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Algae in the Colorado River Basin

1. INTRODUCTION

Algae is a term used to describe a wide range of primary producers that do not have highly differentiated cells. Algae serves as indicator species of ecosystem function. Changes in algal productivity can be used to measure areas of environmental stress, where anthropogenic forces cause lake and river ecosystems to deviate from their normal range of variation (Denicola, and Kelly, 2013; Vadeboncoeur et al., 2008). Algae is used as an indicator because it is easily visible from the shoreline, reacts rapidly to changing conditions and plays a critical role in many freshwater processes including nutrient cycling, energy flow, and food web interactions (Denicola and Kelly, 2013; Vadeboncoeur and Steinman, 2002). In fact, because they are so rich in fats, algae are considered to be the base of the food web in freshwater river and lake systems, including the Colorado River, USA (Hecky et al., 1995; Umek et al., 2010; Yoshii, 1999). As a result of algae's significance to the interpretation of freshwater-ecosystem health, it is important to monitor and understand their composition and abundance.

The main types of algae in the Colorado River Basin include Cyanobacteria (blue-green algae), Cholorphyta (green algae), and Bacillariophyceae (diatoms). Cyanobacteria are bacteria with a simple prokaryotic structure that can photosynthesize. Some Cyanobacteria can fix nitrogen, enabling them to use nitrogen sources that non-fixers cannot. Cholorphyta is an extremely diverse group of algae that are often flagellated. Diatoms are algae with silica cell walls. Each of these types of algae have phytoplanktonic forms that float freely in the water column and periphytic forms that attach to substrate (Wetzel, 2001). Algae biomass and speciation at a particular location is dependent on a range of physical, chemical, and biological variables including light, temperature, nutrients, grazing, fluid movent, and shear stress (Cattaneo, 1990; Hagerthey and Kerfoot, 2005; Kilroy and Bothwell, 2014).

2. ALGAE IN THE COLORADO RIVER AND ITS TRIBUTARIES

The first dam on the Colorado River, Laguna Diversion Dam, was completed in 1905. Unsurprisingly, no algae survey of the Colorado River was done before or at this time (Blinn and Cole, 1990). Instead, 12 dams were built on the Colorado before algae resources were surveyed. The first algae study was published in 1959 and focused on Glen Canyon before the Glen Canyon Dam was built (Blinn and Cole, 1990).

2.1 Before Glen Canyon Dam

Before the Colorado River was impounded, phycology was in its infancy resulting in incomplete and problematic data from this time. Even today, new algae taxa are routinely discovered and old taxa are regularly reclassified. Therefore, it is not surprising that the information on algae before the Colorado River was dammed is limited. In these cases, knowledge of environmental conditions can bolster phycological data and help assess which algae likely thrived during these times.

The conditions of the river affect what algae are best suited to live in it. Light, substrate type, temperature, and water chemistry all play a role in determining what algae is able and competitive in specific environments. When considering algae, it is important to also understand the physical and chemical environment that control them (Wetzel, 2001).

River Conditions

Pre-dam, Colorado River algae were present despite extreme changes in conditions. For example, a 1959 report described that conditions varied seasonally (Woodbury et al., 1959). The main river channel had high clarity in the summer's low flows (113 $m^3 s^{-1}$) (Woodbury et al., 1959). In contrast, winter torrents brought high levels of suspended solids and reduced photosynthetically available radiation in the river (Woodbury et al., 1959). Receiving ample light is vital for the photosynthesizers in the high shade of a canyon stream (Duncan and Blinn, 1989).

These high flow periods also affected the substrates within the river. During this pre-dam period available substrates for algae colonization consisted of sandy material in the river's eddies and hard rock and boulders within the river's central channels (Woodbury et al., 1959).

Effects on Planktonic Algae

For planktonic algae, the low flows of summer allowed for high light penetration within the water, aiding photosynthesis. The winter high flows cause algae to mix into deeper darker water. In these situations, algae can spend more than half of their daylight hours in darkness (Wetzel, 2001). The increased turbidity reduces photosynthesis in algae far from the surface and reduces algal populations (Wetzel, 2001). These conditions would have favored the resilient diatoms in winter and green algae in summer. While planktonic cyanobacteria can thrive in eddies they tend not to thrive in the high flow areas of large rivers (Wetzel, 2001). We know that these conditions resulted in algal cell densities that ranged from 400–1600 cells ml^{-1} (Williams and Scott, 1962).

