# Impacts of Climate Change and Changing Seasonal Flow Regimes on the Columbia River Basin

by Joseph Friedland, 2016-17 State of the Rockies Project Fellow

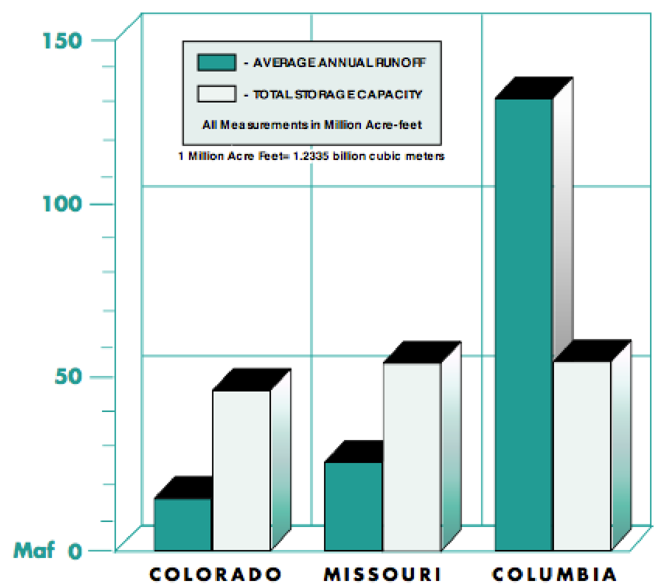
## Introduction

The Columbia River is the lifeblood of the Northwest United States, and its drainages stretch across the entire region. The Columbia River Basin comprises over 258,000 square miles across southwestern Canada, Washington, Oregon, Idaho, Montana, Wyoming and small sections of northern Utah and Nevada (see **Figure 1**). Over the course of a single year 130,000,000 acre-feet of water pass through the system (BPA 2001). Millions of people rely on the Columbia River system for municipal, agricultural and industrial uses.

What sets the Columbia River Basin apart from many other large basins in the United States is its reliance on mountain snowpack and spring runoff as its primary water source (Clow 2009). Approximately 70% of annual flows in the Columbia River Basin originate from snowpack in the Rocky and Cascade Mountains. According to the USGS, snowpack alone provides 60%-80% of the annual water supply for 80 million people across the American West (Struzik 2014).

Across the Columbia River Basin, approximately 70% of total annual precipitation has historically fallen as snow during winter and early spring (Guido 2008). More localized climate and precipitation patterns exist within the basin, however, this figure makes it clear that the Columbia River Basin is dependent on winter precipitation as its primary water source. With such a large proportion of annual precipitation falling over a relatively short period of time, it is critical that water can be stored during the wet part of the year for use during dryer times. Historically, snowpack has accumulated at high and middle elevations over the course of the winter in the mountains of the headwaters region (U.S. Department of the Interior 2011). As winter becomes spring and temperatures warm, this snowpack begins to slowly melt, providing steady flows of cold, fresh water to the system over the course of the summer when precipitation is sparse (FWEE 2017). Although significant development of man-made water storage infrastructure has occurred in the Columbia River Basin (see **Figure 2**), snowpack is still by far the most important storage method. The capacity of reservoirs, dams and impoundments in the Columbia River Basin is significantly outweighed by the storage capacity of mountain snowpack (Clow 2009). Unlike other western river basins such as the Colorado River Basin,

### Figure 2: Average Annual Runoff vs. Storage




This graph shows the average annual runoff (expressed in millions of acre-feet) compared the storage capacity of man mad impoundments in the Colorado, Missouri and Columbia River Basins. Source: BPA 2001

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**Figure 1: Map of the Columbia River Basin**


The Columbia River Basin spans seven states as well as British Columbia and contains an extensive network of dams. The dams' cumulative storage capacity, however, pales in comparison with the water stored in mountain snowpack. Source: ESRI, Bureau of Indian Affairs, National Watershed Boundary Dataset, National Inventory of Dams, Canadian Department of Natural Resources, Columbia River Inter-Tribal Fish Commission, National Elevation Dataset dams and reservoirs in the Columbia River Basin were constructed expressly for the purposes of hydropower generation and flood control, not long term water storage for municipal, agricultural and industrial use.

Consequently, water storage infrastructure in the Columbia River Basin only has the capacity to store 40% of the basin's total annual water volume (Bureau of Reclamation 2011). This means that snowpack and spring runoff are absolutely vital to ensuring ecosystem health and water supply viability in the Columbia River Basin.

## Effect of Warming on Snowpack Development and Spring Runoff

Natural systems of snowpack development and snowmelt runoff have sustained the Columbia River system for modernity. Now, however, climate change and rising temperatures are threatening the delicate water supply balance of this snowmelt driven basin (Stewart 2004). The western United States is warming faster than the global average, and increases in winter, spring and summer temperatures have been observed across almost all of the western United States (Stewart 2005). Although aggregate temperature changes and rates of change vary across the region, average warming has been about 1°C (1.8°F) per century. Additionally, the rate of increase from 1947 to present is roughly double that of the longer period from 1916 to present, and the majority of the observed warming has occurred since 1975 (Tohver 2014).

Over the course of the next century, mean annual temperatures in the western United States are expected to rise by 2°C to 4°C (~3.6°F to 5.4°F) at the low end of the uncertainty range, to 4°C to 6°C (~8.9°F to 10.7°F) at the upper end of the uncertainty range (Canziani 2007; Miles et al. 2007). Future changes in temperature will be largely dependent on greenhouse gas emissions, which will depend upon human activities and development.

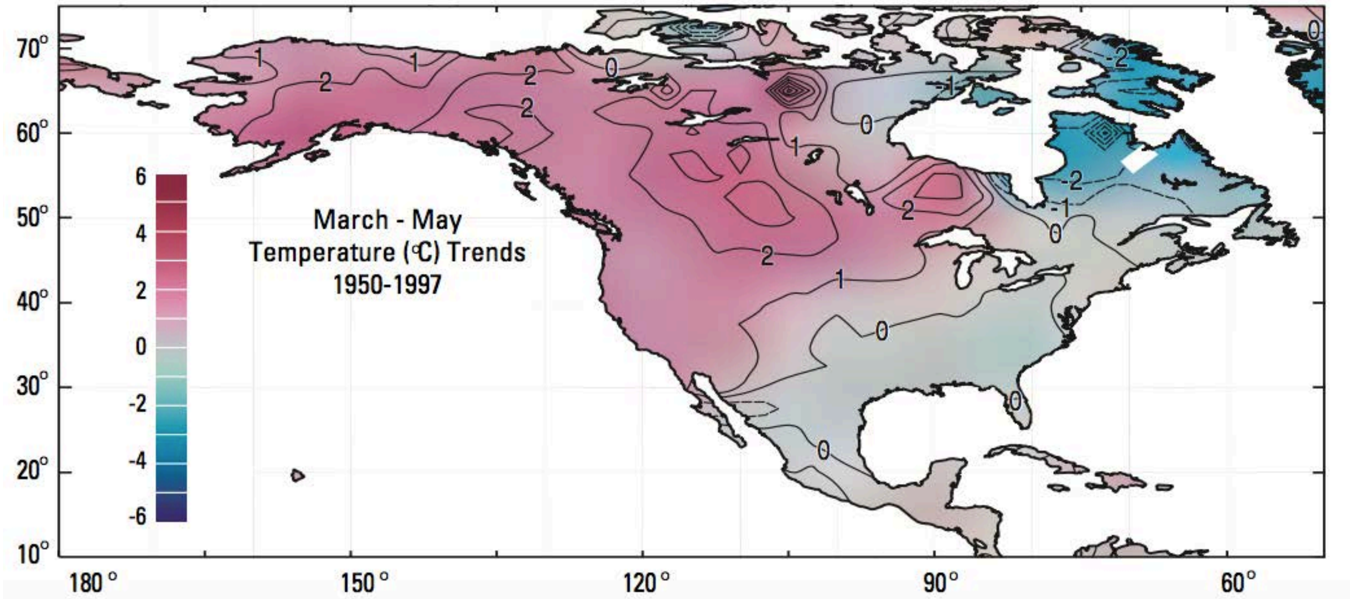
The Columbia River Basin in particular has experienced a mean annual temperature increase of approximately 1°C in the last 40 years, and like in the Colorado Basin, winter and spring temperatures have seen the greatest increase, causing temperature changes to have significant impacts of snowpack development and spring melt and runoff (Washington State Department of Ecology 2016). Additionally, temperature increases in the Columbia River Basin are expected to continue well into the 21st century, with some models predicting mean annual temperatures to rise by an additional 2°C by 2050 (Graves 2009).

