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CHANGE IS THE ONLY CONSTANT: A SNOWPACK RETENTION ANALYSIS
AND CLIMATE VULNERABILITY ROAD MAP FOR THE SKALKAHO CREEK
SUB-BASIN

By

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Bachelor of Science in Psychology, The University of Georgia, Athens, GA, 2013

Professional Paper

presented in partial fulfillment of the requirements
for the degree of

Master of Science
in Environmental Studies

The University of Montana
Missoula, MT

Summer 2020

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ABSTRACT

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Environmental Studies

Change is the Only Constant: A Snowpack Retention Analysis and Climate Vulnerability Road Map for the Skalkaho Creek Sub-Basin

Chairperson: Dr. Len Broberg

Climate change is impacting the whole of North America, although the impacts differ depending on regional geography. In the Intermountain West, climate change is contributing to lower overall snowpack totals and diminished late season streamflows. These changes will likely contribute to vulnerabilities in how much water is available to irrigators, municipalities, and fisheries dependent upon a consistent yearly flow of meltwater. This paper explores how snowpack retention has changed via the NASA dataset Daymet, which provides gridded estimates of weather parameters including Snow Water Equivalent in the Bitterroot River Basin of western Montana. This analysis showed that snowpack retention from April 1 – June 1 has declined over the period of record (1980 – 2018). Secondly, this paper uses the snowpack analysis to explore climate vulnerability in the Skalkaho Creek sub-basin and offers suggestions for what a future researcher may consider when investigating vulnerability to reduced snowpack retention and resultant lower late season streamflows.

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INTRODUCTION

Skalkaho Creek rises high in the Sapphire mountain range of far western Montana. It drains approximately 134 square miles from east to west before feeding into the much larger Bitterroot River just south of Hamilton, Montana. Because of the varied topography through which the creek flows, the distinct public and private ownership mosaic, and its consistent yearly snowpack, Skalkaho Creek has acted as a dependable source of irrigation water for Daly Ditches Irrigation District (DDID) in the downstream flats and as a stronghold for native salmonids in the upper reaches. However, that balance is potentially tenuous; reports list Skalkaho Creek as critically dewatered, suffering from elevated pollutants due to nearby agricultural and irrigation activity, and yet still supporting a vibrant fishery (Northwest Power and Conservation Council, 2009; Clark Fork Coalition, 2017). Looking into the future the effects of global warming and climatic change, the governance reality of overallocated Skalkaho Creek meltwater, and the competing demands for that water will potentially contribute to future climate vulnerabilities to social-ecological systems.

Social-ecological systems thinking emerged as a theoretical framework to address the disconnect between researchers who study natural systems (i.e. non-human nature) and those who study human social systems. It is largely argued that in order to address pressing environmental concerns, human social systems and ecological systems must no longer be considered as separate entities but rather interdependent systems. Glaser et al. (2012) defines this system as "... a complex, adaptive system consisting of a biogeophysical unit and its associated social actors and institutions. The spatial or functional boundaries of the system delimit a particular ecosystem and its problem context" (p.4).

In line with this conception and theoretical framework, Skalkaho Creek can be considered a distinct social-ecological system consisting of the native biota occurring across the 134 square mile sub-basin as well as the interdependent social actors and institutions. Figure 1 below displays a recent conception produced by Dunham et al. (2018) that argues for considering rivers as social-ecological systems. On the right-hand side are ecological systems that can be envisioned as containing a determined capacity to produce riverscape conditions. These conditions then flow to the left-hand side as ecosystem goods and services (e.g. water, food, recreation, flood protection, etc.) and are then utilized (or not) by the human social system. The use of these goods and services are mediated by the social conditions at play, which largely determine the pressures placed on the ecological system. This conception of rivers as distinct SESs' is useful when considering Skalkaho Creek, its current ecological system, the flow of those goods and services to the human social system, and how the human pressures in turn effect the ecological system. This paper will largely focus on the ecological systems' capacity, specifically the climatic conditions effecting water quantity and will offer avenues for inquiry into sub-systems and social conditions on-the-ground.

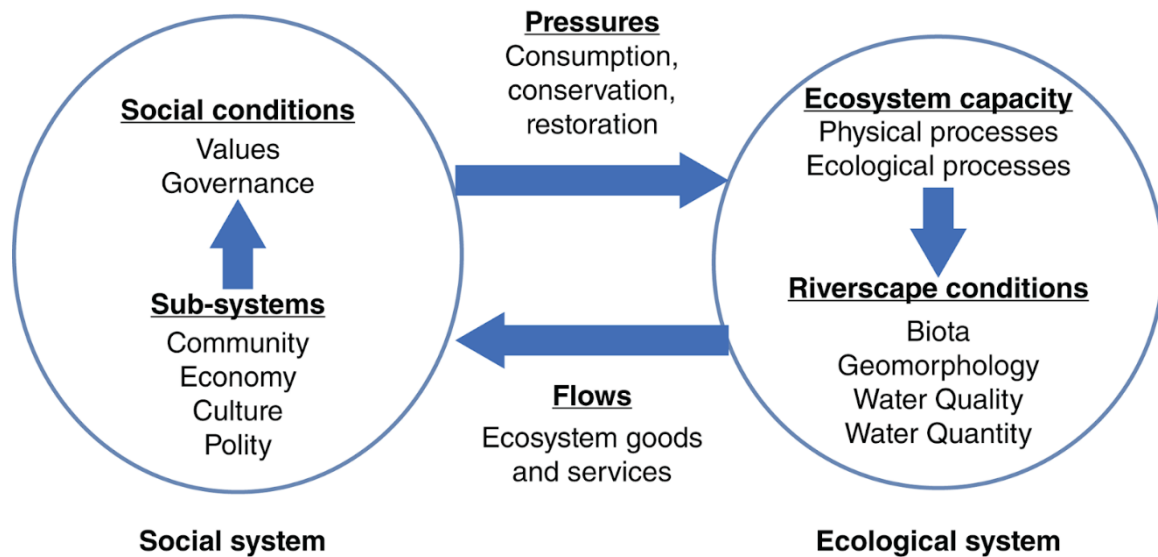


Figure 1. Adapted from Dunham et al. (2018)

In social-ecological systems research, change is a given. All social-ecological systems experience change and must adapt to their current bio-geophysical conditions. The ability for a system to absorb changes and continue to develop is referred to as its resilience. Adger (2006) posits that “... resilience refers to the magnitude of disturbance that can be absorbed before the system changes to a radically different state as well as the capacity to self-organize and the capacity for adaptation to emerging circumstances” (p.269). A system that is more susceptible to various disturbances is considered vulnerable.

In terms of social-ecological systems, vulnerability can be adequately summarized as the potential for loss. To better understand how the concept can be applied, the following type of questions should be considered: what is being lost; what factors may or may not contribute to that loss; will the loss be felt equally across human or non-human systems? These questions continue to stretch across academic disciplines. Susan Cutter (1996) penned an important vulnerability synthesis piece where she described three distinct themes in vulnerability research: vulnerability as a risk/hazard exposure,

vulnerability as social response, and vulnerability of places. The third—vulnerability of places—is described as a “third direction [that] is emerging [and] combines elements of the two, but which is inherently more geographically centered” (Cutter, p.533). This new direction opened the door for exploring climate vulnerability as a product of biophysical outcomes affecting a particular geographic location and the social response of the people inhabiting that locale.

Neil Adger (2006) refined the definition of vulnerability as the susceptibility to harm occurring when social or ecological systems are exposed to stresses associated with environmental or social factors and when the systems do not possess the capacity to adapt. The concept can be thought of as any variable’s sensitivity to stress divided by the system’s current state relative to its likely threshold multiplied by the probability of exposure to stress. Another way to conceive of a systems vulnerability is by considering how exposed a system is to certain stressors combined with its sensitivity to the same or similar stressors minus its adaptive capacity. In essence, social-ecological vulnerability is analogous to low levels of system resilience. To put it a bit more elegantly, “ $V = E + S - AC$; whereby V = vulnerability; E = exposure; S = sensitivity; AC = adaptive capacity” (Bennett et al., 2016).

Considering vulnerability as it applies to social-ecological systems, the following analysis conducted in chapter 1 examines ecosystem capacity through an investigation of historical snowpack retention via a Geographic Information System (GIS). The GIS looks across the entire Hydrologic Unit Code (HUC) 8 Bitterroot watershed in order to discern differences in snowpack retention over time for the sixteen HUC 10 sub-basins that make up the larger watershed. This analysis was conducted at the basin scale to consider the

Skalkaho Creek sub-basin relative to the 15 other Bitterroot watershed sub-basins in terms of snowpack retention. This consideration facilitates a discussion of how vulnerable Skalkaho Creek is to diminished snowpack retention and resultant lower late season streamflows. In chapter 2, I use the discussion and results from chapter 1 to lay out a roadmap for a future researcher to follow with suggestions regarding a full-fledged vulnerability assessment of the distinct Skalkaho Creek HUC 10 sub-basin. This roadmap acknowledges the nested nature of Skalkaho Creek within the larger Bitterroot HUC 8 watershed, the water governance reality in Montana, and larger national and global trends arguably affecting the system's functionality.

All told, the snowpack analysis and subsequent vulnerability roadmap should be useful to a future student, governmental, or nongovernmental researcher attempting to better understand Skalkaho Creek as a social-ecological system. More importantly, this paper should illuminate ways to consider the various contextual elements outlined hereafter to better understand current social-ecological complexity and the potentially tenuous situation Skalkaho Creek, its dependent irrigators and social system, as well as the existing ecological system currently reside.

Intermountain West Trends Toward Smaller and Smaller Snowpack

Averages

Mountain ranges across the western United States act as “water towers” for the valleys below, which tend to include human settlements. These water towers typically accumulate snow throughout the winter months, store them as snowpack, and slowly release that snowpack downgrade throughout the summer season as liquid water. In western Montana, including the Bitterroot basin, snowmelt runoff directly provides a

large share of water for agricultural uses, human consumption, and aquatic ecosystems. Indirectly that same snowmelt contributes to human-induced groundwater recharge, which is becoming an increasingly popular source of domestic water supply for both Ravalli County residents and municipalities. The variability of this spring runoff is of critical importance to irrigation district managers, fisheries' biologists, and private water-right holders attempting to balance the myriad demands for the precious meltwater. Furthermore the timing has become increasingly variable, and as a general rule, a shift toward earlier snowmelt and earlier peak runoff date has been observed across the Intermountain West and Western Montana (Mote et al., 2005; Stewart et al., 2005; Whitlock et al., 2017). These findings and predictions represent a potent exposure to less available meltwater. However, the degree to which water users and fisheries experience them depends on how sensitive they are and how much adaptive capacity they possess.

Findings indicating changes in snowpack behavior prompted Montana researchers to take a more critical look at future climate scenarios and their impact to snowpack. The Montana Climate Assessment was first published in late 2017 to provide Montanans with research-driven predictions. It gives the likelihood of those predictions based on expert consensus and amount of credible evidence. The contributors to this publication follow guidelines for assessing confidence set by the National Climate Assessment and Intergovernmental Panel on Climate Change (IPCC). For clarification and from here on out:

Each key message provided in the Montana Climate Assessment is followed by a parenthetical expression of confidence. We asked our authors to assess their confidence in the key message by considering a) the quality of the evidence and b) the level of agreement among experts with relevant knowledge used to craft the message. We then used these two factors and the criteria used in the National Climate Assessment (see

graphic below) to assign the confidence ratings expressed in the MCA. (Whitlock et. al., 2017, “Introduction,” para. 9)

The Montana Climate Assessment points out that as Montana warms over the next century, snowpack at mid and low elevations (below 8,000’) is likely to be reduced (high agreement; robust evidence); historical observations show that peak spring runoff has occurred earlier and earlier in the season and this trend is likely to continue (high agreement; robust evidence); and arguably most importantly, earlier snowmelt coupled with earlier peak spring runoff is likely to decrease water availability in snowmelt dominated watersheds for late-season uses (high agreement; robust evidence) (Whitlock et. al., 2017). These predictions are likely to negatively impact meltwater availability across the 16 Hydrologic Unit Code (HUC) 10 sub-basins, but these predictions are especially of concern for the Sapphire range sub-basins constituting the eastern Bitterroot watershed boundary. This boundary does not rise much higher than 8,000’ above sea level that the Montana Climate Assessment points out as a relative threshold for concern: those areas above 8,000’ are likely to be less impacted than areas below 8,000’ elevation.

Snowpack accumulation and ablation have been extensively studied in the scientific community, and for snowmelt-dominated watersheds the data and predictions are critically important. Snowpack accumulation in the Northern Rockies is largely driven by global and continental scale climate processes (Selkowitz et al., 2002). However, at the watershed level, a complex relationship between “...regional precipitation and temperature regimes coupled with landscape and landform factors such as elevation, slope, aspect, canopy, and latitude ultimately drive local scale variation of snowpack accumulation” (Broberg, 2019). Natural resource managers and farmers, as well as others interested in overall snowpack totals, tend to rely on snow water equivalent

(SWE) to understand how much liquid water will be made available upon snowpack ablation. In large part, the SWE is depended upon because it is unaffected by short-term changes in snow depth from settlement, compaction, and spring freeze/thaw events. Most importantly, it provides interested parties the most accurate characterization of liquid water available for the summer irrigation season.

It is well understood that as global warming progresses, overall snowpack and ablation rates are expected to change. The Northern Rockies are predicted to see increased periods of precipitation falling as rain as opposed to snow during the normal peak accumulation season (Knowles, Dettinger, & Cayan 2006). Furthermore, studies conducted by Mote et al. (2005) and Pederson, Betancourt, and McCabe (2013) have documented the links between climate change processes and overall snowpack reductions in Intermountain West snowpack. In fact, Pierce et al. (2008) found that up to 60% of overall snowpack decline between 1950 and 1999 in the Intermountain West was attributable to human carbon emissions and resultant climate change processes.

Studies have also pointed to the fact that extreme precipitation events (i.e. heavy snowfall or abnormal rain events) have an outsized effect on precipitation regimes (Lute & Abatzoglou, 2014), and that these events tend to occur when temperatures are at or near freezing (O’Gorman, 2014). However, the balance between warming temperatures and resulting precipitation as rain is uncertain. While uncertainty may exist regarding extreme precipitation events, snowpack observations indicate snowpack has declined over the period of record. This negative trend is expected to continue, and, most importantly, it is highly likely anthropogenic forcings are playing an outsized role when compared to more traditional, non-human drivers of global climate changes. In fact, some

projections estimate that snowpack in the western United States will decline by as much as 60% in the next 30 years if business-as-usual emissions scenarios remain (Fyfe et al., 2017).

Snowpack and streamflow timing studies exist at the watershed (Farjad, Gupta, & Marceau, 2016), river basin (Kang et al., 2016), regional (Stewart, Cayan, & Dettinger, 2005), and global scales (Adams, Hamlet, & Lettenmaier, 2009). However, these studies are either too coarse in scale for managers to make informed decisions or the methodology by which predictions are made is too onerous for managers and water dependent communities to utilize effectively (i.e. complex mathematical model). Moreover, irrigation district managers, especially those dependent on smaller HUC 10 sub-basins, need information at a finer scale than most interpolated climate products allow. However, Daymet interpolates SWE across 1km² pixels, which would allow irrigation district managers to assess SWE changes over time at the HUC 10 scale. By doing so, these managers could use that information to tease apart challenges to adaption, identify opportunities for mitigation, and ultimately help resolve the allocation of water resources. Climate change poses myriad threats to Montana, the Pacific Northwest, and North America at-large, which include: increasing overall average temperatures, changing hydrologic regimes, increasing prevalence and severity of drought, and the resultant challenges to human society.

