Tahoe Keys Lagoons:

Contributing Sources of Nutrient Pollution

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Glossary:

Achenes:	One-seeded fruit, small and dry, that does not open to release the seed
Allochthonous:	Sediment or rock that originated from a distance from its current position
Autochthonous:	Sediment or rock that is indigenous; formed in its current position
Baroclinic:	Movement of stratified fluid as a factor of pressure and density gradients
Cultural Eutrophication:	Increase of plant nutrients that leads to the aging of an aquatic ecosystem; made faster by nutrient input from sewers, detergents, and fertilizers
Denitrification:	Conversion of nitrate (NO_3) into nitrogen gas (N_2)
Evapotranspiration:	The sum of evaporation from land surfaces combined with transpiration; accounts for the movement of water from soil, canopies, and waterbodies to the air
Graben:	A block of land displaced downwards creating a valley with a distinct deep slope that is bordered by faults parallel to one another
Inflorescences:	An arranged cluster of flowers
In situ:	Found in place of origin
Lacunar system:	The smallest functional structural unit of an organism with cytoplasm, nuclei, and organelles surrounded by semipermeable membrane
Photoperiod:	Response to duration and length of day (especially amount of light); mechanism to measure seasonal time
Meristematic tissue:	Region of embryonic tissue; undifferentiated; primarily for the formation of new cells
Mesocosm:	A controlled outdoor experimental system meant to examine the natural environment.
Rhizome:	An underground stem, typically horizontal
Senescence:	Age induced deterioration of plant tissues
Sessile:	Attached directly by the base of the leaf; sessile leaves lack a petiole and a sessile flower lacks a pedicel
Stomata:	Pores along the epidermis of a leaf or stem that allow the movement of gases and water in and out of intercellular (function of evapotranspiration and turgor pressure)
Turgor Pressure:	The pressure within a cell due to the movement of water (important for cellular growth)
Turions:	Vegetative bundle, akin to an axillary bud containing meristematic tissue that can form anywhere on the macrophyte and be dispersed
Whorl:	An arrangement where 3 or more leaves or floral parts arise from a node in a circular pattern

Acronyms:

BBMWD:	Big Bear Municipal Water District
BMP:	Best Management Practices
CARB:	California Air Resource Board
Dpm:	Disintegrations per minute
FSP:	Fine Sediment Particles
FTW:	Floating Treatment Wetland
GHG:	Greenhouse Gas
IMP:	Integrated Management Plan
Lahontan Board:	Lahontan Regional Water Quality Control Board
NASA:	National Aeronautics and Space Administration
NPDES:	National Pollutant Discharge Elimination System
NPS:	Non-point source
PS:	Point source
TERC:	Tahoe Environmental Research Center
TKPOA:	Tahoe Keys Property Owners Association
TMDL:	Total Maximum Daily Load
TN:	Total Nitrogen
TP:	Total Phosphorus
TRPA:	Tahoe Regional Planning Agency
USDA:	United States Department of Agriculture
US EPA:	United States Environmental Protection Agency
USGS:	United States Geological Survey
WDR:	Waste Discharge Requirements

Section 1: Introduction

Figure 1. Map of the Tahoe Keys Lagoons and Lake Tallac

1.1 Background

Lake Tahoe is an oligotrophic lake known for its exceptional clarity that has led to its being listed as an Outstanding National Resource Water by the United States Environmental Protection Agency (USEPA) and the State of California. Urbanization and subsequent development of the area has altered the ecosystem in the Tahoe Basin, starting a gradual shift towards cultural eutrophication. The clarity and striking blue color often associated with Lake Tahoe has been altered slightly by the doubling of productivity and concomitant decline in Secchi disk transparency (Coats 2004). Currently, the spread of aquatic weeds in the Tahoe Keys, located at the southern point of Lake Tahoe, is a critical concern for the Tahoe Keys Property Owners Association (TKPOA), Tahoe Regional Planning Agency (TRPA), and the Lahontan Regional Water Quality Control Board (Lahontan Board).

The Tahoe Keys are comprised of three water features including Lake Tallac, the Main Lagoon, and the Marina Lagoon; the latter two lagoons have direct connections to Lake Tahoe via the West and East Channels respectively. The Tahoe Keys encompass 372 surface acres of waterways with 1,529 homes, as well as, townhouses, marinas, and a commercial center. The lagoons are relatively shallow with a maximum water depth of 30 feet, which often leads to warmer temperatures than Lake Tahoe. Furthermore, according to Sierra Ecosystem Associate's (SEA) Draft Integrated Weed Management Plan for the TKPOA, the shallowness of the lagoons combined with wave action and aquatic plant activity result in the water often being more turbid (IWMP 2015).

Today, there is an overabundance of submerged aquatic macrophytes, an organism that is part of the macroscopic plant life of an aquatic ecosystem, growing in the lagoons of the Tahoe Keys. While aquatic plants are generally beneficial to aquatic ecosystems, providing habitats and nutrients for benthic invertebrates, fish, and waterfowl, unchecked proliferation can be harmful.

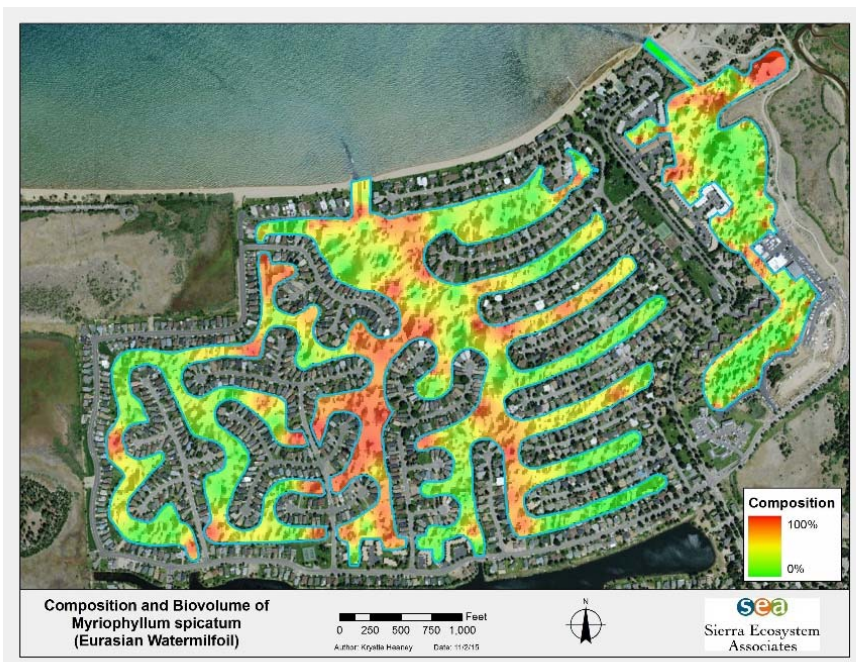


Figure 2. Composition of Eurasian watermilfoil in the Tahoe Keys Lagoons

These aquatic plants can entrap swimmer's legs, wrap around boat propellers, and reduce water quality. According to the Tahoe Keys 2015 Aquatic Macrophyte Survey Report prepared by SEA (TKPOA 2015), in 2015 the volume of aquatic weeds harvested was 18,600 cubic yards. Instances of aquatic invasive plants have increased as well. The Main and Marina lagoons were found to have high occurrences of *Ceratophyllum demersum* (coontail) and *Myriophyllum spicatum* (Eurasian watermilfoil) (TKPOA 2015), specifically (see Figure 2 above).