Rising temperatures, especially during the late winter and early spring, have the potential to significantly disrupt natural patterns of snowpack development and spring runoff. In the Columbia River Basin, warmer late winter and early spring temperatures are already causing and will continue to cause a greater proportion of annual precipitation to fall as rain rather than snow (Knowles et al. 2006). Warming temperatures and changes in the form of precipitation occurring have already begun to cause earlier snowpack melt, as well as decreases in overall snowpack in some watersheds. These trends are expected to worsen in the coming decades (Struzik 2014).

The 2008 Intergovernmental Panel on Climate Change (IPCC) report estimates that mountain ranges across the western United States will see a significant reduction in snowpack by 2050, however, estimates on just how much snowpack will decrease vary greatly (Washington State Department of Ecology 2016). With snowmelt providing between 70% and 90% of the annual water supply to watersheds in the Columbia River Basin, even minor changes in patterns of snowpack development and seasonal snowmelt have the potential to significantly alter natural flow regimes in rivers and streams (United States Bureau of Reclamation 2016).

Projections for mountain snowmelt–dominated watersheds in the Columbia River Basin suggest that the most significant changes in annual stream flow will not be seen in the quantity of water, but rather in the timing of when the water passes through the river basin. Warmer winter temperatures and earlier springtime warming (see **Figure 3** and **Figure 4**) will cause snowpack to begin melting earlier in the year and cause a higher proportion of annual precipitation to fall as rain rather than snow. The shift towards rain dominated precipitation patterns and earlier spring snowmelt will have a variety of impacts on seasonal flow regimes (Mote et al. 2005; Knowles et al, 2006; Luce and Holden 2009).

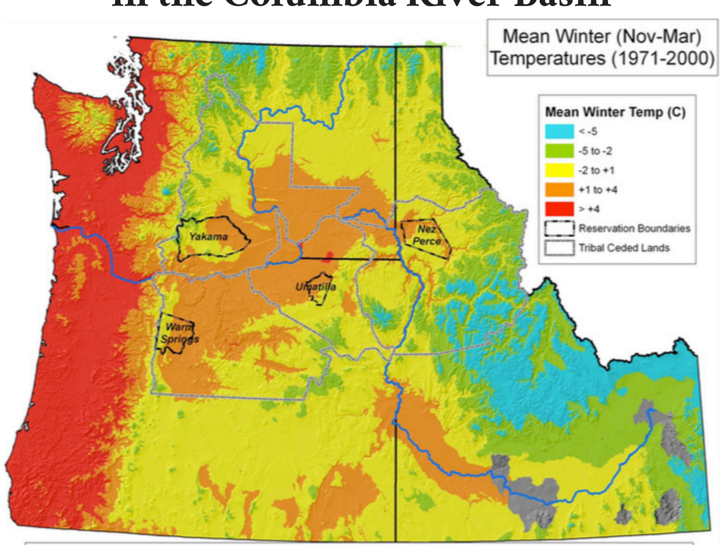
## Figure 3: Spring Temperature Changes Across North America




The Northwest has experienced more significant warming than other regions of the country. Source: Dettinger 2006

When precipitation falls as rain rather than snow, it cannot be retained in snowpack and a critical "natural reservoir" or source of water storage is lost. Rather than being stored and slowly released into the watershed during the dry summer months, the water will pass through the system at a time of year when precipitation is already plentiful (Knowles et al. 2006). Additionally, when rain falls on snowy hillsides, large amounts of snowmelt and associated runoff can occur over a very short period of time. This further reduces the amount of snowpack that is available to provide water to the basin later in the year and has the potential to cause significant flooding events (Mote et al. 2005). Earlier springtime warming also contributes to earlier snowpack melt, which further reduces the amount of water available to the system in the form of runoff during low precipitation summer months (Ibid.). Reductions in summer streamflow as well as an increased frequency of winter flood events could have major implications for fisheries, wildlife, water supply, and agriculture, particularly in drier regions. The current and expected future trends in hydrology suggest a coming crisis in water supply for the Columbia River Basin and the western United States (Barnett et al. 2008).

## Figure 4: Winter Temperature Changes in the Columbia River Basin




Parts of the Columbia River Basin have warmed with the rest of the Pacific Northwest. Source: Graves 2009

## Changes in Streamflow Timing

While projections indicate that natural spring runoff regimes will change significantly in the future, these projections are already being borne out in watersheds across the Columbia River Basin. This shift has been documented through trends towards earlier timing of the initial pulse of snowmelt runoff, earlier timing of the center of mass of flow, and a redistribution of the average monthly fractional flow from the historical snowmelt season towards earlier in the water year (Stewart et al. 2005). The trends in stream flow timing, as well as their inter-annual and long-term variability, have been most strongly connected with spring air temperature variations, in the sense that warmer temperatures have led to advances in snowmelt timing. Studies examining shifts in snowmelt and spring runoff timing often use three primary indicators: seasonal fractional flows, spring pulse onset and the date of the timing of the center mass of annual flows (Stewart et al. 2004).

