Running on Empty: Water Scarcity and Sustainability in Bozeman, Montana

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Introduction

Bozeman, Montana is the third fastest growing ‘micropolitan’ area in the United States (Mackun et al., 2021). From 2010 to 2020, Gallatin County's population increased by 33% (Miller, 2021). By 2045, it is projected to grow by another 27,000 residents (Shelly, 2020). In a perfect storm of urban growth and climate change, the environment in Bozeman’s Gallatin Valley is under attack. Warming temperatures and population growth both contribute to straining the water supply. During 2021, Bozeman experienced an extreme case of water scarcity and climate temperatures. Water availability and subsequent water conservation will drive the future of much of the American west as forces such as climate change, and increased populations change both supply and demand of this vital resource. With an overshoot of water demand projected for 2030 or earlier, this problem will soon impact all of those who call this beautiful area home. Thus, exploring both the issues of increasing urbanization and increasing demand on water resources, as well as discussing potential solutions has never been so relevant.

This paper will include an analysis of water and water usage in Bozeman, Montana. First will be a description of water rights and how this affects how water is used in the state of Montana. The following section will discuss temperature and precipitation trends in relation to climate change and the direct correlation with population growth. Next will be an exploration of the sources of water for Bozeman and an analysis of watershed-based planning in use for the city of Bozeman. A discussion of the various problems that are currently impacting our water supply and water quality as a result of this intense population growth will follow. Finally, an in depth discussion of potential solutions that could help to mitigate these issues with some conclusions drawn from the data provided throughout the paper.

Water Rights

In Montana, there is a system in place that distributes the available ground and surface water amongst residents. The water rights system is intended to ensure that community members are permitted to use enough water to fulfill their needs. However, history shows that indigenous nations, those experiencing poverty, and recent residents have been excluded from water access by the system. With a diminishing water supply and growing population, the distribution of water across the state for agriculture, municipal use, and natural resources will become increasingly challenging.

The water rights system, managed by the Water Rights Bureau of Montana, is founded upon seven main principles. These principals act as guidelines to ensure that the available water is equally distributed and available for all necessary uses. The first principle is that all of the ground and surface water is public property of the state. Those who have water rights simply are permitted access, but do not hold ownership. The eastern United States distributes water based on the Riparian system. Property owners that have land adjacent to water have the right to that water. Montana, and most of the western United States, does not follow this principle. West of the Mississippi, living next to a stream or river does not give you any right to draw from the water. Water rights are a form of property right, and the two can be separated.

The next principles dictate how water is allocated. All permit holders are allocated a fixed quantity of water based on the total available water, other permit holders use, and quantity needed for that purpose. Additionally, if a permit holder does not use their fully allotted amount of water one year, they are not guaranteed the full amount the following year. In order to obtain a water right, the water must be for a “beneficial” use. Under the law, all beneficial uses are equal. Since all uses are beneficial, the priority in the event of drought is given to those who were first in time. First in time refers to the time of which that water right was established.

As of July 1st, 1973, all water rights are assessed on an application basis. Before 1973, there was not a system in place to monitor how much water people were using for various purposes. Water rights were thought of as a public agreement, relying on word of mouth to communicate who was using water. To this day, the Water Rights Bureau of Montana is working its way around the state to resolve the water right claims that preceded 1973. The seventh principle is that any change in the purpose, place of use, place of storage, or point of diversion of a water right must be approved by the Water Rights Bureau of Montana, and cannot have an effect on any other permit holder's water (Sigler, 2017).

With the rapid population growth affecting Gallatin County, the natural resources of the region are strained. Located in a region with a semi-arid climate, the surrounding areas do not have the water resources to supply the growing population. By 2030, Bozeman is expected to outgrow the current water supply of 11,500 acre feet (Ahlstrom, 2021). In order to supply water to the members of our community, the city and county need to learn to work within the current system to best benefit our community.

Incorporating a philosophical view when amending these systems is essential to ensure equity. Bill Mckibben was one of the first people to address the ethical analysis of climate change in a *New York Times* article in 1999 entitled “Indifferent to Planet Pain.” He says:

> “I used to wonder why my parents’ generation had been so blind to the wrongness of segregation; they were people of good conscience, so why had inertia ruled so long? Now I think I understand better. It took the emotional shock of seeing police dogs rip the flesh of protestors for white people to really understand the day-to-day corrosiveness of Jim Crow. We need that same gut understanding of our environmental situation if we are to take the giant steps we must take soon”

Twenty-two years later, and less than half of Montanans believe that any action should be taken to reverse the effects of climate change (Fahys, 2020). Similar to getting food from the grocery store without thinking about agriculture, most of us open taps and flush toilets without considering the challenges of supplying the water we use. Having access to water is not a privilege, but a basic human right. The Pontifical Council for Justice and Peace (2006) dove into the idea of human responsibilities and water availability in their piece titled “Water, an Essential Element for Life". It heavily emphasizes that water is an integral pillar of human life. When discussing the economic viability of water, it is important to consider that all life deserves access to clean water. The Council highlighted a few points in order for this to occur: humans need to have respect for life and become active subjects within water policy. Abiding by this ideal can have positive impacts on the people within our community that do not have current access to clean water or dependable water availability. With a significant demand compared to the supply, the water supply of Gallatin Valley can easily be capitalized and turned into an economic commodity. This venture poses significant consequences for water quality and availability to our community. Specifically, those living in chronic poverty are faced with extreme uncertainty.

As environmental scientists, we feel an ethical duty to advocate for the ecosystems that surround us. In our senior capstone class of 10 students, not one of us grew up in Bozeman. Only one student grew up in Montana, and not a single student is indigenous to this land. As we speak on environmental degradation due to urban development, we cannot ignore the fact that we are a part of the problem. The rapid growth and development of Gallatin County is due to the high migration rates, to which we all contribute. Beyond just recent population booms, this land is traditional ancestral grounds of the Bitterroot Salish, Pend d'Oreille, Kootenai, Blackfeet, Northern Cheyenne, Crow, Chippewa Cree, Assiniboine, Gros Ventre, Dakota, and other Indigenous nations of this region.

Of these nations, none hold rights to the water within Gallatin County. Water rights have been claimed by settlers as early as the 1800s. Indigenous Nations have been using the surrounding water for significantly longer, but have no seniority within the water rights system because they didn't officially file water claims (Figure 1). It was not until late 2020 when the Confederated Salish and Kootenai Tribes worked together to restore water rights on the Flathead Reservation (Oxendine, 2021). After fighting for decades, the tribes gained water rights and funding for stream habitat conservation in exchange for relinquishing their claim to thousands of non-reservation water rights. When making public policy for the masses, it is pivotal to have a pluralistic view and factor in the cultural beliefs of all. For most groups indigenious to the west, the rightful longtime tenants of this land, water is a living sacred entity that holds knowledge (Corachán, 2017). Many tribal councils of the region pride themselves on being conservationists and protectors of their sacred landscapes. It is a long awaited success for the Salish and Kootenai to have finally restored their rights to the water of the Flathead River. Though this is a major win for cultural equity, it is a single case of thousands that have yet to be resolved in the western United States. As of 2010, just over 1.5 million Tribal water right cases had been resolved, with almost 7 million unresolved (Figure 1).

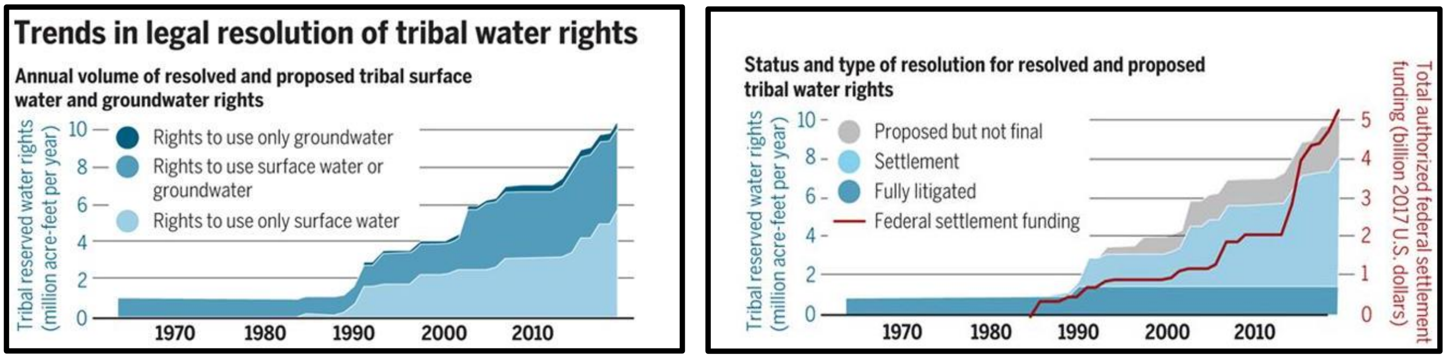


Figure 1: (Left) Annual volume of resolved and proposed tribal water rights in the United States since 1965. (Right) Status and type of resolution for resolved and proposed tribal water rights in the United states since 1965.

The water rights system in Montana is flawed, and has significant room for improvement. It served its intended purpose for the last 50 years, but is sure to fail in light of current climate change concerns. By taking an ethical approach to reworking this system, our community can ensure that all members, regardless of ethnicity, class, or background, have access to enough clean water to fit their needs. Though recent migration rates have exacerbated this situation, historical climate trends show that global warming is a driving force in the water crisis.

Climate Trends

The greenhouse effect was first discovered in the 1860's by physicist John Tyndall. He noted that any changes to the natural composition of the atmosphere would bring about 'climatic variations' (NASA 2021). In 1896, scientist Svante Arrhenius predicted that atmospheric changes to carbon dioxide levels would lead to increased surface temperature via the greenhouse effect (NASA 2021). Paleoclimate evidence from ice cores, sedimentary rocks, ancient tree rings, ocean sediments, and coral reefs reveal that current warming rates are around 10 times faster than previous warming events (NASA 2021). The average surface temperature has increased by around 2.12 degrees F (1.18 °C); with the most drastic warming occurring in the last 40 years. The years 2016 and 2020 are currently the two warmest years on record (NASA 2021). These rates are undoubtedly from anthropogenic activity in highly developed countries that have large industrial complexes, which largely correlate with rapidly growing cities.

Water is a limiting resource for human populations, as most everything in this society involves water. As the population increases, the need for water increases. Bozeman relies on the Gallatin watershed basin as its source of water, which is fed by mountainous snowmelt and precipitation. Climate change has caused snow to fall later in the year and melt earlier. This means the watershed has less time to replenish and increases drought potential. The following data will explore climate change at a local level and how the relation to population growth will affect water availability.

The climate classification of Montana is cold semi-arid. Semi-arid climates get more precipitation than arid climates, but not enough to be classified as humid. The cold distinction is due to the semi-arid climates being at higher elevations with cold winters. An important characteristic to note is cold semi-arid climates get less snow than humid climates at similar elevations. These characteristics are typical of the climate of Gallatin County, Montana. Data collected in Gallatin County from 1895 to 2020 reveals the average temperature increased 0.2 °F per decade (Figure 2). The average precipitation has increased 0.10 inches per decade (Figure 3). The question is in what form is the precipitation increasing. Bozeman heavily relies on the amount of snow each winter to recharge the water system. This recharge comes from the amount of liquid water within the snowpack, known as the snow water equivalent. Figure 3 shows the snow water equivalent of the Gallatin Watershed Basin as of December 7, 2021, which is 73% of the normal capacity, based on data collected from 1891 to 2021. If warmer winters cause less snowpack, precipitation during spring and fall will become increasingly important. However, if the rates of precipitation remain the same, there will be an increase in drought severity and length. Paired with Figure 4, the decrease in mountainous snowpack points to the decrease in available water to Gallatin County, pointing toward an increasing deficit.

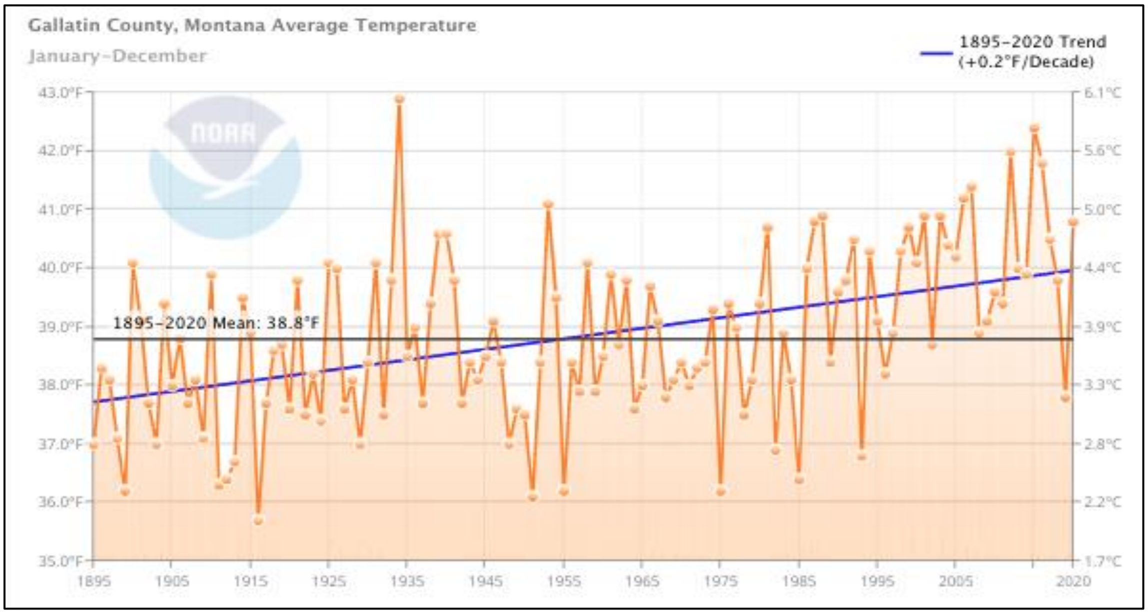


Figure 2: Gallatin County Average Temperature (NCEI 2021)

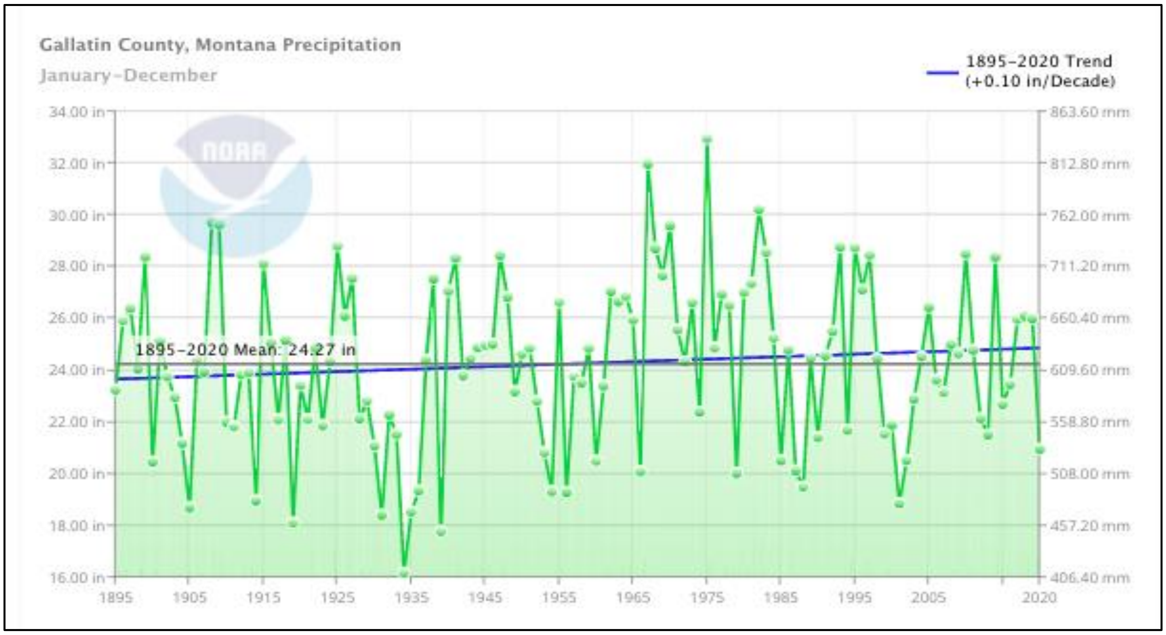


Figure 3: Gallatin County Average Precipitation (NCEI 2021)

As the population nears the carrying capacity of water, Gallatin County has approximately 10 years to find a way to alleviate the stress on the water system (Figure 5). This requires analysis of the population growth of Gallatin County. The difference in the population of Gallatin County between the 2010 and 2020 census is surprising. For Gallatin County, the population changed by at least 20 percent (Figure 6). If the population continues to grow at this rate, the reliable supply of 11,500 acre feet will be met by the population before or at the next census in 2030. As water availability decreases and the population increases, what does this mean for the future? If the annual average precipitation in Montana is generally increasing, where is the water going? How do we get it to remain in the system?