Nitrogen and phosphorus are the key nutrients for the regulation of macrophyte productivity (Boyd 1971). Organic and inorganic forms of nitrogen are readily found in the Tahoe Keys Lagoons. These forms include: amino acids, urea, uric acid, nitrate, nitrite, ammonium, dissolved nitrogen gas and nitrous oxide. The processes of ammonification, nitrification and denitrification, driven by microbial activities and the presence of oxygen, are responsible for the transformation between the various forms of nitrogen in the water column. The organic nitrogen amino acids are transformed to ammonia through ammonification. Ammonia is subsequently converted to ammonium in acidic solutions. The process of nitrification converts ammonium to nitrate while denitrification transforms nitrate into nitrogen gas (Saeed et al. 2012). There is a higher concentration of ammonium than nitrate in the sediment than in the water column. Therefore, based on the importance of nutrient uptake from sediment by rooted aquatic macrophytes, most nitrogen absorbed by the plant is ammonium (Smith et al. 1990). Phosphorus forms in freshwater include soluble reactive (ortho) phosphorus and inorganic phosphorus. Most phosphorus in nature is found as phosphate, including orthophosphorus, and has a high affinity to bind with cations that possess positive charges (especially iron). This includes binding to sediment or clay particles, called sorbed phosphorus, which is often the case in aquatic ecosystems.

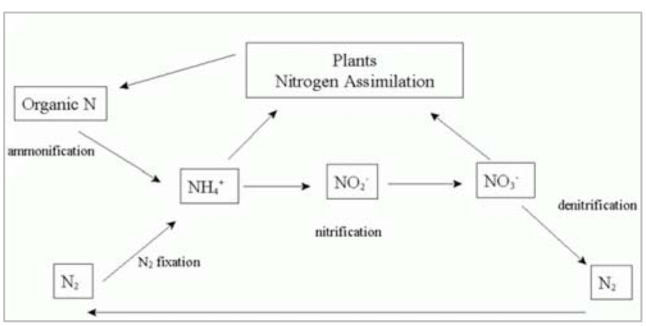


Figure 3. Nitrogen assimilation by plants. Image property of Weber State University 2011

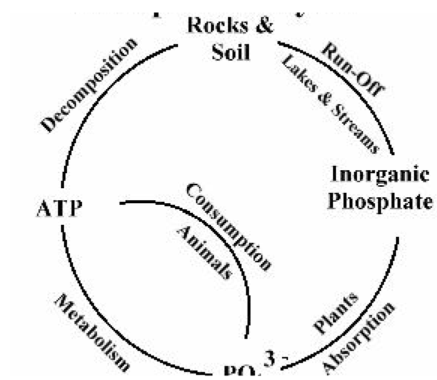


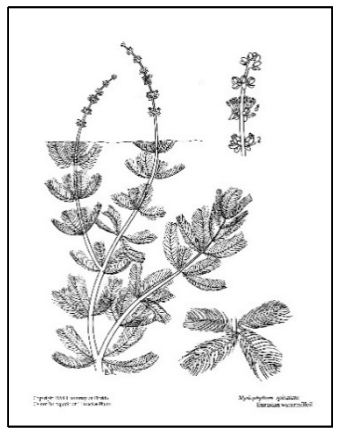
Figure 4. Phosphorus cycle. Image property of Seven Hills Lake

Urbanization of the Lake Tahoe Basin has led to increased levels of pollution and urban runoff, causing high nutrient loading in the streams and lakes. The Implementation of Best Management Practices (BMPs) to reduce the external input of phosphorus, a crucial determiner of water quality according to Søndergaard et al. (2003), and other nutrients have aided Lake Tahoe's shift towards phosphorus limited productivity. However, even with the reduction of external phosphorus loading, resuspension and the release of phosphorus from sediment can lead to persistent concentrations in the water column. Macrophytes in littoral zones of lakes act as indicators of changes to nutrient conditions (Melzer 1999) and the spread of invasive aquatic weeds in the Keys is indicative of high nutrient pollution, especially nitrogen and phosphorus. Understanding the nutrient cycling undergone by aquatic plants and identifying components that act as primary nutrient sources are important for the development of long-term management strategies. As such, this paper will compare nutrient sources for the Tahoe Keys and determine which component(s) have the largest impact on the persistence and proliferation of the underwater weeds *Myriophyllum spicatum* (Eurasian watermilfoil), *Potamogeton crispus* (curlyleaf pondweed), and the native *Ceratophyllum demersum* (coontail).

1.2 Aquatic Macrophytes in the Tahoe Keys Lagoons

Eurasian watermilfoil:

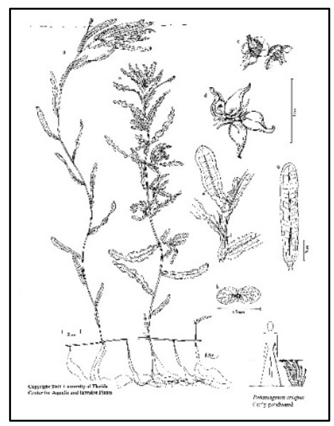
Eurasian watermilfoil is a rooted perennial plant native to Asia, Europe and parts of Northern Africa. It was introduced to the United States during the 1800's and was first identified in the Lake Tahoe Basin, along the California-Nevada border, in the early 1980's (Chandra 2015). It is now the most prevalent aquatic invasive species (AIS) in North America.



Eurasian watermilfoil is typically found in shallow water, between depths of 3 to 13 feet, but has been documented at 30 feet in water with high clarity (Smith et al. 1990). The formation of rhizomes with multiple, fibrous branching roots allows Eurasian watermilfoil to maintain its shallow rooting depth and permit them to overwinter without becoming dormant. The feather-like leaves, arising from long stems, are pinnately compound with whorls of four; each whorl producing innumerable hair-like leaflets (DiTomaso 2003). Growth towards the surface of the water allows for the development of milfoil canopies that can block light from reaching native species of macrophytes near the base of the water column, which can alter pH and the concentration of dissolved oxygen (Søndergaard et al. 2003).

Eurasian watermilfoil can reproduce sexually and vegetatively. Sexual reproduction includes the formation of floral structures above the surface of the water and later, the development and dispersal of seeds. Each plant develops red-brown colored terminal spikes that each produce four seeds, called achenes (DiTomaso 2003). Each seed has the ability to germinate in water warmer than 10°C and can remain dormant for up to seven years in dry conditions (Smith et al. 1990). Wind dispersal of seeds may be responsible for the quick spread of milfoil across North America. Vegetative reproduction on the other hand is the main mode of reproduction and the reason it is extremely difficult to manage as an AIS. New plants are generated from fragments of the stem, created by mechanical harvesting, waterfowl feeding, and wave action (Smith 1990). Such fragments can travel between bodies of water in boat ballasts, and attach to hulls and outboard motors. Furthermore, residual rhizomes and the release of axillary buds also produce new plants (DiTomaso 2003).

