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# An Examination of the Effects of Glacial Retreat in the Colorado River Basin

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## 1.0 Introduction

Located on the upper slopes of the mountains of the Colorado River Basin are an uncharted number of alpine glaciers, providing a habitat and conditions that would be inaccessible to the life forms of the area were the glaciers to disappear. In many cases throughout the world the issue of global warming is most clearly emphasized and noticed earliest by the receding of alpine glaciers. This is as true in the Colorado River Basin as anywhere else, since glaciers are incredibly sensitive to even very slight differences in average annual temperature. However, the retreat and possible disappearance of glaciers within this area will have effects much more far-reaching than the simple visual changing of a landscape.

Glacial retreat within the alpine tundra of the Colorado River basin, largely as a result of global warming, is having and will continue to have substantial effects on the environment and ecosystems of the Colorado River Basin and the surrounding areas. This will in turn substantially affect the human population of the entire Western United States. In the animal kingdom, those most immediately affected by glacial retreat will be the creatures living upon or next to the glaciers, which depend upon them for camouflage and maintaining a cool temperature even during the summer months. A disappearance of any of these species will likely have wide-reaching effects upon the ecosystem of the area, in addition to the likely appearance of new species that may have only been able to survive lower on the mountains earlier because of the presence of the glacier. Immediately after the glaciers disappear, an entire variety of new microbial life will appear in their wake, some of it possibly deposited by the glaciers as they melt, which will also affect the ecosystem of the area. Finally, for a period of time the soil left behind by the glacier will likely be barren and entirely devoid of the nutrients necessary for any plant life. Given enough time, however, the soil will once again become capable of supporting plant life, and those plants hardy enough to survive tundra conditions will repopulate the area, which in turn will allow a new group of animals to move in.

In addition to the ecological impacts that retreating glaciers will have on the area that they recently inhabited, their disappearance will have much more far-reaching effects on both the environment of the Colorado River Basin and the human population of much of the Western United States. Glaciers store vast quantities of fresh water within them and even while advancing they melt a substantial amount during the summer. In the area being focused on here, this means adding their waters to the Colorado River, from which much of the Western U.S. obtains water for drinking and irrigation. During seasons of drought this is of particular importance, and would be devastating to those people and animals that depend upon water from the river were the glaciers to vanish.

In this paper I plan to explore all of the topics outlined above, to create a scenario describing what may possibly happen in and around the Colorado River Basin if its glaciers were to disappear due to climate change related to global warming. Through case studies from various parts of the world, I will be examining the various ways in which glacial retreat affects microbial, animal, plant, and human life in the areas in which it occurs. This information will then be used to create what I feel to be the most likely scenario of the results of glacial retreat within the Colorado River Basin.

## 2.0 Background

### 2.1 Global Warming

Global warming is the increase in the overall global climate change and is causing adverse effects to our environment. The most common effect of global warming is the rise of average temperature worldwide. Since 1880, global temperatures have risen 0.8°C; all studies were done by NASA's Goddard Institute for Space Studies. The Intergovernmental Panel on Climate Change says that 11 of the past 12 years have been the warmest since 1850[1].

This has thus caused the average temperatures in the arctic to rise and is causing arctic ice to rapidly melt and cause problems for the indigenous species in that area. With the habitats getting damaged by these extreme weather patterns from natural changing of climate, many animal and plant species will face extinction. This is because some may not be able to handle the new warmer climate and need a cooler climate to live. A great example is the Arctic Circle where the ice is melting in the seas, which helps support polar bear survival by allowing them to travel on the sheets of ice. With warmer weather, less ice will be the norm and the habitat for the polar bear will be shrunk[2].

Figure 1- Polar bear yearling. Credit: Susane Miller / USFWShttp://www.fws.gov/home/feature/2008/polarbear012308/polarbearphotos.html

Those are not the only ice forms that have been melting around the world; many mountain glaciers have disappeared and about 113 glaciers have disappeared from Montana's Glacier National Park. Climate change is not only limited to affecting colder climates, but even the coral reefs are experiencing bleaching, which causes many of these coral reefs to die off[3].

The cause of global warming is a very widely debated topic amongst experts and the one common cause is human impact. The rise of greenhouse-gas emissions has in turn made many experts feel it has indeed caused global warming. The probability that humans have caused this problem is around 66%. This study was done by a panel set up by National Geographic in 1990, 1995, and 2001. These conclusions are not exact because this panel may not have been made up of experts, but however many people speculate that with placing more blame on human activity, more of an effort will be placed in ultimately lowering harmful emissions. The before mentioned facts were stated by Henry Jacoby, co-director of the Center for Energy and Environmental Policy Research at MIT[4].

Greenhouse gases are emitted from many different sources with the most common being the combustion of fossil fuels, such as the emission from cars, power plants, factories, and any other emission. Think of it this way, thousands upon millions of more emissions occur daily in the United States that did not previously occur 100 years ago. The amount of people driving cars has risen and energy plants have also become more common to fit society's energy needs.

Many measures have been taken to reduce the amount of energy emissions recently and these include hybrid cars, electric cars, and scrubbers placed on many smoke stacks to coal power plants and many industrial buildings. These efforts have been proven to reduce the amount of greenhouse gas emissions from the plants have reduced with these scrubbers, which also take out harmful sulfur, but have not been implemented worldwide due to the cost. Countries like China are putting up a coal burning power plant about once a month to accommodate their growing middle and upper classes, do not have the same environmental considerations or philosophies that the United States does. This is the case for many countries that are going through economic and social growth and cannot afford to put in place environmental concerns.