For many Bitterroot sub-basins (Skalkaho Creek included), the available surface water is largely controlled by irrigation districts who manage and maintain water distribution infrastructure and deliver that water to all district members provided they pay membership dues. DDID is one such example of this water management system. DDID,

like many other irrigation districts, is dependent on a certain amount of snowmelt realized as irrigation water each year. However, access to this surface water is unequally distributed and limited by year-to-year hydrographic variations. It is reasonable to argue that Skalkaho Creek is overallocated in terms of irrigation water, let alone that which would be necessary to support a sustainable fishery. In fact, a local Hamilton, Montana, resident and DDID employee informed me that if DDID wanted to fill all of their Skalkaho Creek water rights during the regular irrigation season, they would “run the creek dry” (personal communication, September 1, 2018). Additionally, a local newspaper has corroborated fears regarding low water years on Skalkaho Creek and stress to various downstream users as a result (Backus, 2013). These observations are corroborated by Figure 2, taken from the United States Geological Survey (USGS) showing yearly hydrographs for Skalkaho Creek from 1958 - 1983. Unfortunately, stream gauges on Skalkaho Creek are no longer operational, and thus current data is unavailable. However, this data does provide insight into average flows from the past. Of importance to DDID are distinct peaks of typically around 600 cubic feet per second (cfs) in early summer and a quick decline to under 100 cfs by mid to late summer. DDID holds at least 22 separate rights for irrigation water ranging from 1 cfs to 53 cfs and with priority dates from 1865 to 1891. In total, these various water rights to Skalkaho Creek meltwater add up to 318 cfs for the period of April 1 through October 31 each and every year.

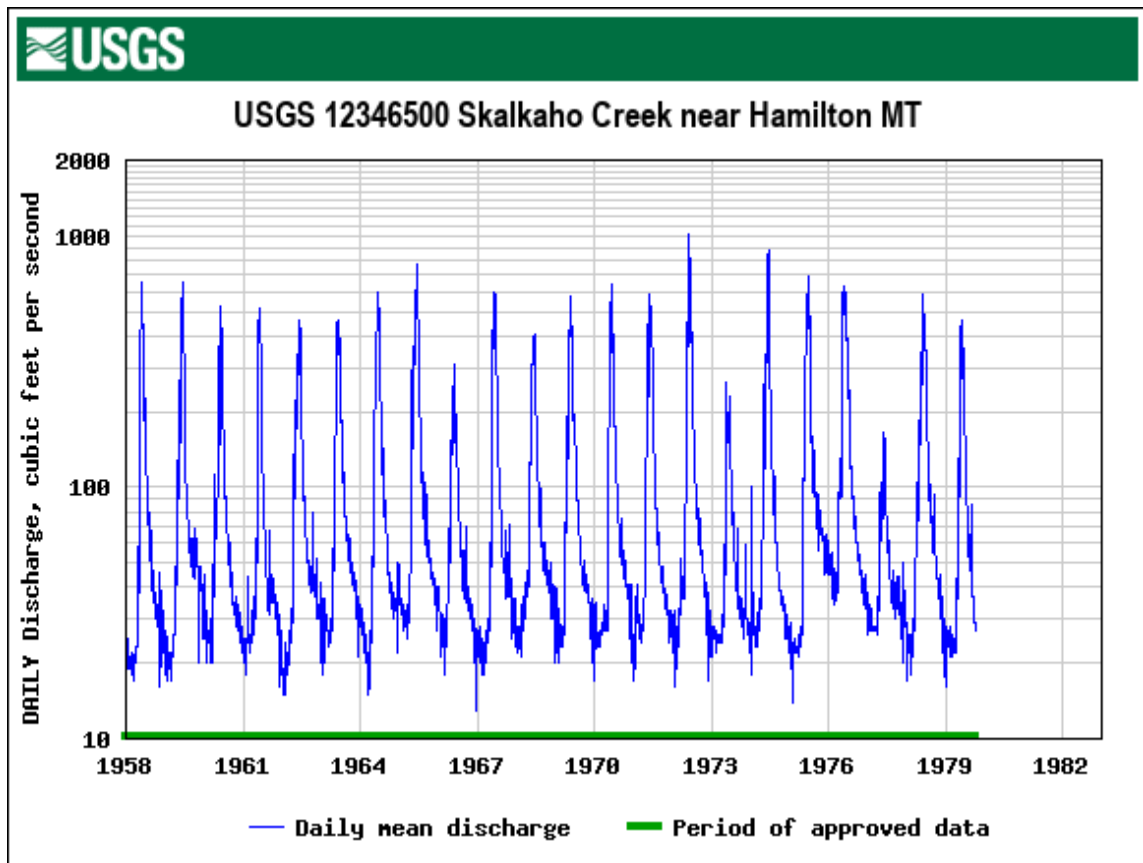


Figure 2. Skalkaho Creek hydrograph from 1958 to 1983. From U.S. Geological Survey, 2020, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed June 10, 2017, at URL <https://waterdata.usgs.gov/nwis/>

The reality of water shortages in times of below average snowpack or above average ablation is further complicated by the legislative closure of further claims to Bitterroot Valley surface water due to potential overallocation. Rapid population growth, increased subdivision of large parcels, a continuous flow of new water right applications, and a lack of accurate records pertinent to historic water claims gave the state of Montana reason to close the Bitterroot River Basin and all of its tributaries to new surface water allocation effective March 29, 1999. This closure was intended to give the DNRC time to sort out all of the claims, and it meant that the Montana Department of Natural Resources

and Conservation (DNRC) could not process a new surface water right application until after all Bitterroot watershed surface water rights had been adjudicated. Now a little over twenty years later, the closure is still in effect. The combination of diminishing surface water availability and a rigid governance structure that prioritizes the earliest use above all else presents a complex or “wicked” problem for DDID and other valley appropriators.

Wicked problems, as first introduced by Rittel and Webber (1973), are characterized as those problems which are ill-defined and rely upon human judgement for resolution. These problems are different from more traditional natural scientific pursuits or problems which can be readily defined and that may have findable solutions. On the contrary, wicked problems occur at the intersection between science and policy and therefore are infused with societal, cultural, and historical context.

The irrigation district, its members and otherwise affected non-members, and their associated dependencies on and interactions with the hydrologic regime and resultant naturally occurring non-human life can be considered a distinct social-ecological system. Broadly defined a “distinct social-ecological system” is a system consisting of a biogeophysical unit and its associated social actors. This concept argues and is built upon the foundation that human social systems and naturally occurring ecosystems cannot be considered without the other because they are inextricably connected. However, social-ecological systems (SES) also interact with one another across space, time, and can be considered at nested scales. These temporal and hierarchical considerations are known as a “panarchy.” This concept beckons researchers to consider the myriad connections between one SES and another when analyzing a particular piece of the puzzle at a finite

focal scale. Considering the above definitions and concepts, I will focus the following analysis and roadmap on the distinct social-ecological system encompassing the distinct Skalkaho Creek HUC 10 sub-basin while acknowledging its nested nature.

Research Design

A case study differs from all other research methods in that it is not a methodological framework. It is rather a means of inquiry that spans disciplines and can thus employ numerous methodological approaches (Hesse-Biber & Leavy, 2011). I used a mixed-methods approach, initially employing a GIS to examine snowpack retention through time via Daymet snow water equivalent (SWE) data and then sought to validate Daymet against observed SNOTEL SWE records. This snowpack analysis provides a jumping-off point and informs potential subsequent considerations: by DDID members whose water comes exclusively from Skalkaho Creek; for other irrigation districts and their members whose water originates from a finite source; or to inform valley-wide economic trends. This consideration of vulnerability will be conducted in the spirit of Adgers' (2006) conception as the equation: $V = E + S - AC$; whereby V = vulnerability; E = exposure; S = sensitivity; AC = adaptive capacity. For instance, DDID is exposed to the various consequences of a rapidly changing climate, and as such, the district and its Skalkaho Creek users will likely face more frequent water shortages. These shortages will likely be driven by diminished snowpack totals, earlier onset of spring snowmelt, and lower late season flows as a result. Users' sensitivities will more likely have to do with individual users' distance to main lateral, purpose for water usage and size of operation, understanding of district by-laws, and other yet unidentified factors.

CHAPTER 1: SNOWPACK ANALYSIS

Material & Methods

To ground my analysis of the irrigation district and its challenges, I first assessed snowpack retention over time. This analysis shed light on the potential spatial differences in exposure to snowpack loss and heightened ablation rates. To do this, I employed a methodology outlined by Broberg (2019) which utilizes Daymet data from 1980 - 2018 and investigates snowpack retention over time. Daymet was chosen because it is the only gridded climate product with a fine enough scale (1km x 1km) to compare HUC 10 watersheds, and it is one of the few products to interpolate SWE. I looked at the Bitterroot basin at-large in order to compare the various HUC 10 sub-basins to each other based strictly on snowpack retention over time. To calculate this sub-basin retention, I derived SWE values for April 1 and June 1 for the time period 1980 - 2018 via Google Earth Engine and imported those rasters to ArcMap for subsequent work with ArcGIS Spatial Analyst. Finally, I calculated mean SWE for April 1 and June 1 for each watershed polygon for each year from 1980 - 2018. Snowpack retention to changing climatic conditions was then estimated by $[(\text{June 1 SWE}/\text{HUC 10 sub-basin}) / (\text{April 1 SWE}/\text{HUC 10 sub-basin})] * 100$ to yield a snowpack retention metric (% retention). This metric will allow for a more nuanced analysis and discussion of Skalkaho Creek, DDID, and the dependent social-ecological system when viewed in comparison to other Bitterroot Valley sub-basins or irrigation districts.

In order to verify, corroborate, and justify April 1 and June 1 as adequate dates to assess snowpack retention, I first investigated average air temperature and temperature maximum trends for two SNOpack and TELEmetry (SNOTEL) sites located within the

Skalkaho Creek watershed: Daly Creek (figure 3) and Skalkaho Summit (figure 4). Daly Creek SNOTEL station is located just off a small Daly Creek tributary at an elevation of 5780' and precise location of latitude (46° 10' 59") longitude (113° 51' 0"). Just upstream along Daly Creek from the Daly Creek SNOTEL site lies Skalkaho Summit SNOTEL site. This site sits just below the rugged ridgeline that make up the Sapphire Mountain range. Skalkaho Summit SNOTEL site sits at an elevation of 7250' and precise latitude (46° 15' 0") longitude (113° 46' 0").

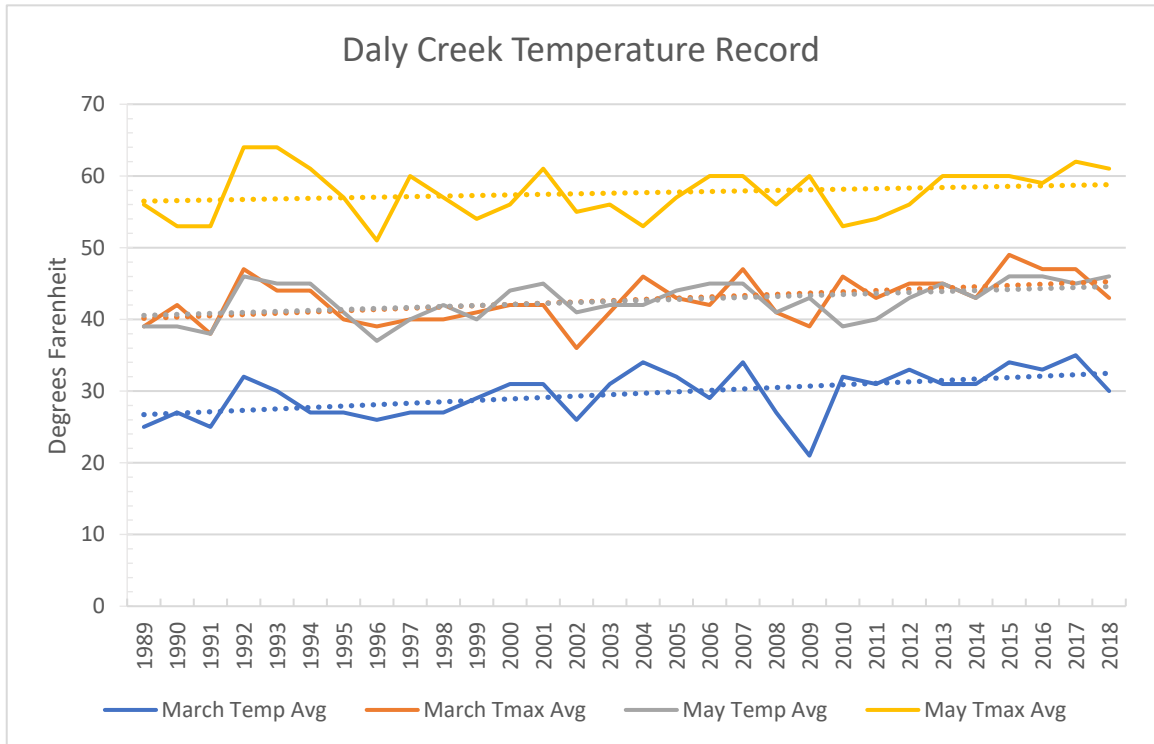


Figure 3. Daly Creek SNOTEL site temperature record from 1989 to 2018.

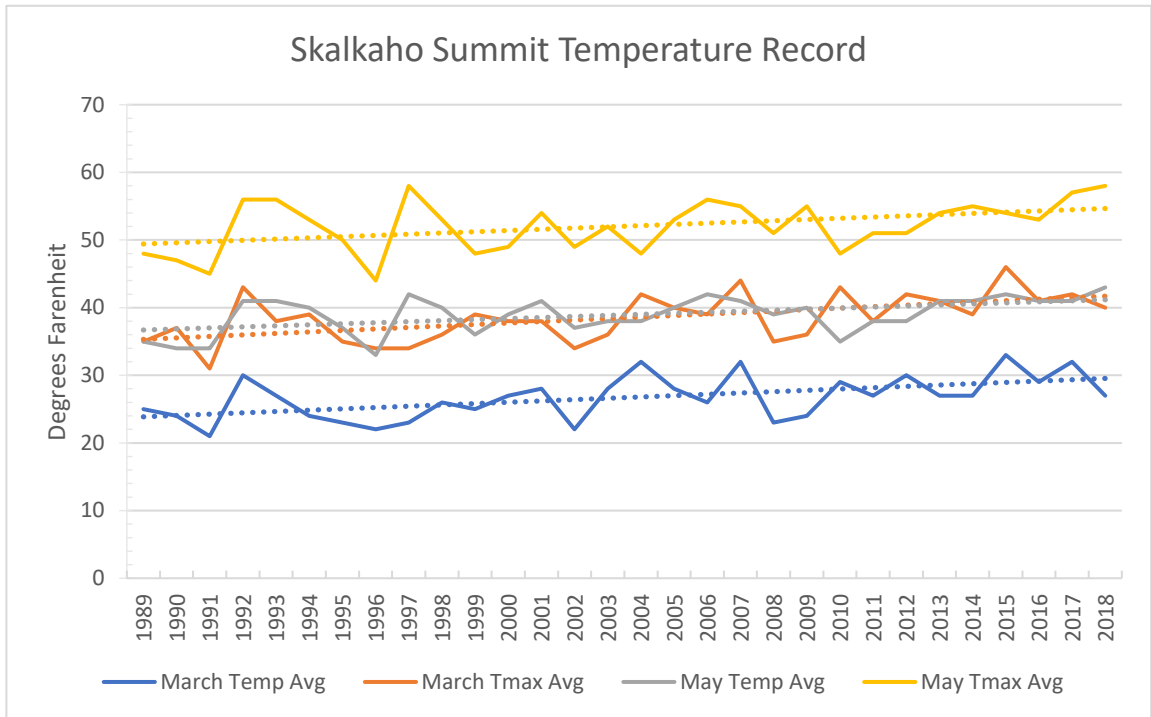


Figure 4. Skalkaho Summit SNOTEL site temperature record from 1989 to 2018.