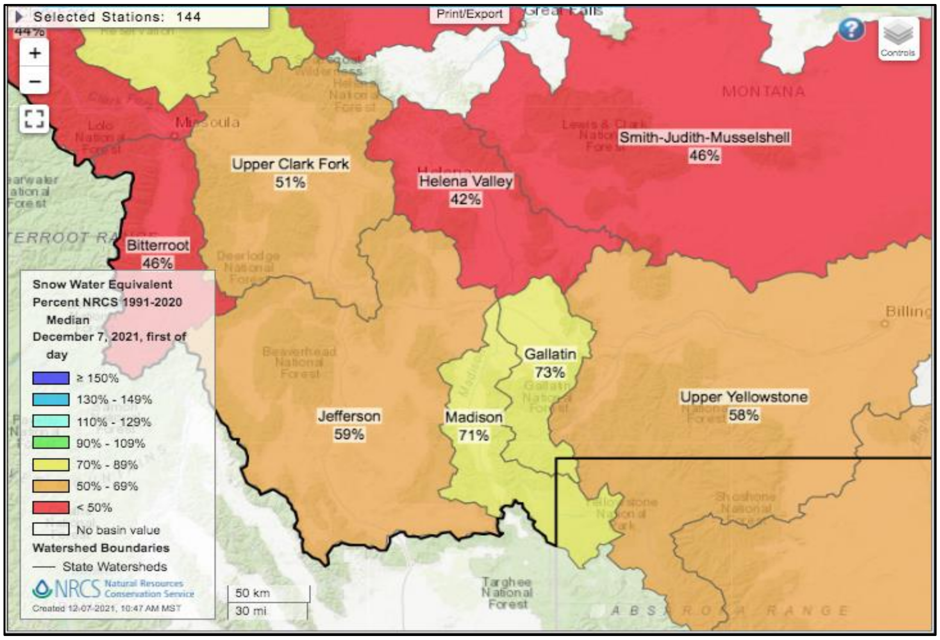


Figure 4: Watershed Basin Snow Water Equivalent Percent of Normal December 2021 (NRCS 2021)

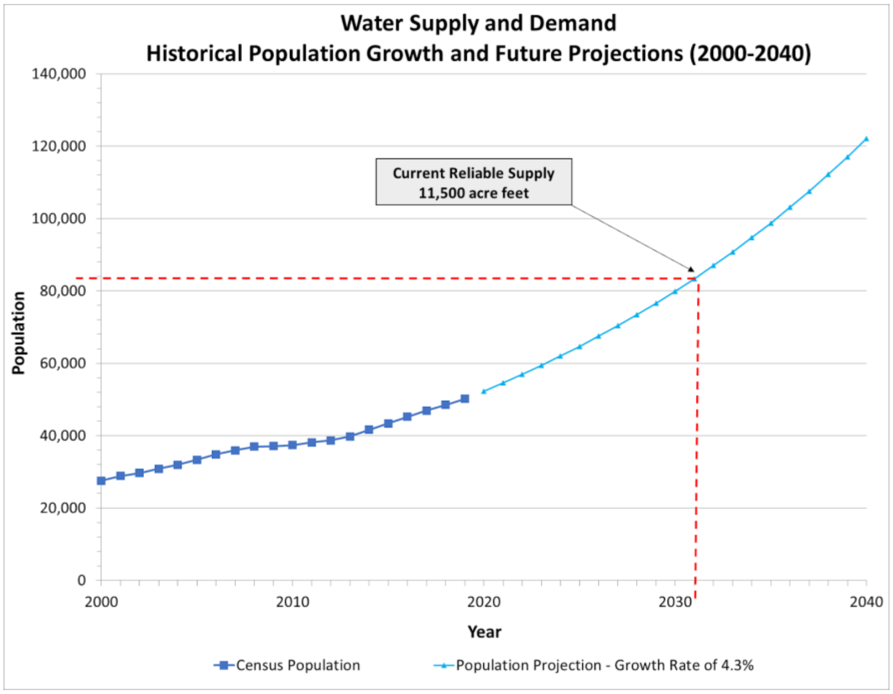
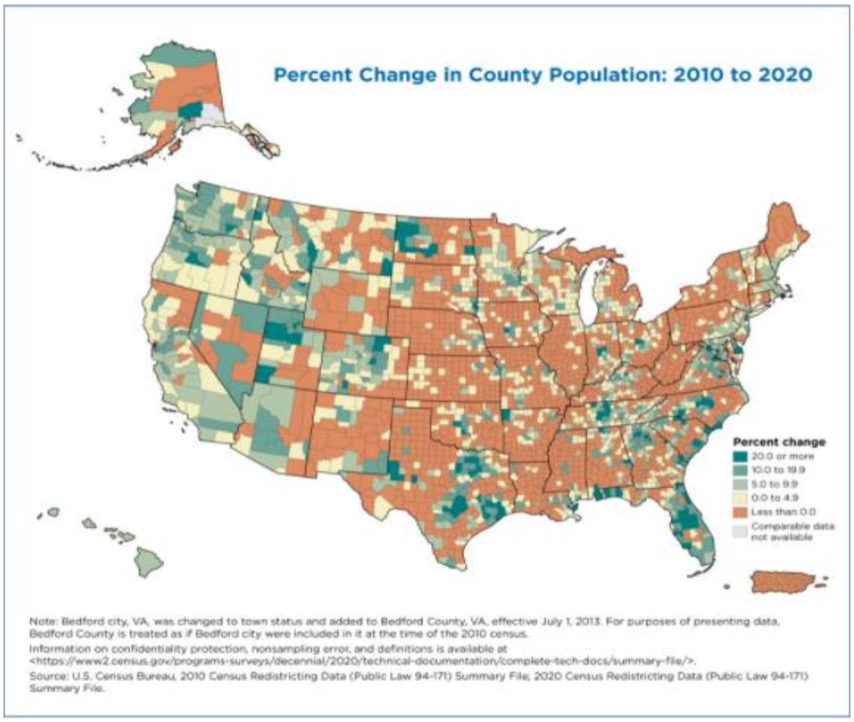


Figure 5: Bozeman Water Supply and Demand (Bozeman Water Conservation)


Percent Change in County Population: 2010 to 2020

Note: Bedford city, VA, was changed to town status and added to Bedford County, VA, effective July 1, 2013. For purposes of presenting data, Bedford County is treated as if Bedford city were included in it at the time of the 2010 census.

Information on confidentiality protection, nonsampling error, and definitions is available at <https://www2.census.gov/programs-surveys/decennial/2020/technical-documentation/complete-tech-docs/summary-file/>.

Source: U.S. Census Bureau, 2010 Census Redistricting Data (Public Law 94-171) Summary File; 2020 Census Redistricting Data (Public Law 94-171) Summary File.

Figure 6: 2020 U.S Census Data (US Census Bureau 2021)

Using GIS in watershed-based planning to identify issues of water sustainability.

Watershed-based planning is a crucial component of natural resource management, especially in Bozeman’s arid climates as previously discussed. However, the conventional strategies of watershed analysis do not include analysis of other factors, such as sustainability and conservation (Azarnivand and Banihabib, 2016). Rapid expansion and high demand of water must be addressed with a long-term management plan with effective participation of residents and local governments (Azarnivand and Banihabib, 2016).

Watershed-based planning can simplify to two disciplines, hydrology and topography. The topography of Bozeman is incredibly complex, with elevation changes in the thousands of feet over a short distance. The hydrology of watersheds cannot be understood by analyzing the watershed output alone. The watershed must be studied as a whole, accounting for parameters such as snowmelt, precipitation, and outflow (Payne, 2021). To best delineate, analyze, and monitor these types of watersheds, interactive spatial tools such as Geographic Information

Systems (GIS) and Snow Telemetry (SNOTEL) must be implemented into the management plan. SNOTEL is an automated station system operated by the Natural Resource Conservation Service (NRCS) that monitors snowpack along with related climate sensors (NRCS, 2021). GIS and SNOTEL are two long-term management tools that are highly effective, accurate, and vital to analysis of areas with large elevation change, such as Bozeman. An approach used in recent studies using GIS techniques to analyze flash flood susceptibility (Ames et al. 2010; Bajabaa et al. 2014; Youssef et al. 2016) can be altered to analyze basic hydrologic processes of watersheds.

The importance of watershed-based analysis was evident during the 2021 water year. The western United States experienced low precipitation, watershed outputs, and recharges. Bozeman was no exception to the extreme drought. Bozeman can and has the capabilities to use watershed planning, GIS and SNOTEL data to make accurate predictions of water availability throughout the summer, based on snowpack data and predicted spring temperatures.

Approximately 80% of Bozeman's drinking water comes from the Bozeman Municipal Watershed which encompasses, but is not limited to, Hyalite Creek watershed and Sourdough (Bozeman) Creek watershed (BMW project, 2021). A third source of water for Bozeman is a natural spring in the Bridger mountains, Lyman Spring recharge area (BMW project, 2021). The Hyalite and Sourdough Creek watersheds are adjacent to one another, south of Bozeman in the Gallatin National Forest (Figure 7). Bozeman's water treatment plant sits at the outflow of the Sourdough watershed (Figure 7). The USGS stream site that is used to monitor stream discharge, the source of this paper's hydrologic data, is located at the outflow of Hyalite watershed (Latitude 45°33'47.98", Longitude 111°04'18.80", Elevation 5,539.6 ft). Bozeman has an elevation of 4,793 feet above sea level. Hyalite and Sourdough watersheds record an elevation around 5,000 feet to 10,000 feet (ArcPro, 2021).

Figure 7: Delineated watersheds and treatment plant of Bozeman, MT.

US Department of Agriculture SNOTEL site 578 is located along Lick Creek within Hyalite Watershed (Latitude 45°30’N, 110°58’W, Elevation 6,860’; Figure.8). The Lick Creek SNOTEL site has been reporting data since October 1963.

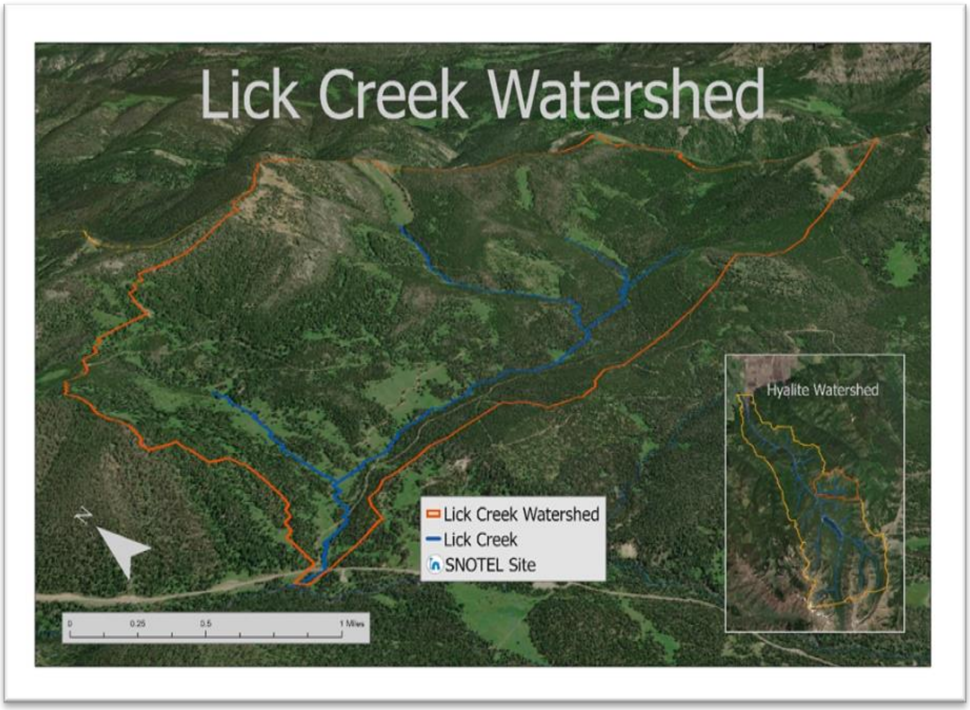


Figure 8: Lick Creek watershed and SNOTEL site 578 delineated within Hyalite watershed. GIS modeling and SNOTEL

The GIS models presented are visual projections for defined parameters of Bozeman's watersheds. The delineation process used the simplest of methods of which GIS is capable. An important data piece of this analysis is the projection of the maps. Bozeman sits inside Zone 12 of The North American Datum of 1983 (NAD 83), 2011 adjustment. NAD 83 is the horizontal and geometric datum for the United States (National Geodetic Survey, 2018). Put simply, NAD 83 Zone 12 is the most accurate coordinate system for Montana, confirming any lines drawn on a map are accurate if drawn on the landscape.