In 1959, Woodbury and his team collected algae samples from the side canyons of Glen Canyon. Unfortunately, only 26 samples total were collected resulting in little more than a list of the most common taxonomies. From this effort, 52 species were found of which 40 were successfully identified (Woodbury et al., 1959). Chlorococcales (a green algae) and diatoms were the most frequently observed planktonic algae. Phytoplankton density was higher in stagnating pools and in tributaries than in the main channels (Woodbury et al., 1959).

Effects on Periphytic Algae

For periphyton, the low flows of summer can lead to increased biomass. Low flows allow for increased light penetration, allowing deeper substrates to become habitat open to colonization. Importantly, the constant flows of the Colorado provide new nutrients to growing algae cells. However, high winter flows present a challenge to periphytic algae. The fast moving Colorado water carried sediment that likely buried algae away from the light or dislodge it from its substrate (Wetzel, 2001).

In terms of taxonomy, a 1959 study found that the most common filamentous green algae were *Spirogyra*, *Zygnema*, and *Cladophora*. Cyanobacteria were uncommon. Unfortunately, many of the Glen Canyon periphyton samples were not successfully identified (Woodbury et al., 1959).

2.2 After Dams

In 1963, the completion Glen Canyon Dam further regulated the river's flow (Blinn and Cole, 1990). As compared to the pre-dam conditions, much more algae research has been conducted since the river's impoundment (Blinn and Cole, 1990).

River Conditions

After the Grand Canyon's dams were erected, the stretch of the river below the dams changed. After dams, the river's sediment load was reduced by 350 percent (Dolan et al., 1974; Stanford and Ward, 1986). This increased light availability for algae and changed the substrate as less and less sand flowed from the river's source. Further, dam regulation of river flows changed the river's natural flow regime affecting the amount and timing of discharge.

Effects on Planktonic Algae

Crayton and Sommerfeld documented a snapshot of planktonic algae in tributaries of the Colorado River. As is typical with dammed rivers, cell densities were reduced from 400–1600 cells ml^{-1} before impoundment to 0.25 – 1 cell ml^{-1} after impoundment (Crayton and Sommerfeld, 1978). This is likely because damming the Colorado reduced the variability of habitat within the river and reduced the ecological niches that phytoplankton once filled. In sampling the river water for algae, 127 species of phytoplankton were found though many were periphytic algae that had been detached from their substrate by high flows. (Crayton and Sommerfeld, 1978,1981). Nearly 58% of the phytoplankton was made up of diatoms (Crayton and Sommerfeld, 1978, 1981). Many of the species found in the reservoirs were also the most common in the rivers suggesting that the river algae may have originated in the lakes (Stewart and Blinn, 1976; Czarnecki and Blinn, 1977).

Effects on Periphytic Algae

Duncan, studying a tributary of the Colorado River, showed that the algae in the basin are dependent on river conditions that change seasonally. Diatom densities were correlated with light, water temperature, and stream discharge (Duncan and Blinn 1989). In low flow times (current velocity ≤ 25 cm sec^{-1}), was negatively correlated with diatom density. Further, each group of algae had a specific environmental niche. The highest diatom cell densities were found at mean river bed light levels of < 400 $\mu E\ m^{-2}\ s^{-1}$ and water temperatures greater than 16ºC. Cyanobacteria was most abundant at mean river bed light levels of 900-1200 $\mu E\ m^{-2}\ s^{-1}$ and between temperatures of 16-20°C. Green algae were found at mean river bed light levels of >400 $\mu E\ m^{-2}\ s^{-1}$ and between temperatures of 6-16°C.

Surprisingly, most algae density was not correlated to chemistry levels in the river. Dolan's team found that there was no correlation between algae abundance and NO_3-N, O-PO_4, SiO_2, or pH. One exception to this finding occurred when extensive leaf drop led to a sudden increase in NO_3-N and rapid growth of *Nostoc pruniforme* (Duncan and Blinn 1989).