Figures 3 and 4 based on Bitterroot Basin SNOTEL stations show a gradual warming trend over the time period 1989 - 2018. The approximately 5.0°F rise in temperature from 1989 - 2018 falls in line with Whitlock et al. (2017) who noted that across Montana temperatures have increased between 1950 and 2015, and that change in temperature were most pronounced during winter and spring. Put another way, figures 5, 6, 7, and 8 display the difference for each year from the average temperature for that SNOTEL site period of record and the respective month. Again, the difference from the average is generally lower than average for the period 1989 - 2002 and generally above average for the period 2002 - 2018.

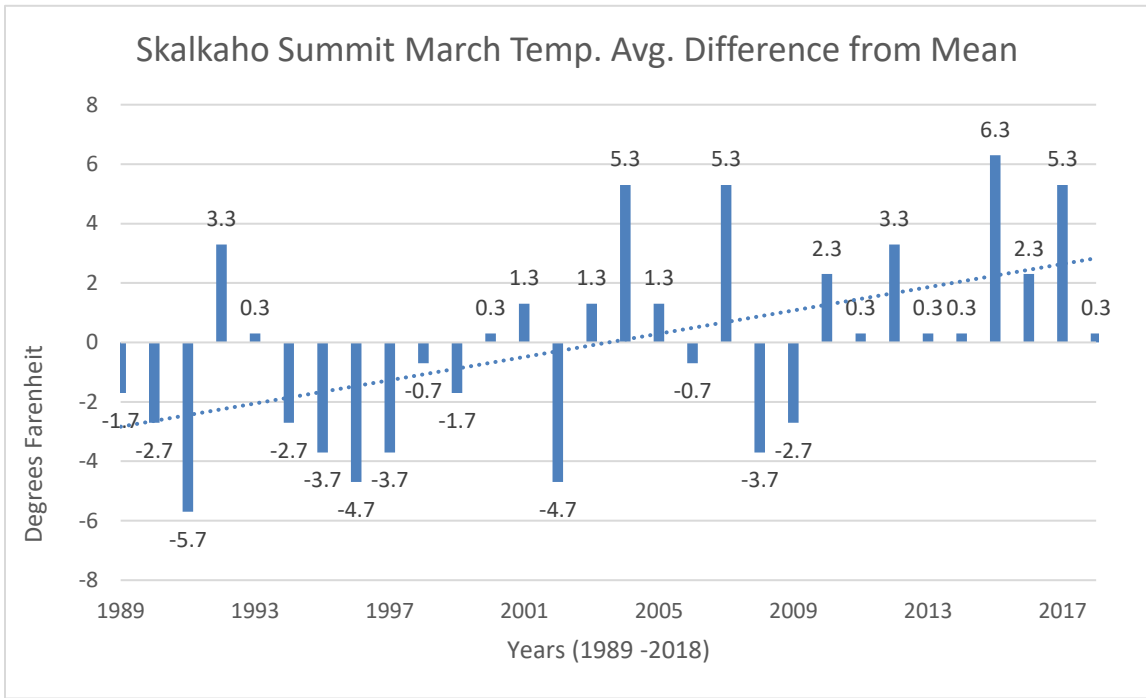


Figure 5. Skalkaho Summit SNOTEL site March temperature average difference from the mean over the period of record.

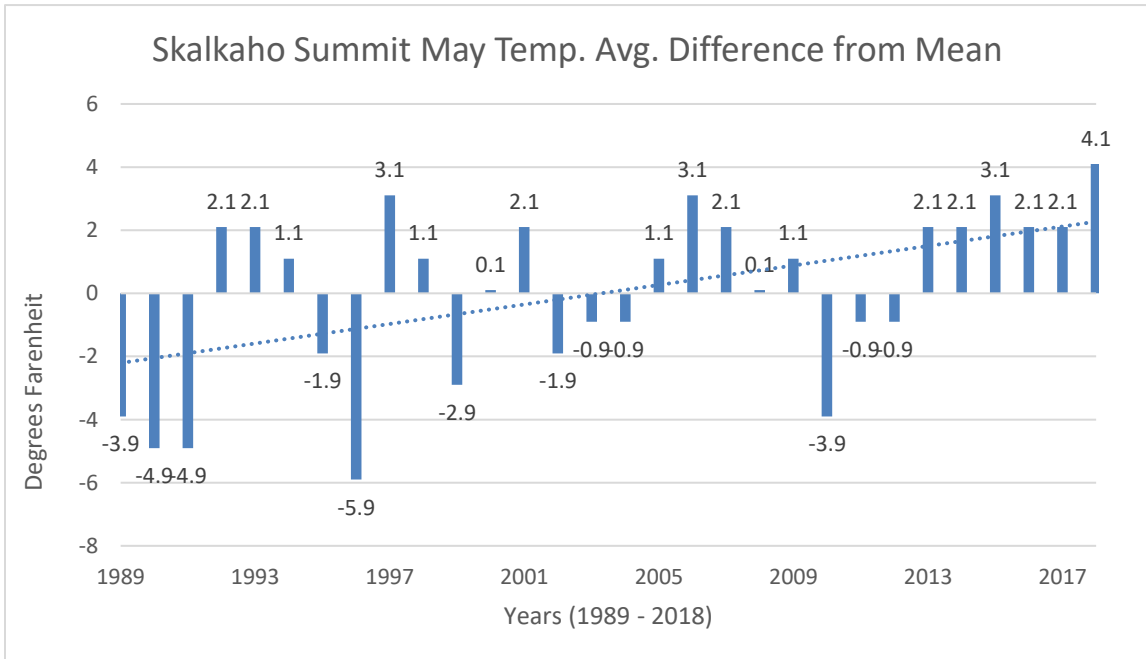


Figure 6. Skalkaho Summit SNOTEL site May temperature average difference from mean over the period of record.

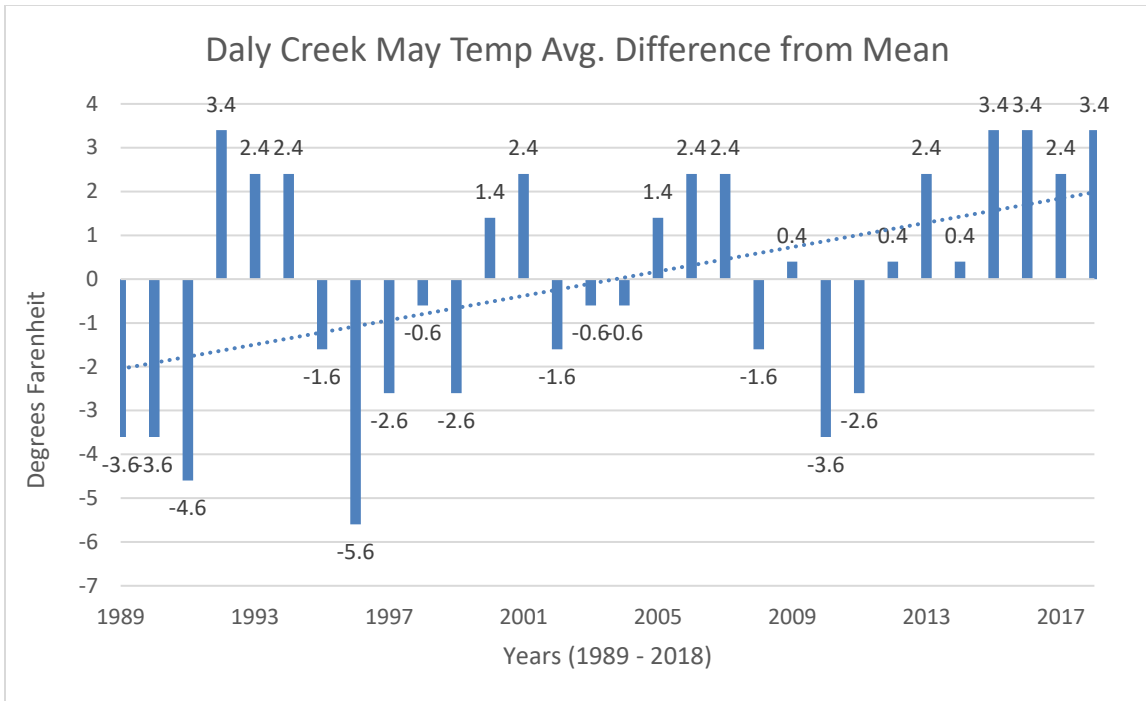


Figure 7. Daly Creek SNOTEL site May temperature average difference from the mean over the period of record.

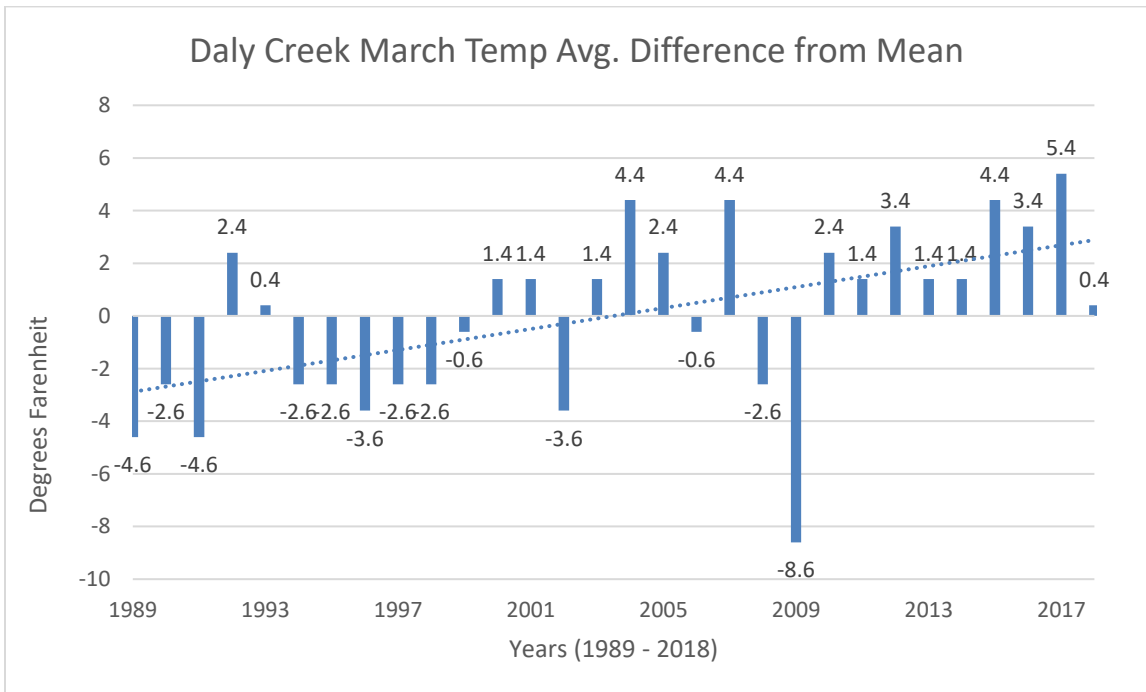


Figure 8. Daly Creek SNOTEL site March temperature average difference from the mean over the period of record.

One potential effect of this observed warming trend is an earlier beginning to the spring snowmelt season. Assuming the warming trend continues at the current pace, ablation rates and runoff onset timing will likely be higher and earlier during the spring snowmelt season. This result has consequences for both the human social and economic systems that rely on consistent yearly flows to replenish reservoirs, fill irrigation canals, and provide recreational opportunities along healthy rivers and streams. Natural ecosystems, too, are accustomed to such predictable seasonal hydrologic variation. Past conditions ensured enough water to facilitate migratory behavior and relatively cool stream temperatures crucial to many species' biology. This warming trend validates the investigation of snowpack retention rate change over time, and how well Daymet predicts this trend when compared at the pixel level to SNOTEL observations.

Importantly, Daymet calculates SWE by requiring inputs: T_{min} , T_{max} , and precipitation. Daymet temperature observations come from two sources: National Climate Data Center and SNOTEL (Thornton et al., 2016). Approximately twenty-five years ago, a field campaign was launched that lasted through the mid-2000s to replace these SNOTEL sensors due to likely temperature bias. Recently, Oyler et al. (2015) found that SNOTEL temperature sensors significantly bias both T_{min} and T_{max} , and the new sensors appear to be biasing T_{min} towards warmer readings. This bias is more pronounced during the relatively colder winter months, but it is also present during the spring snowmelt season.

Due to the above findings, I also sought to validate SWE derived from Daymet with SWE as measured at the five Bitterroot Watershed SNOTEL sites: Skalkaho Summit, Daly Creek, Twin Lakes, Twelvemile Creek, and Nez Perce Camp. This

validation was performed by converting SWE (in.) to SWE (kg/m^2). First, SWE (in.) was converted to a snowload (lbs/ft^2) estimate by multiplying SWE (in.) by 5.2 (Natural Resource Conservation Service, n.d). After converting to snowload, I converted snowload to the metric equivalent through multiplying lbs/ft^2 by 4.88. This resulted in a comparable value to Daymet, which calculates SWE as kg/m^2 . However, Daymet is a gridded raster mosaic with individual pixels measuring $1\text{km} \times 1\text{km}$, so for each pixel, Daymet assigns what could be considered an average kg/m^2 for the entire km^2 . This value was then compared to Daymet SWE derivations for model fit and consistency.

Results

Snow Water Equivalent is an important metric for Intermountain West communities dependent on a consistent yearly pulse to recharge streams, provide irrigation potential, and sustain drinking water supplies. Analysis of Daymet data at the HUC 10 sub-basin level indicates an overall decline in SWE retention from April 1 - June 1 (see figure 9) for the entire HUC 8 Bitterroot River Watershed. Additionally, two SNOTEL sites that regularly record snowpack on June 1, Twin Lakes and Skalkaho Summit, have also seen a decline in amount since 1989 (see figures 11 and 14, respectively). Interestingly, all five of the SNOTEL sites have trended slightly upwards in April 1 SWE values. However, a closer inspection of April 1 SWE values via Daymet (see figure 9) shows a probable decrease in April 1 SWE values when looking at the entire sub-basin. This data point underscores the importance of considering snow accumulation across a particular geography and not just in one fixed location. Furthermore, the observed increase of April 1 SNOTEL SWE values and observed declines in June 1 SNOTEL SWE values lends credibility to conclusions that snowpack ablation is likely occurring earlier in the spring snowmelt season, which is consistent with the upward temperature trends observed at the two Skalkaho Creek SNOTEL sites.