ESRI ArcPro and NAD 83 were implemented for this watershed analysis. The watersheds are delineated using a digital elevation model (DEM), acquired from USGS. A DEM is a graphic representation of elevation data to represent terrain. Flow direction and flow accumulation analysis were run in preparation to delineate the watersheds. Flow direction follows the largest weights through the DEM; larger weights accumulate at steeper slopes (ArcPro, 2021). Flow accumulation confines the flow to only weights that are downslope from one another, creating a flow path (ArcPro, 2021). Watershed delineation requires one point location (pour point) which is the outflow or "beginning" of the watershed. ArcPro used the flow accumulation, direction, and pour point to project the watershed.

The SNOTEL site data is provided and available for download and analysis on the USDA website (Figures 10). All data is provisional and is subject to revision. The snow water equivalent and temperature data collected by the SNOTEL site are used in this analysis. The SNOTEL site can be referenced to the stream gauge data as the SNOTEL is upstream from the stream gauge and contributes to flow. The data cannot be compared with complete certainty as there are a multitude of variables promoting error. Error includes evapotranspiration, human interference, surface water used to recharge ground water and Hyalite Reservoir restricting or intensifying flow.

When referenced to the City of Bozeman municipal watershed project, the delineations of each watershed were projected accurately (Figures 7, 8, and 9). This can be referenced for the creation of other watersheds or simple boundaries. The use of ArcPro's local scene, a 3D projection, allows for a complex visual of general terrain within each watershed. Feedback from reviewers was positive, describing a new interest and understanding of Bozeman watersheds.

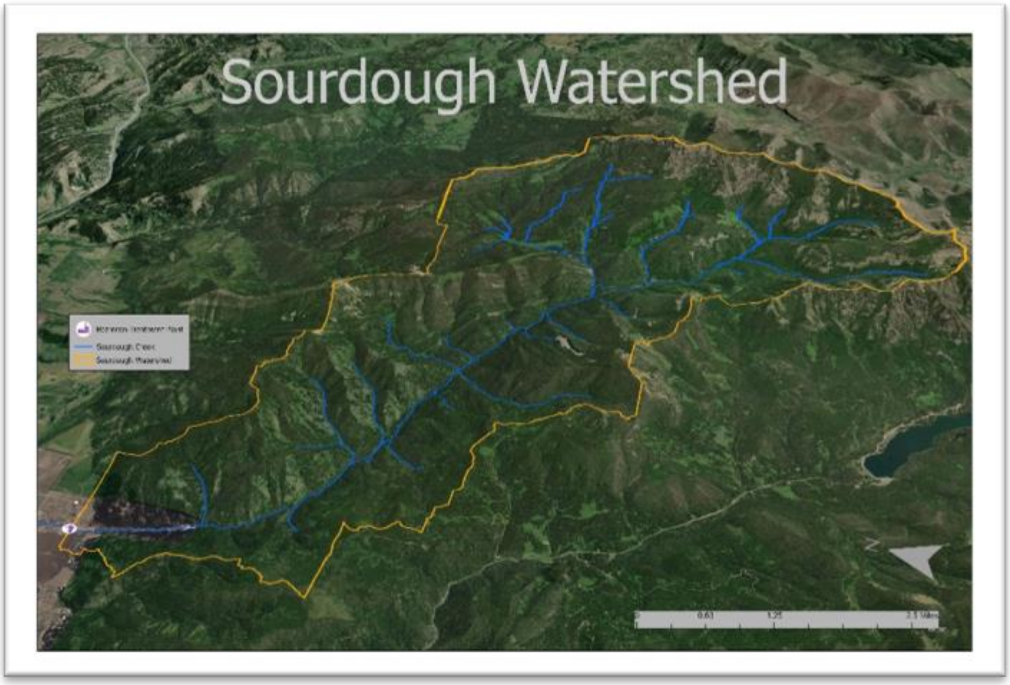


Figure 9: Delineation of Sourdough watershed and Bozeman water treatment plant.

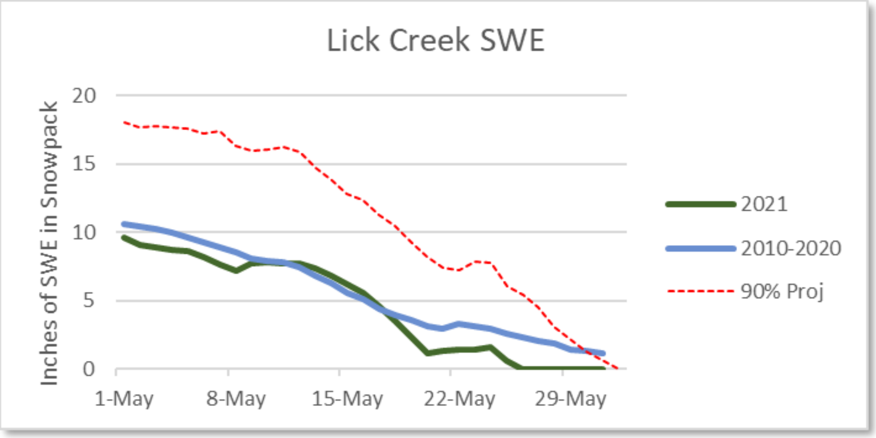


Figure 10: Lick Creek SNOTEL site Snow Water Equivalent within snowpack during the month of May.

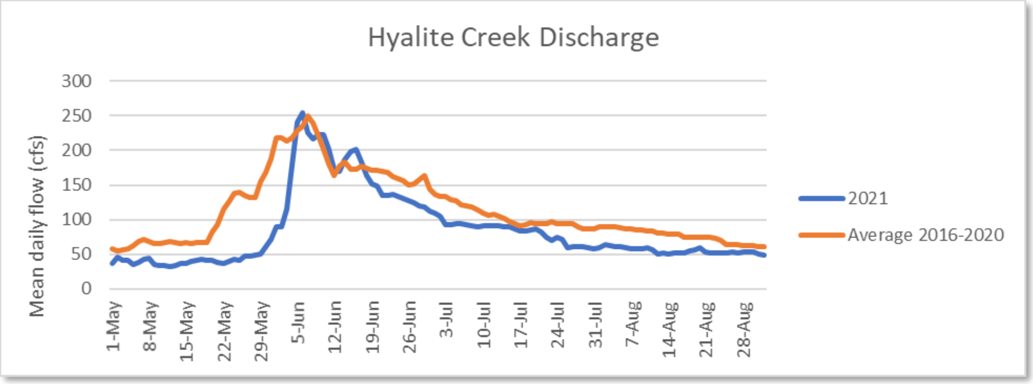


Figure 11: Mean daily flows (cfs) of Hyalite Creek from May 1 to September 1.

The 2021 water year reported rapid changes in mean daily flow and snow water equivalent (SWE) in the snowpack. The overall daily flow and SWE recorded in 2021 was less than the average (2016 to 2020). For a more detailed comparison, May 16 can be referenced in both graphs (Figures 10 and 11). The inches of SWE declined substantially between May 16 and May 22 (Figure 10). Acknowledging it takes time for water within the watershed to reach the main discharge, in this case Hyalite Creek, the largest spike in daily flow began soon after the snow melt (Figure 11). The 90% projection of Lick Creek SWE is the average of SWE during the top 10% of precipitation over the last 38 years of SNOTEL site record (Figure 10). This rapid entry into the output phase can be noticed in the mean daily flow of Hyalite Creek by the rapid increase in flow, followed by a rapid and continual decrease (Figure 11).

The comparison of data can be related to the water issues Bozeman faced over the summer of 2021. The high temperatures put the snowpack in the output phase, the melt and release of water, much sooner than is normally recorded (Payn, 2021).

Further analysis of watershed-based planning should include specific attributes relating to the watersheds and their data. Hyalite Watershed is not the most appropriate watershed for an analysis based on treatment plant capabilities. The treatment plant is located at the outflow of Sourdough watershed, which contributes to much of the plant's water collection. A groundwater analysis could be developed through the lens of watershed recharge and the water budget. An applicable estimate of evapotranspiration can be made to have a more accurate estimate of how much water is lost before it reaches outflow. Using GIS, a soil type analysis can help to understand groundwater, surface water, and where water may be held too long or released throughout the watershed. Some soils have impervious qualities that can restrict waterflow—an accurate soil assessment could identify these areas. The same could be said for soils that promote appropriate flow of water. Either soil identification could be used to argue for restoration or preservation to encourage decisions that are best for the watershed.

Using this method to predict future watershed outputs would require a larger time frame. Data used for the analysis is only representative of the 2021 water year and is not a good predictor of future water years. A more accurate predictor would use data from all 38 years of SNOTEL data and all available USGS water data. Even then, a relative prediction may not be accurate due to recent years presenting precipitation, temperature, and water data that have largely strayed from a Bozeman average.

High intensity flow over a short time is a great concern for water sustainability. A worst-case scenario regarding these variables would be a low precipitation winter, producing a minimal snowpack which experiences a rapid melt due to early spring high temperatures. Bozeman cannot capture an intense flow and contain it for an entire summer season. The ;treatment plant has a maximum capacity of 22 million gallons and storage capacity of 11 million gallons. Eleven million gallons of storage could at one point provide water to Bozeman for only one day if city growth continues. A greater understanding for sustainability, conservation, and water-shed based planning will provide the continual, necessary information to best prepare and confront water availability issues.

Population Growth and Land Use Change

Bozeman’s population is growing at approximately 4%, which is roughly 1,600 people coming into Bozeman each year. As referenced in the data below, as of April 1st, 2010, there were 37,280 people that lived in Bozeman. As of April 1st, 2020, there were 53,293 people that currently reside in Bozeman. The growing demands for water are accompanied by climate change that is altering water availability. Rapid development in Bozeman is illustrated by the distribution of people within the city limits, the lighter color is 0-74 people per square mile, the orange is 75-387 people per square mile, and the dark red is 388-1594 people per square mile.

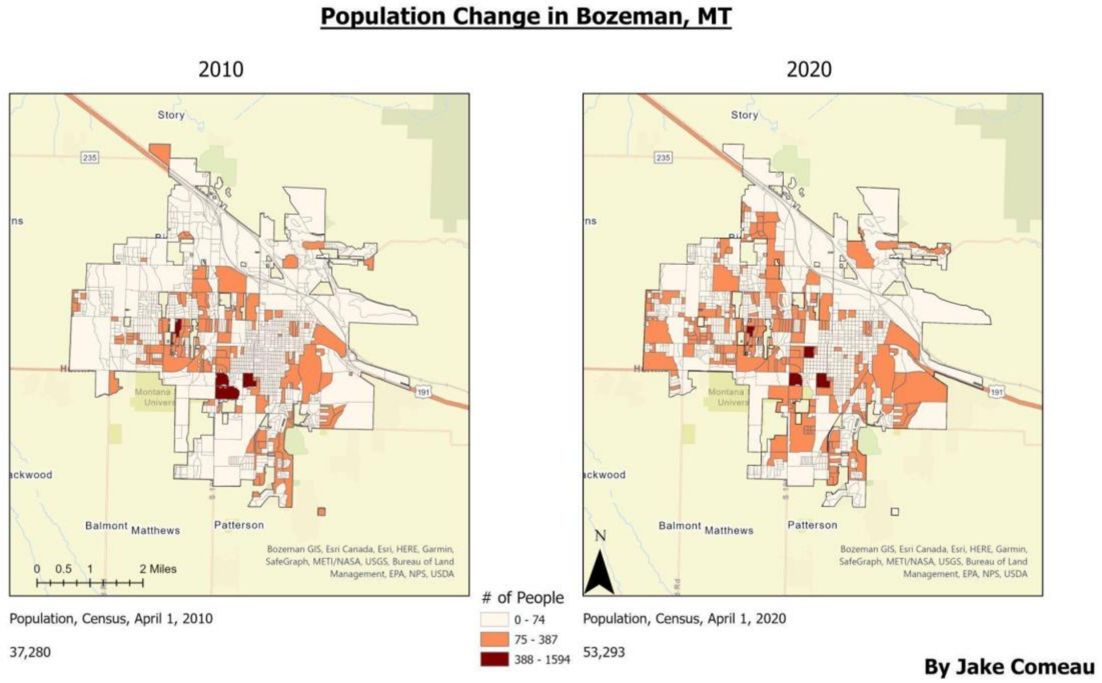


Figure 12: Population growth between 2010 and 2020.

Population growth and industrialization has and will continue to put stress on water resources, as increasing amounts of water are required to sustain communities. The growing demand for freshwater and groundwater is a critical resource that is used to meet agricultural and drinking water demands. When surface water availability is limited, rapidly growing populations and many high value crops require large amounts of water. In some regions, this has led to land subsidence, which causes a permanent loss of groundwater storage (Smith, 2020). Population growth in the western United States has risen by nearly 7%, or approximately 22 million people, since 2010. There have been increases in water use efficiency that have somewhat counteracted the impact of population growth on demand (Schwabe, 2020).

Population growth has stimulated rapid expansion and development in the Gallatin Valley, resulting in the conversion of agricultural and unmanaged land to urbanized areas. Along with a multitude of ecological implications, this land use change has altered both hydrologic processes and water consumption patterns. Water is a critical and limiting resource across the western United States, and climate change is further threatening the reliability of water supplies. Considering the impacts of land use change as an additional factor for water availability and conservation is necessary for a city experiencing a rapid growth rate. Supporting developments and increased urban activities along with sustaining crop production and natural ecosystems in the Gallatin Valley will require an understanding of how development impacts water resources, and how future growth will change land use and hydrologic patterns. Land use driven changes in impervious surface cover and vegetation distribution will be particularly important in addressing questions on the sustainability of population growth along with continued and dependable access to water.

Alterations to Hydrologic Processes

Transitions from agricultural or undeveloped areas to urban lands impacts water movement through the environment. Change in impervious surface cover is one of the major driving factors in altered hydrologic processes in urban areas (Shuster 2005). Undeveloped landscapes and agricultural soils have a higher capacity to absorb and retain water from precipitation events than the compacted and non-porous surfaces that dominate urban landscapes, such as pavement and buildings. Water contacting impervious surfaces is more likely to enter streams or other surface water pools directly rather than first being held in soils. This reduces the soil storage that would allow water to either percolate further into groundwater supplies or be available to plants (Shuster 2005). Increases in impervious surface cover result in reduced water infiltration capacity during storms, which means similarly sized storm events can cause more dramatic rises in streamflow (Shuster 2005) This has the dual implication of above ground water resources that are “flashy”, or increasingly sensitive to precipitation events, as well as depleted below-ground water resources due to minimal recharge (Haase 2009). Flashiness refers to the response of a watershed to a precipitation event, with more flashy systems showing larger increases in the water volume in a stream following a storm. Urbanization and runoff from impervious surfaces may increase the flashiness of hydrologic regimes, which can result in higher vulnerability towards floods as larger quantities of water may overwhelm stream channels (Depietri 2012). Low groundwater recharge for prolonged periods of time, which can occur with urbanization and impervious surface increases, can also reduce base streamflow. Streams are generally fed through a combination of precipitation and snowmelt along with groundwater, and with the chronic lowering of groundwater levels, an important contribution to stream flow will be reduced (Shester 2005). These impacts of urbanization have the cumulative result of increasing precipitation entering a stream following a storm, decreasing moisture levels in soils, and lowering base flow conditions for streams.