Effects of the 1996 Test Floods on Algae

In 1996, a flood level flow was released from Glen Canyon Dam in order to increase the variability of flow within the Grand Canyon and reestablish sand bars. Shannon et al. monitored four locations for periphytic algal biomass before, during, and after the test flows (Shannon et al., 2001). They learned that the test flows affected algae differently in different locations. The biomass of algae at the site 0.8 R km below the dam, Lees Ferry, was not significantly changed (Figure 1). This site was above the Paria River inflow and therefore did not receive the scour produced by additional sand input. However, at the three sites below the Paria River inflow (3.1 Rkm, 109.6 Rkm, and 294.2 Rkm below the dam), algae levels were significantly reduced. The algae at the sites were scoured and sloughed off their substrates (Shannon et al., 2001).

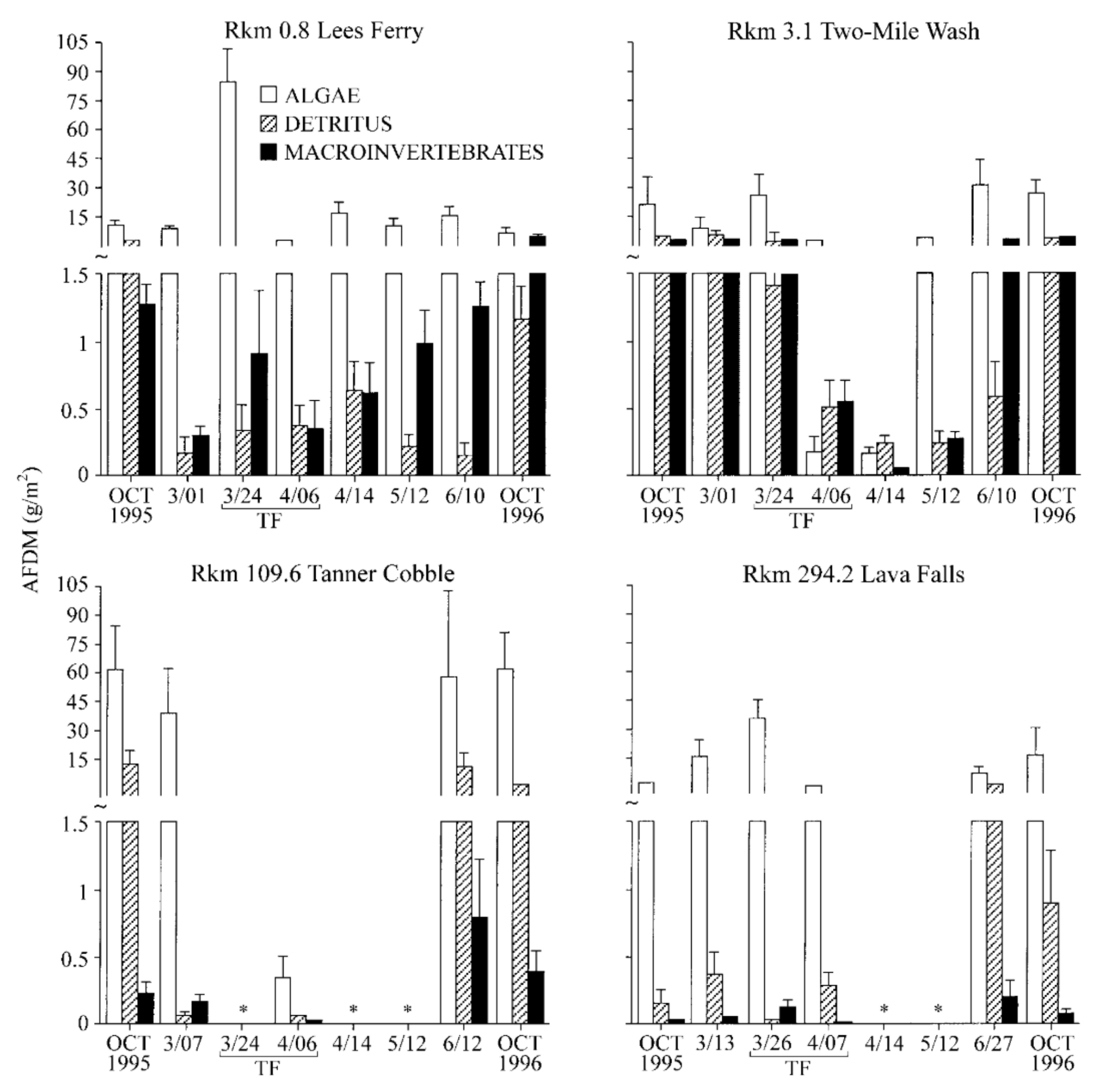

Figure 1. Average ash-free dry mass (g/m^2 +1 SE) of periphytic algae, detritus, and macroinvertebrates before, during, and after the Glen Canyon Dam test flood (TF) (Figure from Shannon et al., 2001).