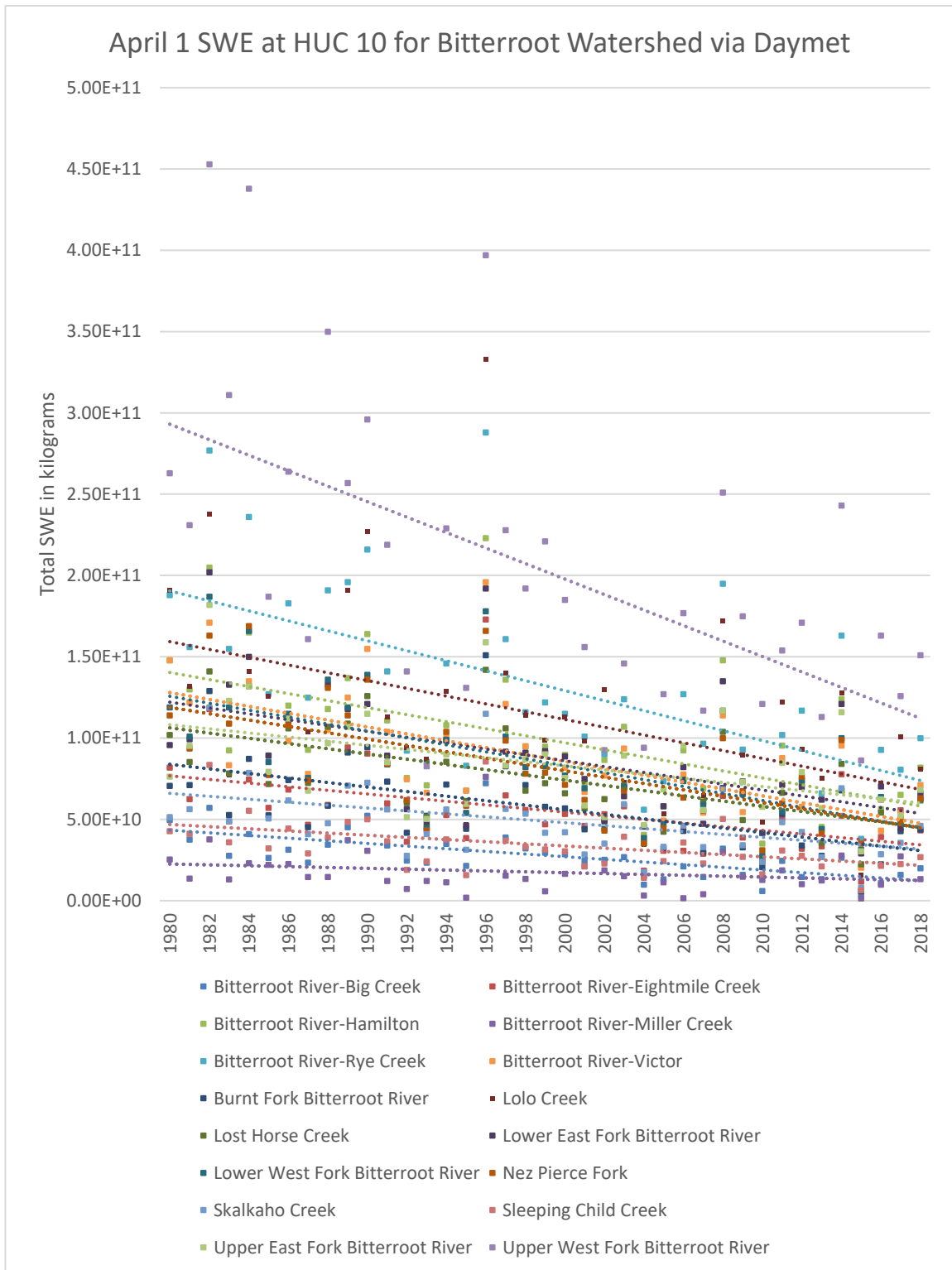


Figure 9. April 1 SWE values calculated via Daymet dataset.

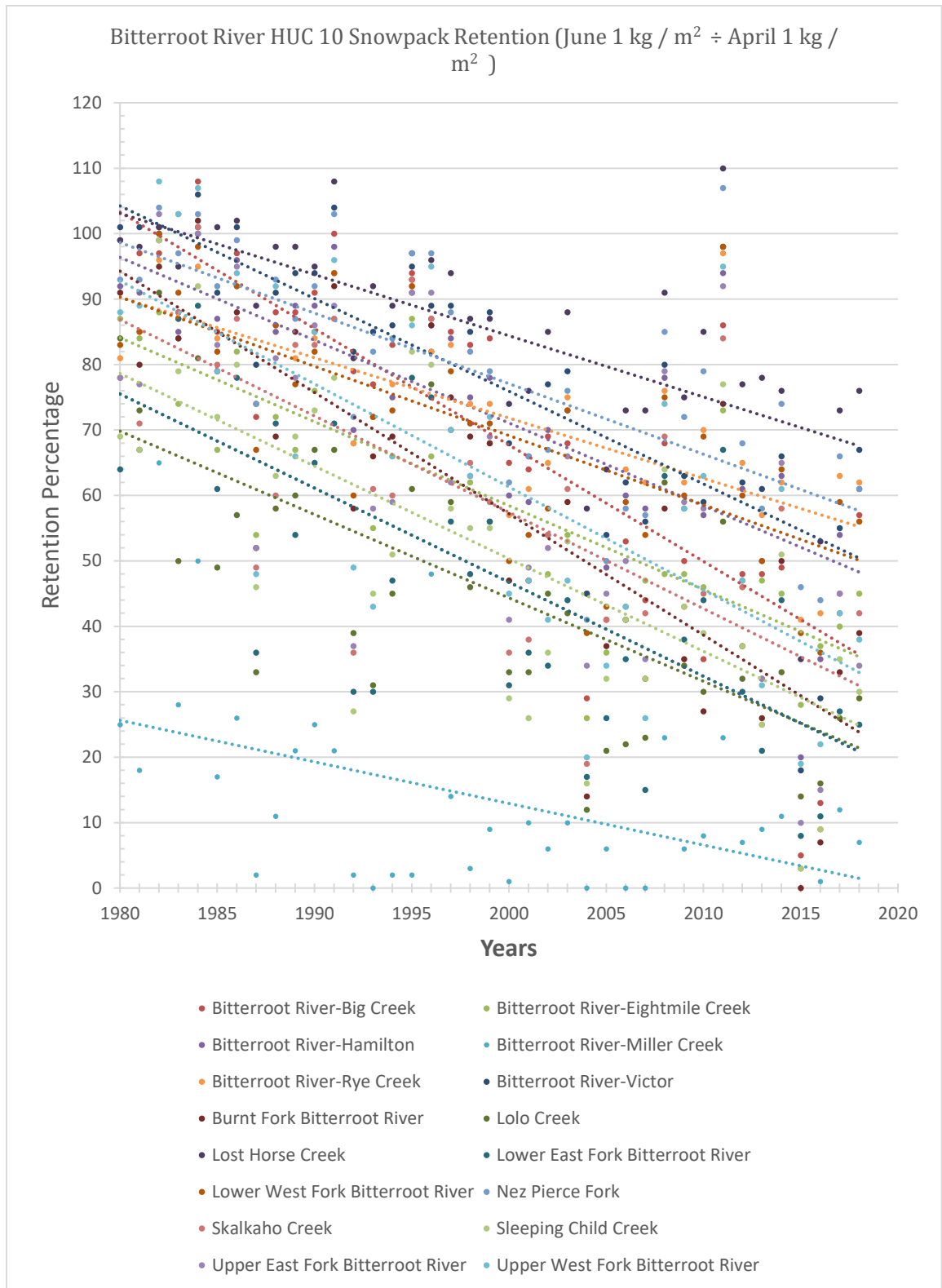


Figure 10. Retention percentages over time for the 16 HUC 10 sub-basins of the HUC 8 Bitterroot River watershed as calculated via Daymet data.

Figure 10 shows that SWE retention, as calculated with Daymet data, has dropped over 30 percentage points for all HUC 10 sub-basins except Miller Creek, which has dropped approximately 25 points and now hovers just above zero. This trend brings into focus the likely reality of less available freshwater for both human social systems and naturally occurring ecological processes, especially in the late summer. The steady downward trend in snowpack retention over time falls in line with the abovementioned various predictions laid out in the 2017 Montana Climate Assessment.

Figure 11 (pictured below) geospatially displays the mean retention percentage distribution across the 16 Bitterroot Watershed sub-basins for the years 1980 - 2018 and breaks them down into four quartiles. While the overall retention has diminished for all basins, the figure shows that those basins on the west side that make up the Bitterroot Range likely being more retentive now and moving forward than those on the eastern Sapphire side. This is likely due to the Bitterroot Range having significantly more land above 8,000' than the relatively lower on average Sapphire Range. For example, the highest point in the Bitterroot Range is Trapper Peak (10,157') compared with Kent Peak (8,999') the Sapphire Range high point.

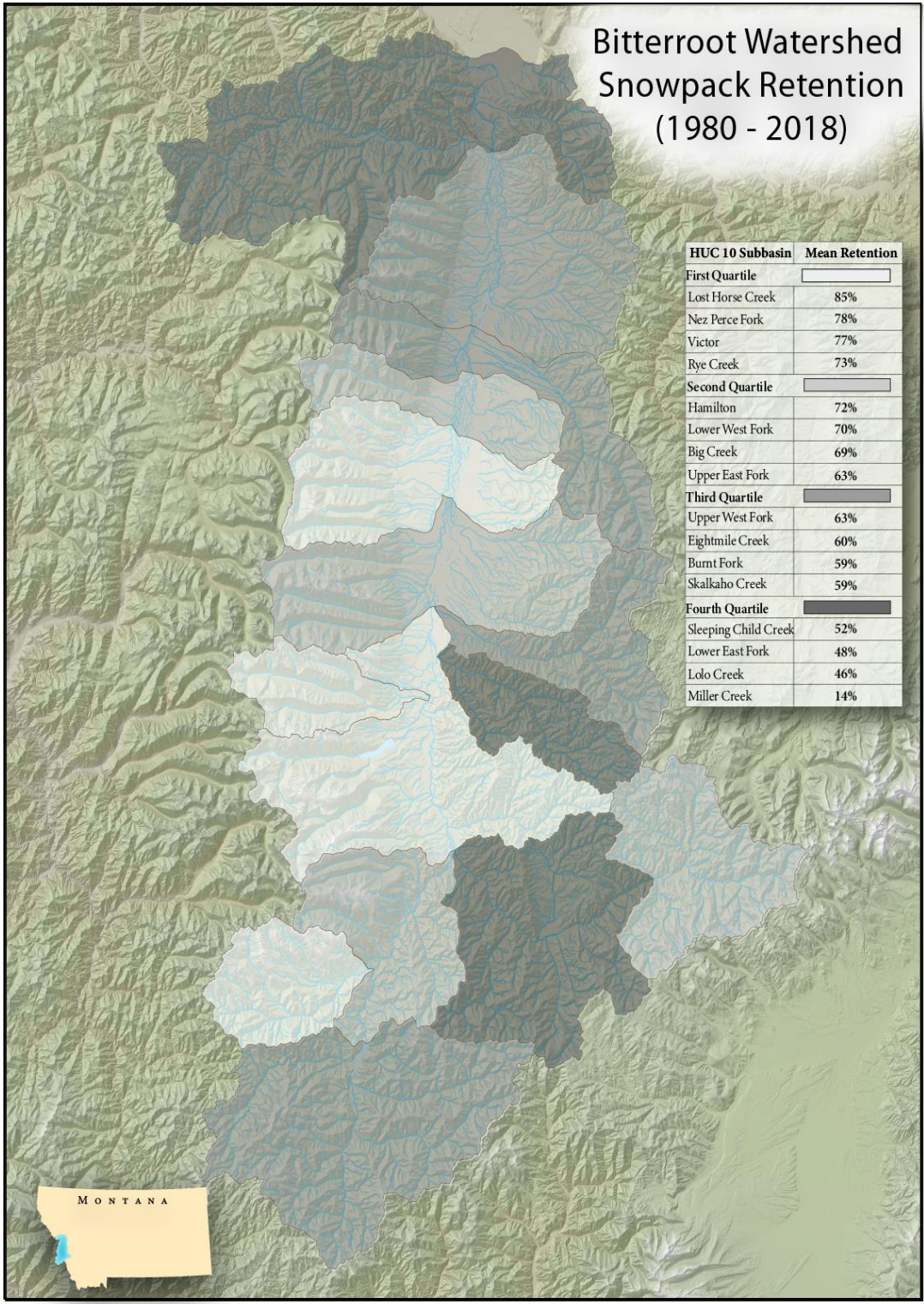


Figure 11. Mean retention percentage (1980 - 2018) for all HUC 10 sub-basins ranked and displayed as quartiles.

Figures 12, 13, 14, 15, and 16 below display the results from the Daymet validation exercise. For the five SNOTEL sites investigated, April measurements do not line up well at all. For instance, the index of agreement calculated for April 1 values at Daly Creek SNOTEL site were >0.5 , which indicates paltry agreement between the observed and predicted values. This trend of low agreement was noted for all April 1 values with Nez Perce Camp and Twelvemile Creek faring a bit better with index of agreements of 0.57 and 0.53, respectively. June 1 values, on the other hand, revealed more varied results. The three lower elevation SNOTEL sites: Daly Creek (figure 16), Twelvemile Creek (figure 13), and Nez Perce Camp (figure 14) revealed almost zero agreement between the observed and predicted values. However, June 1 measurements line up much better at the two relatively higher elevation sites: Twin Lakes (figure 12) and Skalkaho Summit (figure 15) with index of agreement values at 0.72 and 0.84, respectively. Overall, this lack of model validation and inconsistent correlations point to Daymet being able to only do so much for managers looking to leverage it in order to make recommendations at the HUC 10 sub-basin level.

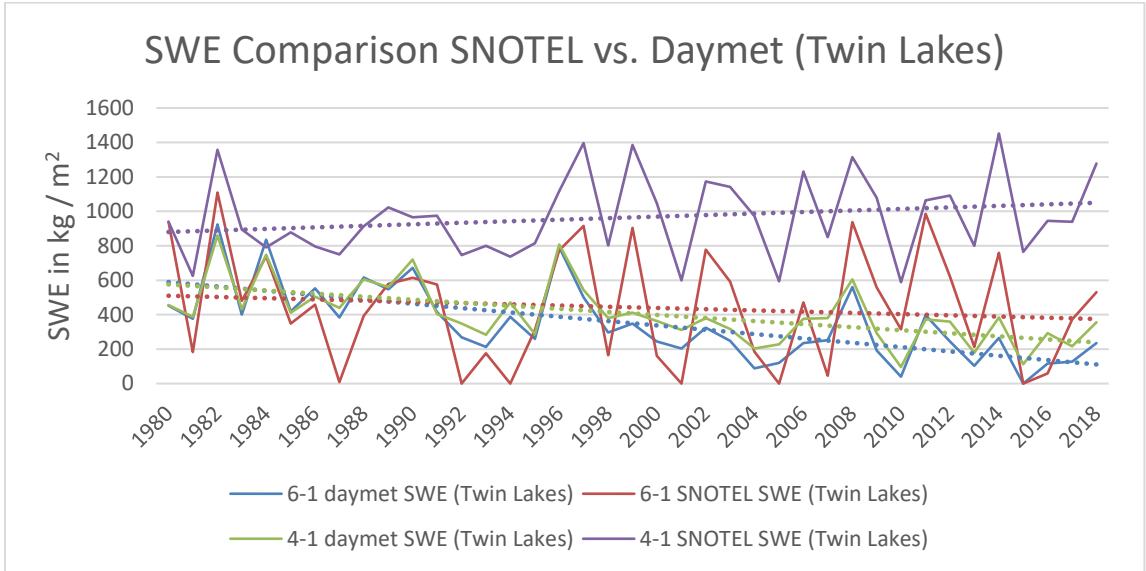


Figure 12. A visualization of how consistent Daymet is at predicting SWE values when comparing them to SWE values as observed at Twin Lakes SNOTEL station.