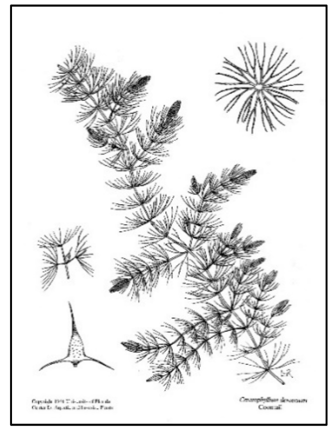
<ins>Curlyleaf pondweed:</ins>



This macrophyte is known as a swift growing rooted perennial that can survive and grow in ice covered waters during winter months (Minnesota Department of Natural Resources 2015) making it an aggressive competitor against both native and non-native species. Curlyleaf pondweed has a long slender stem that alternately produces sessile oblong leaves between one and three inches long that possess a wavy-edged margin. It is typically found in shallower waters (3 to 6 ft) but has been seen as deep as twenty feet depending on water clarity and ability to absorb available light. Dense mats composed of multiple pondweed plants can form near the surface of the water and interfere with boat navigation and entangle swimmers. Mats also impede light absorption and photosynthesis by native vegetation affecting the exchange of oxygen in the water column and decreasing the population of fish and invertebrates. These conditions are also a favorite for producing mosquito habitats (IWMP 2015).

Comparable to *M. spicatum*, curlyleaf pondweed has two main modes of reproduction. Floral inflorescences develop above the surface of the water between May and mid-summer. Achenes with 1-3 keels are produced by these inflorescences, which are later dispersed via wind or waterfowl (DiTomaso 2003). Vegetative reproduction can occur through residual rhizomes and dispersal of turions. A turion is a vegetative bundle, akin to an axillary bud containing meristematic tissue that can form anywhere on the macrophyte and be dispersed (Minnesota Department of Natural Resources 2015). Once released, the turion will begin to sprout, forming the next generation of pondweed.

<u>Native coontail:</u>



There are also populations of native aquatic species in Lake Tahoe that continue to play a large role. *Ceratophyllum demersum* (the native coontail) is one such aquatic plant. It is a free-floating, completely submerged macrophyte that lacks true roots and produces dark green, forked leaves arranged in whorls, becoming increasingly dense towards the tip of the stem. The margins of the leaves appear tooth-like, and are typically hard and crunchy (Washington State Department of Ecology 2016) due to deposition of calcium on the epidermis. Coontail can modify its stems to become anchored to other aquatic plants and can form dense mats, comparable to curlyleaf pondweed. Overall, coontail is a hardy plant that demonstrates plasticity in its ability to grow in different aquatic ecosystems nearly worldwide. Reproduction can occur via vegetative means, turion and stem fragment dispersal (DiTomaso 2003), as well as development of small, submerged flowers and production of oval shaped fruits (Washington State Department of Ecology 2016).

<u>Common Elodea</u>

Elodea canadensis, otherwise known as common elodea or Canadian waterweed, is also found in the Tahoe Keys and typically provides habitat for fish and aquatic invertebrates and also acts as food for waterfowl. It is completely submerged, rooted to the sediment and reaches between four inches to three feet in height. Elodea is generally found in water depths less than fifteen feet (TKPOA 2015) and can dominate a water system when there are low levels of iron, and high levels of bicarbonate and phosphorus (DiTomaso 2003).

Section 2: Literature Review

As previously stated, understanding the cycling of nutrients that is undertaken by aquatic plants combined with the identification of components that act as primary nutrient sources are important for the development of long-term management strategies. In the following section, routes of nutrient uptake are discussed, as well as the natural leaching of nutrients following plant senescence followed by the concept of nutrient pumping. A wide range of studies have been conducted on the impact of excess nutrients, cultural eutrophication, and presence of aquatic macrophytes. This literature review compares some of these papers in an effort to determine not only the importance of each potential source, but the process by which each occurs, including: the cycling of nutrients, nutrients from previous marshland sediment, surface runoff, and atmospheric deposition.

2.1 Nutrient cycling, loading, and pumping

Aquatic plants differ from land plants through a variety of characteristics. Terrestrial plants possess stomata that permit the movement of gases in and out of intercellular spaces and the uptake of water by their roots. The structure of the cell wall, along with lignin, provide rigidity and allow land plants to stand upright. Aquatic macrophytes are either emergent or completely submerged and generally lack the rigidity of their land siblings allowing them to bend and not break. Below the water leaves are narrow and highly dissected, generally lacking stomata, while the leaves and stems above the surface of the water will appear similar to their terrestrial counterparts. Plants growing on land have a more extensive root system than submerged plants, aiding water and nutrient uptake. Aquatic plants, specifically submerged, have a greater cellular turgor pressure than land species as they cannot undergo transpiration and water loss through stomata (Eichhorn 2013). Most plants, whether terrestrial or aquatic, can move nutrients from sediment into their tissues via root uptake.

Aquatic plants are unique as they have the ability to uptake necessary nutrients through their roots or shoots, depending on nutrient demand and availability. Eurasian watermilfoil and curlyleaf pondweed possess rhizomes and are considered rooted aquatic plants, therefore they are more efficient at sediment uptake of nitrogen and phosphorus. Free-floating plants without roots must absorb all necessary nutrients from the water column as they have no connection to nutrient-containing sediment (Angelstein et al. 2008). Almost all phosphorus, estimated between 50-100% (Melzer 1999), and a majority of nitrogen, mostly as ammonia, are moved into macrophyte tissues via root uptake (Smith et al. 1990). Typically, the pool of available phosphorus in sediment is a hundred fold of that found in the surrounding water column (Søndergaard et al. 2003), which makes uptake via roots and the mobilization of phosphorus so important.

Chloroplasts are distributed throughout the entire epidermal layer of aquatic macrophytes, as light is more difficult to capture in submerged environments. Leaves are thin and often highly dissected with a slight cuticle. These characteristics allow for light penetration and diffusion of dissolved gases necessary for photosynthesis. Oxygen, carbon dioxide and bicarbonate diffuse into the lacunar system in leaves and stems before photosynthesis can occur. Upon cessation of photosynthesis, oxygen diffuses from the stem into the roots and is released into the sediment (Sculthorpe 1967). Terrestrial plants absorb nutrients by their roots through a combination of water potential, transpiration, and root pressure. However, uptake of nutrients by aquatic macrophyte roots is driven by exudation pressure, a combination of both metabolic processes and osmosis. The accumulation of carbohydrates, gases and ions create a concentration gradient that favors movement through the tissues of the xylem and phloem in the plant (Sculthorpe 1967).

Absorbed nutrients are translocated and stored in various locations throughout the plant. Plant shoots always have higher concentrations of nitrogen and phosphorus than roots (Walter 2000). These nutrients are used in a variety of metabolic processes and are released into the surrounding environment upon senescence and decay (Smith et al. 1990). Senescence is important for nutrient conservation and cycling in the environment. The production of proteolytic enzymes leads to the breakdown of the cellular components of the plant. Byproducts from this process, such as carbohydrates, can be mobilized and used in other tissues of the plant for further growth or can be stored in the root system (Aerts 1996); for example, in the rhizome of Eurasian watermilfoil or curlyleaf pondweed.