In addition to the importance of location, the sudden change to the flow regime affected each species of algae biomass differently. For example, species that attached to the fine sand and sediments were likely to be disturbed as their substrate was taken away in the fast current or buried (Shannon et al., 2001). In contrast, species like *Cladophora glomerta* that attach to stable large substrates like boulders were more likely to be unscathed in the high flows (Shannon et al., 2001). These sediment size driven effects were observed through instability of the taxonomic makeup for up to eight months past the end of the test flood (Shannon et al., 2001). Algae on the more stable substrates grew back within one month at Lees Ferry and within two months at the scoured sites downstream (Shannon et al., 2001).

3. ALGAE IN DAMMED IMPOUNDMENTS IN THE COLORADO RIVER BASIN

While algae has been viewed as a vital resource in the Colorado River Basin's rivers, it has become somewhat of a pest to control in the reservoirs. Cyanobacteria in particular are well adapted to thrive under anthropogenic changes such as eutrophication, water withdrawal systems, and increasing temperatures (Paerl, 2013). Human influences are contributing to the formation of large blooms that are harmful to the environment and human health (Paerl, 2013). As a bloom dies off, it decomposes, depleting oxygen levels and releasing harmful cyanotoxins (Paerl, 2013). These toxins can affect the human liver and be problematic or even fatal for humans, livestock, and other biota upon contact or ingestion (Tietjen, 2015). These harmful algal blooms (HABs) have been documented behind Flaming Gorge, Hoover, Davis, and Parker dams (Tietjen, 2015).

Lake Mead, held back by the Hoover Dam, NV, USA, will be analyzed as a case study of harmful algal blooms. Algae in Lake Mead have been well studied relative to other Colorado River Basin dams because Lake Mead is the largest reservoir in the United States by volume and provides water to much of the Western United States (Holdren and Turner, 2010). Beaver et al. monitored planktonic algae at 17 sites in Lake Mead showing that algae biovolume in Lake Mead is relatively stable between years and that it exhibits a clear annual cycle (Beaver et al., 2018). In spring and summer, when water temperatures were between 18°C and 30°C, phytoplankton biomass was highest. However, when algae samples were collected and analyzed in more depth by Labounty, it was evident that each type of algae carried its own seasonal niche (Figure 2) (Labounty et al., 2005). Green algae peaked in May, Diatoms peaked in June, Golden brown algae peaked in July, dinoflagellates peaked in August, and cyanobacteria peaked between October and November (Labounty et al., 2005). During some times of the year, algal biodiversity in Lake Mead is lower than in many other South Western reservoirs (Labounty et al., 2005). This is because of the competition between small green algae and cyanobacteria that prevent these taxa from coexisting (Labounty et al., 2005). The Las Vegas Bay arm of Lake Mead has higher average algal biomass than the other arms because of heavy human impact (Labounty et al., 2005, Beaver et al., 2018).