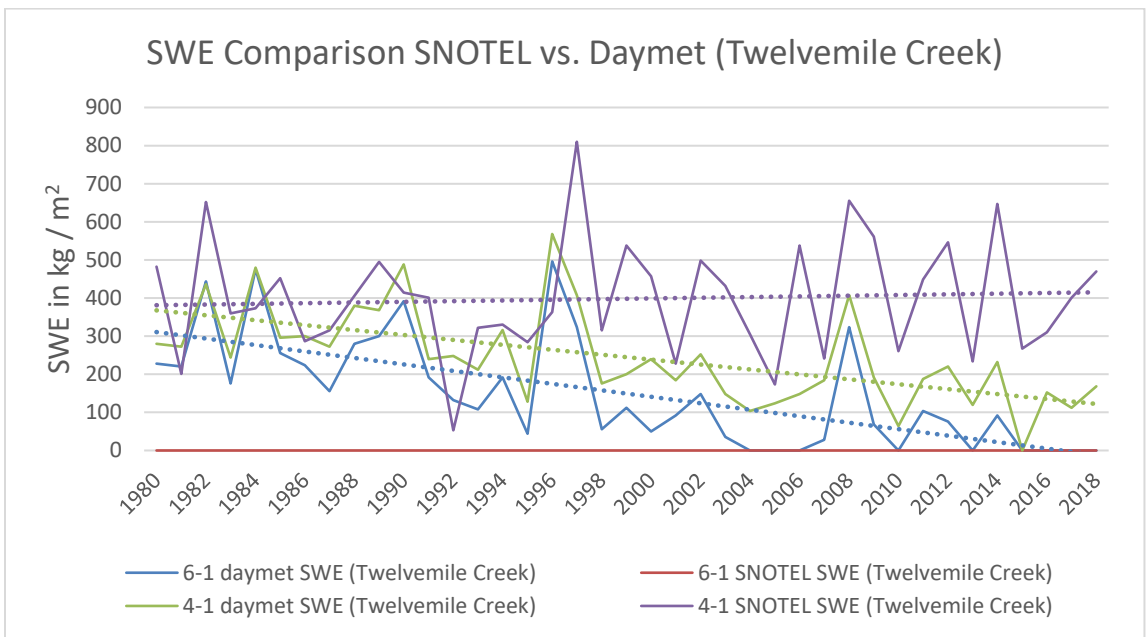


Figure 13. A visualization of how consistent Daymet is at predicting SWE values when comparing them to SWE values as observed at Twelvemile Creek SNOTEL station.

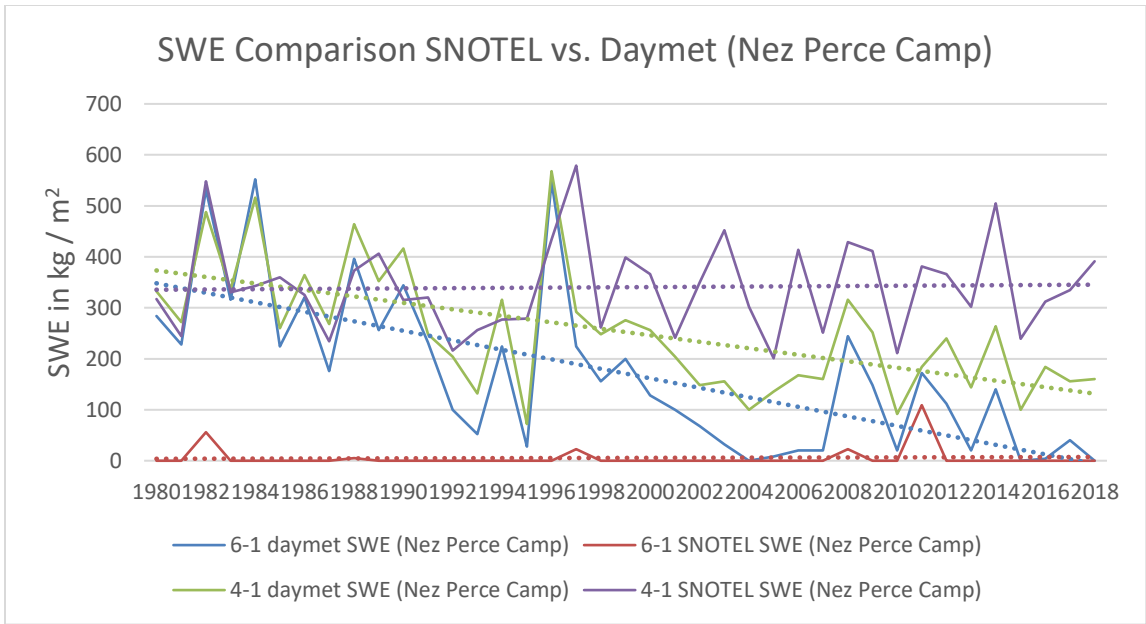


Figure 14. A visualization of how consistent Daymet is at predicting SWE values when comparing them to SWE values as observed at Nez Perce Camp SNOTEL station.

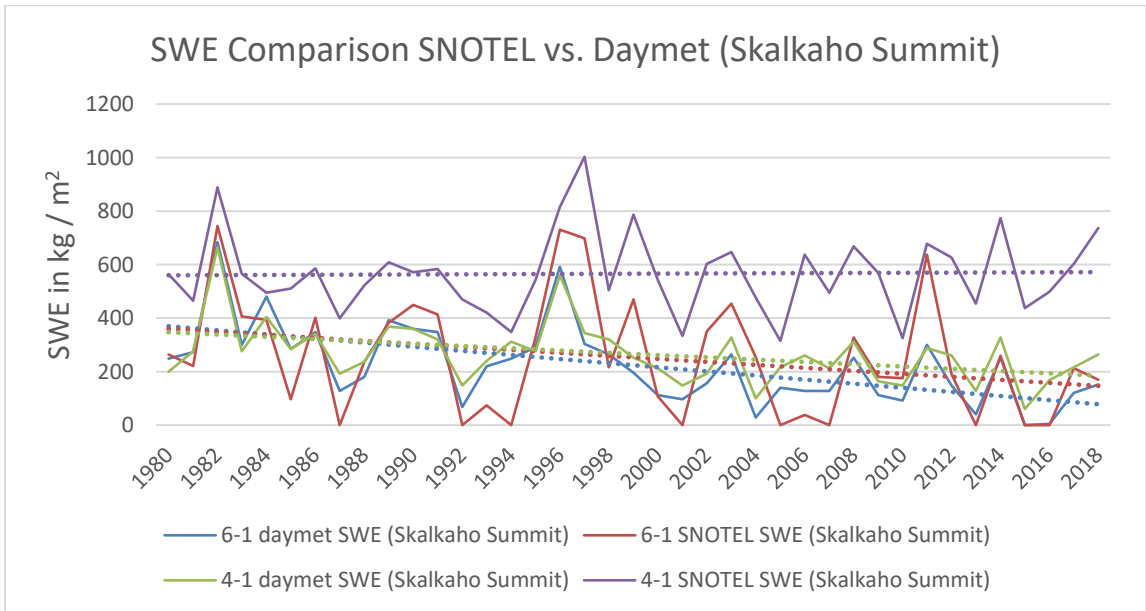


Figure 15. A visualization of how consistent Daymet is at predicting SWE values when comparing them to SWE values as observed at Skalkaho Summit SNOTEL station.

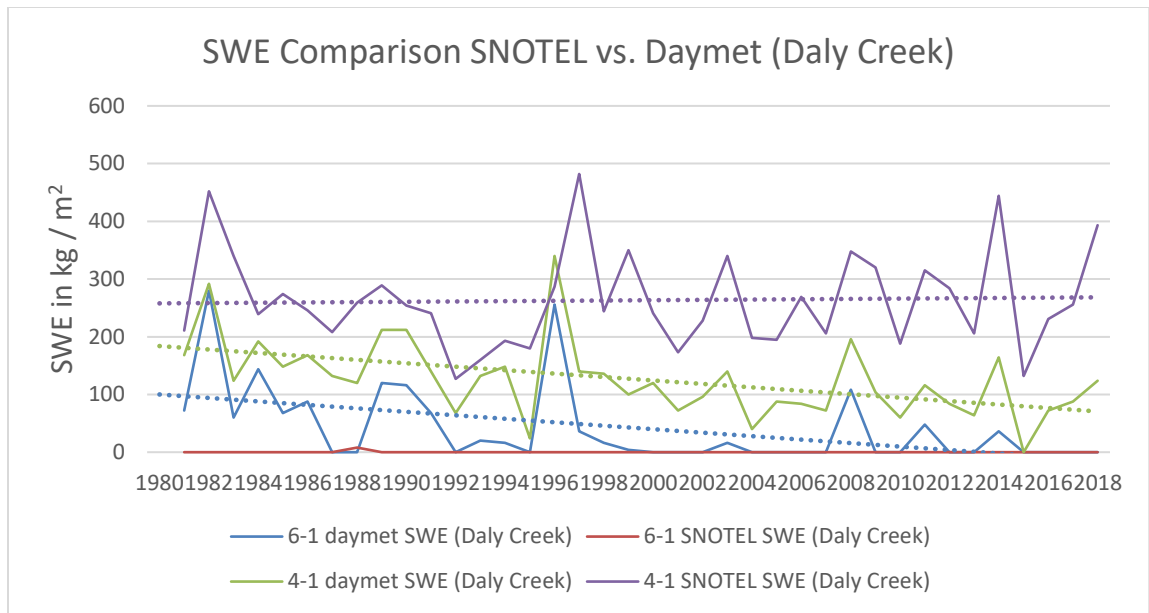


Figure 16. A visualization of how consistent Daymet is at predicting SWE values when comparing them to SWE values as observed at Daly Creek SNOTEL station.

Discussion

Changes in overall seasonal snowpack reductions, ablation rates, and spring snowmelt timing have been observed across the Intermountain West and in western Montana (Mote et al., 2005; Stewart et al., 2005; Whitlock et al., 2017). These changes have primarily resulted in less water available later in the summer season, and as a result, the observed alterations and future predictions represent arguably significant exposures to both water users and fisheries (Backus, 2013; Clark Fork Coalition, 2017; Northwest Power and Conservation Council, 2009). Causes for these changes have been linked to earth’s changing climate, and it is highly likely the mass combustion of fossil fuels and subsequent release of greenhouse gases into earth’s atmosphere are significant drivers of climate change processes (Fyfe et al., 2017).

Daymet is a powerful collection of gridded estimates that spatially represent daily weather parameters, and being the only gridded climate product at 1km x 1km resolution

that offers SWE as a data point, it is arguably the best, if not only, choice available to researchers looking to investigate SWE trends over time at the HUC 10 level. Overall, Daymet proves consistent with past trends and research which have noted a precipitous decline in snowpack across western Montana. As such, Daymet proves a decent research tool for managers looking to examine SWE trends over time. The retention ranking scheme, as demonstrated here for the Bitterroot watershed, could offer insight towards which HUC 10 sub-basins are more likely to be more resistant to climate change moving forward in time. This knowledge can help contextualize the hydrologic reality at the HUC 10 scale and act as a decision-making starting point or baseline for irrigation managers, fisheries biologists, and other interested stakeholders looking to balance the myriad needs for variable meltwater.

Of course, the decisions made with regards to a dataset can only be as good as the data being relied upon. In the case of this analysis utilizing Daymet datasets, certain results appear problematic if a manager intends to use Daymet to drive decision-making at the sub-basin scale. Considering the inconsistent agreement indexes found between Daymet and SNOTEL, it is worth considering if there are more appropriate gridded climatological products offering more accurate predictions. Oyler et al. (2015) recommended using TopoWX as it was the most accurate when predicting temperatures across the United States. However, TopoWX only looks to provide more accurate temperature trends over time, which does not help researchers in search of more accurate gridded SWE estimates. PRISM, on the other hand, offers both temperature and precipitation estimates, but instead of differentiating between liquid and frozen water, PRISM offers precipitation as rain + melted snow. Additionally, Oyler et al. (2015) found

PRISM temperature bias to be fairly similar to the bias found in Daymet. SNOW Data Assimilation System (SNODAS) contains snowpack properties, including SWE, and was developed by the NOAA National Water Service's National Operational Hydrologic Remote Sensing Center (NOHRSC). It models conditions based on specific point observations as well as remotely sensed satellite data. Broberg (2019) found April 1 SNODAS values to correlate strongly with Daymet. However, that positive correlation could be partly due to Daymet accuracy bias towards northerly latitudes pointed out by Oyler et al. (2015). As such, an important next step would be to validate SNODAS against Daymet in the Bitterroot Watershed to further understand how well Daymet can be relied upon as a management tool.

Another consideration for further validation and to tease out inconsistencies between Daymet and SNOTEL are to both find a geographically more precise conversion metric for converting SNOTEL values (inches) to Daymet (kg/m^2) and to better estimate Daymet at the m^2 level. The method I employed to convert Daymet pixels to the m^2 value did not consider the varied topography found in any given square kilometer of mountainous regions. The varied topography and interspersed forests and meadows greatly affect how snow settles and compacts across the landscape. As such, SNOTEL sites are likely to be located where humans and equipment can access them with relative ease. Higher resolution Digital Elevation Models (DEMs) could offer insight into how varied a given square kilometer is on the ground, and potentially offer a way forward in accounting for that variation.

The USDA Natural Resources Conservation Service maintain snow course data across the Intermountain West, which could offer additional opportunity to validate

Daymet SWE values. These sites are “...permanent site[s] that represent snowpack conditions at a given elevation in a given area... Generally, the courses are about 1,000 feet long and are situated in small meadows protected from the wind” (Natural Resources Conservation Service, n.d.). As this data is observational and covers a much larger reach than much smaller SNOTEL sites, it offers a more nuanced observation of snowpack variation across the landscape. However, these snow course sites still exist in areas of relative homogeneity and do not completely represent conditions found in any given square kilometer.

Daymet offers the ability for researchers and managers to examine climatologic change at a finer scale than any other gridded raster product. However, this fine resolution does not come without inconsistencies. Interpolated data like Daymet require observational data inputs to interpolate that across physical space. As noted above, however, the outputs are only as good as their inputs. For Daymet, the SNOTEL temperature station bias noted by Oyler et al. (2015) have hampered the products ability to accurately predict SWE across high elevation mountainous regions common to the Rocky Mountains. However, even with the temperature bias, temperatures across Montana are trending upwards (Whitlock et al. 2017).

The combined findings from Daymet and SNOTEL sites, which show a steady decline in June 1 SWE values, validate that indeed snowmelt dominated watersheds should expect to see lower than average late season flows in the near future. Additionally, at the Skalkaho Summit and Daly Creek SNOTEL sites, a precipitous temperature increase is also observed for the entire months of March and May. It is important to note that these observations may be impacted by the abovementioned sensor bias.

Furthermore, the general decline observed in June 1 SWE values for both observational data collected at SNOTEL sites and Daymet interpolations combined with an interesting upward trend in April 1 SNOTEL SWE values lend credibility to the conclusion that snowmelt timing is earlier and overall ablation rates are higher. When factoring anthropogenic forcings into this equation, it is reasonable to conclude this trend of temperature increase and ablation rates resulting in lower late-season flows is likely to continue along its current trajectory. This reality is likely to contribute challenges to both the human social systems and naturally occurring ecosystems dependent and accustomed to predictable and consistent year-to-year hydrologic fluctuations.