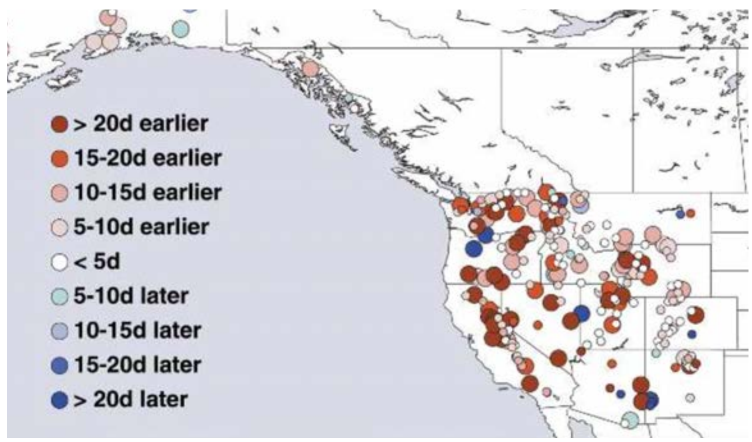
Seasonal fractional flows are defined as the ratio of the stream flow that takes place in a given month or season to the total stream flow in the given water year. The spring pulse onset date is simply the day on which the beginning of the spring snowmelt derived stream flow pulse begins. This is calculated by determining which day the cumulative departure of the daily flow from the mean flow is minimum. The timing of the center of mass of annual flows (CT) is the day on which half of the water years' total flow volume has passed through the Columbia River system. The spring pulse onset date is the best indication of actual earlier snowpack melts. CT timing and seasonal fractional flows provide the best overall picture of changes in temporal distribution of flows throughout the year. Essentially, spring pulse onset date shows that snowmelt is occurring earlier, and CT timing and seasonal fractional flows highlight the effects this earlier melt has on actual stream flows and temporal distribution of water over the course of the entire water year. It is these factors that will have the most significant implications for ecosystem health and water management (Ibid.; Stewart et al. 2005).

Spring pulse onset data from stream gauges across the western United States show widespread trends towards an earlier onset of the snowmelt spring pulse. Although the exact nature and magnitude of this trend varies across the West, one study found that the most prevalent regionally coherent trend was a 10-30 day shift towards earlier spring pulse onset since 1948 (see **Figure 5,** Stewart et al. 2005).

The same study found that CT timing correlates well with spring pulse onset date, and determined that a corresponding 10-30 day shift towards earlier CT timing had occurred over the study period (see **Figure 6**, Stewart et al. 2004).

In addition to changes in CT and spring pulse onset timing, studies have shown concurrent changes in seasonal fractional flows, particularly spring and summer flows. In the Columbia River Basin, April, May, June and July (AMJJ) fractional flows have shown significant declines since the mid 20th century. A study of watersheds within the Columbia River Basin found that 81% of snowmelt dominated drainages exhibited a decline in AMJJ fractional flows. For most snowmelt-driven watersheds in western North America, AMJJ flows are the most important contribution to the annual streamflow, comprising 50%–80% of the annual total (Ibid.). June fractional flow represents a significant portion, 10%– 30% for many gauges, of average annual flow for the snowmelt-dominated gauges. The sizable and widespread trends toward decreasing June fractional flows appear to be a compensation for the increase in fractional flow during March. Decreases in June average fractional flow range from 5% to 25% (Ibid.; Graves 2009).

## Figure 5: Observed Trends in Spring Pulse Onset Since 1948




Spring pulse onset is now occurring 10-30 days earlier in the year across the Columbia River Basin. Source: Stewart 2005

## Figure 6: Observed Trends in Center of Mass Timing since 1948


The center of mass of flow is occurring approximately 10-30 days earlier in the Columbia River Basin. Source: Stewart 2004

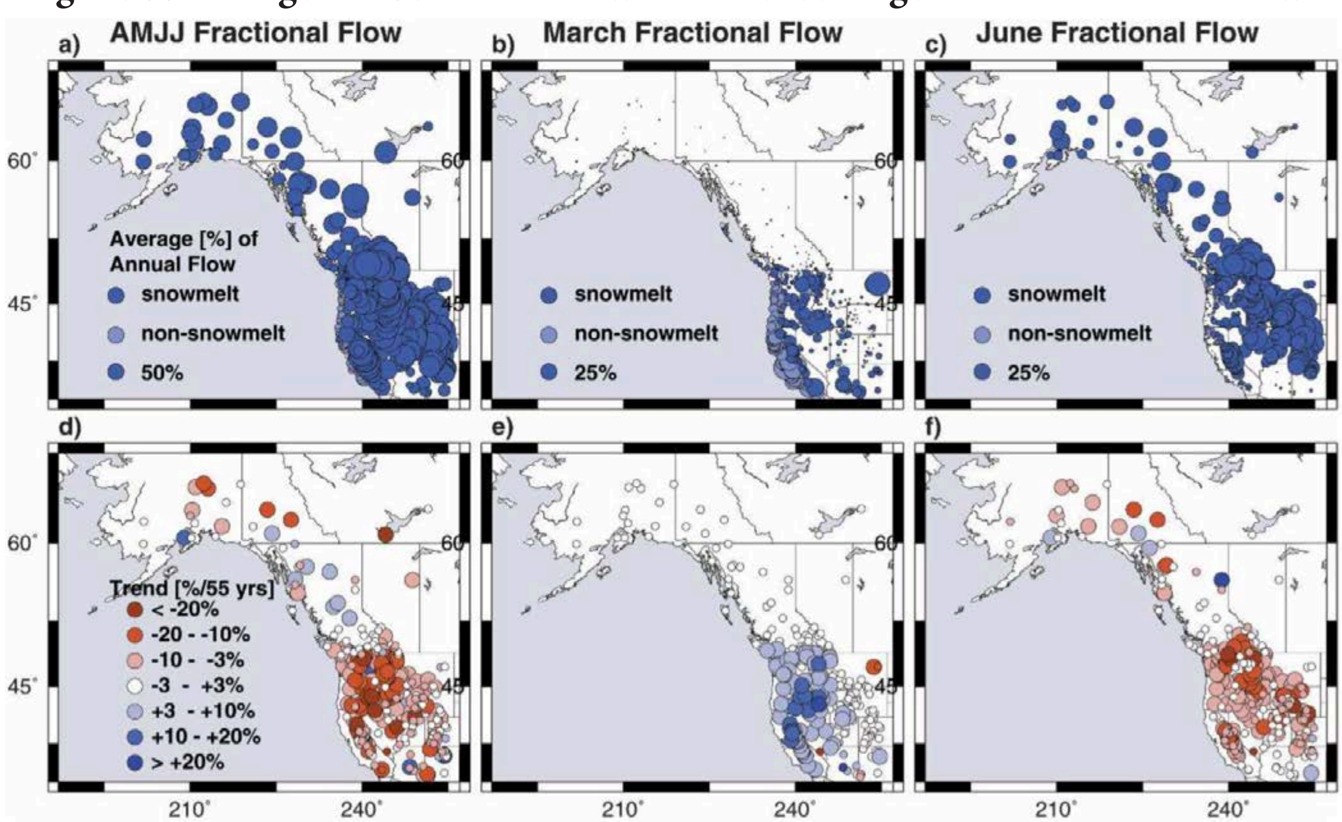
In the Columbia River Basin AMJJ fractional flows and the timing of spring pulse onset have changed dramatically. During field research in the Pacific Northwest, I was fortunate to meet with David Graves and Kyle Dittmer of the Columbia River Intertribal Fish Commission (CRITFC). Their research has shown that snowpack is, in fact, melting earlier in watersheds that are home to traditional tribal fisheries, leading to important changes in seasonal flow regimes. Perhaps most importantly, average spring flow onset date has shifted earlier by an average of 5.7 days in the Columbia River Basin, with some watersheds shifting towards an earlier onset date by as much as 17-31 days (Kyle Dittmer, personal communication 2016). Additionally, the timing of peak spring runoff has shifted 34 days earlier in just the last 80 years (Graves 2009).