The problem that has occurred due to all of these industrial emissions, deforestation, and other carbon releasing acts humans do to nature is that plants and the ocean cannot absorb all of this excess carbon fast enough for there to not be an accumulation of it. With this occurring, concentrations of carbon dioxide, methane, and nitrous oxide are getting trapped in our atmosphere and causing the ozone to reflect radiation coming off the Earth, thus causing global warming.

Some experts oppose the idea that global warming is being caused by human disturbance and they suggest the warming cycle is naturally occurring whenever the Earth shifts orbit, even though this process of climate change usually happens over hundreds of thousands of years and is now appearing to happen in the span of a single century. The excuse of a naturally occurring cycle makes it hard to ignore that humans have been cutting down trees that help assimilate the carbon dioxide, and have been releasing harmful emissions more than ever into the atmosphere as a possible explanation.

What will happen to the Earth if global warming continues on the trend it seems to be heading? One answer is that the experience of extreme weather will continue to get more prevalent and perhaps even more dangerous. Coastal cities alone would experience high levels of coastal erosion, stronger hurricanes, storms, and various other extreme weather occurrences. The Environmental Protection Agency estimates that a 1m rise in sea level along United States coastlines will cost up to four hundred billion dollars[5]; with sea levels estimated to rise between 0.18m to 0.59m from 1990 to 2100, according to a report released from the Intergovernmental Panel on Climate Change, this estimated cost may become a reality[6].

## 2.2 Alpine Tundra

Alpine tundra is roughly described as an alpine area above tree line (roughly 12,000 feet in the Niwot Range of Colorado). Although both alpine and arctic tundra are defined by the same parameters, a lack of trees, there are distinct differences. While in the tundra the climate is so harsh that many plants are not able to grow, the arctic tundra has more permafrost than alpine, furtherlimiting the types of plants that can grow. Despite having a slightly broader range of plant life, the alpine tundra supports fewer native animal species.

The climate in an alpine tundra is one of the harshest found on the planet. The weather is so extreme that it is on the edge of not being able to sustain any form of life. For eight months of the year the mean temperature is below freezing. This creates a short growing season; affecting the types of plants that are able to grow in the tundra. While the tundra receives a large amount of precipitation yearly,the majority of this comes in the form of snow during the winter months. In addition, the treeless tundra is very susceptible to high winds, as it is so much higher than all other ground and the wind has very few obstructions. These winds increase the affects of the cold temperatures which in turn further decreases the tundra's ability to sustain life.

Due to altitude and climatic affects, the terrain in the alpine tundra is somewhat barren, primarily consisting of a mix between grasslands, rock patches, and glaciers.Lower elevations in the tundra support grassy plains with flowers and small shrubs. At these lower altitudes the growing season is longer due to slightly warmer temperatures and the snow pact melting earlier. The middle regions of the tundra do support some plant growth but often contain only rocky outcrops. These regions are covered in snow for a large portion of the year and have a short growing season. The highest elevations in the tundra are the tops of the mountains. These mountains are often made up of jagged rocky peaks that support only a small number of the hardiest life forms.

Glaciers also cover large areas of the tundra. A glacier is roughly described as an area of land that is covered in snow for over two years. As a result of this buildup, glaciers are a mass of snow and ice that moves down through a valley, often with a pond, lake, or stream at the bottom where snowmelt accumulates. Some glaciers have been present in the tundra for thousands of years, and it is not always certain what lies in the ground below them. Glaciers are the main source of water for the plants in the tundra. Since the summers have very little precipitation, runoff from the melting glaciers becomes the main source of water for the tundra. In recent years shrinkage of glaciers in the Rookies has been particularly pronounced, creating more open land for plants and animals to inhabit.

The vegetation in alpine tundra is controlled by the topography and weather. Harsh winds do not permit the growth of trees, and cold temperatures create a short growing season. The rocky outcrops in the mid to high elevations of the tundra are only able to sustain small lichens, and often even lack snow cover throughout the year due to the high winds. In the middle and lower altitudes of the tundra many different types of grass and flowers are able to grow in the grassy plains, as a result of the nutrient-rich soil. In addition, these areas tend to have the longest growing seasons, sometimes lasting 200 days, depending on snow pack and snow melt. The only areas in which plants may grow that are larger than grass and flowers are on the edges of ponds and streams. These shrubs generally grow to roughly eighteen inches tall. However, all of the alpine tundra's vegetation is very fragile, and may be seriously affected by variations in yearly weather patterns including temperature and precipitation.[7]

The availability of food and the weather conditions of the alpine tundra greatly limit the number and type of species that can survive there, and so the native animal species consist primarily of herbivores. The majority of species that live in the tundra are voles, marmots, and shrews. These small herbivores feed off the grass and flowers that grow in the grassy plains, and are very good at insulating themselves, allowing them to survive extreme temperatures. Mountain Sheep, Elk and Deer also graze the grassy plains and are good at protecting themselves from the harsh environment. The only carnivores that are found in the tundra are Coyotes, Wolves, Bears, and Weasels. These larger animals prey on the small herbivores that are also in the tundra[8].