In general, 50% of nitrogen and phosphorus are resorbed upon leaf senescence. The nutrients not resorbed by the plant are deposited in litter, which is made available to plants upon the decomposition and subsequent mineralization of detritus (Aerts 1996). For plants with growth patterns similar to that of Eurasian watermilfoil, with increased productivity and quick biomass turnover, there is a high level of nutrient mobilization (Barko 1998). Generally, aquatic macrophytes contain higher tissue concentrations of nitrogen and phosphorus, and decompose at a faster rate than terrestrial plants (Enriquez et al. 1993). Eurasian watermilfoil, for example, has a decay constant[1] (*k*) of 0.0109 (Walter 2000) while *Pinus Sylvestrus* (Scot pine) has *k* between 0.0007 and 0.0010. The half-lives for aquatic plant detritus is between 17 to 58 days while for perennial trees and shrubs it is 2 to 3 years. As such, more nutrients can be released right above or directly into the sediment upon senescence of aquatic plants (Enriquez et al. 1993).

Deep lakes like Lake Tahoe tend to have anoxic sediment and water column stratification. Shallower waters, however, are well mixed and are mostly comprised of the photic zone creating optimum conditions for primary productivity. The sediments are oxic[2], with a high affinity to bind phosphate. Resuspension of solids, driven by wind and wave action can increase the likelihood of phosphorus release. Mobilization of phosphorus requires elevated pH and a reduced redox potential (Søndergaard et al. 2003). The discharge of photosynthetically generated oxygen gas by the roots of submerged macrophytes produces increasingly oxic conditions in the sediment, favoring bacterial activity and mineralization. Aerobic mineralization can elevate the level of available nitrogen (Karjalainen et al. 2001). However, in the presence of dense macrophyte beds and thick canopies, pH has a tendency to rise while the concentration of oxygen in the soil declines from lack of photosynthetically available light, favoring phosphate release (Søndergaard et al. 2003).

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[1] Calculated with the equation: $y = e^{-kt}$ (y is the fraction of remaining mass [dry weight] and t is time in years)

[2] Sediment with available oxygen

The release of nutrients due to senescence is one part of nutrient cycling. The pumping of nutrients, especially the leaching of phosphorus, is another part of the cycle. The leaking of nutrients from plant tissues, combined with the alteration of pH and concentration of dissolved oxygen that occurs in dense canopy environments allows aquatic plants to contribute phosphorus to the water column (Walter 2000). Common Elodea, and Eurasian watermilfoil, are both present in the Tahoe Keys and release phosphorus during their growing periods (Moore et al., 1984).

The uptake and release of phosphorus by Elodea is dependent on light availability, photosynthesis and respiratory processes. In a study using radioactively tagged phosphorus for detection and measurement (^{32}P) in mesocosms with *E. nuttalli* and *E. canadensis*, 36% of phosphorus was absorbed by the plants during the day, the rate of uptake decreasing over time, and experienced release of phosphorus during dark periods (Angelstein et al. 2008). In a second study using tracer phosphorus, it was found that Eurasian watermilfoil and Elodea release oxygen, carbon dioxide, nitrogen, phosphates, silica, and other organic compounds during photosynthesis. Between the two macrophytes, it was determined that Eurasian watermilfoil releases more phosphorus than Elodea, at a rate of 4491.4 dpm/ plant/ day. By the end of the experiment, almost 50% of the tracer phosphorus loaded into the microcosms containing Eurasian watermilfoil was leaked into the water column. Elodea leaked only 0.05% of the ^{32}P into the water column. Furthermore, levels of ammonia-nitrogen and soluble reactive phosphorus were higher in microcosms with Eurasian watermilfoil. Overall, milfoil releases phosphorus into the water column during growth and senescence regardless of photoperiod causing spikes in chlorophyll a and nutrient concentrations. From these results it appears that Eurasian watermilfoil has a more negative effect on water quality than Elodea (Walter 2000).

2.2 Nutrients from Marshland Sediment

The Lake Tahoe Basin forms the westernmost graben physiographic province that is considered to have originated 7.4 to 2.6 Ma. Lake infilling began about 1.9 million years ago when the northern end of the lake was blocked by volcanic activity (Gardner et al. 2000). The late 1840's witnessed the discovery of gold in El Dorado County, California transforming the Lake Tahoe Basin as the philosophy of Manifest Destiny reshaped the nation. The mining of gold and silver, logging of the surrounding coniferous forests, and the construction of homes, roads, and dams lead to a shift in the ecosystem, and an increase in the overall acidity and nitrate concentration in the lake (Kim et al. 2001). The Upper Truckee River is the largest watershed into Lake Tahoe and has been the most influenced by urbanization (Stubblefield et al. 2006). By 1859, numerous lumber mills were directly discharging debris in the Truckee River, a primary water source for the Tahoe Basin and active spawning habitat for native fish, causing erosion and an increase in the discharge of nutrients/pollutants into Lake Tahoe (USFWS 2003). During this time, almost 60% of the surrounding forest had been clear-cut (Raumann et al. 2008).

Figure 5. The original Truckee Marsh in 1930. Photo by Dr. Robert Orr, property of the California Tahoe Conservancy

Figure 6. Tahoe Keys and Lake Tahoe. Photo property of Pyramid Peak Properties.

Almost half of the original wetlands have been destroyed since 1949, associated with the increase in the rate of anthropogenic alterations and land development in the Tahoe Basin. The addition of dams to moderate the release of water and urbanization of land surrounding Lake Tahoe contributed to this decrease. Furthermore, this loss of wetlands may be a large contributor to the decrease in water quality and clarity seen today in Lake Tahoe. Wetlands play an important role in filtering runoff through the trapping of sediments, the uptake of nutrients by wetland flora (Raumann et al. 2008) and by acting as sites of denitrification (Carpenter et al. 1998). Phosphorus is often bound to particles of silt or clay, and can be an indicator of high sediment input from the watershed (Kim et al. 2001) and urban runoff.

The Tahoe Keys were built towards the end of the 1960's in the center of the original Truckee marsh, once the largest wetland in the Tahoe Basin. Construction of the Keys included dredging marshland, installing bulkheads and capping with fine sand to create a suitable building substrate. Overall, about 740 acres were developed in the creation of the Keys. This split the original marsh, creating the current Pope and Truckee marshes (Kim et al. 2001). The Upper

Truckee River was diverted around the Tahoe Keys, although some branches of the delta continue to drain into Lake Tallac.

It has been postulated that nutrients deposited in the sediment from the original Truckee marsh before the creation of the Tahoe Keys lagoons are one of the main sources for current prolific macrophytes. A study by Rejmánková (2005) showed that the soils of wetlands in the Tahoe Basin are rich in organic matter, containing high levels of nitrogen (3.5mg/cm^3) and phosphorus (0.46mg/cm^3), meaning that neither phosphorus nor nitrogen are limiting factors in the wetlands surrounding the Keys. Between 87-96% of the sediment in the Tahoe Keys is sand, with 1-9% silt/clay (Walter 2000). While there may be a layer of fine sand above the pre-existing sediment of the marsh that could stand between macrophytes and underlying sediments, studies have shown that roots, especially for *Potamogeton* species, can become extensive and grow deeper into sandy substrates (Denny 1972) in order to uptake necessary nutrients. Moreover, it has been determined that a majority of phosphorus used by aquatic macrophytes is derived from sediment nutrient uptake (Walter 2000).