This earlier flow onset date combined with higher summertime temperatures has caused April-July fractional flows to decrease by an average of 16% across the Columbia River Basin with April-June fractional flows decreasing by as much as 22%-28% in some basins (see **Figure 7**, Ibid.). Research from the Columbia River Intertribal Fish Commission has shown that as spring runoff has begun occurring earlier, AMJJ fractional flows have decreased in tributaries, and summer flows in the main stem of the Columbia River have decreased by between 10% and 50% (Ibid.).

In addition to regional trends towards earlier snowmelt and spring runoff, Native American tribes have also observed these types of trends on a more localized, watershed level. Tribal fisherman and water resource departments from both the Nez Perce Tribe and Confederated Tribes of the Colville Reservation have reported earlier peak spring runoff in the watersheds and on their reservations. Rebecca Miles of the Nez Perce Tribal Council informed us that tribal fisherman have observed the timing of spring snowmelt and runoff move forward by nearly a month in the Clearwater River and its tributaries. Changes in the headwaters region of the Clearwater River located near the Nez Perce reservation in Lapwai, Idaho have significant implications for the health of the Snake River and main stem of the Columbia River.

The water resources department of The Confederated Tribes of the Colville Reservation reported

## Figure 7: Changes in Seasonal Flows as a Percentage of Total Annual Flows




AMJJ, and especially June fractional flows, have decreased throughout the Columbia River Basin while March fractional flows have increased. Source: Stewart 2005 a similar trend in the tributaries of the Columbia River located on their reservation. Changes in these smaller watersheds have the potential to significantly impact the Columbia River Basin system as a whole.

## Impacts of Streamflow Timing on Salmon Survival and Water Quality

Earlier spring snowmelt and changes in AMJJ fractional flows in tributaries of the Columbia River have significant implications for water conditions throughout the basin. During my meeting with Mr. Graves and Mr. Dittmer, they were able to provide a clear picture of how climate change, earlier snowpack melt, and changes in seasonal stream flow patterns have negatively impacted water conditions throughout the Columbia River Basin (Independent Scientific Advisory Board 2007).

Both Mr. Dittmer and Mr. Graves indicated that as AMJJ fractional flows have decreased, spring and summer water temperatures in the Columbia River Basin have increased drastically. One of the most notable consequences of changes in seasonal flow patterns and increasing water temperatures is the potential for additional damage to salmon populations which are already struggling to recover from decades of dam construction and overfishing (Mantua 2010).

Lower spring and summer water levels allow rivers to heat up more quickly and decrease the number of cool, deep pools salmon can seek refuge in when temperatures are high. Additionally, earlier snowmelt means less cold melt water is entering river systems during the hot summer months. In the past, melt water has helped to keep rivers cool during hot summer months. Now, however, this natural cooling mechanism is disappearing due to earlier snowmelt (Crozier 2008).

As a result of lack of snowmelt, even tributaries high in the Columbia River Basin watershed are warming to a dangerous degree. Water temperature monitoring on Lapwai Creek, a tributary of the Clearwater River located on the Nez Perce reservation, found that maximum daily temperatures in the creek regularly exceeded Idaho State Department of Environmental Quality guidelines in June through September (Rebecca Miles, personal communication 2016 ). This is particularly alarming as small tributaries such as Lapwai Creek have historically supplied cool, fresh melt water to the lower watershed. Without sources of cold water in the upper watershed, the lower watershed and the main stem of the Columbia will suffer.

A study examining water temperatures passing through the Bonneville Dam on the main stem of the Columbia River found that the number of days in which water temperatures exceeded stressful levels for salmon (above 68°F) had increased dramatically, and the time of year at which these temperatures were reached came far sooner. Additionally, the study found that average monthly temperatures for April-August exceeded the 75 year monthly averages in all months in both 2015 and 2016 (Graves 2016). Although water temperatures are, for the most part, not higher than temperatures seen in the past, rivers in the Columbia River Basin are becoming hotter earlier in the year and remaining at higher temperatures for longer periods of time.

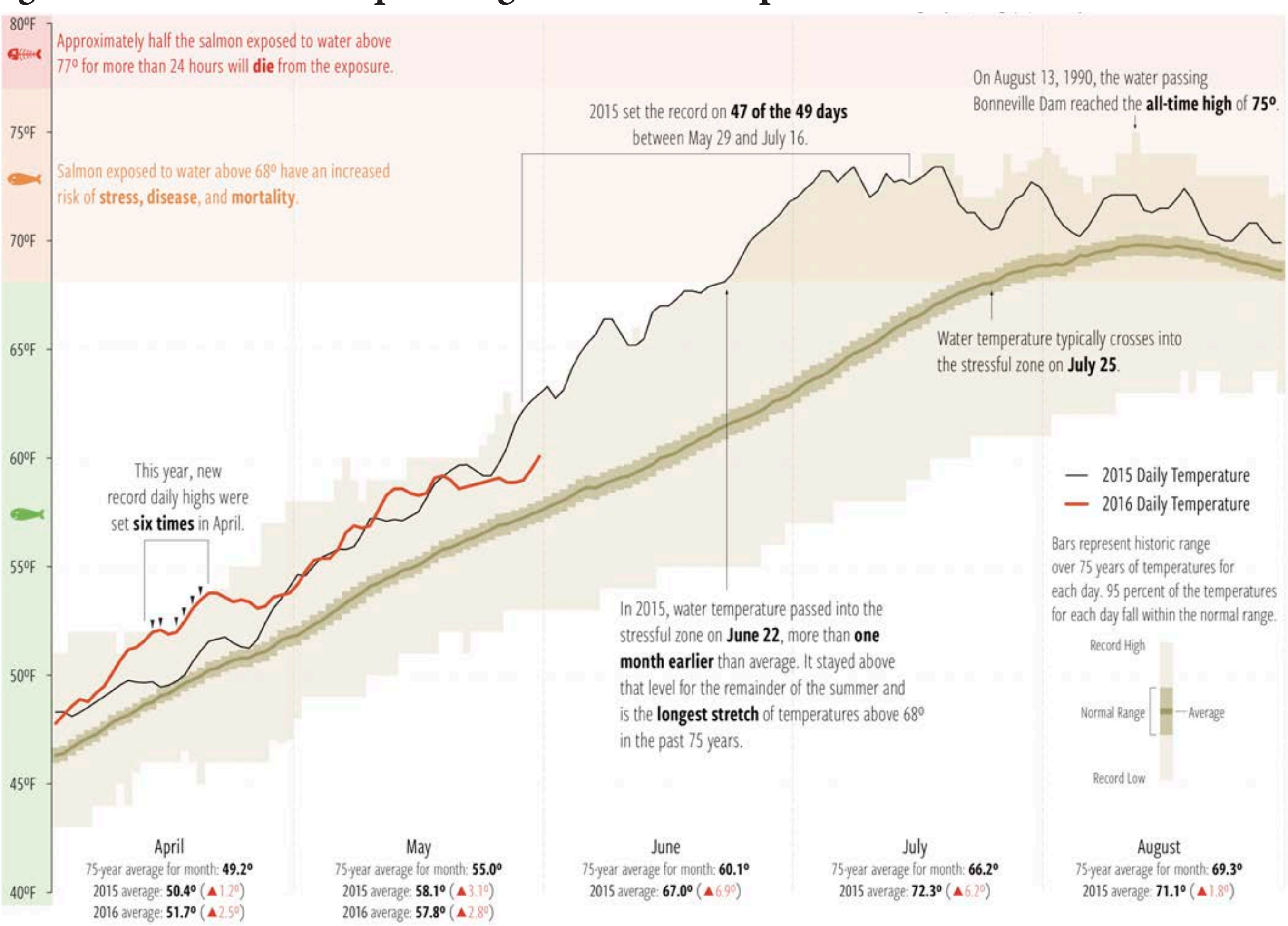
Decreases in spring and summer flows and associated increases in water temperatures are of special concern to salmon populations as these changes are occurring at the time of year when mature salmon are entering the Columbia River system to spawn. Low flows can disrupt habitat continuity and significantly increase migration times, or even prevent the salmon from reaching the spawning grounds completely (Mantua 2010).