It is evident that precipitous declines in overall snowpack retention across the 16 HUC 10 sub-basins of the Bitterroot Watershed represent potent climatological exposures that valley residents are variably sensitive to, possess differing levels of adaptive capacity to manage, and ultimately are differentially vulnerable to future change involving lower snowpack retention, earlier snowpack ablation rates, and resultant diminished late-season streamflow. As such, I will now shift focus towards the DDID, Bitterroot Valley and its varied residents, and stream ecology, which are all potentially vulnerable to shifting hydrologic regimes brought on by climate change, utilizing social-ecological vulnerability as a starting point and explore the myriad ways in which a full-scale vulnerability assessment might consider some of the interrelated elements identified hereafter.

CHAPTER 2: SKALKAHO SUB-BASIN CLIMATE VULNERABILITY ROAD MAP

Skalkaho Creek, DDID or one of the other 9 irrigation districts, and the Bitterroot Valley at-large are all variably exposed to diminished snowpack retention depending on sub-basin water source and subsequent lower late-season flows. Important, however, is the interconnectedness between meltwater availability and timing and the two dominant economic engines: agriculture and tourism. Farms and ranches must have secure, consistent, and low-cost access to water in order to maintain business stability and long-term profitability. These farms are either private appropriators with their own water rights or they are members of an irrigation district (such as DDID) and are therefore beholden to district by-laws and water availability. Furthermore, the effects regarding changing economic circumstances are not ubiquitous throughout the valley. Any changes past, present, or future interact with the individual's socioeconomic reality and that individual's participation in an irrigation district, and, if they participate, how secure the districts' water source is to variable snowpack conditions; how well maintained the irrigation infrastructure is; and how well district by-laws reflect and effectively manage the allocation of water to all members.

The Bitterroot Valley at-large and its associated water for irrigation is important to agricultural production in the area, and while it has changed a lot over the nearly two centuries of Euro-American occupation, agriculture has remained critical to the Bitterroot's social fabric. More recently, however, the amount on non-qualified ag land (i.e. agricultural land with under \$1,500 in profits) has grown by approximately 24,000 acres between the 1980s and 2000s (Swanson, 2006). The most up-to-date United States Department of Agriculture farm census from 2017 reports Ravalli County as having

1,576 total farms. Figure 17 below breaks down the total number of farms into their operational size. Interestingly, 1,175 of these farms are less than 50 acres in size.

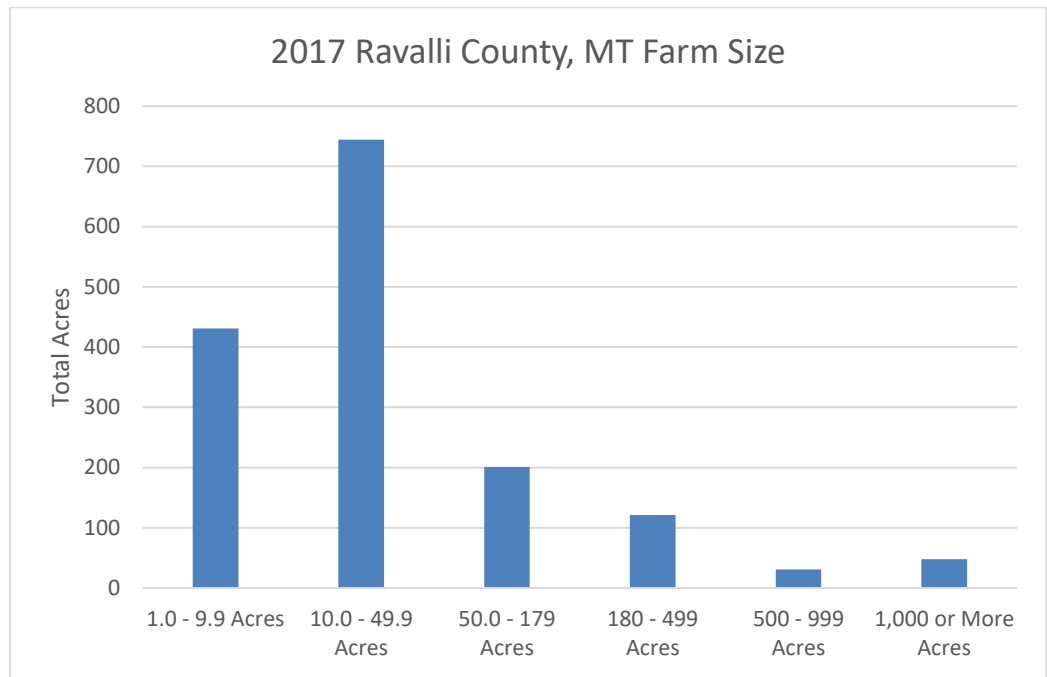


Figure 17. Total number of farms in Ravalli County categorically displayed by their size.

Furthermore, cash receipts from livestock and crop sales totaled \$42,662,000 in 2017 and figure 18 below breaks that number further to show how many farms fall into USDA determined income brackets. Concurrent with figure 16 and the trend towards more and more non-qualifying ag. land is the glut of marginally profitable farms. In fact, 1,196 farms make less than \$10,000 per year. This reality of smaller farms overall and a sizeable portion of them making less than \$10,000 per year begs the question of what else drives the valley economy.

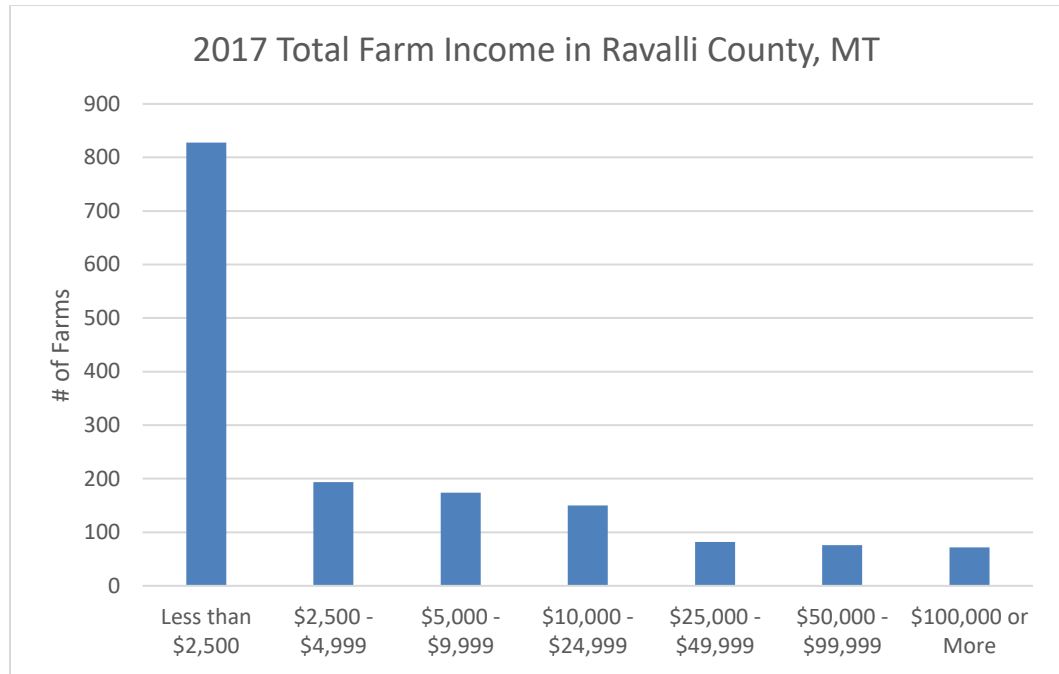


Figure 18. Total farm income in Ravalli County categorically displayed by income ranges.

The transition from commercially viable ag land to non-qualifying ag land is important context to consider as it may be indicative of an economic shift from a more traditional agrarian community towards one trying to balance agricultural heritage with an amenity-based service economy largely dependent upon tourism and outdoor recreation pursuits. Somewhat paradoxically, tourism both depends on the pastoral setting and associated appeal the valley holds as a place of rural culture and expansive views, but it also depends on well-watered streams for the maintenance of recreation-related ecosystem services. Figure 19 below shows how tourism expenditures have trended upwards in Ravalli County over the past 8 years, with the exponential growth trend in hiring an outfitter or guide standing out as the fastest growing sector. This upward trend represents a significant portion of Ravalli County’s economic activity acting in tandem with agriculture to constitute most of the overall economic activity.

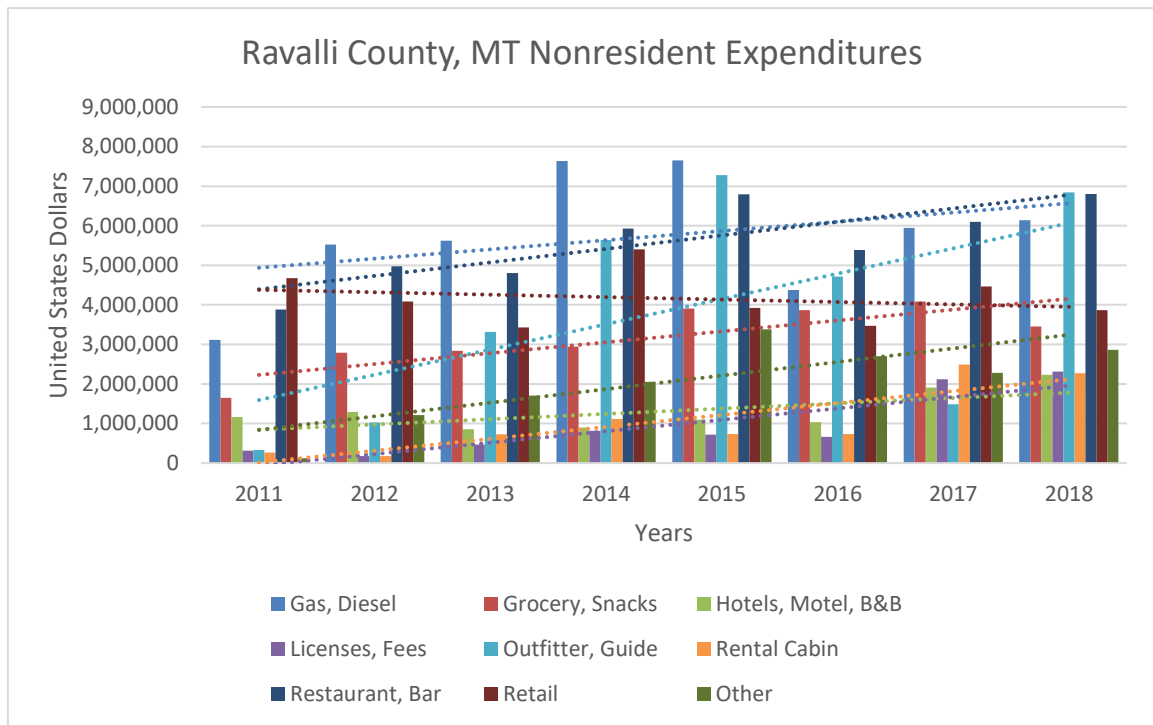


Figure 19. Nonresident expenditures in Ravalli County, MT by category from 2011 to 2018

In addition to altering the social fabric, the economic transition has brought with it conflict between more traditional irrigators who are attempting to carve out a living and newcomers who utilize irrigation to maintain a certain lifestyle largely constituted by lush landscaping, hobby farming, and other non-agrarian water uses (Niemi, 2008). These changes and resultant conflicts are necessary to consider when investigating whether a particular irrigation district, such as DDID, possesses adequate amounts of adaptive capacity to overcome the numerous climatic and social exposures and sensitivities. What follows is a roadmap of how a future researcher may investigate climate vulnerability regarding less late-season meltwater and a rapidly changing economic reality.

Vulnerability is a social-ecological systems' susceptibility to harm that occurs when the system is exposed to stresses associated with environmental or social factors. Furthermore, when the systems do not possess the capacity to adapt, these systems may enter a new stable state and become fundamentally changed systems. There are several ways to conceive of vulnerability. It can be thought of as an outcome by focusing solely on the impacts of a hazard. However, this leaves out the question of what socio-ecological conditions or characteristics led to this outcome. Vulnerability can also be thought as the "starting point." This approach focuses on historic factors or current characteristics of people, households, communities, and nations and uses those characteristics to determine the susceptibility to harm. For the purposes of this road map, I will utilize the latter approach and contextualize vulnerability as a starting point and make recommendations for how to examine vulnerability through this lens.

Exposure

All biosocial groups (human or other species), ecosystems, and/or social-ecological systems are exposed to hazards that could have a significant impact on that system's ability to maintain functionality. Bennett et al. (2016) describes exposure as a spectrum on which regions, resources, and groups experience hazards, and this experience is driven by changes at various scales. Exposure can be thought of as a necessary but not exclusive determinant of risk, and therefore it cannot be thought of as the sole determinant of system vulnerability. Table 1 below offers guidance for identifying and exploring potential exposures.

Table 1*Elements of and Investigatory Options for Exploring Exposure*

Elements	Investigatory Options
Crops Grown	<ul style="list-style-type: none"> • Determine through methodologically sound district appropriator survey • Determine through GIS via remote sensing whereby different crops provide different NDVI signatures and segment based on these signatures • Utilize the USDA “Cropscape” tool to investigate crops grown over the past two decades
Irrigation Infrastructure Condition	<ul style="list-style-type: none"> • Inquire with the district management and administration as to their perception of district infrastructure condition, mechanisms by which it can be repaired or remedied, and appetite amongst members for taking the necessary steps to do so • Request ride along with ditch rider(s) in line with participant observation method to assess and/or document infrastructure condition • Investigate how any planned or discussed upgrades would impact ditch seepage and the direct impact on groundwater recharge, which could negatively impact shallow private water wells
Appropriator Distance from Main Ditch or Lateral	<ul style="list-style-type: none"> • Conduct methodologically sound survey of appropriators and inquire how far their point of diversion (POD) is from the district-maintained ditch or lateral <ul style="list-style-type: none"> ○ Potentially verify that information by utilizing a simple GIS to trace the route from main lateral to the individual appropriator’s POD
Present and Future Climatic Conditions	<ul style="list-style-type: none"> • Determine how more frequent and possibly intense droughts will impact water resources by speaking with University of Montana system and State of Montana climatologists and hydrologists • Utilize a GIS to investigate how higher average temperatures could increase evapotranspiration, determine how that differs amongst crops, and

	consider the combined impacts on available water resources
National and global supply chain demands	<ul style="list-style-type: none"> • Determine how connected and dependent agricultural producers are to hierarchical systems of production, distribution, and consumption <ul style="list-style-type: none"> ○ For example, do producers rely on local consumers, or do they rely on national and international consumers to meet their production? • How dependable is this demand moving forward?

Exposure in the Bitterroot Valley and regarding DDID takes many forms. For instance, lack of water for late-season irrigation driven by flash droughts in concert with rapid population growth creates uncertainty for DDID users who rely on late-season water to sustain their livelihoods. This problem, however, is not exclusive to district users as exposure can be conceived of as occurring on a spectrum. Some users are likely more exposed than others, including: irrigators who are at the end of a long lateral that has to be properly maintained for them to receive adequate water; instances when the water resources are so strained due to drought conditions that the amount of ditch loss due to groundwater seepage is too high for an end of lateral user to receive their apportionment; or in the event one irrigator does not properly maintain their portion of the lateral, any downstream irrigator's water availability is inhibited. However, the degree to which these individual users are vulnerable is heavily dependent on how sensitive their irrigation needs are, and just as importantly how much adaptive capacity they possess to offset low-water years.