In a study by Melzer (1999), it is stated that phosphorus uptake via roots is over 50%, illustrating the importance of sediment composition for rooted macrophytes. The presence of dense macrophyte beds and canopies preventing light from reaching the bottom of the lagoons may cause the pH to rise and the concentration of oxygen in the soil to decline, favoring phosphate release (Søndergaard et al. 2003) and an increase of soluble reactive phosphorus in the water column. Bacterial and phytoplankton activity also increase available nitrogen and phosphorus in the water column (Cottingham et al. 2015). A combination of nutrient cycling by macrophytes, bacteria, and phytoplankton with high levels of sediment nutrients remaining from the pre-existing wetlands could be a strong source for the high levels of nutrients used by the aquatic weeds in the Tahoe Keys. Moreover, if this is the case, then the prolific growth and spread of invasive aquatic macrophytes will continue as they seek to deplete the available pools of nitrogen, phosphorus and carbon found in the sediment. Future experimentation is necessary to determine the validity of this hypothesis.

2.3 Surface Runoff

Runoff with regard to nutrient loading is often categorized as originating from either a point or nonpoint source. Point sources (PS) include discharge from pipes and outfalls while nonpoint sources (NPS) include direct deposition from surface runoff, often circumventing the filtering abilities of riparian biota (Trombulak et al. 2000), and can be caused by snowmelt, stormwater, or lawn irrigation (NPS Plan 2015). Nonpoint sources are the dominant source of nitrogen and phosphorus for most rivers in the United States (Carpenter et al. 1998).

Urban runoff, especially NPS urban runoff, is important to consider with respect to the increased nutrient pollution in Lake Tahoe and the Tahoe Keys (Kim et al. 2001). In the study by Booth et al. (1997), it was determined that the clearing and soil compaction as well as the addition of roads, ditching, draining and roofs attributed with urbanization has caused an increase in the magnitude of pollutants and sediments delivered to aquatic ecosystems. Roads alter the environment in which they are placed as they are impermeable surfaces acting as a barrier, minimizing infiltration of stormwater and evapotranspiration (Morgenroth et al. 2012) while also conveying runoff to stormwater drains that feed into waterways (Barbec et al 2002). Vehicles release salts, heavy metals, ozone, organic materials (particulate matter) and other nutrients (like ammonia) into the air that can become deposited on the road surface, surrounding soil, or in water (Trombulak et al. 2000). Paved surfaces typically contain oxides of aluminum, silica, calcium, iron, titanium, and other organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), which can also be transported via runoff. Improving roads, by paving and maintenance, can reduce their FSP runoff impact (Dolislager et al. 2012). Using pervious concrete in the place of normal pavement for driveways, sidewalks, road shoulders, and parking lots allow stormwater to infiltrate the soil where pollutants can be naturally removed while reducing the amount of stormwater runoff and increasing the removal efficiencies of both FSP and total nitrogen above 80% (Duluth Streams 2005).

According to the Lake Tahoe TMDL 2015 Performance Report (NDEP 2015), stormwater runoff, from both urban and non-urban sources, contribute more than 70% of the fine sediment particles (FSP) that have a large impact on the clarity of Lake Tahoe. These FSP typically have a diameter less than 16 microns (NDEP 2015) and are bound to the vast majority of phosphorus that is loaded into the lake. Since phosphorous more readily binds to soil particles, more phosphorus is deposited via runoff than nitrogen (Karjalainen et al. 2001). Nutrients from runoff enhance microbial activity (Sahoo et al. 2010), leading to the mobilization of inorganic nitrogen and phosphorus in the water column (Coats 2004).

Furthermore, urban runoff can also originate from lawn irrigation. When the Tahoe Keys were constructed, the original Truckee Marsh was dredged and filled with decomposed granite sand, producing a homogeneous soil type (*Oxyaquic xerothents*) throughout the Keys. This soil does not have a high capacity to store water or the ability to hold sufficient concentrations of nutrients for plant growth. It is therefore important to manage the use of fertilizers and irrigation to prevent runoff into the lagoons (NPS 2016). In the 2002 study by the United States Geological Survey (USGS) in Florida, the impact of fertilizer runoff into aquatic ecosystems was studied. Runoff from lawns fertilized with either phosphorus containing fertilizer, non-phosphorus fertilizer, or unfertilized was measured for the amount of NH_3-N, NO_3-NO_3, and dissolved phosphorus present. Table 1 below depicts the collected data.

Table 1. Nutrient Concentrations from Lawn Runoff in Florida

Lawn Conditions	mg/L NH_3-N	mg/L NO_3-NO_3	mg/L dissolved phosphorus
Phosphorus containing fertilizer	2.18	0.17	0.93
Non-phosphorus containing fertilizer	3.95	0.57	0.14
Unfertilized	1.12	0.17	0.43

Runoff from lawns fertilized with phosphorus and non-phosphorus fertilizer had very little difference in nitrogen concentration. In general the concentration of NO_3-NO_3 was low for all treatments. The amount of dissolved phosphorus, important due to its immediate availability for plant growth, did see a change between the three treatments. Regular fertilizer, with phosphorus, (0.77mg/L) produced 22-45% TP in runoff while non-phosphorus fertilizer (0.33mg/L) and unfertilized lawns had similar TP concentrations (USGS 2002). The TKPOA Nonpoint Source Water Quality Management Plan suggests the use of non-phosphorus containing fertilizers (phosphorus fertilizer use was banned) and BMPs to direct runoff away from the waterways as strategies to reduce nutrient pollution from this source (NPS 2016).

The Upper Truckee River system drains the largest watershed in the Lake Tahoe Basin and was impacted by urbanization through the development of South Lake Tahoe as well as being diverted around the Tahoe Keys (Stubblefield et al. 2006). The soil of the watersheds in the Sierra Nevada is typically hydrophobic (Miller et al. 2005) and much of the surface runoff from forested areas is limited to rock outcrops and human-made compacted areas (Eagan et al. 2007), including: public facilities (campgrounds), roads, and trails. Water rushes over these areas, picks up particles and nutrients, and then deposits them in nearby surface water that will drain into Lake Tahoe. The Upper Truckee River along with Blackwood Creek and Ward Creek contribute almost 96% of FSP load to Lake Tahoe conjointly (NDEP 2015). Atmospheric deposition of nitrogen and phosphorus, in both forested areas (called nitrogen saturation) and along the surface of a water body, is responsible for over 55% of total nitrogen and phosphorus loading in Lake Tahoe (Sahoo et al. 2010). Nutrients deposited in soils, including ammonium, nitrite, nitrate, and orthophosphorus, are among the compounds carried in surface runoff. South shore runoff has been found to contain between 1.49-8.51 mg/L Nitrate-Nitrite and 0.06-2.85 mg/L phosphate, where higher levels are attributed to storms (Miller et al. 2005). There is also evidence of groundwater seepage following the path of the Upper Truckee River that may move nutrients into the littoral zone (Loeb et al. 1988). Although no FSP is contributed, between 13 - 15% of the TN and TP load (calculated from all potential sources, including runoff and atmospheric deposition) is attributed to groundwater seepage (Sahoo et al. 2010).