Urbanization and land use also impact water return to the atmosphere and associated benefits with cooling and plant growth. Case studies in major urban centers have identified urban heat islands, or intensely developed areas with much higher daily temperatures than surrounding non-urban landscapes (Chow and Brazel 2012). Along with the generally more reflective surfaces in urban landscapes, this higher temperature is due in part to changes in evapotranspiration. Lower evapotranspiration results from reduced vegetation uptake of water and hence lower transpiration rates in urban areas. This lowers the achieved evaporative cooling effect that occurs naturally through evapotranspiration processes and reduces the return of water to the atmosphere (Chow and Brazel 2012). Impervious surfaces result in lower water availability for plants as infiltration rates are reduced and soil water storage is depleted, creating a strain on plant available water in and around urban areas.

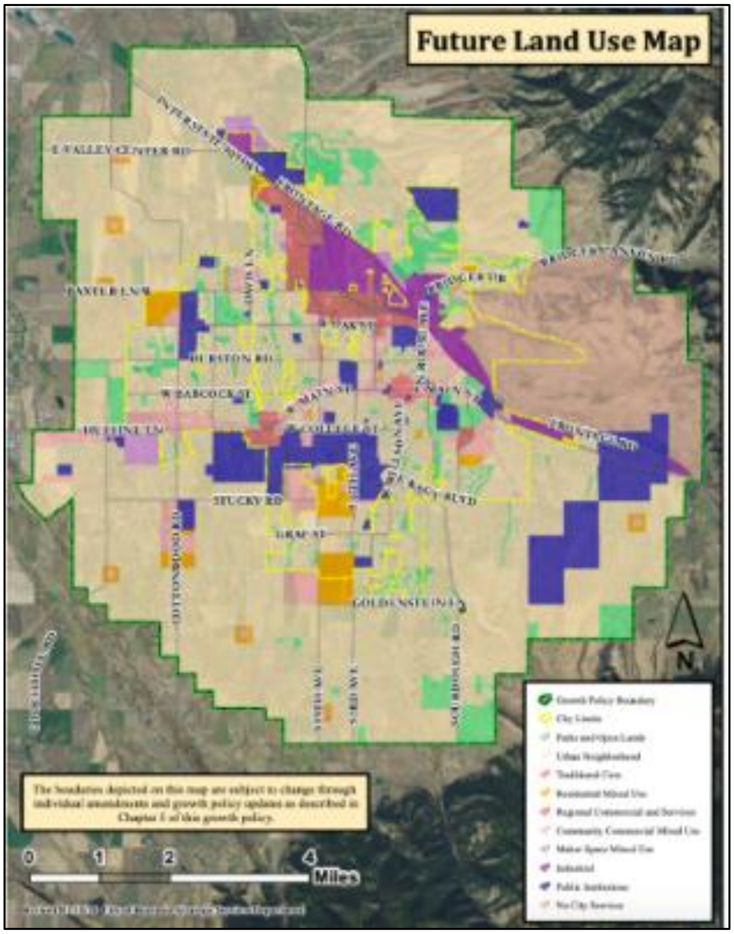


Figure 13: Map of Potential Future Land Uses for Bozeman, MT

Alterations to the hydrologic cycle from urban expansion will become increasingly important for the future of Bozeman and the greater Gallatin Valley. The city of Bozeman forecasts between 2,600 to 3,900 acres of space required for future urban use, which necessitates expansion into agricultural and wild landscapes (City of Bozeman, 2020). An estimated 70 to 80 percent of this land will need to be developed for neighborhoods and residential establishments to meet the growing population's needs (City of Bozeman, 2020). Figure 13 is a map created by the City of Bozeman that reflects current or potential land uses associated with the estimated growth. On the map, pink represents commercial zones, purple designates industrial areas, blue indicates public or governmental buildings, and tan indicates residential zones. Current Bozeman city limits are represented as a yellow line, with the limits on possible city growth based on current policy agreements shown in green. The driving factor in land conversions resulting from Bozeman's growth will be the increase in residential developments, as is illustrated in Figure 13.

While residential land uses do not have the highest total impervious surface cover of all urban land use types, the increase from non-urbanized landscapes will still be significant. Figure 13 depicts average impervious surface cover based on current land plots in Bozeman. Commercial and industrial land classes have the highest impervious surface cover among identified land uses, ranging between 60 and 70 percent of plots covered with impervious surfaces. Single family homes in the Bozeman area have an average of approximately 45% impervious surface cover.

Using the estimated figures on growth from the city of Bozeman and current land cover data, the approximate increase in residential areas will be 1950 to 2,900 acres, resulting in a total impervious surface increase between 900 and 1,300 acres. This increase in impervious surface cover has the potential to greatly increase the amount of precipitation partitioned to runoff and decrease the infiltration capacities of land in the area, altering the hydrologic processes in Bozeman. This data also focuses on the growth of Bozeman specifically, however growth in Belgrade, Four Corners, and other communities in Gallatin county may contribute to land use change and impervious surface cover increase as well.

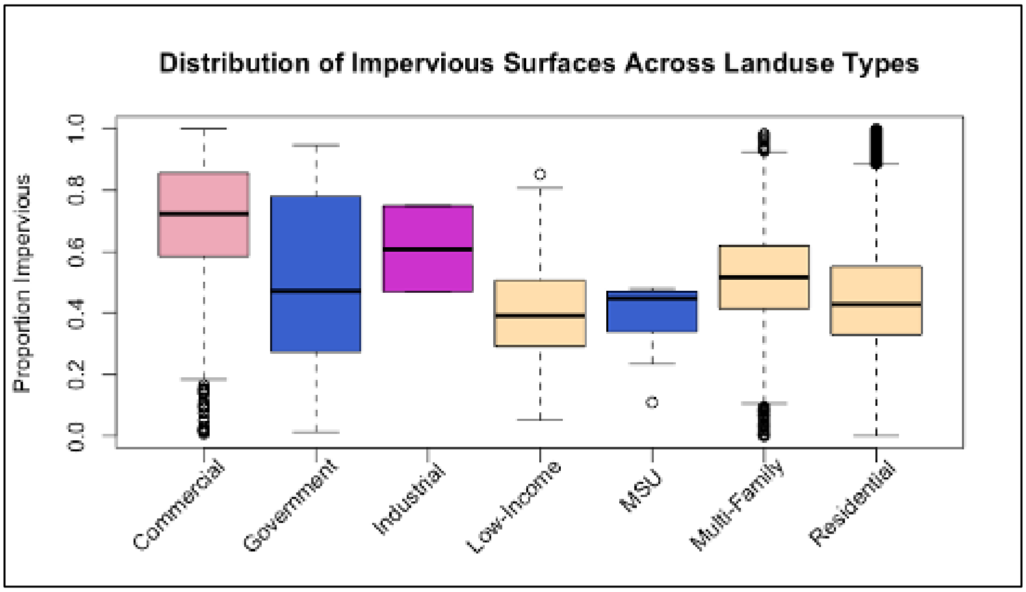


Figure 14: Impervious Surfaces Across Land Use Types

Water Quality

Land use driven changes in runoff patterns alter water quality as well as water availability (Beck 2016). The larger input of overland flow may increase the sediment and pollutant concentrations in water entering streams from urban areas, diminishing water quality. Urban Surface Runoff (USR) is one of the largest contributing factors regarding pollution in the watershed. USR levels are elevated in urban environments due to the increase of impervious surfaces and overland flow, causing the volume of USR to be up to 16 times higher than that of unimpaired or rural areas. This leads to higher water discharges, shorter travel times, greater flooding, and increased pollution loads (Qinqin, et al. 2015). This increase in runoff directly increases the amount of total suspended solids (TSS), nitrogen, copper, and zinc found in urban runoff as referenced by Figure 15. The pollutant wash off load displayed in Figure 15 is reported in mg/m^2 on a logarithmic scale in relation to the total runoff volume, measured in depth in mm. The logarithmic scale helps display the data because contaminants such as TSS will contain a much higher mg/m^2 load than that of a heavy metal such as copper, which is found at very small concentrations that can still cause detrimental effects. The scaling also helps display the relative rate of increase of each pollutant as total runoff depth increases (Wang, et al. 2011). The P values of KN and Cu of <0.001 and the R^2 around 0.5 display strong statistical significance of the data, with the curve tightly matching the data points and accounting for almost half of the variability. The lower R^2 associated with TSS and Zn mean that the lines of best fit do not account for as much variation in the data set. This may be due to a larger number of outliers recorded for the TSS and Zn mg/m^2.

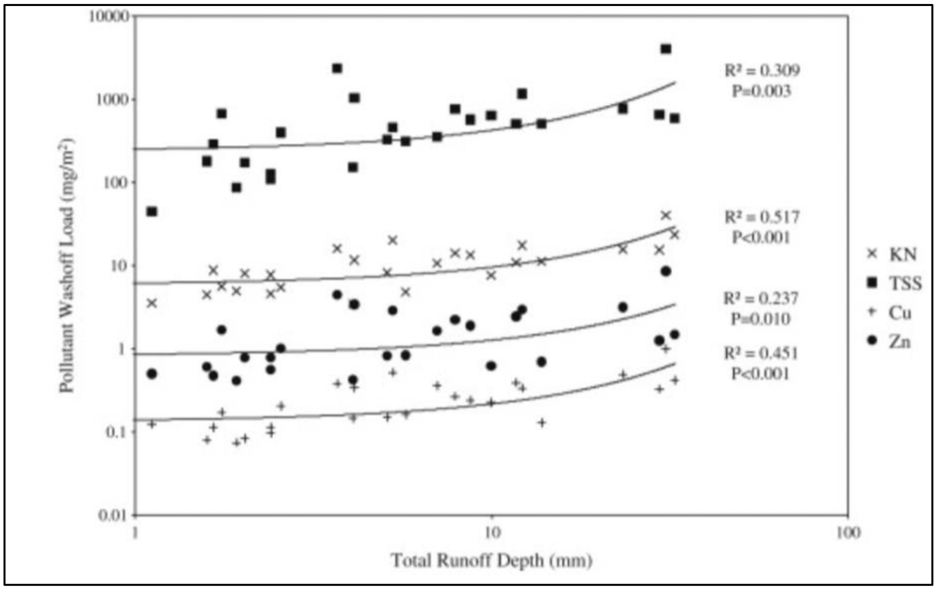


Figure 15: Total suspended solids (TSS), Kjeldahl Nitrogen (KN), Copper (Cu) and Zinc (Zn) measure in mg/m^2 at varying depths and over the total amount of runoff in mm (Wang et al. 2011)

The lack of filtration through soils can reduce the quality of water entering streams. Forest soils, for example, act as a pool that retains pollutants and improve water quality entering a stream, whereas lawns are a source of contaminants like fertilizers that might elevate nutrient levels in streams (Beck 2016). The pollutants affecting water quality can be placed into four major groups: sediments, organic pollutants, nutrients, and heavy metals.

Although sediments can originate from natural terrain, urban development and construction elevates the levels of aggregates such as gravel and sand. One problem sediment pollution poses is an increase in total suspended solids (TSS) in water runoff. An increase in TSS decreases the photosynthetic capacity through water as less light can make it through the water, which can have severe consequences for photosynthetic water plants and microorganisms. Increased TSS also decreases water visibility which affects fish populations as they can no longer see prey or predators, significantly influencing the populations of aquatic populations. Adsorption from sediment particles is another issue in which agglutination (clumping) of particles of other contaminants make the sediment particles potentially hazardous and thus contaminating the water (Filho et al. 2011).

Organic matter pollution comes from domestic sewage, which is the used water from houses and apartments, industrial effluents or discharges of various chemicals and organic pollutants from industrial sources. Increase in urban runoff that contains elevated levels of organic pollutants from human and animal waste, fertilizers, and other surface bound organic chemicals, contributes largely to organic matter pollution. Organic matter pollution lowers the available oxygen in water, causing the death of invertebrates and plant life. It also leads to an increase in turbidity, decreasing photosynthetic capability. Organic matter also tends to settle at the bottom of waterways making it difficult to remove and prolonging the effect of the pollution as it is deposited in the sediment beneath the surface.

Nutrient pollution is generally measured in elevated levels of nitrogen, phosphorus and potassium (Filho, et al. 2011). These nutrient pollutants originate from an increased presence of industrial and domestic waste, animal excrement, fertilizers, carrying soaps and detergents. The main water quality issue associated with nutrient pollution is eutrophication, the rapid growth of algae to elevated nutrient loads, resulting in the depletion of oxygen in the water leading to the death of any respiring organisms in the water system. Nutrient toxicity is another major issue, in which high levels of nutrients cause illness, shock, and even death to organisms as their biological cycles are impacted due to increased nutrient loads (Filho, et al. 2011).

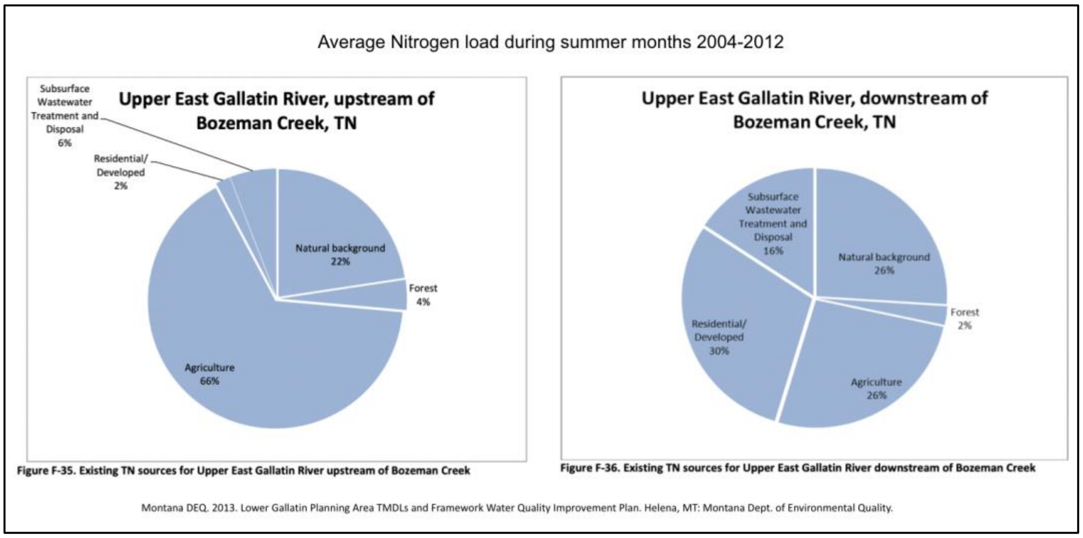
Heavy metal pollution stems from higher concentrations of zinc, copper, and lead in urban water. It is the most directly influenced source of pollution from urbanization due to leaching metals from construction materials, roofing, and painted structures that deposit heavy metals in runoff. Vehicle exhaust and tire wear contain considerable amounts of zinc, copper and lead. Atmospheric deposition of heavy metals that build up on impervious surfaces also contribute to increased heavy metal pollution, specifically in larger urban areas with poor air quality (Filho, et al. 2011). Heavy metals are toxic to many plants, animals, and microorganisms in high concentration as they are non-degradable making treatment and remediation especially difficult. Furthermore, heavy metals can cause a decline in water pH, leading to numerous water and environmental issues.