The Columbia River Basin is home to fall, spring and summer runs of Chinook salmon as well as smaller numbers of Sockeye and Coho salmon. The earliest spring salmon begin entering the Columbia River in March with fall runs concluding by the end of October. While salmon migrations in the Columbia River Basin occur over approximately six months, the majority of salmon complete their journey to the spawning grounds in the late summer and early fall (Ibid.). This makes Columbia River salmon particularly susceptible to decreases in summer flows and increases in summer water temperatures. Studies have shown that higher water temperatures and low flows significantly increase upstream migration times for returning salmon (Kyle Dittmer, personal communication 2016).

Increases in water temperature combined with delays in upstream migration significantly increase the amount of time migrating salmon are exposed to temperatures above their lethality threshold. High water temperatures can have a variety of impacts on spawning salmon including heat shock, stress, and reduced disease resistance (see **Figure 8**). Both Mr. Dittmer and Mr. Graves pointed to the mass die off of Sockeye salmon in the Snake River during the summer of 2015 as an example of the severity of this problem. During this event salmon traveling upriver became trapped in rapidly shrinking pools as normally reliably flowing tributaries became intermittent. As the salmon became trapped, water temperatures rose, eventually killing 99% of the salmon that returned to the Snake River that year (Kyle Dittmer and David Graves, personal communication 2016).

Discussions with representatives of the Nez Perce Tribe and Confederated Tribes of the Colville Reservation Tribes further confirmed that high water temperatures are having a negative impact on returning salmon populations. Members of both tribes spoke of how tribal fisherman have observed greater numbers of unhealthy or diseased fish as water temperatures have warmed. Rebecca Miles of the Nez Perce Tribe also informed us that tribal fishermen have begun to observe that the quality of the meat obtained from migrating salmon is deteriorating earlier in the season as water temperatures have warmed (Rebecca Miles, personal communication 2016 ). This means that while fish may still be able to spawn before they succumb to the heat, tribal fisherman now have a shorter window to catch their annual quota of salmon before the fish deteriorate to the point where the meat is no longer a viable food source. Although this may not have a direct impact on the viability of salmon populations, it does threaten the viability of subsistence and commercial salmon fisheries, as well as a tremendously important cultural resource.

## Figure 8: Increases in April-August Water Temperatures at the Bonneville Dam




April-August water temperatures in the main stem of the Columbia River has increased dramatically between 1946 and 2016. The chart shows that water temperatures are now warming earlier in the year and that summer temperatures often exceed stress thresholds for salmon. Source: Graves 2016

Many projects, some meant to help protect existing habitat and others to create new salmon spawning habitat, are underway throughout the Columbia River Basin. Most of these projects are focused on planting riparian vegetation to help shade rivers and creeks in the upper watershed in an effort to reduce water temperatures. Ms. Miles explained that while these efforts are helpful, and similar habitat restoration efforts are underway on the Nez Perce reservation, creating good salmon habitat in the upper reaches of the Columbia River Basin will not be sufficient to ensure the survival of salmon. Even if water temperatures in spawning grounds are successfully lowered, the effort will be for nothing if warm water continues to persist in the lower basin (Rebecca Miles, personal communication 2016). Mr. Graves and Mr. Dittmer explained that if salmon encounter a patch of warm water during their migration it can act as a thermal barrier preventing the salmon from travelling any further upstream. According to both Mr. Dittmer and Mr. Graves, the temperatures recorded at the Bonneville Dam are potentially warm enough to act as a barrier to further migration. Consequently, temperature issues on the main stem and lower reaches of the Columbia River Basin must be addressed before the full benefit of habitat restoration in the upper basin can be realized. Unfortunately, the process of regulating temperatures on the larger rivers in the basin presents a far more difficult challenge than restoring habitat in the tributaries (Kyle Dittmer and David Graves, personal communication 2016).

Increases in water temperature are not just killing migrating salmon, but are also having significant impacts on the biogeochemistry of the Columbia River Basin. According to The Columbia River Intertribal Fish Commission and sources at the Nez Perce Tribe and the Confederated Tribes of the Colville Reservation, higher water temperatures are also increasing the rate of mercury methylation in tributaries of the Columbia River. Although mercury levels in the sediment of the Columbia River Basin have long been a concern due to mining pollution, the mercury present has historically remained in an un-methylated form. In this form, the mercury has a low bioavailability and largely remains in the abiotic levels of the ecosystem. Studies have shown, however, as water temperatures warm, the rate at which mercury undergoes methylation increases dramatically. Once methylated, the bioavailability of the mercury increases significantly. This allows for mercury uptake at the producer level of the food chain. Once the methylated mercury has entered the food web of the river, it bio-accumulates up the food chain to herbivorous species and eventually all the way up to predatory species such as salmon and sturgeon (CRITFC, personal communication 2016). There are significant concerns that increases in methylated mercury are causing significant reproductive harm to salmon and sturgeon and that mercury methylation may be the culprit for the disappearance of salmon from some spawning grounds (Rebecca Miles, personal communication 2016).

Although mercury levels in the tissue samples of fish from studied parts of the Columbia River Basin do not exceed levels considered hazardous by FDA guidelines, members of the Native American tribes of the Columbia River Basin consume fish such as salmon at significantly higher rates than non-Indigenous people. The FDA guidelines do not account for this discrepancy and, as such, this means that mercury poisoning could become a very real concern for members of Indigenous communities. Even slight increases in mercury methylation due to rising water temperatures pose a significant threat to a historic and culturally important food source (CRITFC, personal communication 2016).

Higher water temperatures have also led to increased predation of migrating spawning and juvenile salmon populations. The Columbia River Intertribal Fish Commission reports that as water temperatures have warmed, populations of predatory species such as sea lions have increased in the estuaries of the Columbia River. Sea lions are responsible for killing thousands of migrating adult salmon as they enter coastal waters and estuaries to begin their journey to the spawning grounds. Warmer temperatures in inland waterways have also been blamed for the proliferation of freshwater predator species such as bass, which are normally found in more temperate watersheds. These species have become efficient predators of juvenile salmon, killing them before they have a chance to reach the ocean and grow to maturity (CRITFC 2016).