These animals found in the tundra also live in the krummholz, the regionjust below the alpine tundra, in which primarily small Elfin Trees can be found. Being a less harsh climate, more animals and plants are able to survive in the krummholz than the alpine tundra. As a result, the animals of the tundra often wander into the krummholz zone or even lower. Many animals of the krummholz, however, are known to hunt and live in the tundra from year to year. Many other species are occasionally found in the tundra-however, if they are not a working part of the ecosystem from year to year they are not considered native to the tundra. By this reasoning, however, none of the "native" species of the alpine tundra are truly native, as all spend their winters in sub-alpine zones[9].

Birds are also found in the alpine tundra. While very few species of birds actually breed in the tundra, a large number of visiting birds still play a large role in the ecosystem. Birds of prey include hawks and falcons, which hunt the open grassy plains during snowless months. Other birds regularly found in the tundra include doves, crows, sparrows and finches,which forage the open grassy plains to feed themselves and their young[10].

The alpine tundra is an intricate ecosystem greatly affected by the climate and terrain. Because of the high elevations and remote locationshumans have very little direct impact on the tundra. Alpine tundras are places of extreme weather, forcing the flora and fauna that live there to have adapted to the harsh environment and survive. However few of them are able to survive all year, as many move further down the mountain in the winter months. In addition, slight variations in annual weather can affect the plant growth and diversity during the summer, which in turn affects the animals that can survive in the tundra.

**2.3 Colorado River Basin Features**

Running over 1,400 miles through the Western United States, the Colorado River is a key feature of the US, providing water, irrigation, and power to millions of people, while creating and influencing the habitats and environments of untold other forms of life in the area surrounding it. At its beginning, the Colorado River runs through the Rocky Mountains, at an elevation of nearly 10,000 feet. While it does eventually does reach the ocean (after passing through Colorado, Utah, Arizona, Nevada, California and Mexico) the majority of the water that enters the Colorado River is used by humans for the purposes of drinking and agricultural irrigation primarily. Coincidentally, the areas through which the river passes on its way to the ocean are some of the most arid parts of the United States (with the exception of Mexico), making the fresh water of the Colorado River essential for many people. Despite the fact that the majority of the land through which the Colorado River passes receives substantially less than 15 inches of rain annually, the river still amasses 17.5 million acre-feet per year of water flow at its strongest, making it the sixth largest river in terms of flow in the US[11]. This water is put to use not only providing freshwater to approximately 31 million people living in the Western United States- including the residents of Phoenix, Las Vegas, and Las Angeles- but also providing irrigation to two million acres of land in the West[12].


**Figure 2- Obtained from http://www.doi.gov/images/colorado-basin.jpg on February 15, 2009**

Despite flowing through an incredibly dry area, the Colorado River is still able to amass a considerable volume of water because of the size of the basin from which all water flows into Colorado River. This watershed covers approximately 244,000 square miles of land area, or one thirteenth of the total area of the United States. Water comes to the river from seven different states- in addition to those already stated, it also flows from Wyoming and New Mexico- flowing into ten different major river systems (the Green, Yampa, White, Virgin, Little Colorado, Verde, Salt, Gila, San Pedro, and San Juan Rivers) which themselves eventually join the Colorado River. Within these rivers and the Colorado River, there are 10 major dams and 80 major diversions set up, creating reservoirs for drinking water and with 4000 megawatts of hydro-electric generating capacity[13]. Within the Colorado Basin are a large portion of the Rocky Mountains, and all the environments contained therein, in addition to various desert regions, a considerable amount of agricultural land, and several natural wonders such as the Grand Canyon. The basin itself is split into two sections: the Upper Basin including parts of Wyoming, Colorado, Eastern Utah, and Northwestern New Mexico; and the Lower Basin, including parts of Nevada, Southwestern Utah, Arizona, and California. Each section has its own rules and regulations for the use of the Colorado River and as a result there is a politically-defined line between the two.

### 2.4 Glaciers and Role in Tundra Ecosystem

At the top of any mountain of considerable size is an area of alpine tundra, upon which one may often find glaciers, although their size and position may vary depending upon when the sighting is done. Throughout the world, glaciers contain 75% of the available freshwater, despite covering only 10% of the Earth's land (approximately 15,000,000 square kilometers), although the majority of glacial area is in the poles rather than alpine glaciers, and these numbers are subject to gradual change- in the last ice age, which ended about ten thousand years ago, glaciers are estimated to have covered 32% of the world's land surface. In addition to major ice ages, minor climate shifts that affect glacial coverage are relatively common, as shown by the “Little Ice Age”, which lasted from the 17$^{th}$ to late 19$^{th}$ century, and allowed substantial glacial advances.

Glaciers themselves are ice masses that are formed by snow buildup that does not melt through the year and so are able to form solid ice, individual crystals of which have been known to be the size of baseballs. However, this ice is of such considerable mass that the pressure of its own weight is enough to transform it into a plastic material and allow it to flow, albeit very slowly, on the order of 10-200 meters per year. This flow results in several characteristics of glaciers. First, the top of the glacier tends to flow faster than the bottom as a result of friction with the ground. Also, when the glacier surges and flows faster than the ice bonds are able to handle, crevasses form where it is flowing fastest. Finally, glaciers will grind up the material they flow over, leaving bands of debris and ground stone behind them. There are a wide variety of types of glaciers, depending upon their shape, orientation, flow direction, and where they are situated. While “ice fields” and “valley glaciers” will likely have little to do with the alpine tundra, types such as “ice caps” and “mountain glaciers” will likely be of more relevance[14].