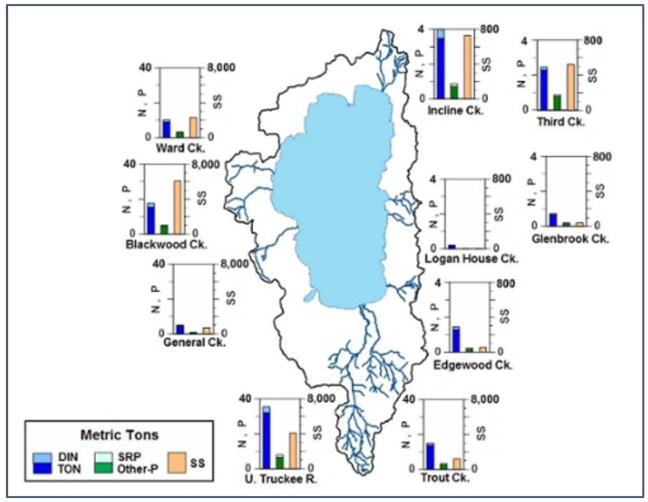

Figure 7. Watersheds of Lake Tahoe. Image (2015) property of the Tahoe Environmental Research Center

Most precipitation in the Tahoe Basin falls as snow between November and March, according to Dolislager et al. (2012), with the greatest discharge rates occurring during snowmelt between April and June (USFWS 2003). Snow accumulated in urban areas acquires small particles and added nutrients from road sanding and deicing materials. Road salts used to help lower the freezing point of water increase levels of calcium and sodium in freshwater. This can cause salt stress in native species and permit tolerant species, typically AIS, to prosper (Kim et al. 2001). Snowmelt transports road sand towards Lake Tahoe, increasing both the rate of sedimentation and amount of FSP suspended in the water column (Dolislager et al. 2012). Recently, the California Department of Transportation (Caltrans) has instituted the use of salt brine to reduce the amount of sand and salt and the sand that is used is recaptured with sweepers, in order to reduce the amount of fine particulate matter in highway runoff.

Upon the development of the Tahoe Keys, as previously discussed, the middle of the original Truckee marsh was filled forming the current Pope and Truckee marshes (Kim et al. 2001). In a study by Stubblefield et al. (2006), it was determined that the Truckee marsh, through which the Upper Truckee River runs, no longer retains sediments as efficiently when compared to historic data. The Pope Marsh is no longer connected to the Upper Truckee River, and only a small watershed drains into Lake Tallac and Pope Marsh. The loss of floodplain for the Upper Truckee River has placed an increased discharge burden at the mouth of the Truckee River resulting in erosion of streambed and banks.

Sensitive areas[3] for NPS loading in the Tahoe Keys include TKPOA common areas where parking lots, walkways, and tennis courts are located. Furthermore, homes and townhouses with yards can directly drain into the lagoons if BMPs have not been implemented. Lastly, areas where snow is stored during winter can become a sensitive area as well due to the subsequent runoff from snowmelt (NPS 2015).

2.3.1 Changed Conditions

Since 2013, the State of California has suffered severe drought conditions and a decrease in annual surface runoff from snowmelt (Swain et al. 2014) and, according to the California Department of Water Resources (CDWR 2016), as of January 2016 California is entering its fourth year of drought. Average rainfall fell to less than 34% of the typical annual precipitation during 2013, the smallest amount in 119 years (Swain et al. 2014). The rapid onset and long duration of drought conditions has impacted both ecological and economic systems (CDWR

[3] As defined in the Nonpoint source Water Quality Management Plan as areas that drain directly into the waterway from private and shared areas

2016). Lake Tahoe's water level dropped below the natural rim in October of 2014. According to the Tahoe Environmental Research Center's State of the Lake Report 2015 (TERC 2015), dipping in the lake level has occurred several times over the past 114 years; however the frequency of occurrence has increased. Evidence from Kleppe et al. (2011) suggests a pattern of recurring droughts every 600-1050 years in the Sierra Nevada during the late Holocene. In both Fallen Leaf Lake[4] and Lake Tahoe a combined eighty trees were identified along the lake floor, up to a depth of 197 feet. Upon evaluation of the roots, it was determined that these trees, some of which are 98 feet tall and 3.6 feet in diameter, grew upright *in situ*. Tree ring sampling, sediment cores, lake levels and fire reconstructions determined that less than 60% of the normal precipitation fell during the late Holocene (Kleppe et. al. 2011).

The reduction of annual precipitation, both rain and snow, slow nutrient input from some external sources. Wildfires, common occurrences in California due to drought conditions, increase the levels of ammonium and phosphate (Miller et al. 2005) in aquatic ecosystems and surrounding soil. Dry soils continue to build up nutrients that will eventually be loaded into the lake once precipitation occurs. Water levels, both in Lake Tahoe and the Tahoe Keys Lagoons, drop from lack of precipitation and higher levels of evaporation from warmer air temperatures, as has been seen over the past few years. The effects of drought on standing freshwater cause FSP to settle and prevent the dilution of detritus and nutrients (Lake 2003). Nutrients levels will therefore increase in shallow zones, becoming more concentrated as the amount of water decreases. With a lack of water movement, the available habitat for aquatic and riparian species shrinks, sometimes trapping organisms, causing an increase in predation and competition. This minimizes the distance between the bottom of the lagoons and the water surface that in turn produces shorter submerged plants with higher aquatic plant densities. Furthermore, shallower water can allow light to penetrate further into the water column and favor plants that require more light than is generally available during years of higher water levels. Rising water temperatures are also observed, influencing water column mixing that promotes faster growth rates for aquatic plants and algae (DiTomaso 2003).

The combination of little to no water movement with a high level of light penetration and warmer average water temperatures cause a loss of submerged aquatic plant diversity and high

[4] Located one mile south of Lake Tahoe

density of Eurasian watermilfoil, curlyleaf pondweed, and coontail within the water column of the Tahoe Keys Lagoons. The volume of aquatic weeds removed from the Keys annually has increased to from 100 cubic yards in 1984 to 18,600 cubic yards in 2014. Both the Marina Lagoon and the Main Lagoon (East and West Channels, respectively) are dominated by the native Coontail and invasive Eurasian watermilfoil. The documented percent of area covered (PAC) is above 80% for both lagoons and, based on hydroacoustic data, a little more than three fourths of the water volume is filled with plants (TKPOA 2015).

Many factors influence nutrient pollution of the Tahoe Keys Lagoons. Allochthonous input of nutrients and FSP originating from PS and NPS runoff in the Lake Tahoe Basin watershed and urban developed areas is important to consider in order to understand the source of nutrients cycled by the aquatic plants found in the lagoons. Stormwater runoff alone contributes more than 70% of the FSP to Lake Tahoe; the Upper Truckee River along with Blackwood Creek and Ward Creek contribute almost 96% combined (NDEP 2015). The Tahoe Keys have virtually no natural watershed inputs, but comparatively high inputs from non-stormwater sources, such as lawn irrigation. With documented studies and water quality monitoring identifying nutrient sources and concentrations in streams and rivers that act as tributaries to Lake Tahoe, surface runoff is important for the identification of components that act as primary nutrient sources for aquatic ecosystems, such as the Tahoe Keys lagoons.

