocyanin

Daily Surface measurements of Chlorophyll a (Chl a) and Phycocyanin values again showed a fairly uniform behaviour throughhout the lake, when the three measurement sites are compared. Please note again, that only the data sets from the bouy 2 miles of Vineyard are complete, the buoy 1 mile E of Bird Island did not perform in Midjune tot he beginning od Jule and the buoy 1 mile W of Provo Marina stpped sending valid data after November 5th.

While Chl a values remainded at around 5 µg/L from May to Midjune, two Chl a peaks were observed areound Midjuly and approx. 2-3 weeks in August and values ranging slightly higher than at the beginning (10-17 µg/L) until the end oft he measurement period. With Chl a values between 8- >25 µg/L the lake can be considered eutrophic. Phycocyanin values started low (0.5 µg/L), peaked early in June (6 µg/L) and again remained stable at around 0.5-3 µg/L thereafter.

*Fig 5 a: Chlorophyll a and Phycocyanin (µg/L) May – Nov 2017, Buoy 2 miles W of Vineyard (x̅ ±SEM; n=96/d; grey=probe malfunction)*

*Fig 5 b: Chlorophyll a and Phycocyanin (µg/L) May – Nov 2017, Buoy 1 mile E of Bird Island (x̅ ±SEM; n=96/d; grey=probe malfunction)*

*Fig. 5c: Chlorophyll a and Phycocyanin (µg/L) May – Nov 2017, Buoy 1 mile W of Provo Marina (x̅ ±SEM; n=96/d; grey=probe malfunction)*

## Data Set 2017: Comparison of Parameters

Behaviour of general paramters and algal growth parameters corresponds well in stable and changeable periods: While algal growth (Chl a) is exhibiting peak values in Midjuly and August, pH is slightly elevated, Turbidity values are more stable and Oxygen saturation values are elevated and mroe changeable in all three buoy measurement sites. Sites behave similarily in change of values over time with a slightly less pronounced change in the Buoy 1 mile E of Bird Island at the more southern part of the lake.

*Fig. 6. Comparison of buoy parameters over time May – Nov 2017 (x̅ ±SEM; n=96/d; grey=probe malfunction)*

**Buoy 2 miles W of Vineyard Buoy 1 mile W of Provo Marina Buoy 1 mile E of Bird Island**

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## Prediction of Parameter Development

As climate change is to be considered as an option in the Lake Utah region, some thought as to future development of annual temperatures, preciptiation and consequently evaporation and possible nutrient concentration should be given in order to determine, whether these effects may add to eutrophication processes in Lake Utah.

## Air Temperature and Precipitation Development

For trend estimation annual air temperature and precipitation data were investigated from Salt Lake City as the nearest measuring station to the Lake Utah region with an unbroken data record ranging from 1875 to 2017 (Data derived from US Dept of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Salt Lake City Weather Forecast Office, 2017). Linear regression reveals an annual increase of +0.0087°C yr-1 (0.087°C per 10 yrs), a value similar to an average annual increase estimated for Salt Lake City earlier (+0.015°F yr-1; Bardsley et al., 2013). This is accompanied by a slight an decrease in precipitation of 0.1013 mm per year, but correlation coefficients (R² = 0,1684 for air temperature and R² = 0,0021 for precipitation over time) show the uncertainty of the assumptions due to variation within the annual data set (Fig.7). Based on these data not much of a change in annual evaporation rates is to be expected, but as one factor possibly affecting lake nutrient concentrations it should be looked into nevertheless.