## Hydrology and Salmon Migration

Warmer temperatures and decreases in AMJJ fractional flows are not the only way in which earlier spring snowmelt and runoff are impacting salmon populations. Changes in the timing of spring runoff can have significant implications for the migratory patterns of juvenile salmon in the Columbia River Basin (Kyle Dittmer, personal communication 2016). In the Columbia River Basin, most salmon hatch from their nests sometime in the early spring and spend the early part of their lives feeding and growing in the freshwater tributaries of the Columbia River. After developing for a short period of time, these juvenile salmon begin their long and dangerous migration out to the ocean to begin their adult lives (CRITFC 2017). What exactly stimulates juvenile salmon to begin their seaward migration is not completely understood, however, Kyle Dittmer and David Graves were quick to point to the beginning of the April/May freshet (spring snowmelt) as a primary biological indicator for juvenile salmon to begin migrating towards the ocean. As a result, early spring snowmelt may cause juvenile salmon to begin their seaward migration earlier in the year (Kyle Dittmer and David Graves, personal communication 2016).

A change in the timing of seaward migration in juvenile salmon is potentially problematic for a variety of reasons. One issue that was highlighted in interviews with the Columbia River Intertribal Fish Commission was that the seaward migrations of juvenile salmon have historically been timed to match nutrient upwelling in the Pacific Ocean. The timing of the start of seaward migrations in Columbia River salmon has been such that the juvenile fish arrive at the ocean at a time at which nutrient levels are high. This ensures that the young fish are able to grow quickly upon entering the ocean, increasing survival rates (Ibid.). If alterations in the timing of spring freshet cause changes in the timing of juvenile salmon migration, their arrival at the ocean may no longer closely coincide with times of high biological productivity. Several studies have shown that survival rates for juvenile salmon entering the ocean are highly dependent upon the salmon's ability to find food and grow quickly. Consequently, lower biological productivity at the time juvenile salmon are arriving at the ocean could significantly increase mortality in juvenile salmon populations, threatening the future of Columbia River salmon (Scheuerell 2009).

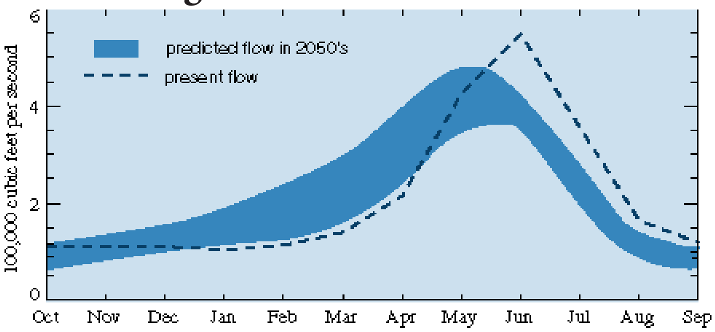
A substantial spring freshet at the time juvenile salmon are migrating towards the ocean is also critical to ensuring the fish are able to successfully complete their long journey. Due to their small body size, juvenile salmon are relatively inefficient swimmers and must expend considerable amounts of energy to travel even short distances. In some cases, however, juvenile salmon must travel nearly 1000 miles from their natal streams to the ocean (Dittmer 2013). Consequently, juvenile salmon rely on high instream flows during the spring and early summer to carry them from the spawning grounds in the headwaters out to the ocean. As snowmelt and peak runoff occur earlier and earlier in the year, however, periods of high runoff flow will no longer coincide with the time juvenile salmon are migrating (Scheuerell 2009).

Additionally, peak flows are not as high as they once were. Without these high flows, juvenile salmon will encounter longer stretches of slack water and low flows along their migratory route (see **Figure 9**). This will force fish to expend more energy during their migration which will reduce the size of the juvenile salmon reaching the ocean. Studies have shown that the larger juvenile salmon are when the reach the ocean, the higher their survival rates will be.

Lower flows will also significantly increase the amount of time it takes the salmon to reach the ocean (Ibid.). According to the Columbia River Intertribal Fish Commission, migration times for juvenile salmon have historically averaged between 2 and 3 weeks. As spring runoff has moved earlier in the year and fallen out of sync with the timing of seaward migration, however, migration times in some areas of the Columbia River Basin have increased to almost 2 months. (Cosens 2017) This significantly increases the likelihood the salmon will fall prey to predators before reaching the ocean.

Longer migration times mean that juvenile salmon will remain in inland waterways further into the summer. This fact combined with decreasing summer flows and increasing water temperatures could also cause more salmon to die of heat stress during their migration to the

## Figure 9: Changes in Timing and Magnitude of Peak Runoff




Peak runoff will occur earlier and release less water than historical averages. This may mean that high flows will occur at the wrong time to help catalyze juvenile salmon migrations, or that flows will not be sufficient to help juvenile salmon migrate downstream. Source: Scheuerell 2009

ocean (Scheuerell 2009). Delays in reaching the estuaries could also cause juvenile salmon to miss periods of nutrient upwelling in coastal waters. The loss of large numbers of juvenile salmon could seriously threaten the future of salmon in the Columbia River Basin.

Decreases in AMJJ fractional flows and warmer water temperatures are not the only consequence of climate change and earlier spring snowmelt impacting the Columbia River Basin. Since 1949 the proportion of total annual precipitation occurring as rain has increased by 75% (Guido 2008). In addition to decreasing winter snowpack and natural water storage capacity, this phenomenon has also lead to a drastic increase in the occurrence of severe fall and winter floods. A study conducted by the Columbia River Intertribal Fish Commission found that October, November and December floods are now occurring 49% more frequently than historical averages (Graves 2009).

Winter flooding has always been a part of the hydrology of the Columbia River Basin and is, in fact, vital to maintaining healthy riparian ecosystems. Even salmon have relied on winter high flow events and floods for the success of their reproductive cycle. During the spawning season, salmon make nests in the gravel of riverbeds throughout the basin. Salmon eggs then develop in these nests over the winter before hatching in the spring. In order to develop properly, the salmon eggs require fast flows of cold, highly oxygenated water. During the winter, high flow events help keep nests clear of silt, allowing for a continuous flow of water over nest. Additionally, flooding events temporarily increase dissolved oxygen levels in rivers and streams, which helps to ensure the developing salmon eggs are getting the oxygen they need (Dittmer 2013; Kyle Dittmer personal communication 2016).

While some winter flooding is clearly important for the health of developing salmon eggs, high intensity floods resulting from rain on snow events pose a serious threat to the survival of salmon nests. Kyle Dittmer and David Graves spoke of how in some years, singular severe floods and repeated lower intensity flooding events on tributaries of the Clearwater, Snake and Columbia Rivers have wiped out entire generations of salmon nests from a single mating season (Kyle Dittmer and David Graves, personal communication 2016). Although these types of catastrophic events have typically occurred on smaller tributaries with relatively small spawning populations, if flooding continues to worsen, larger tributaries of the Columbia River that are vital spawning grounds for recovering salmon populations could soon be threatened.