With regard to climate change, the examination of glaciers can give substantial information about both past climate trends and current ones. Since glaciers can be hundreds of thousands of years old, accumulating a new layer of snow each year that is eventually packed into ice, it is possible to remove a core of ice from the glacier and by examining the thickness and composition of the layers ascertain various information about past climates, much like looking at tree rings. As to current climate change, glaciers are very susceptible to changing climates, advancing more rapidly as the climate cools (allowing more snow to stay frozen) and retreating or advancing more slowly in a warming climate (as additional snow melts each year). Therefore by examining the movement of glaciers over a series of years scientists are able to ascertain a general trend of climate change throughout a region or worldwide.

Glaciers, although not being particularly conducive to life in and of themselves, are in fact integral parts of the ecosystems of the alpine tundra. Most importantly, the water that comes from melting glaciers is a primary source of freshwater for both the species of the tundra and those living below the tree line (including humans). Particularly in years of drought, glaciers can be counted on to supply much needed freshwater for alpine animals and plants. In addition, species of animals in the alpine tundra have often evolved so as to be able to camouflage themselves with the glaciers, making these areas key to their survival. These animals also tend to be dependent upon the cool temperatures of the tundra, and so when the temperature is particularly warm during the summer, glaciers are sometimes necessary in order to keep the animals' body temperature down.

## 3.0 Methodology

As this IQP is primarily a research-based report, the methodology was very simple. Research was carried out, bringing together information from around the world relating to glaciers, global climate change, and those aspects of the environment that these forces effect. To ensure accuracy, the vast majority of this information was taken from articles in scientific journals, as can be seen by the citations, many of which describe specific studies that have been carried out on the given topic. Once a sufficient quantity of reliable information was gathered, those parts of it that were applicable to the alpine tundra of the Colorado River Basin were focused upon in order to create a possible scenario of how global warming and the melting of alpine glaciers could effect the basin.

## 4.0 Research

### 4.1 Glacial Retreat and Global Warming

As has been previously stated, glaciers are made up of snowpack that remains year-round, growing or shrinking slightly depending on the season. During the summer months glaciers will melt somewhat, reducing their size, only to grow once again in the winter. However, if the weather becomes warm enough to cause the glaciers to melt earlier in the Spring  they will melt more than usual over the summer and therefore may retreat (decrease in size) over the course of the year. For this to happen on occasion is unspectacular, but historically would be evened out by colder years in which the glacier would advance more than usual. The increases in annual mean temperature worldwide, and particularly within the Western United States, however, have made the retreat of glaciers to become a sufficiently regular occurrence that many already have, or will soon disappear altogether.

Some of the most intensively studied glaciers in the Western US are on Mount Rainier, located in the Southern Washington Cascade Mountains. Among these are the Nisqually and Lyman Glaciers, both of which have been studied and tracked for over 100

**Figure 3 - Image of Nisqually Glacier. Taken from http://www.nps.gov/history/history/online_books/mora/matthes/sec1.htm on February 21, 2009**

years. As is the case with many glaciers worldwide, both of these glaciers peaked in size since the end of the last Ice Age 10,000 years ago during the "Little Ice Age", with the Nisqually advancing its furthest in the mid-1820's (approximately- the Nisqually Glacier was not measured until 1857, at which point it had retreated 300 meters from its furthest point of advance), and the Lyman reaching its peak some eighty years later. Since then, however, both have consistently retreated; the furthest point of the Nisqually is now over a mile further up the valley from where it once reached, and the Lyman has been reduced to less than 40% of its original size[15].

These of course are only two examples out of thousands that exist in this part of the country alone, and many more worldwide. In addition to the glaciers on Mt. Rainier, those that used to exist in Glacier National Park in Montana (the majority of which have vanished) and in the European Alps have been well studied and exhibit similar changes. In Glacier National Park, 17 of the 27 glaciers for which it is named had disappeared by 1980, and recent computer projections estimate that it will be devoid of glaciers altogether by 2030[16]. The loss of glacial land area in the Swiss Alps, while not as dramatic, is still extremely noteworthy. In the 25 years from 1973-1998 the Alps lost nearly 6% of their glacial coverage overall. However, this is only because the larger glaciers, some of which are nearly 100km$^2$, lose area much more slowly than those which are smaller. Among glaciers less than 5km$^2$, approximately 18% of the glacial area was lost, while the very small glaciers (less than .1 km$^2$) lost nearly 65% of their area. However, estimates for the total amount of glacial loss since the Little Ica Age are as high as 40% of the surface area and 50% of the volume of glaciers in the Alps having melted away[17]. All of these examples support the theory that glaciers are retreating worldwide due to increasing annual temperatures, and in many areas will soon be gone altogether, and those of the Colorado River Basin are no exception.