*Fig. 7. Development of Annual Air Temperature (°C; left panel) and Annual Precipitation (mm; right panel) in Salt Lake City 1875-2017 (single values/year)*

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## Development of Evaporation (Dalton Model)

There are numerous models for estimation of evaporation of open water surfaces due to the complexity of the process, the number of influencing factors and boundary conditions. In the present case the fitting application of a model has to bear data availability in mind. As estimates from water or temperature balance as well as estimates based on micrometerologic measurements of surface near air layers (Vietinghof, H., 2002) or the Turc method (Kappas, M, 2009) lack the needed data input, the study opted for the more empiric Dalton approach (Wittenberg, 2011) for estimation of evaporation:

with E = evaporation over open water surface mm/d; b = wind factor [decreasing with length of open water surface, assumed value 1.1 based on lakes of similar length, this factor decreases with increase in length due to water vapor saturation of air on the way]; v = mean wind velocity in 2 m height [m/s; assumed value 3 based on Utah State Park average measurements 2010-2017 giving 6.8mph = 3,03 m/s], es = saturation vapor pressure at temperature TW of water surface [hPa], ea = actual vapor pressure at air temperature TL:

As data set May – November 2017 for TL served the NOAA climate data set (Fig 2a, b) and for TW the buoy data (Location Provo) on water temperature development (Fig. 3c), results of estimate of evaporation are shown in Tab. 1.

*Tab. 1. Lake Utah evaporation data (Merrel, P.D., May – December 2015) and estimate of evaporation in Lake Utah based on buoy and NOAA data sets from May – November 2017*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Evaporation** | **May** | **June** | **Juli** | **August** | **September** | **October** | **November** | **Total** |
| **Season 2015 [m3]** | -50.325.984 | -65.127.744 | -77.215.848 | -69.691.620 | -48.969.156 | -32.933.916 | -18.132.156 | -362.396.424 |
| **Estimate Season 2017 [m3]** | -43.027.561 | -70.336.664 | -89.486.266 | -84.467.251 | -54.484.711 | -32.679.754 | -13.479.644 | -387.961.851 |

Based on these values a change in evaporation can be estimated for changes in air and water temperatures as well as the impact on humidity changes using the Dalton formula (Tab. 2.)

*Tab. 2. Lake Utah evaporation data estimates (Dalton equation) under different climate premises (Temperature, °C; relative Humidity (rH; %)) based on buoy and NOAA data sets from May – November 2017 (assumed lake volume 1.073.129.000 m3]*

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Evaporation**  **[1000 m3]** | **May**  **(Start 05/05/17)** | **June** | **Juli** | **August** | **Sept.** | **October** | **Nov.**  **(End 11/17/17)** | **Total** | **% Lake Volume** |
| **Estimate Season 2017** | -43.086 | -70.556 | -89.487 | -84.468 | -54.485 | -32.680 | -13.479 | -388.241 | 36 |
| **+0.01°C** |  |  |  |  |  |  |  |  |  |
| **rH no change** | -43.055 | -70.380 | -89.540 | -84.518 | -54.519 | -32.701 | -13.488 | -388.200 | 36 |
| **rH \* 0.9** | -46.468 | -74.918 | -95.946 | -90.364 | -59.328 | -35.534 | -15.087 | -417.645 | 39 |
| **rH \* 1.1** | -39.642 | -65.842 | -83.111 | -78.671 | -49.622 | -29.869 | -11.891 | -358.756 | 33 |
| **+0.1°C** |  |  |  |  |  |  |  |  |  |
| **rH no change** | -43.300 | -70.770 | -90.020 | -84.972 | -54.818 | -32.896 | -13.571 | -390.346 | 36 |
| **rH \* 0.9** | -46.734 | -75.334 | -96.460 | -90.850 | -59.655 | -35.745 | -15.178 | -419.956 | 39 |
| **rH \* 1.1** | -39.867 | -66.207 | -83.578 | -79.095 | -49.982 | -30.045 | -11.962 | -360.737 | 34 |
| **+1°C** |  |  |  |  |  |  |  |  |  |
| **rH no change** | -45.828 | -74.774 | -94.940 | -89.637 | -57.900 | -34.892 | -14.413 | -412.381 | 38 |
| **rH \* 0.9** | -49.463 | -79.593 | -101.731 | -95.840 | -63.017 | -37.920 | -16.123 | -443.686 | 41 |
| **rH \* 1.1** | -42.191 | -69.954 | -88.148 | -83.434 | -52.782 | -31.863 | -12.705 | -381.077 | 36 |
| **+10°C** |  |  |  |  |  |  |  |  |  |
| **rH no change** | -79.080 | -127.014 | -158.530 | -149.993 | -98.015 | -61.472 | -25.718 | -699.820 | 65 |
| **rH \* 0.9** | -85.389 | -135.167 | -169.859 | -160.424 | -106.834 | -66.888 | -28.783 | -753.347 | 70 |
| **rH \* 1.1** | -72.769 | -118.861 | -147.199 | -139.560 | -89.197 | -56.056 | -22.652 | -646.294 | 60 |