## Traditional, Ecological, and Economic Values of Salmon

The threats posed to salmon by changing snowpack melt and spring runoff regimes are an especially notable issue as salmon are an ecologically important keystone species throughout the Columbia River Basin. Spawning salmon populations play a critical role in food webs and nutrient cycling in both ocean and riparian ecosystems in the Pacific Northwest (Rahr 2017). Salmon act as a vital source of nutrients for large mammals such as grizzly bears, sea lions and orcas as well as nearly 140 other species of plants and animals (Ibid.). The role of salmon as predators in managing populations of prey species must also not be overlooked. Without salmon, a vital link in the food web of the Pacific Northwest would be lost.

In addition to their roles as both predators and prey in the food web of the Pacific Northwest, spawning salmon populations are also critical to nutrient cycles in the region. When salmon migrate upstream to spawn, they carry nutrients from highly productive areas of the ocean into the relatively nutrient poor headwaters regions of the Columbia River Basin (Helfield 2001). When salmon die and decompose after spawning, the nutrients that have accumulated in their bodies during their time spent feeding in the ocean are transferred to the riparian ecosystems of the headwaters regions. Additionally, terrestrial predators such as bears and birds of prey disperse nutrients derived from salmon deeper into riparian forests through defecation (Rahr 2017). A study conducted in several watersheds in Alaska found that marine derived nitrogen from decaying salmon carcasses can provide up to 25% of the nitrogen present in northwestern forests. This makes salmon critically important to riparian forest health in the Northwest as nitrogen is the primary limiting nutrient in most northern forests. The same study also found that foliage growth rates in watersheds with returning salmon populations were three times higher than forests in watersheds without returning salmon populations (Helfield 2001).

Riparian forests play a critical role maintaining watershed health and water quality. Vegetation helps to stabilize stream banks, prevent erosion and shape stream channels. This helps to limit problems such as siltation and channel widening. Vegetative cover from streamside vegetation also helps to keep water temperature low during hot summer months and provides cover for fish. When trees die and fall across the stream they create log jams that provide habitat and shelter for juvenile salmon. By helping to maintain the heath of riparian forests, salmon populations play a critical role in positive feedback loops that promote healthy riparian habitats and healthy salmon populations (Ibid.).

In addition to being ecologically important, salmon are also a cultural and subsistence resource to many of the Native American tribes in the Columbia River Basin. This aspect of the importance of salmon became abundantly clear when speaking with Rebecca Miles of the Nez Perce Tribe in Lapwai, Idaho. Speaking with Ms. Miles, she highlighted the importance of salmon and salmon fisheries as a cultural and subsistence resource for the Nez Perce and other tribes in the Pacific Northwest. The tribes of the Pacific Northwest have relied on salmon as a primary food source for thousands of years, and Ms. Miles passionately told us about the special place salmon hold in the spiritual traditions of the Nez Perce Tribe. So closely linked are the Nez Perce people and salmon that the Nez Perce sometimes refer to themselves as the "salmon people" (Rebecca Miles, personal communication 2016).

Salmon are not only an important cultural resource to the tribes of the Pacific Northwest, but also have historically been and continue to be an important economic resource for both the tribes and non-native peoples alike. Salmon fisheries and related industries account for $3 billion of economic activity in the Pacific Northwest (Rahr 2017). While this large-scale salmon economy is certainly a more recent development, salmon have long been considered an important commercial resource in the Pacific Northwest. Celilo Falls, once located on the Columbia River in Oregon, was not only a waterfall, but also home to a large number of Native American settlements and trading villages. It was also one of the most productive native salmon fisheries in the region. The area was once the longest continually inhabited community in North America and has been referred to as the former "Wall Street" of the region due to its importance in the salmon economy. Unfortunately, the falls, fishery and surrounding communities were inundated by the construction of the Dalles Dam in 1957. The loss of the falls struck a significant blow to salmon populations and the native economy of the region and represented the loss of an irreplaceable cultural and subsistence resource for the native peoples of the Pacific Northwest (Rebecca Miles, personal communication 2016).

If salmon and salmon fisheries disappear from other rivers and areas of the Pacific Northwest as has happened at Celilo Falls, not only would it be an ecological disaster, but the region and its native peoples would also be robbed of a traditional spiritual, economic and subsistence resource.

Since the first dams were constructed in the Columbia River Basin, dams have presented the most serious threat to the health of the basin's riparian ecosystems. Dams have prevented millions of salmon from reaching their spawning grounds, and untold numbers of juvenile salmon have died going over dam spillways and through hydropower turbines. Indeed, dams have long been the most pernicious threat to salmon survival in the Columbia River Basin. Now, in the face of climate change and an altered hydrograph, however, it seems that dams may offer a solution to some of the Columbia River Basin's most pressing problems.

## Dams and the Future of Salmon

In some areas of the Columbia River Basin, controlled dam releases are already being used to help regulate water temperatures downstream. During the summer as water in the rest of the basin warms, the water at the bottom of reservoirs remains cool. Consequently, dams with bottom outlets or selective release mechanisms can send flows of cold water from the bottom of the reservoir through the dam and into the river below (Martin 2004). The Nez Perce are already using this method at dams on the reservation to release cold water from Dworshack and Hungry Horse reservoirs into the Clearwater River. The hope is that the influx of cold water into the Clearwater River will not only help to manage temperatures in the Clearwater, but that it will also help to decrease temperatures in the Snake River below the confluence of the Snake and Clearwater Rivers (Rebecca Miles, personal communication, 2016). Although this method seems promising, its efficacy is somewhat limited by the fact that the lower Snake River dams prevent the augmented cold water flows from reaching the main stem of the Columbia River. Instead, the cold water becomes backed up in reservoirs behind the Snake River dams where it warms before being released into the Columbia River (Kyle Dittmer, personal communication 2016). As a result, the lower main stem of the Columbia remains a potential thermal barrier for many migrating salmon (Graves 2009).

In order for cold water releases from dams to be effective throughout the Columbia River system, dam operators must coordinate releases so that cold water from upstream does not become trapped in reservoirs where it can warm up. This task is made more difficult by the fact that not all dams have the infrastructural capacity to selectively release cold water. Many dams release water over the top or through spillways higher in the water column. Consequently, dam infrastructure must be altered and cooperation between dam operators increased before selective dam releases can effectively be used to control water temperatures throughout the Columbia River Basin (CRITFC, personal communication 2016).

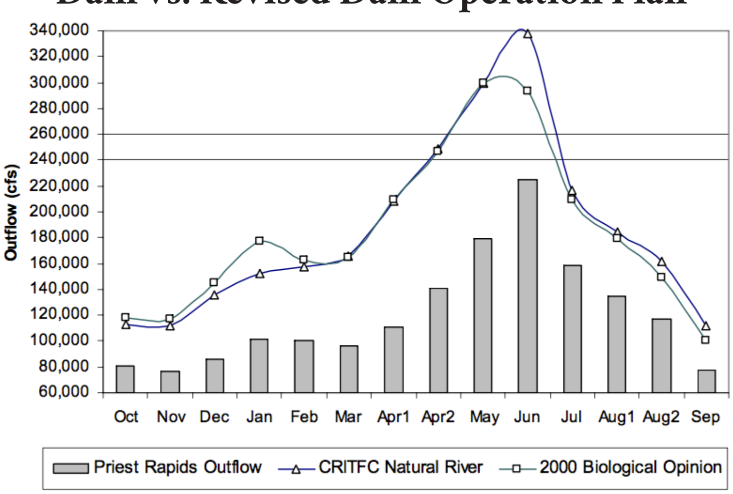
In addition to helping regulate in stream temperatures, dams may also be able to play a central role in restoring seasonal stream flow patterns to a more natural state. According to a study by Mr. Dittmer and the Columbia River Intertribal Fish Commission, dam managers may be able to work with changes in seasonal flow regimes and alter dam operations to recreate a more natural hydrograph and benefit salmon (Martin 2004).