### 4.2 Microbial Life

One aspect of glacial melting that is rarely considered but is in fact very important to the ecology of the areas that glaciers have retreated from is the microbial content of the soil. The soil beneath a glacier tends to be almost entirely devoid of life as it is frozen year-round and receives no sunlight. This causes a loss in nutrients, few though they may be at the elevations of the Rocky Mountain tundra, which in turn means that for several years after a glacier retreats from an area of soil few organic creatures are able to maintain life in the soil. The first life forms that appear and begin to make the soil more hospitable are not plants, but rather cyanobacteria. These micro-organisms inhabit the soil nearly immediately after glacial retreat, within the first year, indicating that some were already lying dormant in the soil. In addition, which organisms are prevalent changes considerably over the first few years as the composition of the soil changes. In one study conducted in the alpine tundra of the Peruvian Alps from 2000-2005 that focused on microbial succession immediately following glacial retreat it was found that although there were nearly undetectable levels of nitrogen in the soil immediately following glacial retreat, the nitrogen content increased substantially over the first few years (often by two orders of magnitude) and by measuring older soil that had been uncovered 79 years ago, nitrogen content was found to continue to increase. The level of nitrogen produced by these organisms over time is key to how the ecosystem of the area develops for two primary reasons. First and foremost, no significant ecosystem may develop without a solid base of plant life, which is not able to grow without significant levels of both nitrogen and carbon. Also, research has shown that even at high altitudes where the variety of plant life that is capable of growing in the harsh conditions is extremely limited, the level of nitrogen content in the soil further limits which types of plants will grow in a given area, which in turn will affect the animal and insect populations of the area[18].

As was stated previously, carbon within the soil is necessary for an ecosystem to develop in addition to nitrogen. Like nitrogen, immediately following glacial retreat, only extremely low levels of carbon will be found within the soil. In order for the micro-organisms initially present in the soil to reproduce and survive there must be an outside source of carbon, as the small amount of ancient carbon present in the soil would only be sufficient for the initial stages of microbial growth, but not the substantial increase that has been seen even in the first few years after glacial retreat. It is likely that aeolian (wind-driven) organic inputs such as pollen are a factor, which would mean that the speed at which recently deglaciated soil could become capable of sustaining more intricate life than the microbial variety would be largely dependent on how much wind a certain area receives and from which direction it is coming. Also, however, the work done in the Andes found that the cyanobacteria themselves are another substantial factor to both the carbon and nitrogen deposition within the soil. Initially the cyanobacteria are frozen and dormant within the glacier, becoming active when the glacial ice in which they have been frozen melted away. As a result there are very few different types of bacteria to be found in the soil immediately following glacial retreat. However, over time other types of bacteria appear in the system, likely having also been spread from nearby areas by wind. In the Andes study, only three phylotypes of cyanobacteria were found in the first year, whereas four years later 20 different phylotypes in 13 major groups were found. The majority of these bacteria are nitrogen-fixing bacteria, meaning that they are capable of taking nitrogen as $N_2$ from the atmosphere and converting it into various compounds within the soil, such as $NO_3^-$ and $NH_4^+$, which make the soil much more hospitable to life. In order to do this, these bacteria tend to grow as a crust on top of the soil, making it a very fragile stage leading up to the development of an ecosystem. In addition, the cyanobacteria present in recently deglaciated soils create a variety of byproducts, such as organic acids that help the soil to absorb carbon and exopolysaccharides that adhere to soil particles and increase soil stability, decreasing the likelihood of erosion by wind[19].

**4.3 Plant Life**

Receding or disappearing glaciers have profound impacts upon the plant life from the alpine tundra where the glacier had once existed all the way to those plants near the river that the glacier's snow-melt had once fed, although these will be discussed later. Although the soil from which a glacier has retreated is virtually uninhabitable by any life form more complex than cyanobacteria for several years after the retreat, as discussed in the previous section, it will eventually become an area in which plant life may grow, once the microorganisms have sufficiently nutrified the soil. At this point the area may become a thriving tundra landscape, with the plants of the tundra and what animals are able to make a new home in a non-glaciated area. Studies have shown that those if a section of soil receives an early snowfall, the snow will insulate it, and paradoxically help to prevent the soil from freezing, which in turn benefits whatever plant life has been able to take up residence in the soil. However, if there is not an early snowfall or the snow is blown away by wind, the ground will likely freeze over the winter, creating a much harsher environment for plant life to grow in[20]. As to the types of plants that will be able to live in either of these environments, they will be primarily limited to those plants that would regularly live in a tundra environment, such as a variety of types of cushion plant (those which grow in small tight clumps) or one of several types of grasses. These plants tend to be small, dark-colored, and able to survive winters in which they receive little to no energy or nutrients[21]. Also, the disappearance of some glaciers may lead to an advancing tree-line, due in part to rising temperatures as a result of global warming, and in part to the new soil that had been previously uninhabitable because of the presence of a glacier.

## 4.4 Animal Life


**Figure 4- American Pika. Taken from http://fieldguide.mt.gov/detail_AMAEA01020.aspx on February 21, 2009**

A severe reduction in the size or disappearance altogether of glaciers may have a considerable impact upon those animals that live in the alpine tundra of the Colorado River Basin. It would also substantially affect those animals within the lower elevations of the basin, but this will be expanded upon later. A variety of animals live in the tundra, and over thousands or even millions of years have adapted to it to such an extent that it would be impossible for them to survive in any other area. While glacial retreat does not necessarily mean that the tundra itself will disappear, it is a marker for climate change which, if it becomes sufficiently extreme, could remove or sufficiently alter the tundra biome such that it would be impossible for certain creatures to live there. The best example for this is the Am erican pika, a small hamster-like mammal that lives only in the alpine tundra of the Western United States (although other types of pika are found worldwide). While pikas do not live on glaciers themselves, as it would be impossible for them to feed doing this, they are incredibly sensitive to heat. It has been shown that a pika can die in under an hour if the ambient temperature reaches above 75ºF[22]. Therefore, the existence of glaciers year-round is crucial for many of these creatures simply as a means of keeping themselves cool on warm days. Of course pika are not the only animals that live primarily in the alpine tundra. Others include a variety of birds, elk, mountain goats, and big-horn sheep[23]. While the birds may be able to fly to a nearby mountain that rises higher, an increase in temperature and loss of glacial coverage would force the other animals into living in a much less suitable habitat, while possibly killing some, such as the pika, entirely. In addition, it would allow an entirely new group of animals that may not have been able to survive the harsh conditions of the tundra to move further up the mountain, possibly introducing new predators or competition for food, putting more pressure upon the creatures of the tundra.