2.4 Atmospheric Deposition

Oligotrophic lakes at high elevations are sensitive to climatic changes and often have observable increases in productivity. Deposition of atmospheric nitrogen and phosphorus play a large role for aquatic ecosystems and accounts for a majority of dissolved inorganic nitrogen, total nitrogen and soluble reactive phosphorus present in Lake Tahoe (Jassby et al. 1994). Most inorganic nitrogen from the atmosphere is used in autochthonous production (Goldberg et al. 2015).

According to the California Environmental Protection Agency Air Resources Board (ARB 2015), greenhouse gas (GHG) emissions in California originate from agriculture (manure and enteric fermentation), transportation, energy generation, and industrial output. GHG sources near the Lake Tahoe Basin include the San Francisco Bay, Stockton, Sacramento and Los

Angeles areas (Dolislager et. al. 2012). Each possess large populations, with high energy expenditure, and fossil fuel consumption that are expected to continue increasing. Furthermore, the Central Valley area includes agricultural farmland where aqueous ammonium and urea give rise to atmospheric nitrogen. From 1961 to 1997, atmospheric nitrogen in the United States increased due to the use of inorganic nitrogen fertilizers and an increase in GHG release from fossil fuel combustion (Fenn et al. 2003). Vertical mixing in the atmosphere permits pollution to travel at high elevations (Dolislager et. al. 2012). That, combined with prevailing weather patterns, transport emissions into the Sierra Nevada foothills and into the Lake Tahoe Basin where deposition and nitrogen saturation occur (Jassby et al. 1994).

In 2008 it was reported that the Tahoe region has a year round population of 55,000. On average there are almost 200,000 visitors to Lake Tahoe on any given weekend and above 23 million visitors annually (Raumann et al. 2008). As such, local and tourist vehicles also act as a source for atmospheric nutrient pollution. A majority of the particulate matter (less than 10µm) in the Tahoe region comes from fugitive dust (non-tailpipe) emissions originating along the road surface from grinding of road traction materials from motor vehicles. Urban roads with high traffic provide the highest emissions, especially winter road dust emissions (Zhu 2009).

Carbon fixation, used to measure productivity, has a demonstrated increase from 48 to 170 g/m2/yr in Lake Tahoe as well as a decrease in the Secchi disk transparency (Coats 2004). Based on the finding of the Lake Tahoe Atmospheric Deposition Study (Dolislager et al. 2012) conducted by the California Air Resources Board (CARB), an estimated 185 metric tons of atmospheric nitrogen, mostly as ammonia, are deposited into Lake Tahoe annually, with motor vehicle exhaust being the primary source of gaseous ammonia. Additionally, 755 metric tons of particulate matter and 3 metric tons of phosphorus are also deposited (Dolislager et. al. 2012). It has been estimated that up to over 55% of the nitrogen and phosphorus loaded into Lake Tahoe originate from atmospheric deposition, although phosphorus is largely transported via runoff (Sahoo et. al. 2010). As more nitrogen is deposited from the atmosphere and urban runoff the character of the lake has changed such that phosphorus rather than nitrogen is the limiting factor for the growth of macrophytes and phytoplankton (Jassby et. al. 1994). Atmospheric loading has been found to influence clarity more rapidly than other sources as the pollutants are directly deposited into the water and the impacts are more immediate and pronounced (Sahoo et. al. 2010). With documented studies regarding atmospheric loading, including sources and observed amounts, there is little doubt that deposition of atmospheric nitrogen and phosphorus play a large role for aquatic ecosystems, such as the Tahoe Keys lagoons.

Section 3: Results

Due to the sensitivity of oligotrophic lakes at high elevations, changes in climate and GHGs influence the concentrations of available nutrients in the Tahoe Keys lagoons. Based on the findings of the conducted literature review on potential sources of nutrients that contribute to the Tahoe Keys lagoon's nutrient pollution, atmospheric deposition appears to be a paramount source of concern. Gaseous forms of nutrients and small particles are carried through the air from areas of dense population and high burning of fossil fuels, or by the exhaust of cars and smoke from within the Tahoe Basin, and then loaded into the surface of a body of water, in this case the Tahoe Keys lagoons. There is also saturation of the soils surrounding Lake Tahoe. Runoff from precipitation and snowmelt carries these nutrients towards the lake. Furthermore, atmospheric deposition is tied to the rise in annual air and surface water temperatures that can affect primary productivity and the growth rates of aquatic invasive weeds. Wildfire smoke, containing particulate matter, nitrogen and phosphorus, can also influence the amount of nutrients loaded into the Tahoe Keys lagoons (and on a larger scale Lake Tahoe).

Since the start of the Industrial Revolution in the 1700's, anthropogenic sources of atmospheric carbon and nitrogen have increased drastically and have been linked to a global warming trend (USEPA 2015). By the year 2100, Lake Tahoe surface water is expected to increase from 33°F to 43°F (Ngai 2013). Since 1910, daily air temperatures in the Tahoe Basin have risen at an average of 4.2°F annually, including the 2.3°F increase between 2013 and 2014. This trend has led to fewer instances of below-freezing air temperatures, a shift towards more rain than snowfall, and an earlier onset of snowmelt. Additionally, the stratification season has lengthened. Mixing of stratified water columns occurs when the epilimnion temperature is decreased causing the cooled water to sink. This process is often driven by intense cooling during winter months. With fewer days below-freezing, the mixing process is affected. In 2014, mixing only occurred to a depth of 440 feet (TERC 2015).

Studies by Jassby et al. (1994), Carpenter et al. (1998), Fenn et al. (2003), Sahoo et al. (2010), and Dolislager et al. (2012) all document the importance of the input of nutrients via the atmosphere. Most data was recorded by monitoring sites where instruments are mounted to a tower and a funnel is used to collect, record, and store precipitation samples that will be used to measure levels of nutrients from atmospheric deposition. Anchored buoys floating on the surface of Lake Tahoe are used to record the amount of nutrients deposited via the atmosphere along the surface of the water. Meteorological data sets are used to determine the movement of air from areas of high pollution to the Tahoe Basin. Agencies including the United State Geological Service (USGS), TERC, USEPA, National Aeronautics and Space Administration (NASA), and CARB collected data that was used in the above mentioned studies discussing deposition analysis and helped to identify changes in the atmosphere (abundance of GHGs and typical daily temperatures) in addition to impacts in the Tahoe Basin.