DDID and other district appropriators are also exposed to aging infrastructure. A local dairy operator from Corvallis, MT, went so far as to say that climate change was certainly a concern but that was more of a problem for his son's generation. His chief

concern was the aging infrastructure that will need to be upgraded to sustain the fairly dependent agricultural sector (personal communication, 2019). First, irrigators rely on the infrastructure for efficient and consistent delivery of water resources. Second, almost all groundwater users inadvertently rely on the infrastructure for groundwater recharge associated with ditch and canal leakage/seepage (Whitlock et al. 2017). In combination, these two dependencies apply to almost all Bitterroot Valley residents: either they directly irrigate or pull surface water via a ditch system or they draw groundwater from a depth that is artificially higher due to groundwater seepage from the unlined complex water conveyance lattice and flood-irrigated fields. The question becomes less if irrigators desire that repairs be made and more how those repairs may fit into a more nuanced climate adaptation strategy.

Sensitivity

Sensitivity can largely be thought of as how susceptible an individual, group, or larger system is to the consequences of an exposure. These susceptibilities can stretch across a broad categorical array. Moreover, existing circumstances driven by “...[H]istorical, social, political, economic, and environmental preconditions determine a system’s sensitivity” (Bennett et al., 2016, p. 908). Like exposure, sensitivity is highly variable amongst individual irrigation district members and districts themselves, and therefore the variation of sensitivity must be considered when assessing vulnerability. Table 2 below offers guidance for identifying and exploring potential sensitivities.

Table 2

Elements of and Investigatory Options for Exploring Sensitivity

Elements	Investigatory Options
Water Right Seniority	<ul style="list-style-type: none"> • Determine within DNRC Water rights query system seniority of water rights for appropriate water source (i.e. which creek, sub-basin, river, or watershed an appropriator draws from) <ul style="list-style-type: none"> ○ Assign a threshold to determine which rights are more senior or “secure” and those that are junior or “at-risk”
Population Growth	<ul style="list-style-type: none"> • Determine likely growth pattern via existing projection information through US Census and/or Montana Department of Commerce <ul style="list-style-type: none"> ○ For instance, Regional Economic Models, Inc. (REMI) projects the Montana population through 2060 • Determine population growth via population growth formula ($P = P_0 * e^{rt}$) <ul style="list-style-type: none"> ○ P = Total population after time “t” ○ P_0 = Starting population ○ r = % rate of growth ○ t = time in years ○ e = Euler number = 2.71828... • Speak with county planning department regarding plans to accommodate this growth and likely strain(s) on water resources and impact(s) to existing social cohesion
Diversity of Income Sources	<ul style="list-style-type: none"> • Survey and speak with district appropriators to determine their income source variation: <ul style="list-style-type: none"> ○ Do they have multiple income sources? ○ Is their income considered on-farm? <ul style="list-style-type: none"> ▪ If so, is it derived primarily from one crop? ○ Is their income considered off-farm? <ul style="list-style-type: none"> ▪ If so, is it tied to the tourism sector? ○ What percentage of their total income do these various sources represent?

	<ul style="list-style-type: none"> ○ Are all of these sources directly tied to a pre-determined water right and allocation amount?
Bitterroot Basin closure	<ul style="list-style-type: none"> ● Determine how close the State of Montana is to adjudicating all water rights within the Bitterroot River Watershed ● How will this result alter the appropriation landscape?

Prior appropriation, or “first in time, first in right” is the law of the land in western States. In contrast to Riparian Rights systems (which are common to states east of the Mississippi River) that grant legal rights to use water adjacent to privately held land, prior appropriation says that senior water rights holders (those who diverted water for ‘beneficial use’ first) are entitled to their entire appropriation before a junior user (those who came later) can fulfill their right. This system of water governance, while historically ensuring agriculture and industry were prioritized, today puts a lot of junior appropriators in jeopardy of not receiving needed water resources. Accentuated by changing climatic conditions where water will be less available for late season irrigation, this governance structure represents a potent sensitivity that appropriators variably experience based on seniority and/or membership within an irrigation district. Of course, this sensitivity is most relevant if the exposed appropriator experiences concurrent sensitivities such as their entire livelihood depending on surface water resources or residing in a drainage basin considered to be overallocated in terms of available surface water.

In 1972, Montanans voted to approve a new state constitution, of which one important outcome was the recognition by policymakers that water rights needed to be better monitored and regulated to ensure adequate supply, future use, and overall stream health. First, the convention declared that “...[a]ll existing rights to the use of any

waters... are hereby recognized and confirmed (Article IX, section 3(1))” (Department of Natural Resources and Conservation, 2012, p.2). Furthermore, the convention acted to ensure that all water rights would be adjudicated by providing for “... the administration, control, and regulation of water rights and a system of centralized records... (Article IX, section 3(4))” (Department of Natural Resources and Conservation, 2012, p.2).

In order to carry out these constitutional provisions, the Montana Legislature passed and adopted Title 85, chapter 2 of the Montana Code Annotated (MCA), also known as the Montana Water Use Act (MWUA). This legislation provided a framework for the adjudication of all water rights existing prior to July 1, 1973, changes of use for already existing water rights, a succinct centralized record system, and a way in which to regulate and administer water use permits applied for after 1973 (Sigler and Bauer, 2017). This important legislation provided a path forward to fully understand the various water uses occurring throughout the state to better manage water resources today and for the future.

The Bitterroot Valley of western Montana is one area of Montana where this legislation is currently having a significant impact. Population growth has been a common theme in many parts of the state, including Ravalli County. In fact, if growth remains between 1.8% and 2.8% per year, it is estimated the population could swell to between 57,000 and 72,000 people by the year 2025 (Swanson, 2006). Relative to the 1990 population of 25,010, this growth represents a percent change of 128% or 188%, respectively. As a result of this growth, a continuous flow of new water right applications, and lack of accurate records pertinent to historic water claims, the Bitterroot River Basin was closed by legislation effective March 29, 1999. This closure was

intended to give the Montana Department of Natural Resources and Conservation (DNRC) time to sort out all of the claims, and the closure would apply until two years after the state water court had decreed the Bitterroot Watershed.

However, this closure still holds today. It is noteworthy that this closure means DNRC cannot process an application for any new surface water right. This legislation, however, contains a few exceptions, two of which are relevant here: the exception for a permit to appropriate groundwater and an application to appropriate water for municipal water supply. This language suggests that development and population growth can continue but only under strictly monitored circumstances. This population growth will require water and the sensitivity of DDID as a district and its member appropriators will need to be considered in relation to other relevant appropriators.

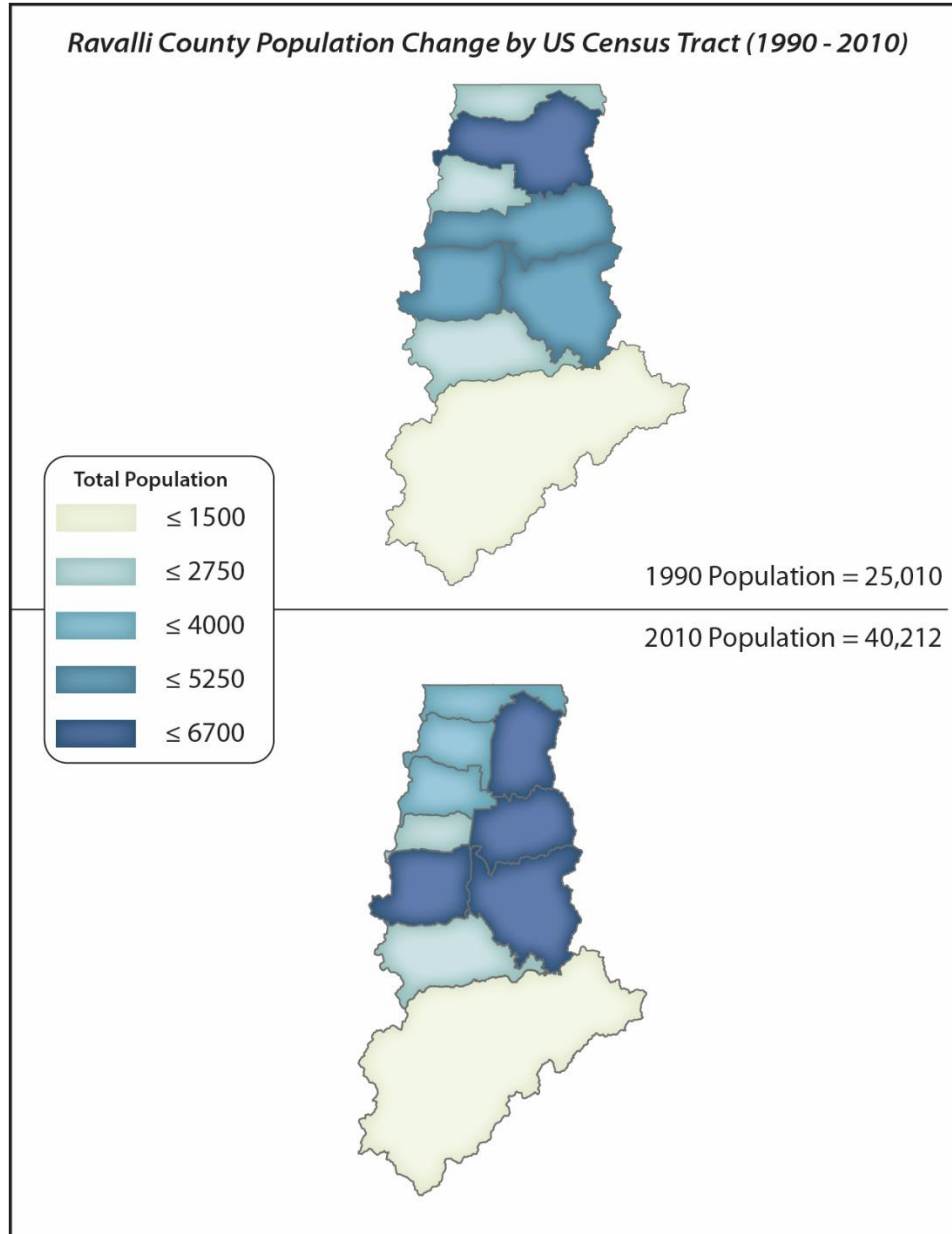


Figure 20. Ravalli County population change by US Census blocks

Adaptive Capacity

Adaptive capacity is the magnitude by which actors residing within a system can influence system resilience, which in turn reduces vulnerability, and they do this through “...respond[ing] to challenges through learning, managing risk, and impacts, developing

new knowledge and deciding effective approaches” (Bennett et al., 2016, p. 909 taken from Marshall et al., 2010). More importantly, adaptive capacity is built-up potential to deal with an event and cannot be fully understood until it is called upon by the community in times of exposure. This poses numerous problems for measuring its effectiveness. If adaptive capacity is only untapped hidden potential, then how can its worth be measured? In the case of DDID water shortages due to low snow years or quicker than average ablation, past examples will provide an opportunity to explore how members of the irrigator community addressed such concerns in the past, which would provide a window into how they may deal with similar—albeit potentially more severe—future challenges. This investigative focus on past adaptations regarding DDID water management could also be applied as method to investigate other irrigation districts, other non-district appropriators, and/or the Bitterroot Valley at-large. Table 3 below offers guidance for identifying and exploring potential instances of adaptive capacity.

Table 3

Elements of and Investigatory Options for Exploring Adaptive Capacity

Elements	Investigatory Options
Past, Present, or Planned Infrastructure Upgrades	<ul style="list-style-type: none"> • Inquire with both district management and district appropriators as to what kinds of efficiency upgrades have been installed, or what future upgrades may be planned • Assess the appetite amongst district members for water conveyance and conservation upgrades, especially how they could be funded and if members are willing to help with costs.
Social Cohesion within the Irrigation District and between Districts	<ul style="list-style-type: none"> • Investigate how often district by-laws are adhered to, and if they are often flouted, determine why this occurs • Determine how communicative members are with one another and managers regarding various disputes and successes

	<ul style="list-style-type: none"> • If relevant, determine how communicative interdependent districts are with one another, especially in regard to the viability of long-term agreements (e.g. DDID “swaps” early spring Skalkaho Creek water with the Bitterroot Irrigation District in exchange for late season Lake Como water)
Perception of Climate Risk(s)	<ul style="list-style-type: none"> • Survey appropriators and managers to assess their attitudes and beliefs regarding current and future climatic risks <ul style="list-style-type: none"> ○ Adapt the already vetted questionnaire from the Yale Program on Climate Change Communication courtesy of Leiserowitz et al. (2019) to fit circumstances ○ And/or, conduct in-depth semi-structured interviews to gain deeper understanding of individual’s perception(s)
Past Instances of Adaptation	<ul style="list-style-type: none"> • Investigate drought past drought years and/or years where streamflows were greatly diminished during the late season <ul style="list-style-type: none"> ○ Survey appropriators and/or managers about those years and how they were impacted by less available water; how social cohesion worked or did not work to alleviate those circumstances; and how institutional norms (i.e. existing by-laws, water right seniority, etc.) mediated those circumstances

Adaptations can be thought of as manifestations of adaptive capacity. For instance, an irrigation district that takes tremendous steps to address climate change (e.g. increased reservoir storage capacity, conversion of open canals to piped and pressurized systems, real-time water meters, etc.) can be thought of as an irrigation district that possesses some amount of adaptive capacity. As defined above, adaptive capacity is latent energy that a social system can employ in times of challenge, so the adaptation employed is a direct reflection of the adaptive capacity that irrigation district possessed.

This capacity to adapt can be driven by many realities. Maybe the irrigation district is a proactive, well-organized group of people who take seriously the challenge of water scarcity; or perhaps, the irrigation district resides in a particular geography conducive to high-value crop production that receives many federal subsidies meant to maintain that productivity. Or, even still, maybe that capacity is tied to something else altogether.

Future Directions and Other Considerations

Recent scholarship has called for future vulnerability assessments to consider seven distinct factors to more fully understand the system and offer productive insight (Bennett et al., 2016). First, analysis must consider linkages between social and ecological subsystems and not consider them separately. Second, researchers should consider multi-scalar drivers that can have unexpected impacts at different organizational levels. Third, research should not presume that exposure necessarily leads to harm. In fact, exposure to harm can have positive outcomes. Fourth, researchers should better incorporate multiple exposures into a vulnerability assessment instead of pinning one variable signifying vulnerability. Fifth, analyses are too often snapshots in time, and as a result, these assessments do not accurately account for various interactions and feedbacks. Sixth, response to exposure should be thought of as either being a coping response or adapting response. Coping responses are typically unplanned or reactionary, and adapting responses are usually preventative actions that strengthen adaptive capacity. Lastly, it is important to consider how institutional and material constraints combined with social structure, governance, and cultural values mediate adaptation options. Of course, all the above variables should be given just consideration in a vulnerability

assessment of DDID, but researcher expertise and other limitations will likely lend credibility to one or more variables over the others.