Data from Tab. 2 show a slow increase in evaporation with rising temperatures, the difference being 19.571 acre feet at a +1°C change, thus 6.2% of Season 2017 total value on the assumption, that relative humidity stays the same. Only assuming a 10°C temperature increase evaporation is estimated to be almost double compared to evaportation estimates for season 2017 (Tab. 2, Fig. 8).

Evaporation (Fig. 8) rises with sinking relative humidity (rH\*0.9 at +1°C: 25.379 acre feet difference) and falls with rise in relative humidity (rH\*1.1 at + 1°C: 25.379 acre feet difference) when compared to values under unchanged relative humidity conditions (± 7.6%).

*Fig 8. Estimated changes in Lake Utah evaporation with changing climate assumptions (temperature, relative humidity)*

**Season 2017**

**+0.01°C**

rH no change

rH \* 0.9

rH \* 1.1

**+0.1°C**

rH no change

rH \* 0.9

rH \* 1.1

**+1°C**

rH no change

rH \* 0.9

rH \* 1.1

**+10°C**

rH no change

rH \* 0.9

rH \* 1.1

## Development of Phosphate in Lake Water and Sediments

Since the influence of increasing air temperatures is marginal Phosphorus concentration over time will not be notably influenced by a slight temperature increase due to climatic changes. However, change in runoff caused by temperature change was not included into the above considerations, but there is indication from observations within the region that temperature changes alone will lead to earlier runoff and reduced runoff volume (flow reduction on average 6.8% °C-1; Bardsley et al., 2013).

Thus, climatic change and subsequent alteration in evaporation will not drastically modify lake size and Phoshorus concentration in the near future, not as much as annual input of the element due to anthropogenic influence (waste water treatment plants, agriculture). Annual Phosphorus accumulation is estimated to be 214.1 t/a based on the annual input (297.6 t/a) and output (83.5 t/a) values, output mainly via Jordan River (PSOMAS, 2009). Phosphorus is described as derived mostly from waste water treatment plants (76%) and to a lesser extend from agriculture with elevated values visible in April and May presumably from fertilization (PSOMAS, 2009).

*Tab.2 Total Phosphorus Inflow and Export - Lake Utah (t/year; monthly average values 1980-2003; Data from PSOMAS, 2009)*

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
| Total P Inflow (t/a) | 22.4 | 22.7 | 23.7 | 29.6 | 29.9 | 23.6 | 23.4 | 22.4 | 25.3 | 26.8 | 25.6 | 22.2 |
| Total P Export (t/a) | -2.6 | -2.0 | - 3.2 | - 5.3 | -12.1 | -12.5 | -15.4 | -14.1 | -9.7 | - 3.2 | - 1.9 | - 1.5 |

## Treatment Options

Thus, measures for lake remediation should start in cooperation with waster water treatment plants serving a growing population around the lake with the aim to diminish that annual load, since elevated total Phosphorus levels – bioavailable as Orthophosphate - enhance algal development along with low dissolved oxygen, elevated pH, and potentially cyanotoxin production by cyanobacteria (blue-green algae). Harmful algal blooms (HAB) occur mostly when nutrient conditions are favourable for cyanobacterial growth, their occurence is enhanced in eutrophic and polytrophic waters (Phosphate values >0.01 mg/L). Thus, Phosphate input from waste water treatment plants would have to be controlled as a means of considerably diminishing the source of Phosphate influx. At the same time release of Phosphate from lake sediments would have to be diminished or remediated in order to restore more natural lake conditions.