**4.5 Contaminants**

For thousands of years, ever since human being learned to control fire, we have been spewing contaminants into the air. It was not until the late 19th-early 20th century, however, when coal burning was the only form of power that it became a serious problem, and even then people viewed the problem as being limited to large cities such as London. In the 200 years since then, we have learned far more about the particles that we emit with our technology and tried to limit them, while simultaneously creating new technologies that emit new and possibly even more dangerous particles and compounds. During all of this time, every since Europeans settled America and began to burn things other than wood, the various particulates have been borne by the wind to settle across the countryside. This has occasionally caused problems, such as with certain pesticides, but has generally not been a huge issue as the areas affected have had at most a few years of buildup of the contaminant. However, these particulates drift down indiscriminately, including onto glaciers. As glaciers by definition do not melt much, much of what falls onto them is simply absorbed, particularly if it is during a cold year. Later, when the glacier does melt, it may release a substantial portion of harmful particles. Regularly this would not be a problem, as glacial runoff is only a very small portion of the water that is gathered in the Colorado River Basin. Unfortunately, as global warming has been and will continue to cause substantially increased levels of glacial melting and hence the retreat that has been discussed in this paper, it is necessary to know what may be contained in the runoff.

**4.6 SVOCs**

Of the various types of particulates and pollutants that may be captured in glaciers and eventually released during snowmelt, semi-volatile organic compounds (SVOCs) are among the most well-studied. One reason for this is simply that they have some of the highest concentrations of any pollutant in snow, which is likely because modern humans use so many of them. SVOCs are released from a vast number of sources including, but certainly not limited to, any burning of biomass (wood, coal, etc), paint thinners, cleaning solvents, and pesticides. Also, SVOCs do not necessarily need to land upon snowpack in order to be absorbed into it, although this is perfectly possible. They tend to cling to snow as it is falling from the atmosphere, being absorbed through the quasi-liquid layer of the snowflake and into the ice itself, and are often brought down this way, increasing their concentration in the snow substantially. While not all SVOCs are particularly harmful (the other examples are methane from cows and several compounds released by trees), many fall into the category of persistent organic pollutants (POPs), which tend to have extremely long half-lives and can be very harmful to a variety of animals. Of course, even among POPs not all will easily be absorbed into the snow- hexachlorobenzene (HCB) for example tends to easily evaporate out of the snow particles, as one study found that concentrations of HCB found in snowpack in the Alps in May/June had nearly disappeared by August/September. They also found that any compound with a high Henry's Law Constant (H) tends to act similarly[24]. However, this still leaves a very high number of POPs and other SVOCs that are harmful to both humans and animals and build up within glaciers.

Many current-use pesticides such as malathion and dacthal are both more volatile, meaning they will be absorbed by falling snow very easily, and have considerably lower H-values than HCB, and so will be retained within the snow after it has fallen. These compounds, and other POPs and SVOCs like them can be contained within a glacier for a substantial amount of time, eventually being absorbed into the meltwater as the glacier recedes. From here the compounds gather in catchment basins (lakes), where the real harm is done. As with DDT, many of these contaminants make their way up the food chain, first being absorbed by phytoplankton and algae, then by fish, and eventually by mammals and birds that eat the fish, increasing in concentration at each level, until there are enough present in the higher life forms that they may actually do significant harm. Various studies have found many different types of SVOCs in lakes and the creatures living in those lakes in the Western United States, from polychlorinated biphenyls (PCBs) to polycyclic aromatic hydrocarbons (PAHs) to organophophate pesticides (OPPs)[25].

**4.7 Other atmospheric depositions**

In addition to the vast number and variety of SVOCs that can be found in meltwater from glaciers and snowpack there are also many other types of contaminants originating from humans and in the alpine tundra snow due to atmospheric deposition. These include lead isotopes, nitrogen, and various heavy metals due to coal burning. Lead isotopes have been measured in ice cores in Greenland and other locations dating back over 3000 years and it has been found that the levels of lead isotope have increased over 100-fold in this time, with the majority of this increase occurring in the past 100 years. The combustion of the fuels most common in this century, such as petroleum, release a variety of airborne pollutants, particularly lead. Until the 1970's, when it was removed due to the emissions issues being discussed here, the addition of lead was a key step in the mixing of petrol gas for motor vehicles. By examining ice cores, it is evident that this same time period was when lead deposition was at its highest[26]. Since many of the glaciers in the Colorado River Basin likely still retain much of the snow from this time period, complete loss of these glaciers would result in massive amounts of lead being released into alpine lakes simultaneously, which may cause lead poisoning among the creatures that use these lakes as their primary source of water over a long enough period of time.