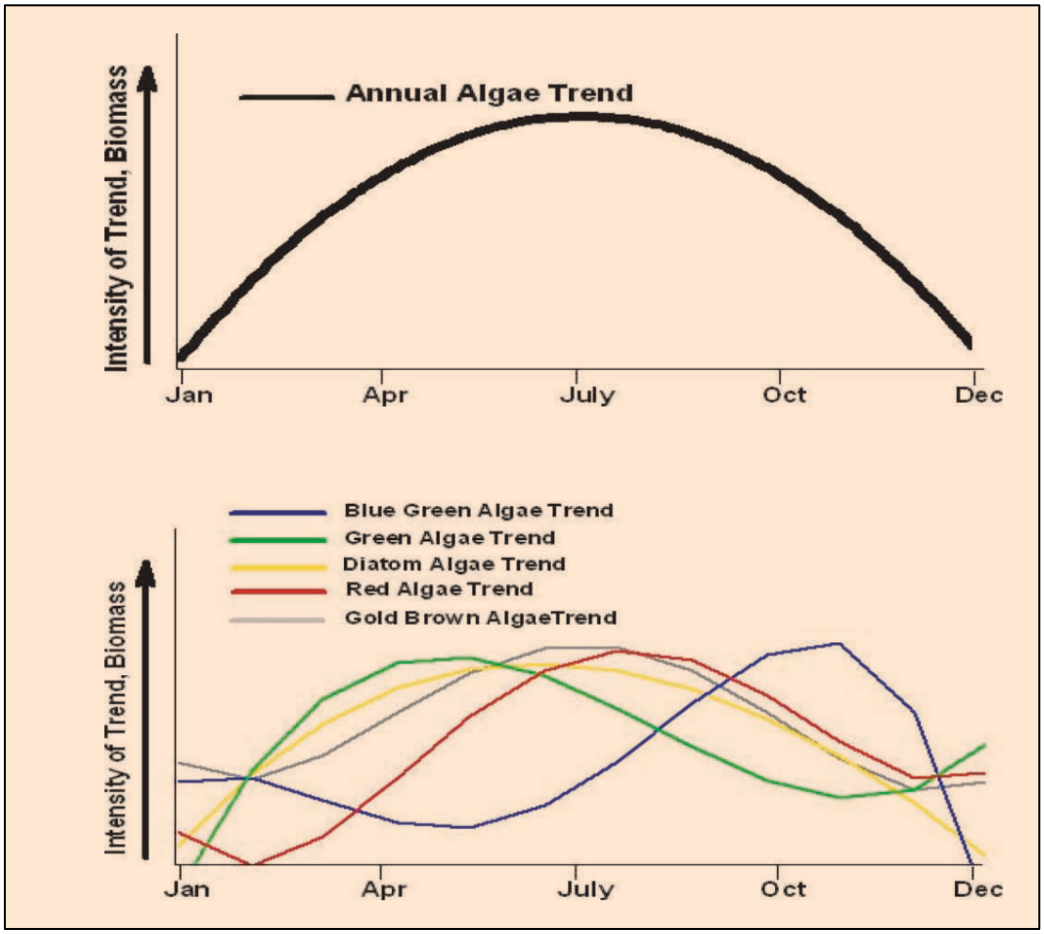

Figure 2. Smoothed seasonal trends of total phytoplankton biomass (top) and main algal groups (bottom) from 2000-2004 (Figure from Labounty et al., 2005).

Lake Mead and its algae are connected to Las Vegas because the lake provides the city with both drinking water and a site for effluent discharge. Since 1956, Las Vegas has discharged its water treatment effluent into Las Vegas Wash, which runs into the Las Vegas Bay arm of Lake Mead (Figure 3). In 1971, the first algal bloom in Las Vegas Bay led to an EPA enforcement action. That same year, Las Vegas began pumping Lake Mead water as a drinking water source. In 1973, the first treatment plant to remove phosphorous from waste discharge was completed. Yet, in 1979 and 1986 there were two more algal blooms in Las Vegas Bay. In 1995, the City of Henderson began discharging their treated wastewater into Las Vegas Bay as well (City of Las Vegas et al., 2014).