Longterm treatment options include Phosphate elimination within waste water treatment plants especially with estimates of a growing population around the lake. As a technology based effluent limitation Phosphorus concentrations should be <1 mg/L from all wastewater discharges into surface waters by 2020 according to Technology-Based Phosphorus Effluent Limits or TBPEL Rule, R317-1-3.3. (Utah State Bulletin, 2016).

In addition, Phosphate loaded lake sediments could be viewed as a ressource for an increasingly scarce element necessary to plant growth and hence agricultural application by waste water treatment plants and used accordingly. The process of hydrothermal carbonization (200°C) for up to 70% dewatering of sludge followed by acid induced pH change 9 to 2 and back is one option promising an >80% Phosphate recovery from sludge alongside hydrochar production (Heilsmann et al., 2014).

However, other studies point out, that despite the excess Phosphate overload the low light availability caused by natural turbidity of the lake is an effective growth-limiting factor impeding algal growth (Merritt and Miller, 2016). The authors also point out, that Phosphorus levels would have to be lowered to near 0.01 - 0.02 mg/l to limit algal development and maintain that this is hard to achieve given the overall lake loading of 60times the 0.01 mg/l value.

Effects of longterm treatment measures will become visible 10-20 years after the onset of improved Phosphorus elimination processes as other examples show. Similarly, a successful Phosphate elimination program has been implemented at Lake Constance, Germany, with considerable water quality improvement after 30 years of combined effort between neighbouring states around the lake shore (Fact Sheet igkb, 2013), which resulted in a Phosphate decrease from 0.08 mg/L PO4-P in 1980 to 0.01 mg/L PO4-P in 2010. Measures were directed mainly at improvement of waste water treatment performance, secondly at the agricultural sector (fertilizing regimens). Lake Constance (Bodensee) in Southern Germany with the border nations of Switzerland, Austria, and Germany is even larger in size than Lake Utah covering an area of 536 km², a length of 63 km, width of 14 km and a volume of 48 km3. However, mean depth of 90 m is much different from Lake Utah lake depth (3.2 m on average). Catchment area is 11.487 km² (mean effluent (1978-90) 381 m³/s, mean rainfall 0.45 km³/a, mean evaporation 0.29 km³/a) and a 1.6\*106 people live around the lake. 223 Waste Water Treatment Plants > 50 p.e. (population equivalent) serve the public.

Shortterm options could include impediment of release of Phosphorus from lake bottom via sediment cover. With the distribution of precipitants, such as calcite, zeolites, aluminum and silicon oxides above the sediment, release can be diminished. Another option is the addition of mineral substances (such as sand or loam) as purely physical barriers or introduction of carrier systems (clay or PU foam) into the body of water. Planting reeds in the shore area as phosphorous sinks can have additional beneficial effects, as the higher plants compete with the algae.

For monitoring HABs, HAB forecast and information to the public more data are needed to implement a reliable model of HAB Prediction, such as algal growth parameters for different strata within the lake (0, 1, 2, 3 m). Such parameters include water temperature (°C), turbidity (NTU), conductivity (µS/cm), oxygen saturation (%) and pH as general parameters as well as optional Chlorophyll a (RFU, µg/L) and BGA Phycocyanin (RFU, µg/L). In addition, measurements of Phosphate at lake bottom and surface will be needed as an additional input to feed a simple general prediction model of HAB after Gotthold et al. (Gotthold et al, 2016; von Orgies-Rutenberg et al., 2017).

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