Focusing on the effect of an urban area on water quality in Gallatin County, the change in water pollutant loads has been monitored by the Montana Department of Environmental Quality (DEQ). For the impact of Bozeman on water quality, the focus of the Hyalite Creek and Sourdough/Bozeman Creek Watersheds are the most significant, as those are the two main water sources for the city of Bozeman. In Table 1, the Nitrate + Nitrite, TN (total nitrogen) and TP (total phosphorus) levels in mg/L are displayed at three locations. The Upper Hyalite Creek sampling site is located at the top of the Hyalite Reservoir, prior to any major influence of human activity. The mean TN levels at this location were <0.01 mg/L and mean TP levels were 0.045 mg/L. The Middle Hyalite Creek sampling site is located at the Bozeman water supply diversion ditch and experiences some anthropogenic influence from the outskirts of the city. The mean TN levels at this location increased to 0.124 mg/L and TP to 0.062 mg/L. The Lower Hyalite Creek sampling site is at the mouth of the East Gallatin River after the creek flows through 21 miles of anthropogenically influenced and semi-urbanized land. The mean TN levels at this location increased to 0.452 mg/L and TP to 0.064 mg/L (Table 1) (Montana DEQ. 2013). From these values it can be determined that the middle and lower sections of Hyalite Creek had a greater concentration of TN by several orders of magnitude as well as a slight increase in TP. This increase of TN in the waterway after the influence of human development in the middle and lower sections is consistent with theory linking urbanization with increased nutrient content of water sources. This data may also be influenced by agriculture which must be considered, as well as the fact the sampling only occurred from 2004-2012. More up-to-date sampling would likely produce different values, in addition to a more current estimate on the influence of urbanization on this water source, as development has increased since 2012 with less agricultural and ranching land influencing runoff.

Table 1: Nitrate + Nitrite, TN (total nitrogen), and TP (total phosphorus) concentrations in mg/L at Upper, Middle and Lower Hyalite Creek sampling locations (Montana DEQ. 2013).

Nutrient Data Summary for Upper Hyalite Creek					
Nutrient Parameter	**Sample Timeframe**	**n**	**min**	**max**	**mean**
Nitrate + Nitrite	2004-2012	14	<0.05	0.09	<0.05
TN	2004-2012	13	<0.01	0.04	<0.01
TP	2004-2012	14	0.03	0.055	0.045
Nutrient Data Summary for Middle Hyalite Creek					
Nitrate + Nitrite	2004-2011	17	0.005	0.104	0.026
TN	2004-2011	16	0.050	0.200	0.124
TP	2004-2011	17	0.042	0.086	0.062
Nutrient Data Summary for Lower Hyalite Creek					
Nitrate + Nitrite	2004-2012	20	<0.01	0.55	0.178
TN	2004-2012	19	<0.05	1.91	0.452
TP	2008-2012	20	0.012	0.14	0.064

Sampling of the upper East Gallatin River for TN provides further evidence for the increase of pollutants in waterways due to urbanization. Sampling of the East Gallatin TN sources, upstream of where Bozeman Creek flows into the river shows that 66% of the TN measured was from agriculture. Residential/developed sources contributed just 2% of the TN load, and subsurface wastewater treatment and disposal contributed 6% of the TN load (Figure 16). Sampling downstream of the Bozeman Creek influx into the East Gallatin found that the TN load of agriculture contributed 26%, 40% less than that of upstream. The residential/developed sources contributed 30% far more than that of 2% upstream, and subsurface wastewater treatment and disposal contributed 16% of the TN load (Figure 16).


Average Nitrogen load during summer months 2004-2012

Upper East Gallatin River, upstream of Bozeman Creek, TN

Upper East Gallatin River, downstream of Bozeman Creek, TN

Figure F-35. Existing TN sources for Upper East Gallatin River upstream of Bozeman Creek

Figure F-36. Existing TN sources for Upper East Gallatin River downstream of Bozeman Creek

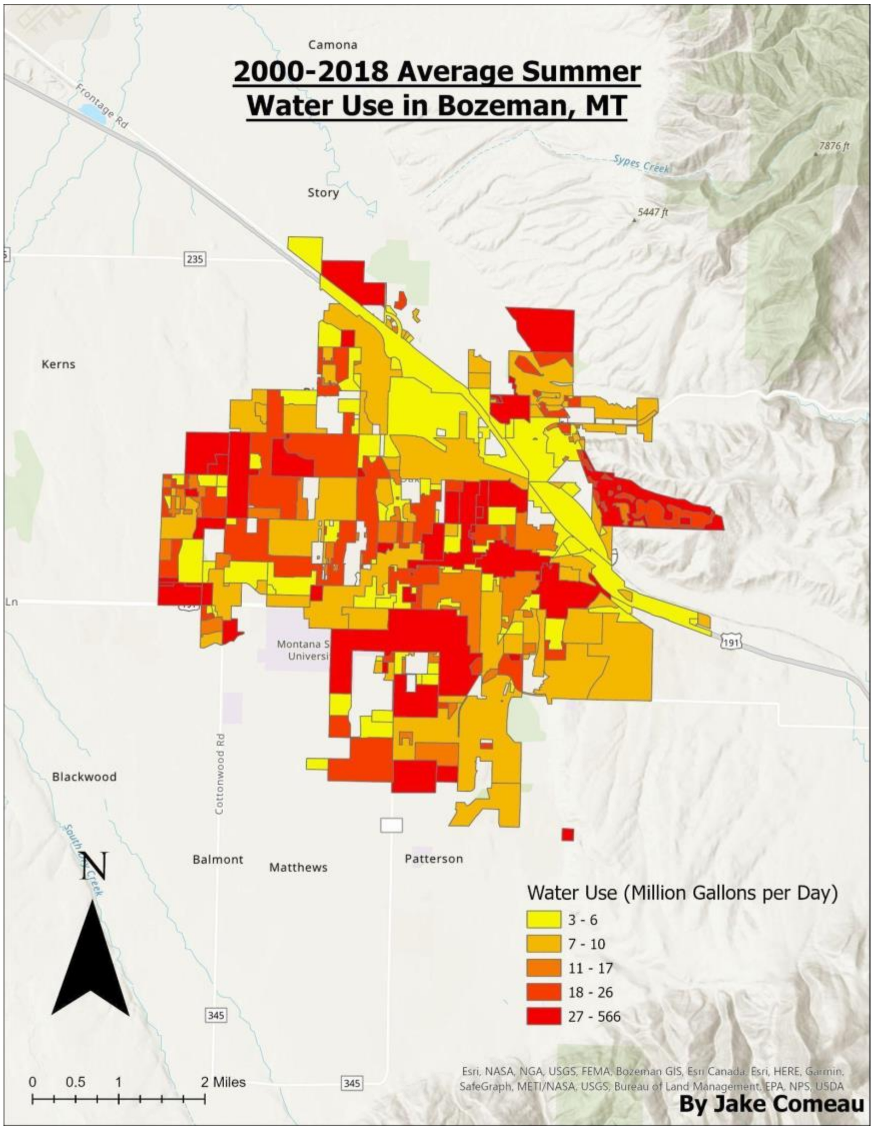
Montana DEQ. 2013. Lower Gallatin Planning Area TMDLs and Framework Water Quality Improvement Plan. Helena, MT: Montana Dept. of Environmental Quality.

Figure 16: Existing TN sources for Upper East Gallatin River upstream and downstream of the Bozeman Creek confluence. Existing nutrient loads were calculated using the median flow and concentration data of the entire available dataset per assessment unit logged by the Montana DEQ (Montana DEQ, 2013).

The influence of development on water quality is displayed well through this figure due to the changes in TN source contributions into the Upper East Gallatin River. The significant increase from 2% to 30% of TN residential/developed sources downstream of the confluence shows the increase of N pollutants as the creek flows through Bozeman. An increase of subsurface wastewater treatment and disposal TN sources from 6% to 16% also displays urban impact on water quality as higher water treatment demand from the city of Bozeman contributes much more N pollution into the Upper East Gallatin River (Figure 16). The sharp decline of Agricultural TN from 66% to 26% sourcing further supports this increase in urban TN pollution as 40% less of the Nitrogen in the Upper East Gallatin comes from agricultural sources (Figure 16) (Montana DEQ. 2013).

Vegetation and Urban Water Demands

Demands on water supplies also vary between land use types, both in quantity of water required and in times of peak water usage. City water usage tends to increase as temperatures rise, with peak water consumption at the warmest points in the summer when lawns require the highest water inputs. Residential land classes have a higher amount of irrigated area than other urban land types, reflecting the prevalence of lawns and the extensive impact of maintaining grass. This change in vegetation type is also driven by land use change, so as the city of Bozeman continues to grow, irrigated yard space will increase the city's water requirements.



Esri, NASA, NGA, USGS, FEMA, Bozeman GIS, Esri Canada, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA

Figure 17*:* Average summer water use between 2000 and 2018

Future predictions of city growth include continued expansion and development of land for single family homes. The yellow shows less water being used and the red shows the most water being used. This is for the summer months in Bozeman, which is an average value of all summer months between the years 2000 and 2018. This data also comes from the City of

Bozeman water conservation, for the parts of town that are occupied by multi and single-family homes, a lot more water is being used. As development expands, so does the increased ratio of vegetated and impervious surfaces compared to less disturbed areas of groundwater recharge. Vegetation absorbs water, especially nonnative species that are not accustomed to the semiarid climate. Open areas, vegetated or not, are also an opportunity for groundwater recharge. Nonnative species that are not resilient in a semi-arid environment need more irrigation to provide the desired aesthetic appeal they were planted for. The lawn of a single-family home on a 1/4-acre lot requires 0.73 acre-feet of water per year (City of Bozeman. 2020). On a larger 3-acre plot of land with a single-family home, an exempt well could provide enough water under the 10 acre-feet per year stipulation to irrigate vegetation and maintain facilities. Most single-family homes can sustain abundant water use by using an exempt well and thus avoiding city water utility charges and regulations. New exempt wells are allowed per plot of land that has not had a previous well drilled.

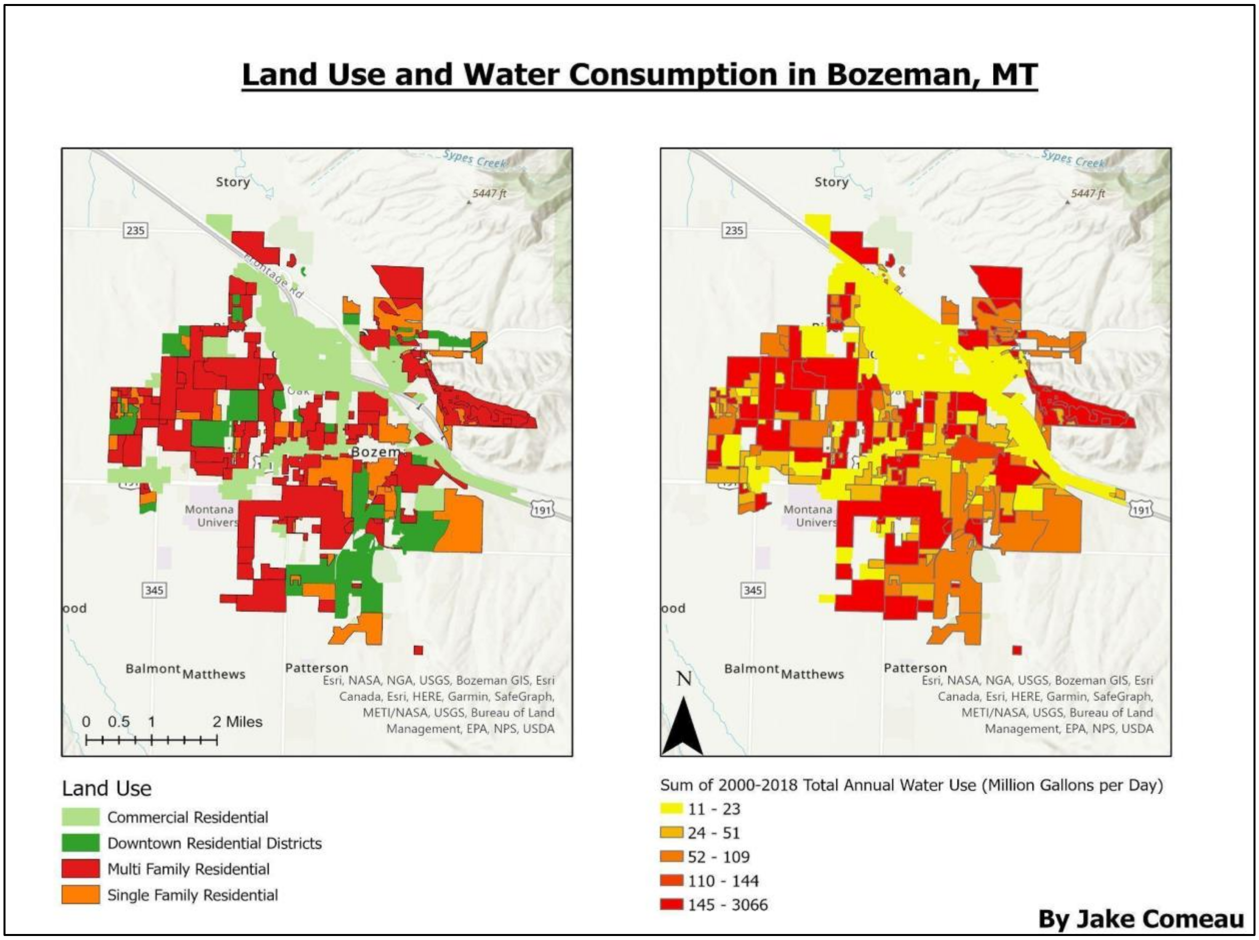


Figure 18: The sum of the 2000-2018 total annual water use is compared to land use

The map on the right shows the water use, yellow is less water being used, while dark orange and red is an order of magnitude more water being used. On the left we have the land use data provided by the City of Bozeman Water Conservation. The commercial residential (light green) and downtown residential districts (dark green) are a concern for water use as well. Downtown residential districts are places such as entertainment venues, restaurants, offices with limited spaces. The main point that you can pick up from the two maps is that the multi-family and single-family residential districts are using the most water. Commercial residential districts often have wells installed, so it is hard to tell how much water they are using.