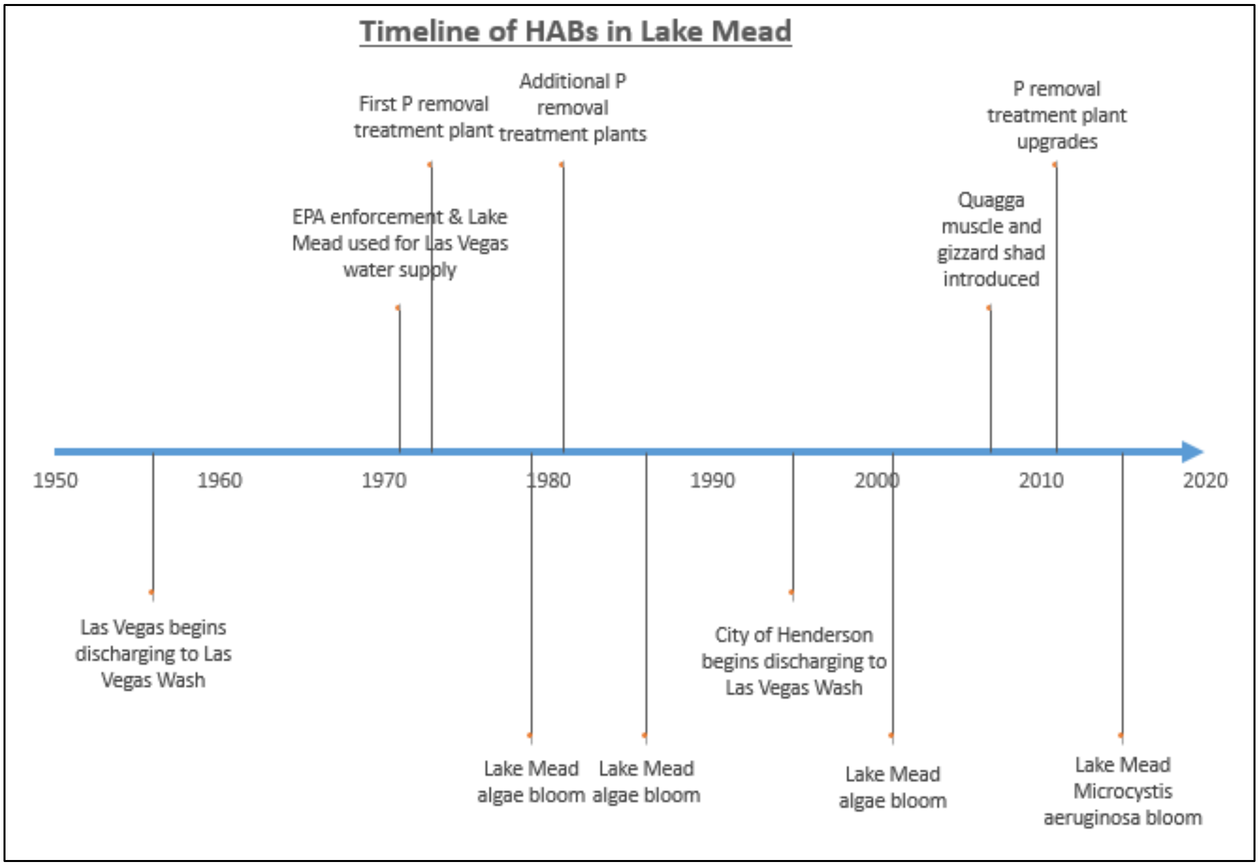

Figure 3. Timeline of events related to harmful algal blooms in Lake Mead (City of Las Vegas et al., 2014).

There were no algae blooms for 15 years (1986-2001); however, this trend was again broken in 2001 (City of Las Vegas et al., 2014) when a major algal bloom took place (Figure 4) that was attributed to a combination of human and natural factors (Labounty et al., 2005). 2001 was the beginning of a drought, which meant that there was less water coming into the lake. Meanwhile, Las Vegas was growing and emitting high levels of phosphorous into the lake in the form of its wastewater treatment effluent (Holdren andTurner, 2010). Finally, it was a hot year with lake surface temperatures reaching higher than average levels. The combination of these events led to the 2001 algal bloom (Beaver et al, 2018).