While nitrogen is a necessary component in many organic systems, as was discussed in reference to the regrowth of plants in glacial planes, excessive, unnatural amounts of nitrogen in an ecosystem can cause extreme and unfortunate changes. One of the main reasons that fertilizer is so effective for the growing of crops is that it has high levels of fixed nitrogen in it (primarily $NO_3^-$ and $NH_4^+$). As a result massive amounts of fixed nitrogen are blown into the air from fertilizers every year. This, in addition to the various nitrogen gasses released from fossil fuel combustion and agricultural production, and various other sources results in a massive amount of atmospheric deposition of nitrogen every year, which continues to increase. In the Rocky Mountains alone 2-5 kg/ha of wet nitrogen and 0.5-1.4 kg/ha of  dry nitrogen are deposited from the atmosphere each year, and this is lower than rates further East in the United States. To put the increase of nitrogen in perspective, the amount of wet $NO_3^-$ deposited per year on Niwot Ridge increased from approximately 1.8 kg/ha in the mid-1980's to 4.7 kg/ha in the early 1990's. Nitrogen deposition alone will have effects on the plant life of both the tundra and non-tundra portions of the Colorado River Basin, but more importantly for this study is the effect of the nitrogen that will be released as glaciers melt. Because of the non-porous nature and low saturation levels of the soil in the alpine tundra, the vast majority of this nitrogen will have no effect on the plant life of the tundra. Rather it, like the SVOCs, will affect the ecosystem of the lakes into which it is deposited. However, unlike SVOCs, nitrogen has been found to have little effect of fish or mammals that ingest it. Instead, it substantially affects the levels of certain types of algae. In lower-elevation lakes, a high level of nitrogen can cause sufficiently significant increases in red algae to reduce the level of oxygen present in the water, killing many of the fish and other creatures living in the lake. Alpine lakes, however have different types of algae which react differently to increased nitrogen levels, although how exactly they react has net been determined as of yet[27].

Finally, coal burning produces an entire slew of heavy metals which eventually may be deposited upon glaciers, creating even more contaminants that will enter alpine lakes as the glaciers retreat. Nowadays, while coal does still provide the majority of the energy needs in the United States, many of the $SO_x$'s and other precipitates and suspended materials can be filtered out (although other pollutants such as $CO_2$ remain untouched). However, there are still many countries in which it is also the main source of power and regulations on pollutants are few to none, and any older coal plants in America do not have these filters. Also, for over 100 years coal was virtually the only power source available, while filters to remove particulates have only recently begun to be used. During this entire time, the heavy metals released by coal burning, such as thallium, cadmium, mercury and lead- all of which are extremely toxic- were released into the snowpack and glaciers of the alpine tundra[28]. The result of these contaminants being released is much the same as that of lead, which has already been discussed, but still an issue that should be considered.

**4.8 Rockfalls/GLOFs**

When looking at a glacier, one may be tempted to think that it is simply a giant mass of ice, which may advance or retreat based upon how much snow it accumulates or how much it melts in a given year. However, while all of these are true, glaciers also act as ice flows and do exactly that- they flow. Although this movement may be extremely slow at times, rivaled only by the geologic movement of tectonic plates, glaciers have been known to "surge" forward at several feet per day. Regardless of how fast they travel, as glaciers move the rocks, trees, and anything else that may be caught beneath them is crushed, so that as glaciers retreat they leave a trail of rubble known as the moraine.

The moraine left behind by retreating alpine glaciers may do several different things. It may, over the course of many years become regular, healthy soil as has already been discussed. However, it may also be the cause of considerable damage. As the moraine consists entirely of various ground up and crushed pieces of the mountain, none of which is firmly attached to the ground a small shift in the downslope part of the moraine has been known to result in rockslides that can be devastating to large portions of the mountain below, including any animals or people that may be unfortunate enough to be in its path.

The final aspect that a moraine may take on is that of a dam. In specific situations as the glacier retreats and melts, rather than the meltwater simply flowing down the mountain into whatever river or lake generally receives snowmelt from the area, it gathers behind the moraine, forming what is known as a proglacial lake. This generally will occur when the glacier has carved out a sort of bowl into the side of the mountain, allowing the moraine to act as a dam against the water. While this may work for a while, long enough for a sizable lake to build up behind the moraine at least, as has been stated moraines are not particularly stable. A variety of events may cause the moraine to fail, including increasing water pressure from the lake, rockslides on the moraine or further upslope, which hit the moraine and knock out enough of it to compromise its stability, or earthquakes, which could themselves cause rockslides. As a side note, studies have shown that glacial retreat from specific faults may remove enough pressure from the faults to allow them to move more freely, thus causing more earthquakes in that area[29].

Unfortunately, when moraines fail it is rarely a peaceful event, instead creating a flash flood-like scenario, known as a glacial lake outburst flood (GLOF)[30].

**Figure 5- Alluvial fan (debris) left by flood water after the moraine holding back Lawn Lake in the Rocky Mountains burst (July 15, 1982). Some boulders in the alluvial fan are the size of large cars. Taken from http://www.rmnp.com/RMNP-Areas-HorseshoePark-Alluvialfan.html on February 22, 2009**

The devastation caused by these floods of course depends upon the location of the proglacial lake and its size, but evidence has been found of this type of flood occurring many times at the end of the last ice age in North America, known as the Missoula Floods, in which approximately 2.6 billion gallons of water was discharged per second (450 times the maximum flow rate ever recorded of the Mississippi River) in each of the floods. In more recent times, there have been recorded GLOFs in nearly every major mountain range, including several in which the same glacial lake has filled and flooded several consecutive years, such as at the Tulsequah Lake, in Alaska, which flooded in 14 of the 17 years from 1987-2004[31].