Bozeman City Water Use and Monitoring

The growth of Bozeman's population, and increase in land use changes undeniably has an effect on the hydrologic cycle. Whether this feedback loop is negative or positive, the data and analysis has not reached any conclusive information. However as supply and demand shifts, the dynamic relationship of government regulation and adaptive management will establish learning opportunities for all. Gallatin County monitors permitting and regulation of water rights and monitors surface water flows, however has little management of urban water distribution as this falls under the city administration. Bozeman City Water provides service to a variety of customer classes, supplying water to residents as a utility since 1889. Sourcing water has been convenient with the valley backing up to two watersheds, Sourdough and Hyalite. To understand the growing issue of water supply, groundwater and surface water need to be studied together for change as urban population increases. Both are inherently linked through infiltration of surface water into the underlying aquifer, recharging the groundwater supply, and outflowing through rivers and tributaries. Groundwater supplies streams and rivers with a vital baseflow and can surface naturally through springs.

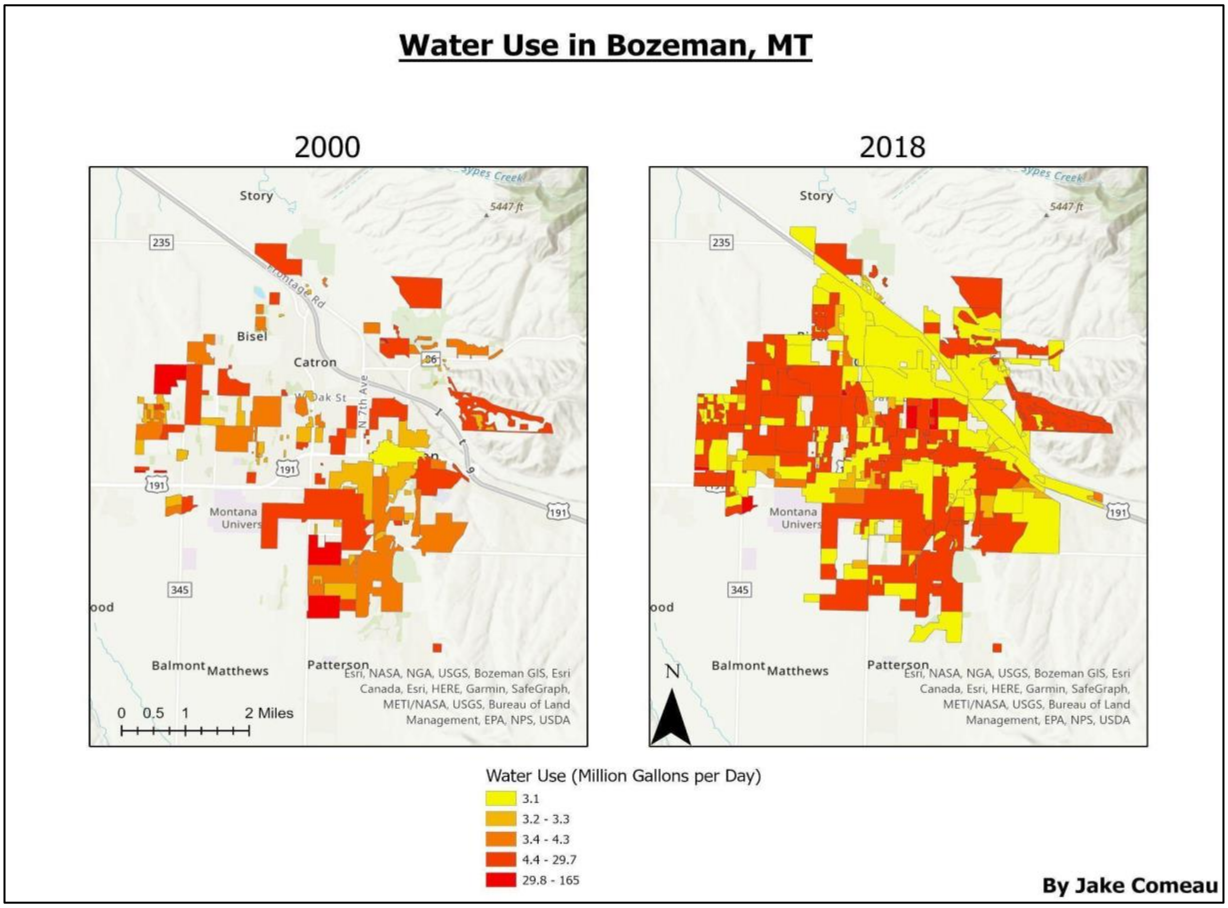


Figure 19: Water use from 2000 to 2018 in million gallons per day annually within the zoning districts.

These data are provided by the city of Bozeman Water Conservation. Far less water was being used in 2000, since there is far less development due to the smaller population of Bozeman in 2000. By 2018, the water use is directly related to the rapid urbanization of western and southern Bozeman. The water use in both these areas increased rapidly from 2000 and much more water is being used per day.

While city water is sourced from surface water collections at a water treatment plant, groundwater is a separate expression from the same source. Since all surface water rights have been parceled and appropriated, groundwater is the remaining source of water to be gathered and utilized. The 1973 Water Use Act further separates regulation and permitting requirements of surface and groundwater. Surface water falls under extensive monitoring and permit regulations as it is directly linked to the sourcing for city water. Maintaining control of a major resource distributed as a utility is in the best interest of the city and state to ensure conflict free supply and demand dynamics. Groundwater is less regulated under the exempt well clause; defined as pumping less than 35 gallons per minute or 10 acre-feet per year (City of Bozeman 1991), enough to cover 10 acres with one foot of water.

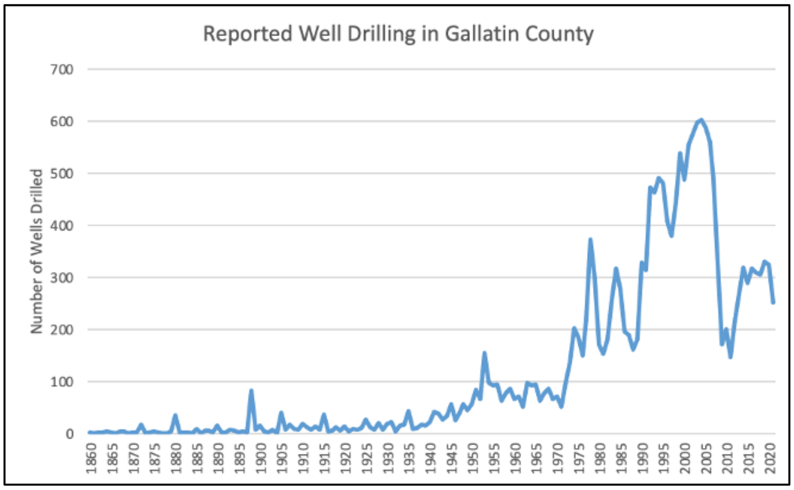


Figure 20: History of wells drilled in Gallatin County has been documented since 1860 by the Montana Ground Water Information Center. Data on individual well depth and method of drilling is available through https://mbmggwic.mtech.edu/

Wells require a one-time survey of the area of installation at time of drilling, where all information is logged into the Montana Ground Water Information Center. There are 19,138 total wells drilled in Gallatin County since 1860;118 of those are unused and 17 are for groundwater quantity and quality monitoring (Montana Bureau of Mines and Geology 2021). Only one well per land use parcel is allotted under the exempt well conditions, being the possible reason for a decline in new wells drilled in the last 10 years (Figure 20). Domestic, single family home wells account for 75% of wells in use. The underlying stipulation of the exempt wells is that water is sourced for individual use, not to be distributed elsewhere and not to have any adverse effects on surrounding groundwater supply. The concern regarding an abundance of unregulated wells drawing on the groundwater source is a depletion of surface water flow. To show that groundwater-utilizing developments will not have a negative effect on surface water, extensive studying of hydrodynamics and GIS modeling is required. Through contracting GIS experts and on-ground water surveyors this information could be made available for future resource management planning.

Population increases create a complex dynamic of resource regulation to ensure sustainable expansion of the city while relying on finite sourcing of water. Because growing urbanization increases water usage, while droughts and climate change decrease availability, addressing conservation includes further study of the capacity limits between surface and groundwater. The previous assumption that 10 acre-feet per year per single family home will not have a negative effect on surrounding water supply may need re-evaluation under the increasing pressure of a growing population.

City Conservation Efforts

The city of Bozeman is in a closed basin and at the headwaters of three major rivers, therefore when natural water supplies become limited, the city will have to search for options external from the valley. External sourcing creates an engineering challenge of overcoming elevation and developing new infrastructures to transport water. Conserving the amount of water drawn from surface water and monitoring groundwater supplies is the most immediate course of action being taken by the city government. The 2014-2015 Bozeman City Water Conservation program invested over $67,000 in rebates and incentives for consumers to reduce water use. Rebate programs incentivize installation of high efficiency appliances in the home and irrigation systems. The 2017 drought management plan provides guidelines of adaptive enforcement and strategy to address water shortages. Primarily monitoring measures for detailed reporting of water quantity is implemented, followed by mitigation of overconsumption by community consumers. The city water utility has developed individual water use monitoring technology with an outward facing app that allows each customer to access their own water consumption data. Based on this information the city initiates excessive water use fees to economically incentivize reducing individual water use. Implementation of this approach involves the community in natural resource awareness and a course of action that increases the public's involvement in conserving this finite commodity.

An additional piece of the water usage structure is the contribution of ranchers and farmers to natural resource consumption. The agriculture industry is mostly outside of city limits but plays a role in the hydrodynamics of the groundwater supply. The amount of artificial recharge in the valley due to the irrigation infrastructure has increased as crop production expands to longer growing seasons with climate changes in the last 10 to 20 years. Flood irrigation would account for significant recharge, however with spray irrigation being the dominant method in the area, the use to recharge ratio is balanced. (Schreffler et. al. 2005) While agriculture plays a large role in water quality monitoring, water quantity information is lacking under urban, and specifically single-family usage.

The most effective way to develop future prediction models and management recommendations for this vital resource is increasing data inputs. Exempt wells requiring no monitoring based on low water usage could benefit from review, as water supply has decreased and demand has increased since 1973. An increased rate of change in natural resource consumption with urban development puts pressure on managing parties (i.e. state, city and county governments) to adjust resource regulations. Ability to monitor outputs from wells would provide information on whether the withdrawal is larger than the recharge, or whether the amount of withdrawal is threatening down-gradient streams and wetlands, even if they do not exceed the recharge. A top-down government approach is the next step in how water is conserved and sustainably managed by amending the Water Use Act to include a connection between surface and ground water monitoring. However, mobilizing the community's voice on this matter is the platform that action for sustainable water management will be built off of.

Land Use Conclusion

Impervious surfaces overall drive changes in water quality, water availability, and water movement through systems. These changes can have negative consequences for local areas that are dependent on these water resources. These alterations to hydrologic cycles will impact water availability in the Gallatin Valley for current and future residents. Supporting a growing population, providing sufficient water for surrounding cultivated lands, and maintaining water for recreational purposes are all priorities for the area; however, serving these needs with an unpredictable water cycle and water resources under increasingly high pressures from climate change creates a significant challenge. Potential avenues to mitigate stress on watersheds from land use change do exist, however, and could be beneficial in the continued growth of the city of Bozeman. Mimicking more natural land use patterns can result in lower necessary water input from irrigation rather than precipitation, and increase water use efficiency. Summer lawn maintenance is a major driver of annual water use trends in the city of Bozeman and constitutes the majority of single-family summer water use. This shows that lawn maintenance holds major potential for improving water conservation in Bozeman. Furthermore, solutions that aid in urban surface permeability could help alleviate problems associated with high impervious surface cover. More extensive permeable surfaces could help recharge ground water and improve the quality of water entering streams. Land use change in urban settings will continue to be a challenge for water conservation, though understanding the fundamental principles that contribute to changes in the hydrologic cycle allows for the identification of more effective and useful management strategies.

Solutions: Green Infrastructure

The population growth of Gallatin County has brought with it an increased number of infrastructure projects. This new infrastructure also leads to an increase in impervious surface area, and more impervious surfaces leads to increases in surface runoff and nonpoint source pollution loads. Infiltration and groundwater recharge are also reduced (Zhang et al. 2019). In Gallatin County, water availability is also becoming more of an issue due to increases in population. This problem may be lessened by the introduction of green infrastructure (GI) to replace the infrastructure that we currently have in the valley. GI is a major innovation that has gained a reputation for relieving urban water problems. With GI, the natural hydrologic cycle is mimicked through enhancing infiltration, reducing surface runoff, recharging groundwater, and increasing the base flow (Zhang et al. 2019). This may help offset the effects of future water deficiency in Gallatin County.

Ground water in the county flows from mountain bedrock aquifers into basin filled deposits, then toward the Gallatin and East Gallatin Rivers. Ground water leaves, or discharges from, aquifers into rivers, streams, wells, and irrigation drains, or as underground flow into adjacent aquifers (Kendy 2001). Unfortunately, impervious surfaces that come with conventional infrastructure block precipitation waters from recharging the groundwater. Green infrastructure throughout the county could lead to higher groundwater recharge and overall increase water health in the valley.

Figure 21: Three forms of green infrastructure

There are many forms of GI that can help mitigate surface runoff and increase ground water recharge. This section expands on three forms (Figure 21) that work in similar ways. These are permeable pavers (left), pervious concrete (center), and porous asphalt (right). Figure 21 shows a generic cross section of pervious surfaces and how they function. On the base is a layer of uncompacted subgrade soils. This is layered on top with coarse material that becomes finer with each layer, creating a reservoir for water to filter through. The topmost layer is the permeable surface material, manufactured either using increased sand content (asphalt), removing finer aggregates (concrete), or spacing materials for drainage (pavers) (Zanoni et al. 2018). These practices create void space, allowing up to 80 percent of water to infiltrate into the material below. For the Bozeman area, that could be as much as 13.6 inches annually. This infiltration brings with it pollutants, trapping coarse solids at the surface and allowing smaller pollutants to pass into the aggregated matrix below. This reduces suspended particles in runoff, leading to approximately 70% fewer contaminants in surface runoff.