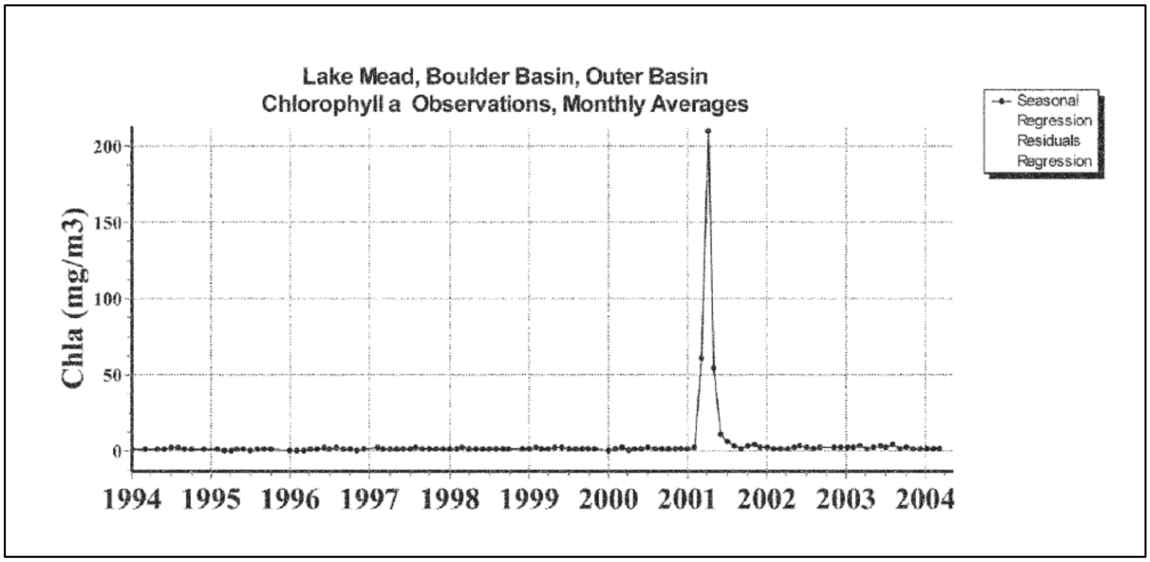

Figure 4. Chlorophyll-a levels in Lake Mead's Boulder Basin from 1994-2004 (Figure from Labounty et al., 2005)

Around 2007, two invasive species that can affect phytoplankton levels were discovered in Lake Mead: the quagga muscle (*Dreissena bugensis*) and the gizzard shad (*Dorosoma cepedianum*). Both of these invasive species are known to feed on zooplankton, which can reduce phytoplankton levels (Wong et al., 2010). However, zooplankton levels have not declined since the introduction of these species (Beaver et al., 2018). Therefore, when Turkett looked at algae levels in Lake Mead before and after the establishment of quagga muscles, he found that there was no significant difference in the Cyanobacteria levels between these two time periods (Turkett, 2016). However, as these invasives continue to spread and affect the ecosystem more monitoring is required (Turkett, 2016).

In 2011, Las Vegas completed a plan to reduce the phosphorous loads emitted from its wastewater effluent. They added a secondary treatment process to remove phosphorous and restored wetlands to act as a natural filter for their runoff before it reached Lake Mead (City of Las Vegas et al., 2014). Despite their efforts, in 2015 many factors led to another major bloom event (Figure 4).

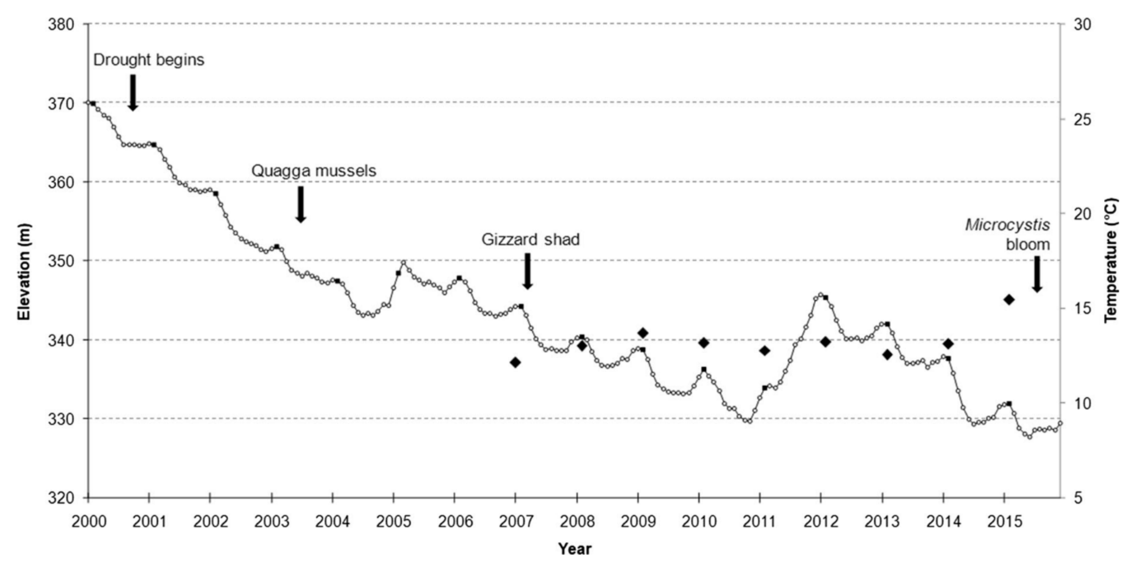

Figure 5. Lake Mead's monthly mean surface elevation from 2000 to 2015. Diamonds show the mean Las Vegas Bay surface water temperature in winter between 2007 and 2015. Arrows show events that affect algal populations (Figure from Beaver et al., 2018).