### 4.9 Snowmelt

As a result of their year-round presence, glaciers tend to even out the levels of water received by rivers each year. During colder years, which also tend to be wetter ones, glaciers contribute only a small amount of snowmelt, hopefully lessening the effects of any flooding that may occur, while during the years of drought in the warmer months glaciers will melt substantially, providing much-needed water. However, global warming shifts this delicate balance, increasing temperatures enough that while they last glaciers will melt substantially even during the wet years- in fact, global warming is predicted to cause increased precipitation along with the obvious increased temperatures. In the past half-century temperatures have increased by 1-2ºC across the Western US, which has already caused shifts forward in the timing of spring snowmelt runoff of 1-4 weeks. It is estimated that over the next century the temperatures are predicted to rise by 3-5ºC, which could move the timing of the snowmelt forward by as much as two months. This would also cause considerably less snow coverage, leaving more ground uncovered and thereby allowing it to soak up additional solar energy and heat up, melting even more snow. In relation to glaciers, this positive feedback loop ensures additional melting at increased rates, and therefore earlier disappearance of the glaciers. As glaciers vanish, which has already begun, there will be a substantial drop in snowmelt-driven runoff, particularly during the hot, dry summer months when the water is most needed in arid areas[32].

## 5.0 Analysis

While all of the information presented thus far has been extremely relevant to the current situation that the world finds itself in with regard to global warming and the resulting worldwide glacial receding, only a few pieces have been referring to the Colorado River Basin or even the Western United States in general. It is therefore necessary to use what has been stated thus far and apply it to the conditions found in the tundra of the Colorado River Basin. This will help us to understand what may occur as a result of glacial retreat, and how it may affect the human, animal, and plant populations of the area.

Earlier it was stated that computer models predicted that all of the glaciers in Glacier National Park will have vanished by 2030. This is probably the closest area to the Colorado River Basin that has been extensively studied, being due North of the basin, and so a good estimation to use for the time it will take for the Colorado River Basin's glaciers to vanish. However, it must also be taken into account the predictions by another study that global warming will cause a Northern shift in precipitation in the Western US, which may increase the speed at which the glaciers South of Glacier National Park melt. Taking both of these factors into consideration, assuming global warming continues as predicted, the glaciers of the Colorado River Basin may have vanished well before 2030 even.

The rapid melting of the Colorado River Basin glaciers that would be necessary for them to disappear in such a short period of time will have effects on all sorts of areas, many of which have been touched on. The snowmelt of the glaciers themselves, if undiluted by a larger water source, such as the Colorado River, most likely has a surprising amount of toxins and dangerous particles in it from hundreds of years of buildup, as was mentioned earlier. With the speed at which glaciers are and will continue to retreat there will likely be alpine lakes below the level of the tundra that, in the near future, will be primarily made up of glacial snowmelt. Water from these lakes would almost certainly be harmful to any animals that drink from them over a long period of time, in addition to likely having an extremely abnormal aquatic ecosystem due to the excessive fixed nitrogen they may be receiving from glacial melt.

Also with regard to the glacial snowmelt, the possible disastrous consequences of glacial lakes have been discussed. To date, the vast majority of the damage caused by the flash floods resulting from these lakes has only been environmental, as many of the areas that have been hit were not heavily populated. However, while the Colorado River Basin is also not heavily populated (although there certainly are cities and towns that should be wary of these lakes on the slopes above them), it is full of dams and diversions. As stated in the background information, 10 major dams, 80 major diversions, and many smaller ones have been set up throughout the Colorado River Basin. If a large GLOF were to occur it could easily damage or destroy at least one of these, and given the amount of glacial melting that will be occurring in the next two-three decades at least several GLOFs are likely.

As the glaciers in the Colorado River Basin melt, there will be a perceived surge in snowmelt, particularly in the late summer and early autumn months, when it is most desperately needed in the Western and Southwestern United States. This surge of freshwater will have several effects. For humans, it will provide the fresh water that is always needed, particularly in the arid southwest, where cities continue to grow despite an obvious lack of resources to support the overflowing population. Animals and plants will also undoubtedly take full advantage of the increased water over the summer. Near lakes and rivers plant species that are able to take advantage of large amounts of water will thrive, while further away the exact opposite will be occurring, as the plants respond to global warming. As a result, when the glaciers disappear entirely, the first effect will be upon the plants bordering the rivers, many of which will die with the substantially decreased summer flows. This will in turn have serious repercussions upon the animals that have come to depend up these very plants for their sustenance, causing massive changes in the animal populations of the various regions of the Colorado River Basin.

It is necessary to keep in mind that the events being discussed will not happen immediately, but rather over a period of 20 years or longer. In this time the humans that are also using the increased glacial snowmelt will have, hopefully, been made aware of the impending disappearance of the glaciers and what it would result in with regard to the availability of freshwater. Already the population of the Western United States is pushing the limits as to the amount of freshwater that is consumed, facing droughts almost yearly, and in the future the number of people residing there is only going to increase. The most recent US Census numbers state that over the next 20 years the population of the United States will likely increase by nearly 25%. In order to maintain their population, the Western states will likely have to do two things. First, they will need to substantially increase their efforts at water conservation, which began years ago and are the only reason Las Angeles has been able to maintain a steady amount of water usage despite an increasing population over the last 30 years. Secondly, a new system of obtaining fresh water will be necessary, whether it is the reuse of wastewater (which is already done to some extent in many countries) or something as economically unviable by today's technology as desalinizing ocean water.

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