In Bozeman, permeable pavers have already been put into practice. This pavement system has a permeable surface that allows stormwater runoff to move through surface voids into an underlying aggregate reservoir for temporary storage or infiltration (DEQ 2017). Some familiar sites are the sidewalks on the corners of Main and Church Street, along North 7th

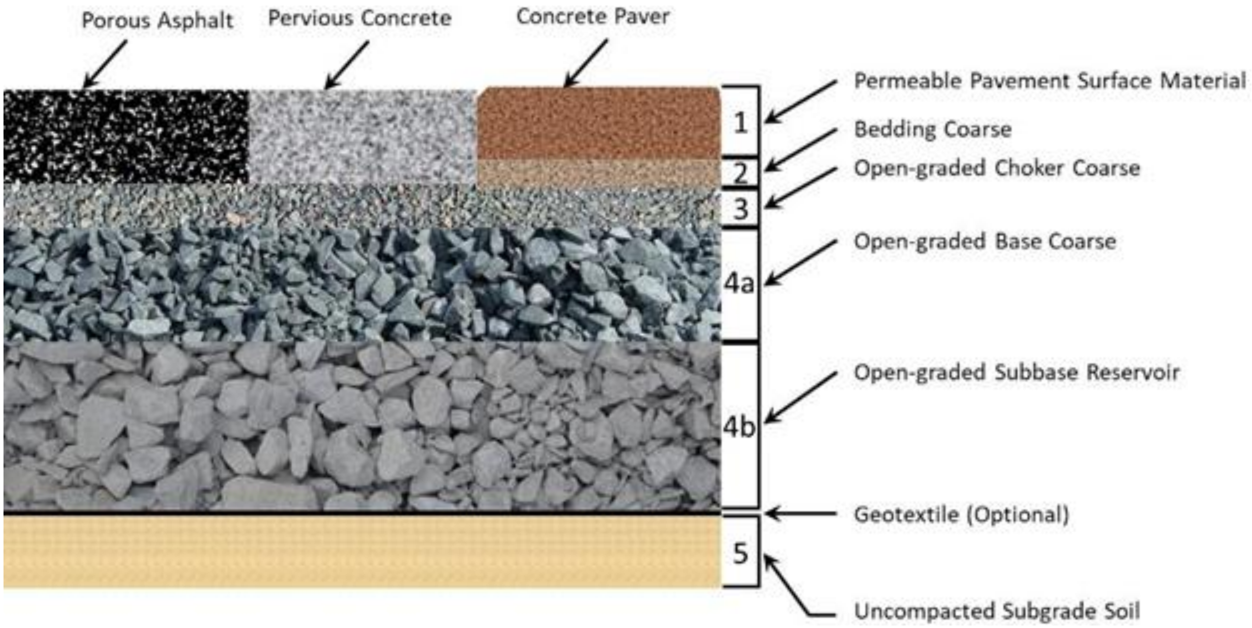


Figure 22: Generic cross section of GI

Avenue, and around City Hall. Two key benefits of permeable pavers are the decrease in effective impervious area and the lower likelihood of developing ice on its surface when compared to conventional pavements. The two largest limitations of the permeable pavers system are the cost, which is nearly double of the conventional counterpart, and that it is limited to pedestrian and low-speed traffic areas.

Pervious concrete was developed in Europe about 50 years ago and the technology has rapidly advanced over the past two decades. The basics of this technology include mixing the concrete with little to no fine aggregates, and only enough cement paste to cover particles of coarse aggregate (Zanoni et al. 2018). Unfortunately, this practice does greatly reduce the structural effectiveness of the hardened concrete (Hein 2016), decreasing the lifespan of the material. An added benefit to pervious concrete's already high infiltration amount is the high albedo that is associated with the composition of the material. Albedo is the amount of solar radiation that is being reflected to space, can decrease temperatures of surfaces and in the case of pervious concrete can cause less wear on vehicles that drive on their surfaces.

Porous asphalt is a likely option in Bozeman's possible green infrastructure future and can absorb nearly 80% of surface runoff. This infiltration brings with it the pollutants picked up by the surface runoff. The GI’s void space would trap coarse solids at the surface allowing smaller pollutants to pass into the aggregated matrix below. Reducing suspended particles in the runoff could lead to up to 90% fewer contaminants in the infiltrated surface runoff. Another benefit of porous concrete is the lack of ice buildup on its surface, similar to permeable pavers. This is due to the infiltration of the water not allowing it to pool on its surface. In addition, there was no heaving of the porous asphalt surface after four winters in a parking lot located at the University of New Hampshire (Houle et al. 2008). Finally, when the porous asphalt freezes, it becomes a frozen porous media that possesses an extremely high infiltration rate. If and when surface water does occur on the porous asphalt, it rapidly infiltrates and thaws the frozen portions of the system (Houle et al. 2008), showing that durability is not affected by freeze-thaw cycles in the northern hemisphere.

Table 2: Cost and life expectancy of GI and its conventional counterpart

Material	Cost Per Square Foot US Dollars $	Average Life (Years)
Porous Asphalt	7 - 13	17.5
Pervious Concrete	8 - 16	25
Permeable Pavers	10 - 30	25-30
Asphalt	7 - 13	25
Concrete	4 - 8	30
Pavers	1 - 15	50-100

When comparing green infrastructure to its conventional counterpart (Table 2), a GI approach tends to be more expensive and has a shorter average life. However, Table 1 only summarizes initial costs of construction and there are many other factors to consider. Researchers at the University of New Hampshire assessed the performance of several low impact development practices including porous asphalt, a form of GI. They found that contrary to conventional wisdom, porous asphalt had the lowest maintenance burden in terms of staff hours and the second lowest in annual cost (Nordman et al. 2018). The higher initial costs are offset by the lifetime benefits of this form of GI. Porous asphalt also has many construction benefits over other forms of permeable surfaces. Roads can be built faster than using other forms of permeable pavements because porous asphalt can be poured and rolled in less time than what is needed for concrete, which needs to be cut and cured. Less construction time leads to less road closure time and a reduction in labor costs (IAPA 2018).

GI also helps limit the amount of ice buildup on roads, parking lots, and sidewalks that could normally pool water that freezes. This could lead to a cost offset in damaged vehicles or injured pedestrians from slips and falls. Other than the direct monetary benefits, GI filters contaminants from stormwater runoff which is beneficial for surface waters downstream from the infrastructure. Through this infiltration GI also recharges the groundwater below providing a healthier water system.

Solutions: Groundwater Management and Xeriscaping

Finding solutions to water supply problems is as important as it is complicated. Two distinct methods of conserving water, the creation of groundwater management areas (GMAs), and xeriscaping will be considered. These two methods, the creation of groundwater management areas and xeriscaping, would require policy changes, along with changes in ecologically and human focused conservation practices. While these two methods will be more attractive to some than others, they both pose interesting solutions to a looming issue, and are worth consideration.

With increasing urbanization in Bozeman, the time for a reconsideration of how groundwater is used and managed is vital. Groundwater management areas provide a potential remedy to overutilization of groundwater resources. These areas are in essence governed by regulations imposed by the state to limit water appropriations based on water availability or water quality. The establishment of GMAs can also control whether new appropriations can be obtained with the confines of the area. Currently there are 17 groundwater management areas in the state, and two within Gallatin County. Many of these sites exist due to water quality issues based on previous environmental pollution. The issue of water quality is important in its own right, as contamination of groundwater is both difficult and expensive to remediate. In fact, shallow injection wells in Montana constitute one of the greatest immediate threats to water quality in the state (Ashley, et al. 1999). Shallow injection wells are in essence any injection of fluids above or into aquifers for the purpose of disposal. Examples of these wells are septic tanks and stormwater injection sites. While water quality isn't the direct focus of this report, contamination to our water resources has an immense potential to impact overall water supplies as it quickly becomes unusable afterwards. Establishment of GMAs could decrease the installations of new exempt wells within the confines of the area, and/or further limit the amount of water that pre-existing exempt wells can obtain. Understanding our current groundwater management is important to understanding why the establishment of GMAs is enticing. While permits are required to install an exempt well, they are able to pull up to ten acre-feet of water per year, with little to no monitoring once installation is complete. Therefore, a GMA approach to water conservation should be thought of as a regulation action to ensure that aquifer resources are not depleted before further conservation methods are applied.

Of the 17 GMA's in the state of Montana, 5 exist to address water quantity issues. While no current GMAs exist in Gallatin County to address water quantity problems, a previous GMA located in Sypes Canyon existed from 2002 to 2008. GMAs have to be proposed to the DNRC, and evaluated before they become law, so initially a GMA is granted on a temporary basis before it is reevaluated and granted permanent status. Two GMAs in Montana that provide insight on groundwater management are the Hayes Creek Basin in Missoula County, and the Horse Creek GMA in Stillwater County. The Hayes Creek Basin in Missoula County has stipulations on the number of wells that can be installed per lot, and implements quarterly monitoring of those wells that are currently in place. Additionally, this permanent GMA creates the potential to further regulate well installation and use in the future if these water resources are being depleted too rapidly.

The Horse Creek GMA also requires groundwater monitoring; however, monitoring is only performed in traditionally high use spring and summer months. Along with monitoring, this particular GMA requires residents to discontinue well utilization for lawn and garden irrigation if precipitation is deemed two low over a three-month period.

While groundwater conservation is not entirely new to the state, without further regulatory action, exacerbation and contamination could result in adverse impacts to water resources. This is the time for Montana to lay the groundwork for preservation and conservation of its groundwater resources, to avoid the problems that many other states are experiencing (Ashley, et al. 1999). While GMAs are not a silver bullet to address water conservation problems, they provide a critical tool to manage and gather information about how groundwater is being used, and more importantly being depleted. They present a step towards an overarching approach to avoid over-utilization of water resources.

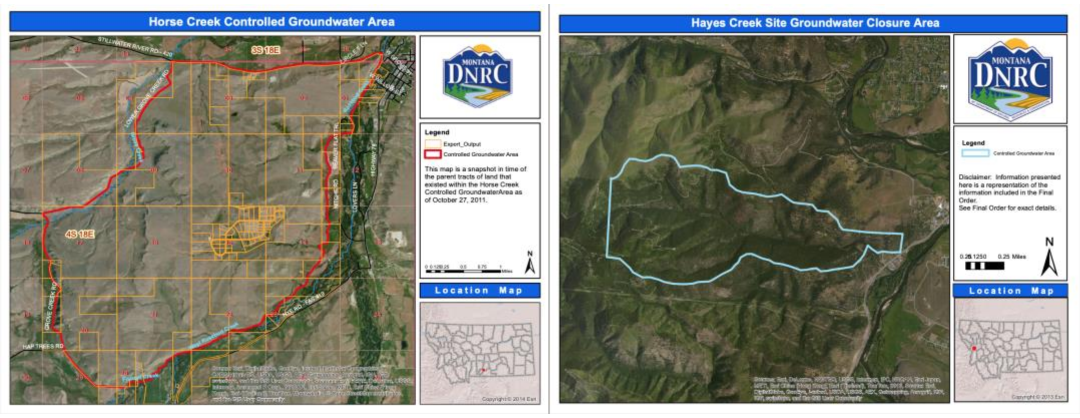
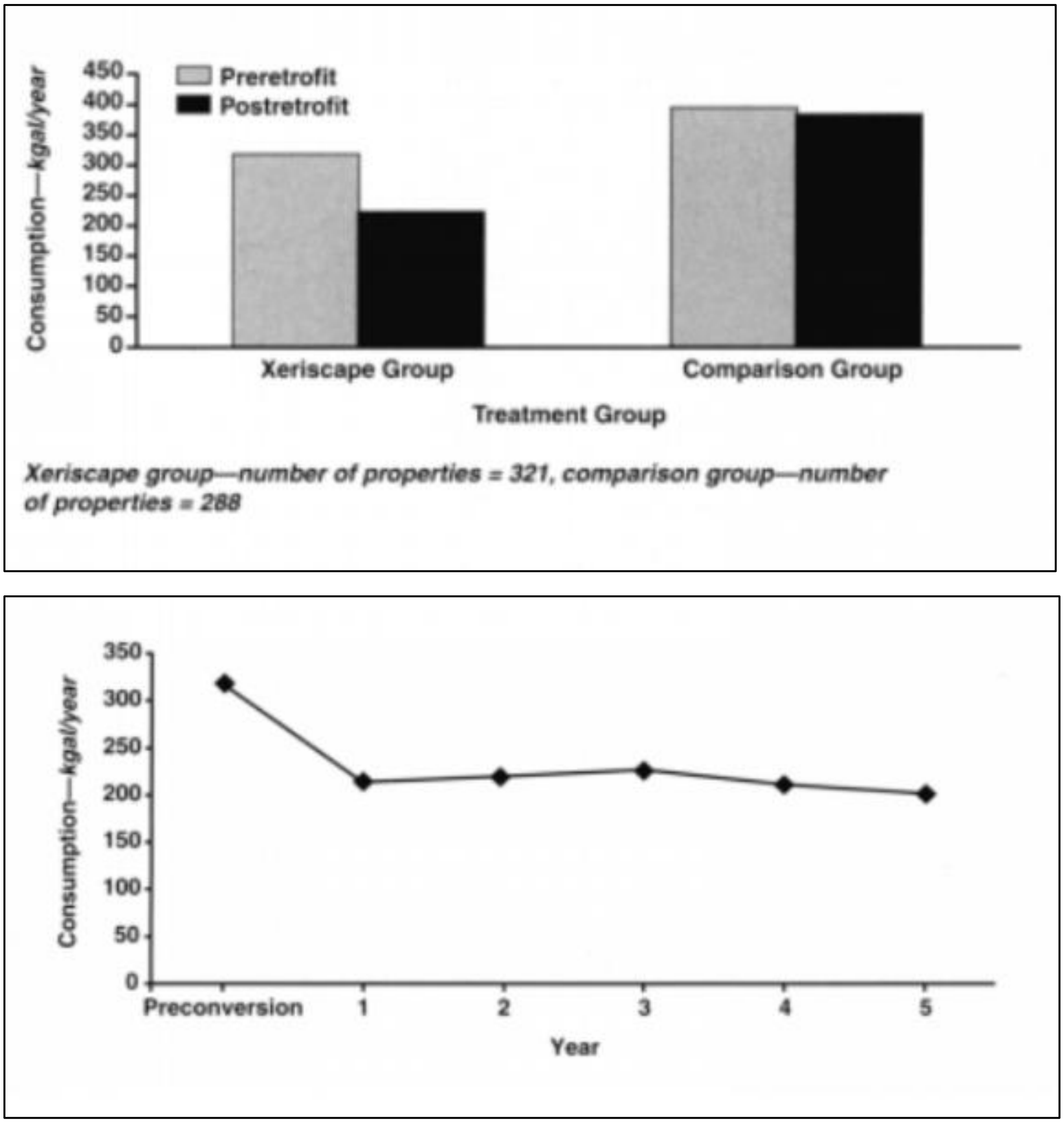


Figure 23 Maps of the two GMA's / Controlled Groundwater Areas in Stillwater County and Missoula County

Another interesting solution to reducing lawn irrigation is the use of xeriscaping. Xeriscaping is the process of land development that either greatly reduces or fully eliminates the need for irrigation of outdoor spaces. Through utilization of native and drought tolerant species rather than a traditional Kentucky bluegrass lawn, irrigation demand is greatly reduced. Given drought trends observed in Bozeman and across the American West, lawn irrigation actively depletes water resources at the most important times of the year, in especially hot and dry summer months. Xeriscaping could combat this problem as even conservative estimates from arid climates predict that switching to native and drought tolerant plants could result in a water savings of 1,482 gallons per week, and 21,198 gallons per growing season based on a 10,000 square foot yard area (Sovocool and Rosales, 2005). These savings in water consumption can be observed in Figure 24, where usage dropped in the xeriscaping group in both short- and long-term periods over a five year study in the Mojave Desert. Along with drastic savings in water, xeriscaping also makes economic sense as the city of Bozeman charges residents for water usage. While tracking water use through retrofitting wells and xeriscaping can address problems of low water supply in different ways, using them in tandem could drastically change our current trajectory of over usage of water. This study also involved the installation of monitoring devices in order to track consumption which itself seemed to slightly reduce water consumption.