The 2015 bloom was brought about by the drought conditions. Having been in a drought since 2001, in 2015 Lake Mead had very low water levels. Additionally, warm temperatures led to little snowpack in 2015 and a longer than usual warm and stable stratification period. These perfect conditions for Cyanobacteria produced the first widespread *Microcystis aeruginosa* bloom in Lake Mead (Beaver et al, 2018). This outbreak was particularly troublesome because Microcystis produces a cyanotoxin harmful to biota within the lake and humans exposed to it.

4. THE FUTURE OF COLORADO BASIN ALGAE

It is clear that surface water quality will change in the future due to climate change (Whitehead et al., 2009). How climate change will affect water bodies is dependent on many factors and specific to influences on that water body. In general, changes in the hydrologic regime will affect sediment and nutrient loads (Whitehead et al., 2009). Increased temperatures in water bodies will affect mixing regimes and the basic kinetic speeds of chemical reactions internal to algae (Whitehead et al., 2009). The future of algae in the Colorado River brings many uncertainties.

4.1 The Future of Algae in the Colorado River

With a changing climate, river algae assemblages will change as well. In general, climate change will lead to more eutrophic, or nutrient rich, river environments (Schneider, 2015). More nutrients will enable greater algae growth. In the Colorado Basin, undammed headwater streams will be most heavily affected by altered hydrology and sediment loads (Schneider, 2015). These changes will affect light availability and scour on periphytic river algae. However, downstream, much will be based on dam operation. The stream sections below dam outlets will be most affected by temperature (Schneider, 2015). High temperatures tend to lead to higher periphytic algae biomass (Schneider, 2015). Overall, it is likely that climate change will increase the biomass of periphytic algae in the Colorado River and its tributaries.

Algae in the Colorado River are an important trophic base for the food web, but with climate change that may no longer be the case. Currently, algae provides highly nutrient rich food for benthic macroinvertebrates and fish (Guo, 2016). However, with changes to nutrient inputs algal fatty acid levels change, making it less nutritious. This may make algae a less nutritious food source with climate change (Guo, 2016).

4.2 The Future of Algae in Colorado River Reservoirs

In reservoirs, algal blooms are likely to increase in the future (Murdoch et al., 2000). Climate change in the Colorado River Basin is likely to bring more drought and hotter temperatures. Both of these conditions will reduce in and outflow of Colorado River water to reservoirs and lead to longer residence times of nutrient pollution within lakes (Murdoch et al., 2000). In addition to increasing nutrients, hotter temperatures and lower water levels due to drought are likely to lead to increased stable stratification in reservoirs that can lead to algal blooms (Jacoby et al., 2000; Cao et al., 2006). This is especially troublesome given the recent trend toward toxic Cyanobacteria blooms (Tietjen, 2015).

These climatic trends may be exacerbated by further anthropogenic influences in reservoirs. If invasive species such as gizzard shad and quagga muscles continue to expand in range, that could increase the likelihood of algal blooms in Colorado Basin reservoirs (Beaver et al., 2018). For Lake Mead specifically, as Las Vegas population grows, so does its wastewater inflow to the Colorado River system (Beaver et al., 2018). This discharge will increase the nutrient input into Lake Mead specifically and increase algal growth.

Further, algae act in a nonlinear fashion to disturbances (Scheffer et al., 2001). Lakes tend to show resilience for years until a vital threshold is reached and effects are shown (Scheffer et al., 2001). The Colorado Basin lakes have been undergoing climatic, biological, and hydrologic stressors for decades. The 2015 toxic HAB at Lake Mead may have been a warning sign for the rest of the system: resiliency can only last so long.

4.3 Recommendations

With a changing climate, understanding the base of the aquatic food web is more important than ever. Yet, algae are still understudied. More research needs to be done to understand the drivers and roles of algae in the Colorado River Basin (Blinn and Cole, 1990). Importantly, more research must be conducted on how changes in dam output are affecting algal biomass and assemblages.

Further, with so many stakeholders relying on Colorado River water, we cannot afford to pollute our water with nutrients, invasive species, and algal toxins. Inputs to the Colorado River need to be carefully monitored and regulated for water quality. While removing many of the current invasive species may be difficult, the addition of further invasive species to the Colorado should be avoided through best management practices. Through these efforts, it may be possible to avoid some of the algal worst-case scenarios in the Colorado River Basin.

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