Finan et al. (2012) looked at the processes by which adaptation occurred over time in a particular southwestern US desert community. Specifically, the researchers explored how climate adaptations arose in a community and what social elements acted and can act as catalysts. Researchers found that “two basic and interrelated factors create the results observed in the valley” (Finan et al., 2012, p.301). The first factor was the systematic adoption by valley residents of new technologies that effectively reduced climate vulnerability. The second factor that contributed to the reduction in climate vulnerability was the reorganization and readjustment of social organizations. The authors likened this readjustment and reorganization to investments in political and social capital. While the researchers found promising processes resulting in decreased climate vulnerability, they were quick to point out that this vulnerability reduction can only be thought about as a short-term reduction, or perhaps simply a coping response. Employing a similar methodology could prove fruitful in better understanding how DDID governs its users and what kind of flexibility exists within the social structure to adapt these rules to changing on-the-ground circumstances.

Brody et al. (2008) investigated the potential relationship between physical vulnerability and perceptions of risk associated with global climate change. Interestingly, the researchers found that geographic exposure did have a positive correlation with climate risk perception when it came to proximity to ocean shoreline. However, proximity to a potential hazard is not nearly as significant predictor of risk perception as socioeconomic and/or attitudinal variables. For instance, a person’s belief in their ability

to influence the discussion, policies, or local community when it comes to climate change is more strongly correlated with climate risk perception than proximity to hazards. This study suggests that geographic proximity should be considered but that social variables should be explored in more depth to search for deeper connections. For DDID, proximity to hazard(s) could be difficult to identify compared with sea level rise and distance from shoreline in coastal communities. However, hazards could be creatively thought of as distance from main laterals and the variable potential for receiving the water those laterals contain. In that vein, it would matter greatly to what degree individual appropriators felt they could influence district leadership and other appropriators to address their concerns regarding the disadvantages of being located at the end of an irrigation ditch.

When using the above two studies as examples to replicate and improve upon for investigating DDID, another Bitterroot Valley irrigation district, or the valley at-large, it is important to remember the results from one community cannot be completely transferable to a different community or geography. However, certain lessons or findings stand out as potential building blocks for a more in-depth Bitterroot Valley investigation. First, Finan et al. (2012) noted that a reorganization of social structure and the adoption of new technological advances decreased climate vulnerability. When considering DDID and other irrigation districts, this could look like adopting more tech savvy methods to improve water delivery efficiency. For example, I heard anecdotally a different Bitterroot Valley irrigation district leveraged member's professional expertise to reimagine the irrigation infrastructure and delivery system to include sensors on each head gate to track water usage in real-time in order to curb access if a member pulls more than their

apportionment. Of course, these changes required a certain amount of adaptive capacity likely in the form leveraged existing social capital, which may not exist in the same form nor amount for each district, to build a robust coalition of stakeholders who could achieve that change. DDID is ripe for an investigation into the ability of members to alter district by-laws to address current challenges, which if found would illuminate how much (or little) adaptive capacity the district possesses.

Pertinent to Brody et al. (2008), it was largely found that socioeconomic and attitudinal variables were much better predictors of individuals' perception of climate risk as opposed to proximity to hazard. This indicates a real need to understand those variables through in-depth semi-structured interviews, a well thought out survey, or focus group interviews to both understand how DDID or another irrigation districts' members perceive the respective climatic risk of less available meltwater and changes in timing, especially as they relate to abovementioned sensitivities. These methodologies could also be used to understand how willing and/or able members are to changing district by-laws to better reflect current attitudes and perceptions. By investigating members' perception of climatic risk, a future researcher will be able to better understand what level of adaptive capacity, or latent energy, a district possesses to address changing hydrologic realities.

A future researcher may also look to utilize social science methods to investigate past adaptations (i.e. change(s) in district by-laws or updates to the water delivery infrastructure), which could offer insight regarding the present ability to adapt to current exposures and overcome sensitivities. Investigating how and when maintenance to water delivery infrastructure is managed, paid for, and ultimately carried out would be

important to understand when investigating the vulnerability of DDID to lower late-season flows. Furthermore, it would be useful to understand how the district incorporates climatic change into the decision-making process regarding ditch, lateral, and pipeline maintenance. For instance, is the district focused on instituting technological solutions that could help to conserve water, and if they are not, what is the reason?

The diversity of water users' income source(s) is an additional consideration for a future researcher to flesh out. More specifically, does the willingness to address district vulnerability hinge on their dependence on it for income. For example, some members may make a sizeable portion of their income through agriculture and thus have more incentive to improve the water delivery infrastructure, alter district by-laws to address changing climatic conditions, and/or institute technological fixes that would help to conserve water already flowing through the irrigation lattice. District members whose income is derived primarily from other sources may have much less incentive to expend time and energy to address these concerns. A final intriguing question regarding income distribution is in regard to those members whose income is tied to tourism and recreation. Maybe a district member owns a guiding service and therefore has a direct incentive to see the streams and rivers running strong for the preservation of fishing opportunities. Other members may indirectly benefit from well-watered streams through operating a local business reliant on tourism dollars. These members and water users may have different ideas for what vulnerability to lower late-season flows looks like for DDID. The distribution of these user groups could be investigated through a survey method and would likely prove useful in helping to explain why some districts are adapting to changing conditions and why others are not.

A future researcher may look to investigate whether informal or semi-formal social groups exist that could promote and facilitate the free exchange of ideas regarding hydrologic changes. The Bitterroot Water Forum is a local non-profit organization that seeks to engage the community to preserve the watershed for future generations. Their focus is on engaging residents in on-the-ground restoration projects and through strategic education exercises. Importantly, this organization is made up of and run by local residents, which likely acts as a positive influence regarding their ability to leverage social capital and community resources. As such, a future researcher may look to the Bitterroot Water Forum as a gateway to identify stakeholders from diverse backgrounds who regularly meet to discuss ways in which they can address exposures, reduce sensitivities, and harness adaptive capacities to lower vulnerability to reduced snowpack retention and lower late-season streamflows.

Challenges to Vulnerability Research

One particular emphasis on vulnerability is noted by Bennett et al. (2016) who claims that vulnerability and adaptation research is often too problem-focused (e.g. global climate change) and not focused enough on the community (e.g. water users, irrigation district members, and the social community in which they reside). In other words, researchers have namely been using large macro problem as the launching point and have not used the individual community enough in developing a methodology. This is not necessarily problematic because it is more a methodological quandary. Certainly there are merits to both generating specific research questions by looking at the larger problem and applying it in certain regions, but it is also true that looking at a particular area and asking

what are the vulnerabilities here is also a worthwhile way to conduct this sort of research.

A recent criticism of social-ecological systems thinking, resilience theory, and, by extension, vulnerability studies emerged out of Fabinyi et al. (2014). The researchers positioned that SES scholarship shows frequent and almost exclusive attention to human/environment interactions. SES literature tends to exhibit three main biases: 1.) assumes people's knowledge, values, and livelihoods are primarily concerned with their physical environment; 2.) homogenizes social groups by assuming that people's interests, experiences, and expectations are more similar than they are different; 3.) and characterizes resilience as a value-laden property. In exhibiting these biases, SES scholarship misses key societal realities of social diversity, power dynamics, and interestingly ignores the valueless nature of resilience by assigning positive values to systems that exhibit resilience and negative values to those that do not. The authors further argue that to better incorporate these crucial dimensions in SES scholarship a firm understanding of social anthropology, specifically critiques of ecological anthropology as reductionist, and incorporation of political ecology and power dynamics would be helpful. Finally, the authors suggest SES researchers frame research questions to "...explicit[ly] focus on different points of view, conflict, contestation, micropower dynamics (intracommunity and intrahousehold), and macrosystem dynamics (dominant political and economic systems)" (Fabinyi et al. 2014, p. 5). By incorporating these considerations, SES scholarship would be better positioned to offer solutions to key societal challenges (e.g. climate change, food security, natural resource distribution, etc).

Finan et al. (2002) certainly painted a neat image of social ecological vulnerability in the desert southwest, but they could have done better by exploring some of the SES shortcomings brought forward by Fibyani et al. (2014). For instance, how did existing power dynamics shape whom the researchers spoke with to gather data, and who was left out due to existing power dynamics? Additionally, were the concerns of local irrigators truly environmental concerns, or were they better characterized as political concerns over natural resource access and distribution?

Our Rapidly Changing and Tenuous Socioeconomic Reality

The current pandemic gripping our communities, counties, states, nation, and world as a whole represents a contextual reality looming over all considerations regarding climate vulnerability in the Bitterroot Valley, especially as it pertains to economic uncertainty. Panarchy and its insistence on considering the myriad connections between distinct yet interconnected SESs’ offers a potential conceptual window through which to

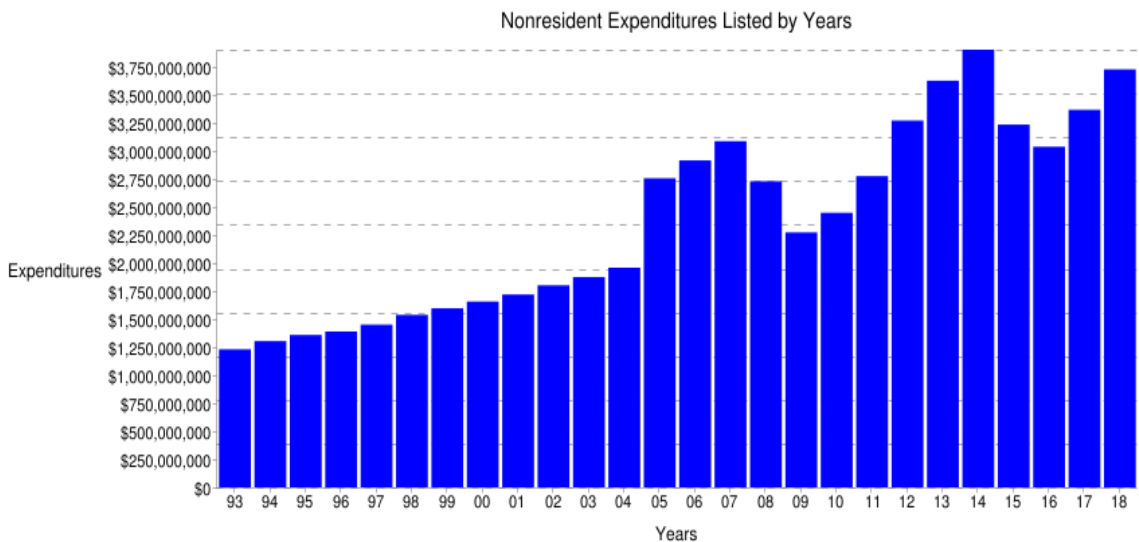


Figure 21. Total nonresident expenditures in Montana from 1993 to 2018

view this ever-present challenge. As was mentioned previously, tourism in Montana is a multibillion-dollar industry. In 2018, for instance, tourism-related expenditures by non-

resident visitors to Montana was just shy of \$3,500,000,000, which make it a potent force in the Montana economy. These expenditures include everything from hiring a fly-fishing or hunting guide and staying at a small-town hotel and dining at local restaurants serving Montana microbrews, to simply driving through the state, grabbing a burger, and refueling your vehicle at a Montana gas station. All these expenditures add up to the total economic impact of non-resident recreation, tourism, and travel in Montana.

Today, July 30, 2020, The Centers for Disease Control in Atlanta, Georgia, is reporting over 4,600,000 cases of COVID-19 across the United States of America. This disease is caused by SARS-CoV-2, a novel coronavirus, originating out of Wuhan, Hubei Province, China, through zoonotic transfer (Andersen et al., 2020). The current number of infections provides the United States with the dubious distinction of being number one in confirmed COVID-19 cases. Furthermore, the United States' GDP shrunk by a little over 32% during the second quarter of 2020, which represents the largest single contraction in post-WWII America. Additionally, the unemployment rate in June was at a staggering 11%.

Questions surrounding how this pandemic will alter the global supply chain, affect small businesses across the United States, and impact the record number of unemployed dominate the conversation today, but ultimately the one thing we know for certain is that humanity will come out on the other side of this pandemic. What we do not know, however, is what the world will look like when we do. What will we value? What we will spend our money on? What industries will grow, and which will crumble under the weight of this global recession? Will we continue to consume fast food at the same rate or more often prefer to eat home-grown and home-cooked meals? Daily one-hour

commutes into the city or more frequent “telecommuting?” The diminishment and admonition of expertise, or revelers of scientific explanation and inquiry? Frequent jet-setters eager to explore exotic new lands, or risk conscious travelers preferring to vacation and explore the culture near our homes? These questions and many others like them are worthy of consideration regarding long-term societal shifts, economic valuations, and lasting impacts to Ravalli County and its current economic dependencies.

Montana’s tourism economy which was mentioned above as a multibillion-dollar a year industry is a model built largely but not exclusively on the ability to transport tightly packed human mass in relatively small aluminum tubes effortlessly through the sky. Before the pandemic, these travelers never much considered communicable diseases. Yes, they were ever present, but nothing significant had posed a real risk to humanity over the last century. The airline traveler has also, in recent years, had their share of affordable tickets due to competition, sheer numbers of flights, and numerous taxpayer funded subsidies. The emerging global health crisis resulting in national calls for social-distancing, shelter-in-place orders, mask mandates, and the effective halt to normal day-to-day life is likely to change our values, attitudes, perceptions, and subsequent actions. This contextualized reality is highly important to consider when applying the concepts of vulnerability, social-ecological systems, and panarchy to DDID, another Bitterroot Valley irrigation district, or the valley as a whole and distinct HUC 10 watershed.

CONCLUSION

Overall, this paper seeks to provide useful information to a future student, governmental, or nongovernmental researcher interested in investigating Skalkaho Creek and its potential vulnerability to lower late season flows because of our changing climate.

Chapter 1 provides useful information for Bitterroot Valley stakeholders and future researchers alike. While Daymet is only one dataset that can offer insight into SWE trends through time, the findings here corroborate numerous other researchers who have identified seasonal snowpack reductions and earlier spring snowmelt timing across the Intermountain West and in western Montana (Mote et al., 2005; Stewart et al., 2005; Whitlock et al., 2017). This reality of less available meltwater will undoubtedly impact DDID and the Bitterroot Valley at-large throughout the coming years. Important considerations regarding confidence in the data should be further investigated through corroborating these findings with nearby Snow Course sites and refining a more reliable methodology for comparing Daymet to SNOTEL.

Social-ecological systems thinking and vulnerability to changing stable states offers future researchers a valuable framework for investigating the potential for DDID to remain in its current form or perhaps shift into a new stable state. The roadmap and potential research directions laid out in chapter 2 offer a future investigator numerous points to consider when looking at climate vulnerability within DDID, another valley irrigation district, or the Bitterroot Valley at-large. Of course, the considerations laid out cannot be thought of as exhaustive but should offer a researcher curious about climate change as it will impact the Bitterroot Valley a starting point for idea and research question generation.

The Bitterroot Valley is steeped in history and culture. The Bitterroot Salish originally called this valley home until Euro-American settlers first entered Montana in 1841 and established the St. Mary's Mission near present-day Stevensville, MT. Tension between the new settlers and historic inhabitants continued to mount over the next 50

years until the Bitterroot Salish were forcibly removed to the Flathead Reservation by the United States Army in 1891. The next century saw many changes that all play a crucial part in framing the present-day challenges regarding vulnerability to diminished snowpack retention, resultant lower late season streamflows, and the impact to those industries and people dependent on meltwater. For this itinerant human, the Bitterroot Valley, its mountains, canyons, wildlife, and cultural pulse will forever be etched upon my soul. My hope is that this paper proves helpful to a future curious mind who looks at the world, its people, plants, and animals as one interconnected and interdependent system moving ever forward. We need not know what the future holds but to always remember change is the only constant.

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