Xeriscape group—number of properties = 321, comparison group—number of properties = 288

Figure 24 Results of Xeriscaping and Water monitoring (Sovocool and Rosales, 2005)

Forming solutions to high water usage is hugely important for two major reasons. Firstly, it conserves a vital and shared resource that all living things need to survive, and secondly, it prevents the need to undergo hugely expensive water transportation systems like pipelines.

Pursuing solutions to current water supply and demand problems will become one of the most important aspects towards fostering a sustainable quality of life in Bozeman. As population increases and climate change continues to negatively impact hydrological processes, it is crucial to work towards solutions that involve using what we currently have. Both solutions mentioned above present interesting avenues in which individuals can participate along with organizations and local/state governments. GMAs can be proposed to the Department of Natural Resources and Conservation by residents, or by governmental and non-governmental organizations. Xeriscaping is a personal choice for home and land owners that comes with both environmental and economic benefits. While tackling problems like water scarcity can seem insurmountable, individual actions can make a difference that will help the entire population of Bozeman, as well as the surrounding ecosystems that also depend on the availability of water.

Solutions: Wastewater Recycling

Although recycling generally applies to waste such as aluminum cans or cardboard, water can be recycled as well. Fundamentally, water recycling is when treated wastewater is used for beneficial purposes, such as domestic use, irrigation, and industrial processes. This technology is employed as a solution to offset strained water sources in communities worldwide. In Montana, wastewater is reused in a few places. In Missoula, treated effluent is used to irrigate poplar trees to minimize phosphorus and nitrogen from contaminating the Clark Fork River ("Hybrid Poplar Project"). Additionally, the Yellowstone Club out of Big Sky, Montana has developed a program to use recycled water for fresh snow for the ski resort, hopefully premiering 2022. Nutrient rich water that would otherwise pollute streams will be reused to make snow. This is in an effort both to recycle water but also to divert water from directly entering streams where high levels of nutrients can result in eutrophication, an issue already observed within the past couple years (Dore and Wilson, 2021). These efforts to reuse gray water are beneficial and forward thinking, but unfortunately the projections for Montana's future climate are bleak, putting extreme stress on this precious resource. With rising global temperatures, water security becomes of utmost importance not only to survival, but also to the quality of the natural resources that urged many of us to move to this scenic valley.

Bozeman's wastewater is processed in the Bozeman Water Reclamation Facility (WRF), where 98% of common pollutants are removed via Biological Nutrient Removal before the water is received by the East Gallatin, downstream of the sources. The treatment method utilizes microorganisms to decompose biological nutrients such as nitrogen and phosphorus to minimize downstream pollution. The WRF processes up to 8.5 million gallons per day to accommodate wastewater flow. The efficiency of the current WRF sets Bozeman up for the facility to be tailored to meet requirements of a planned reuse on a city-wide scale. Since the EPA doesn't fully regulate water reuse, it encourages cities to implement water recycling technology. Thus, the decision to employ water recycling is up to the city of Bozeman itself.

Many cities with arid climates have already adopted water recycling to provide water security and minimize energy usage. For example, water recycling is integral to California's effort to mitigate the effects of severe drought. Currently, the state recycles 714,000 acre-feet of water per year and could improve infrastructure to reuse an additional two million acre-feet ("Water Recycling"). To achieve this, gray water from bathtubs, laundry machines, and sinks is reused for irrigating landscaping and fruit trees. Since 1992, the legislation has been expanded to account for amended plumbing systems that ensure the greywater is safe for reuse. Over the years, communities have worked to ease plumbing codes to make gray water recycling more attainable. Montana gray water legislation allows recycling for irrigation except for plants that are directly consumed by humans, similar to the California rules. Overall, Montana gray water limitations function on an individual scale, where irrigation systems can't cross property lines as a precautionary measure ("Rule 17.36.319: Greywater Reuse"). However, this rule doesn't address larger apartment buildings or public buildings. Legislation and lack of incentives can often be the demise of these types of sustainability projects, especially when individual households likely don't have the ability to adapt their plumbing for gray water reuse.

Although this technology to reuse greywater is well-developed and relatively inexpensive, only about two dozen communities in the United States use recycled water for drinking water. In these communities, the water is sterilized and then mixed back into the source before reuse. This step dilutes the recycled water in the main source, making the "toilet to tap" idea more palatable (AP 2010). The approach to wastewater recycling is currently conservative since these programs only offset a small amount of water intake, but as the demand for freshwater increases, states will be in dire need of cost-effective solutions. Even if recycling water to a quality where it is potable is expensive, there are many other options for the fate of recycled water, all of which minimize the strain on existing freshwater sources.

Colorado houses over two dozen facilities that recycle water for irrigation and industry, but not for drinking. The head of Denver Water, Greg Fisher, suggested in a 2021 article that this may not be enough to minimize the strain the growing population has on the Colorado River (McCan et al. 2021). However, in a small town such as Bozeman, this could be a great step for the city to become accustomed to using recycled liquid waste. Projections of Bozeman's population growth estimate that by 2041, the population of Gallatin Valley will be equivalent to Salt Lake City, and our current water sources will most certainly not be enough (Wilkinson 2019). If Bozeman can begin to adopt wastewater recycling, even just for irrigation of lawns, the onslaught of demand for water within the next decade can begin to be sated.

Despite the promise of this technology, cities that adopt this technology are put in a Catch 22 situation. With water recycled within a city, a question is raised about how the downstream ecosystems will be impacted. Usually, treated water is placed back into the water system. In the Gallatin Valley, water sourced from Sourdough, Hyalite Reservoir, and Lyman Creek is treated and deposited into the East Gallatin, on the downstream side of the valley. Sacramento County, a region that has adopted water recycling, is working to address this issue. A water rights coordinator at Fish and Wildlife, Lauren Mulloy, compared water recycling to a new water diversion where "taking it out is the same as proposing a new diversion" (Weiser, 2016). In another case in Ventura County, treated water goes on to feed the Santa Clara River, home to endangered steelhead trout. Some argue that the depletion seen initially from wastewater recycling programs will eventually balance out as groundwater is recharged. By irrigating with recycled water in agricultural land, the depleted groundwater will be recharged, returning the aquifer to levels that sustain the flows in downstream bodies of water. In this case, it's a question whether populations in downstream ecosystems can sustain multiple years of lower flows, especially with the increasing stress resultant of drought, and additionally if agricultural users would be willing to transfer water rights to the urban districts. As referenced earlier in the paper, the definition for "safe yield" is nebulous and defined in different ways by different parties. This makes monitoring watersheds and groundwater supply difficult and incomprehensive.

In conjunction, another proposed issue is that of downstream water quality. In cases such as the Yellowstone Club's snow project, water quality will increase in the surrounding rivers. However, in cases such as the East Gallatin, a massive concern would be if organisms in this ecosystem would be negatively impacted from water from a recycled water plant, especially since the Gallatin Valley is famed for fishing.

As with any large engineering project, especially one considering impacts to the environment, solutions often act as a double-edged sword. Our solutions can provide additional problems, so large scale engineering projects need to be carefully vetted. To minimize conflict, trade-offs need to be addressed to avoid negative impacts over long term use. In conjunction with xeriscaping, greater water conservation efforts, and environmentally-friendly engineering projects, water reuse could be a great addition to a water-conserving toolbox of a city with a rapidly growing population.

Conclusion

Climate change will exacerbate conditions that limit water availability in the Gallatin Valley along with the rest of the western United States. Increasing temperatures and erratic precipitation can reduce the dependability of water inputs and result in decreased water availability. Increasingly warm temperatures in the early spring can also contribute to a much faster melting of snowpack. Water treatment and storage capacities of the City of Bozeman Water Treatment Plant are limited, so rapid melting events could potentially overwhelm the facility and result in loss of the necessary snowpack water. Snowpack depth and snow water equivalent are declining, meaning this critical input to the watersheds Bozeman is dependent on are vulnerable to the impacts of climate change as well. More severe and frequent droughts are probable with the ongoing impacts of climate change, but vegetation demands in either agricultural or domestic uses will continue to require water inputs. Climate change will hence decrease reliable water supply and annual water quantity, which creates a large challenge in tandem with the growing population and increased demands the Bozeman area will experience.

Changes in land use will also influence the availability of water resources in the Gallatin Valley. Urban growth can fundamentally alter the hydrologic cycle and limit groundwater recharge while increasing runoff. Increases in impervious surface cover will drive this increased runoff, reduced evapotranspiration, and reduced soil infiltration which will all contribute to changing water availability and distribution. The increase in impervious surface cover also has the potential to impact water quality. Increases in sediment loads, nutrient levels heightened to concerning levels, and elevated concentrations of heavy metals or other chemicals in surface waters are all correlated with urban growth and development. Along with increases in impervious surface cover, land use change will alter water demands and vegetation distribution. Residential developments generally have higher water use requirements because of lawn irrigation needs. Water use for single family residences spikes dramatically during the summers in Bozeman, influenced in large part by the increased demand for water to maintain lawns. This seasonal demand can create a strain on water resources during the summer, when water inputs are generally lower. These land use changes are influential on water cycles, quality, and demand, and the impacts of these land use changes will continue to intensify as the population grows.

Laws and regulations on water add a dimension of complexity in meeting water needs for the growing population of the Gallatin Valley. Surface water rights are closely monitored and difficult to change, which limits the extent of possible supplementary water the city can draw from local sources. The lack of regulations for exempt wells, conversely, creates the potential for groundwater resources to be overused without penalty. Groundwater and surface water availability are connected, as groundwater is an important source of streamflow. Depleting groundwater therefore will result in reductions in available water in streams or lakes, which contributes to the lack of water for sufficiently sustaining the growing population. These problems are summarized in Figure 25, showing the decreasing inputs and increasing demand.

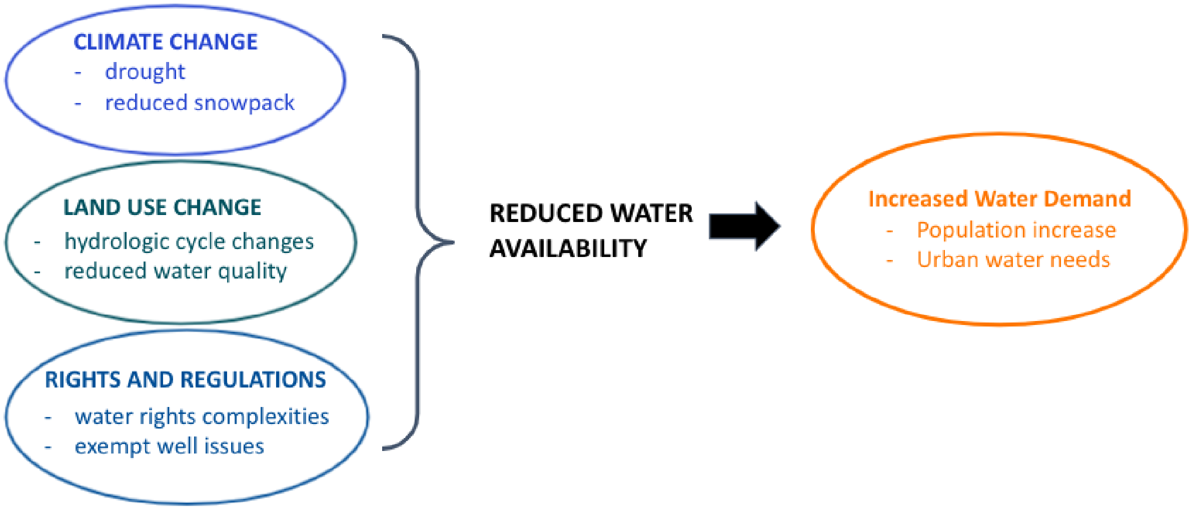


Figure 25: Factors reducing water availability and increased demand.

As the population of Bozeman and the Gallatin Valley continues to grow, now at an accelerated pace in response to the COVID-19 pandemic, finding ways to improve water conservation will be critical. Bozeman sits near the headwaters of the Missouri River, and therefore is not impacted by any upstream users. Considering that Bozeman is projected to have an insufficient water supply for the population by 2031, the question of how this need can be met is increasingly urgent. The potential to construct a pipeline to Canyon Ferry Reservoir, 52 miles northwest of Bozeman, is one solution under consideration by the county. A net gain in elevation of 950 feet separates Canyon Ferry and Bozeman, with the challenging topography of the Horseshoe Hills requiring an intermittent climb in elevation as well (Figure 26). This would be a massive engineering feat, but also raises ethical questions pertaining to downstream users and avoids the problem of inefficient water use or other more sustainable solutions. Failing to address water quality and quantity concerns by simply continuing to find water at greater distances to draw from may have consequences for the Gallatin Valley later on.

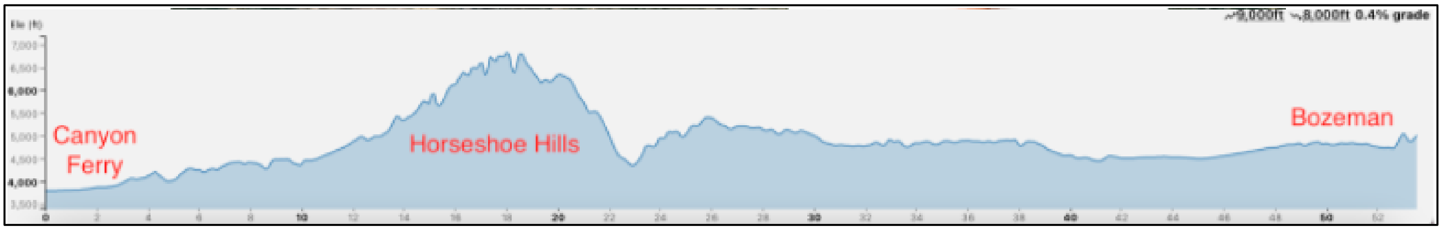


Figure 26: Elevation change from Canyon Ferry to Bozeman

This urgent need for improved water management reflects the importance of considering scientifically sound solutions. Methods such as xeriscaping may reduce unnecessary water consumption during a period of the year when water is generally most scarce. Xeriscaping can reflect more natural water demands, and reduce one of the most major uses of water in the Bozeman area. The integration of permeable pavers and other permeable ground cover technologies can mimic natural hydrologic cycles and water availability in urban areas. These can increase groundwater recharge and limit water pollution by allowing precipitation to infiltrate surfaces like sidewalks, and help provide a solution to problems driven by extensive impervious surface cover. Groundwater management areas are a third approach that could assist in conserving and understanding groundwater, and limiting the quantity of water removed from aquifers. This can improve long term sustainability of wells or other systems dependent on groundwater by ensuring the long-term availability of water stored in the ground. Finally, the investigation of water recycling technologies can increase the efficiency of water already present in the watershed. Recycling water would reduce reliance on high amounts of snowpack or dependable precipitation, both of which are threatened by climate change. Overall, consideration of a myriad of solutions focusing on the wide range of problems from urban development will be critical in ensuring a future of fair and environmentally sustainable water access.

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