Currently, dam operators in the Columbia River Basin must manage for three factors: flood control, hydropower generation and minimum instream flows. Under the current Army Corps of Engineers flood control plan, water levels in reservoirs on the Columbia River are drawn down January-April 30th in anticipation of spring floods. After May 1st, the spillways are shut and the reservoirs are filled in preparation for a hot and dry summer. Currently, water managers aim to have reservoirs refilled by June 30th, after which point releases can be increased to help meet instream flow requirements downstream of the dam. As seasonal flow regimes have shifted due to climate change, however, this management paradigm has become out of sync with nature and the water management needs of the Columbia River Basin (Dittmer 2006). With more flooding occurring during winter, there is no longer a need to continue draining water out of reservoirs so late into the spring in anticipation of floods. Additionally, the fact that spring runoff is now occurring earlier in the year means that reservoirs must begin filling earlier in the spring in order to fully take advantage of the water provided by melting snowpack. With spring runoff occurring earlier in the year, if dam managers do not begin filling reservoirs until May, they are allowing a significant amount of spring melt water to pass through the system at a time when it is not needed, decreasing the amount that they are able to store for use during the summer. In some cases this has caused dam managers to be unable to re-fill reservoirs, making it impossible to simultaneously achieve hydropower, flood control and environmental flow goals (Kyle Dittmer, personal communication 2016).

During a meeting with PacifiCorp, a large utility company that owns hydroelectric dams, Todd Olsen, Director of Compliance, thoroughly explained the nature of this problem. In the Columbia River Basin, where dams and reservoirs have little storage capacity, dam operators must often draw down reservoirs during winter months in anticipation of floods. This practice will become even more critical as rain on snow events and other winter floods increase in frequency. Historically, melting snowpack has been relied upon to refill reservoirs during the spring and summer. As snowpack decreases and melts earlier, however, dam operators may often find themselves unable to refill their reservoirs after winter drawdowns, leaving less water for power generation, environmental flows and recreation during the summer months. Mr. Olsen explained that this exact series of events occurred at PacifiCorp's Lewis River project in the summer of 2015. As a result, recreation opportunities were lost in reservoirs, and PacifiCorp struggled to meet environmental flow requirements and to generate enough hydropower to meet electricity demand. Environmental uncertainty erodes reliability for human and natural stakeholders alike (Todd Olsen, personal communication 2016).

To bring dam management paradigms in line with the new seasonal flow regimes, Mr. Dittmer recommends decreasing spring flood control drafts and beginning reservoir re-charge earlier in the year. Under the new dam management guidelines proposed by Mr. Dittmer, managers should aim to end flood control drawdowns earlier in the spring with the goal of having reservoirs re-filled by May 31st, not June 30th. This will allow reservoirs to capture and hold early spring runoff and decrease the amount of water that passes through the basin in the winter and early spring. The water stored and saved throughout the early runoff period can then be strategically released throughout the summer to augment declining summer instream flows. In this way dam managers may be able to artificially return the Columbia River Basin to its pre-climate change hydrograph by delaying peak runoff and increasing the magnitude of peak runoff through controlled dam releases (see **Figure 10**). According to Mr. Dittmer, this new dam management paradigm will allow for an additional 2.9 million acre feet of stored water that can be used to augment summer flows to benefit migrating salmon, while also ensuring reservoirs are sufficiently filled to meet recreation and hydropower needs throughout the summer (Dittmer 2006).

**Figure 10: Current Hydrograph at the Dalles Dam vs. Revised Dam Operation Plan**




This data compares the current timing and magnitude of peak runoff with the new hydrograph that would exist if the CRITFC-altered flood control plan was implemented. Source: CRITFC

## Conclusion

Stretching across seven states and two countries, the Columbia River Basin is home to a wide array of unique and complex ecosystems. These ecosystems provide homes to countless critically important species, including several threatened or endangered species. Additionally, these ecosystems and their constituent parts provide a wide range of critical services and resources upon which cultures have been built and civilizations have survived for thousands of years.

What sets the Columbia River Basin apart from many other large river basins in the United States is the fact that snowpack, not rain, is the primary source of water to the basin, with water from mountain snowpack comprising upwards of 70% of the basin's total annual flows. The Columbia River Basin receives the vast majority of its annual precipitation during the winter, and relies on snowpack as a natural reservoir to store water for use during the dry summer months. Warmer late winter and early spring temperatures are causing winter snowpack to melt earlier, altering the timing of peak runoff events and changing the temporal distribution of the water supply in the Columbia River Basin.

Both human populations and ecosystems within the Columbia River Basin depend upon the once reliable pattern of snowpack accumulation in the winter followed by slow, sustained snowmelt over the course of the spring and summer. Now, however, climate change is threatening to disturb historic patterns of snowpack accumulation and springtime runoff, posing a threat to ecosystem health and human wellbeing alike.

Warming spring and winter temperatures are causing mountain snowpack to melt earlier in the year, and are leading to a shift from snow to rain dominated precipitation patterns. These factors are significantly diminishing the natural water storage capacity of the Columbia River Basin. As a result, many tributaries within the basin are seeing more of their total annual flow pass through the system in the winter and spring, leaving less for the summer months. Simply put, rivers are drying up in the summer and flooding in the winter.

This temporal redistribution of annual flow has significant ecosystem health and water management implications for the Columbia River Basin. Decreases in summer instream flows are causing water temperatures to warm which negatively impacts salmonid species in myriad ways. Additionally, decreases in snowmelt runoff and earlier peak runoff have the potential to significantly hinder inland migrations of spawning salmon and seaward migrations of juvenile salmon.

Since the mid-20th century, dams have played a critical role in managing the hydrology of the Columbia River basin and currently operate under a mandate to manage for hydropower production, flood control, and environmental flow requirements. As seasonal flow distribution has changed, however, dam management paradigms have fallen out of step with the realities of the basin's hydrograph, making it increasingly difficult for dam managers to meet flood control, hydropower and instream flow demands. These challenges will only become more daunting as climate change continues to alter natural patterns of snowpack accumulation and springtime runoff. As a result, new dam management paradigms must be developed to ensure the Columbia River Basin can continue to meet ecological and human demands.

Although the challenges will be significant, it does seem that new dam management paradigms can be developed that will help restore the pre-climate change hydrograph of the Columbia River Basin. This may allow the Columbia River Basin and its water management infrastructure to continue to support healthy ecosystems and provide vital services to human populations in the face of a changing climate.

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