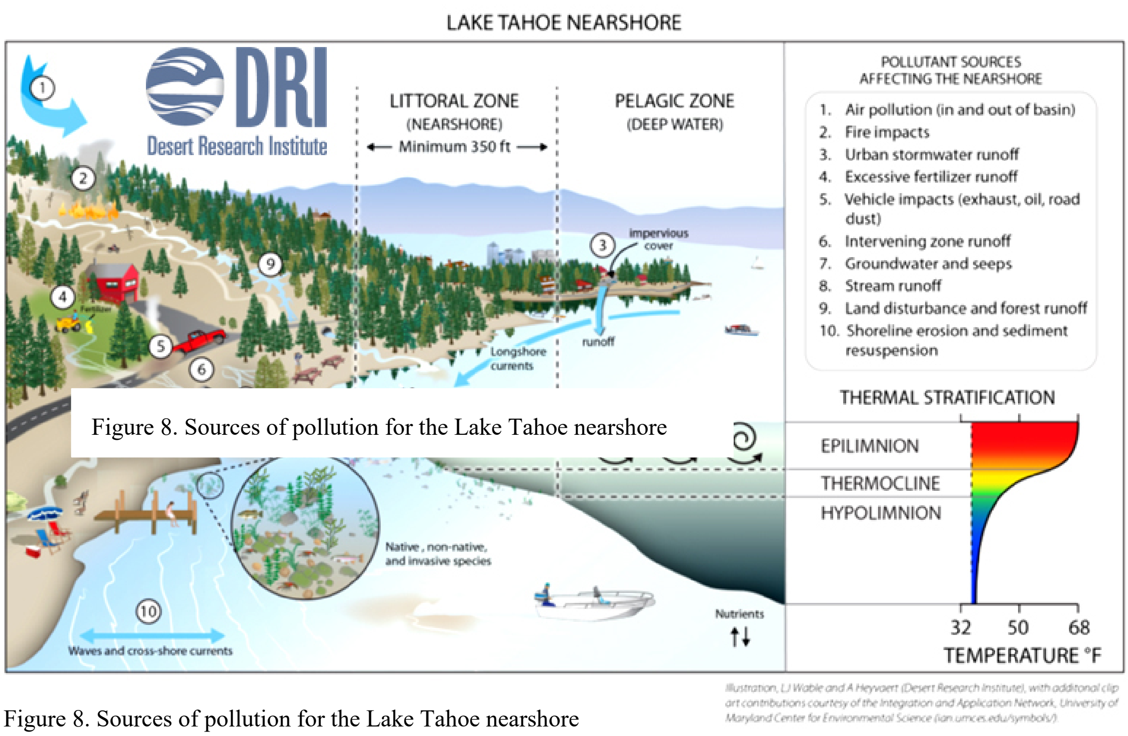

Figure 8. Sources of pollution for the Lake Tahoe nearshore

Water quality samples taken from tributaries of Lake Tahoe, including the Upper Truckee River, are used to calculate the amount of nitrogen, phosphorus, and FSP that originate from watershed surface runoff. Runoff from urban developments and activities (cars, roads, landscape irrigation, construction, and deicing controls) can be directly deposited into the lagoons from stormwater drains and common areas. The water in the Tahoe Keys is phosphorus limited, although both the concentrations of phosphorus and nitrogen are above the water quality objectives set forth in the Lahontan RWQCB Waste Discharge Requirements for the Tahoe Keys (Lahontan 2014), as a larger amount of various nitrogen forms are loaded into the lake from air pollution. There are BMPs in place that ban the use of phosphorus containing fertilizer in the Tahoe Keys. This has reduced the inflow of phosphorus from urban runoff. Runoff from the watershed adds FSP-bound phosphorus to the lagoons. Atmospheric deposition is connected to watershed surface runoff, as the amount of nutrients deposited into the soil increases, so does the amount of nutrients that can be loaded via runoff. Therefore lawns, roads, and snowmelt further add to nutrient pollution.

Studies indicate that atmospheric deposition and runoff collectively lead to more than 50% of the nitrogen and phosphorus loaded into Lake Tahoe. The nutrients deposited from these two sources, especially via atmospheric deposition, cause an immediate change in productivity. Light penetrates through a majority of the water column in the lagoons, so when these nutrients are introduced to the system, they can be immediately absorbed by phytoplankton or macrophytes and used in primary productivity. These introduced FSP are initially suspended and cause an increase in overall turbidity. Particles can refract light that may be beneficial to aquatic macrophyte growth, according to a study by K. Walter (2000), where Eurasian watermilfoil grew better in shaded areas.

Studies involving the external loading of nutrients are prevalent; however, internal loading cycling, especially that of phosphorus, is important to note with regards to nutrients in the Tahoe Keys. Papers by Walter (2000), Moore et al. (1984), Angelstein et al. (2008), Baldy et al. (2015), Boyd (1971), and Enriquez et al. (1993) all illustrate the potential for cycling by the submerged aquatic macrophyte species present in the Tahoe Keys. These studies looked at the milfoil family, *E. canadensis*, and *E. nuttallii* and were conducted in mesocosms. Tracer phosphorus (^{32}P), and in some cases tracer carbon (^{14}C), was introduced to the mesocosm in order to follow uptake, translocation, and leakage conducted by the macrophyte in question. With the increasing abundance of submerged aquatic plants there is more nutrient cycling in the lagoons. A combination of nutrient cycling by macrophytes with high levels of sediment containing nutrients from the pre-existing wetland could be a strong source for the high levels of nutrients used by the AIS in the Tahoe Keys. However, due to insufficient data for nutrient cycling by curlyleaf pondweed and coontail, it is difficult to determine the degree to which this affects nutrient loading of the lagoon's water column. Furthermore, lack of information on the composition of the sediment along the bottom of the lagoons (and therefore the availability and concentrations of nutrients) also hinders this process.

Section 4: Conclusion

The urbanization of the Lake Tahoe Basin has led to increased levels of pollution and urban runoff, causing high nutrient loading in the streams, estuaries, and main lake. Lake Tahoe is an oligotrophic high altitude lake known for its exceptional clarity and striking blue color. The tenacity and spread of the Eurasian watermilfoil, curlyleaf pondweed, and the coontail in the lagoons of the Tahoe Keys are tied to the high levels of nutrients contributed by primary sources, including atmospheric deposition, marshland sediment, and surface runoff. Understanding nutrient cycling and identifying components that act as sources of nutrients is important for the development of long-term AIS management strategies.

Atmospheric deposition appears to be a chief source of concern as gaseous forms of nutrients and small particles are carried through the air and deposited onto the surface of a body of water, in this case the Tahoe Keys Lagoons. The 185 metric tons of nitrogen and 3 metric tons of phosphorus loaded annually into Lake Tahoe are used in autochthonous production and have an immediate effect on clarity and productivity (Dolislager et al 2012).

Nutrient cycling, especially in combination with the sediment from the original Truckee marsh, may also be a primary source of the nutrients used by the AIS in the Tahoe Keys. Most research on the cycling, translocation, and leaching of phosphorus was conducted in laboratory settings with Eurasian watermilfoil, Elodea, or Hydrilla meaning that there is insufficient data on nutrient cycling by curlyleaf pondweed and coontail. It may therefore be advantageous to conduct future studies on phosphorus cycling undergone by Eurasian watermilfoil, curlyleaf pondweed and coontail together with sediment analysis to determine the availability of nutrient and the degree to which these weeds influence nutrient loading of the lagoon's water column.

Management strategies for the control of the current aquatic invasive weeds populations in the Tahoe Keys Lagoons is paramount to slowing cultural eutrophication and prevent further spread into Lake Tahoe. Based on the findings of the literature review, reducing emissions from private cars and the utilization of mechanical harvesters, bottom barriers, and the implementation of BMPs could lessen the input of pollutants originating from the Tahoe Basin. Lastly, based on management programs in similar settings, the installation of rain gardens, ditches and culverts in sensitive areas as well as the use of aquatic herbicides together with mechanical harvesting will further help to reduce the submerged macrophytes to manageable levels.

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