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Modelling water conservation prioritization in the Henry's Fork Watershed

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Dedication

The work in this thesis is dedicated to the late Mr. Al Knight ’51L who established the annual A. Paul Knight Internship in Conservation in honor of his late son, Paul Knight. This internship funds the work of 4 undergraduate and 2 law students at various non-profit environmental organizations. The undergraduate students traditionally have worked for The Nature Conservancy’s Flat Ranch Preserve, Friends of Harriman State Park, and the Henry’s Fork Foundation, which are located within the watershed where this thesis is based.

My academic career, thesis work and future aspirations are a product of this internship program, and I am forever grateful for the generosity of Mr. Knight. Without his investment in me, and countless other students, I would not be the person and academic that I am today.

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The above image on the left shows the author fishing the Henry's Fork Watershed at age 7. The above image to the right depicts the author's first fish caught in the watershed (not to scale- I contend that it was much larger in life).

Abstract

Agricultural water usage has long been at odds with preserving aquatic ecosystems in the Henry's Fork Watershed, which is located in Southeastern Idaho. To address the problem, the Henry's Fork Foundation (HFF), a local science nonprofit, developed a Water Marketing Program aimed at reducing usage of surface water within the watershed. This manifested itself in the form of a multifaceted incentives-based approach that includes renting land, shifting historical crop regimes, and encouraging alternative crops. This thesis outlines the development of a water conservation prioritization scoring system and model to help HFF be most efficient with their funds. To accomplish this, an ArcGIS model was developed to account for net irrigation demand, priority date, geographic location, and place of use. The information collated within the ArcGIS model produces an interactive map illustrating each parcel of interest and their ranking. This map, along with two correlating databases, will be instrumental to the future success of the Water Marketing Program because it allows HFF to target high priority parcels.

1. Introduction

1.1 Historical Background & Motivations

Water usage in southeastern Idaho has been a complicated issue since the Manifest Destiny population movement in the 1800s. The arid, high altitude environment became a hotbed for westward moving settlers looking to establish themselves in the great American West. In the beginning, their ability to establish productive farms and homesteads was limited by the environmental conditions in play, and farmers began to search for ways to conquer the barren, tumbleweed filled lands they now inhabited (Fiege 2009). In the Henry's Fork Watershed, this resulted in the creation of irrigation canals in 1879. These canals diverted surface water flow out of the river basins and into the farmers' fields allowing them to achieve higher crop production and to make lush green fields out of what had once been inhospitable desert (Fiege 2009). These canals were ultimately revolutionized by the Desert Land Act of 1894, also known as the Cary Act, which established irrigation districts and vastly expanded the network of irrigation canals (Fiege 2009).

As the population in the region grew, so did the demand for usage of surface water. There was a clear need for a water usage regulatory system and thus the concept of prior appropriation was born. In present time, prior appropriation water law is the prevailing water usage regulation in states that are located west of the 100th meridian (McCormick 1994). It establishes water as a state governed public resource that allocates water rights to both individuals and entities who put the water to beneficial use (McCormick 1994). These water rights are structured by priority date: the date when a specific amount of water was first claimed and used at a location in adherence with the parameters of beneficial use, which are wide sweeping and varied. This doctrine has traditionally been summarized as “first in time first in right” (Fiege 2009). This system allocates priority of consumption of natural flow, or the amount of flow that moves through a hydrologic system without anthropogenic manipulation, to those who used it first over all other users that follow. As the agricultural water year, which runs from April 1st through October 31st, progresses through time, each year rights that are junior, to those first established fall out of priority, as natural flow decreases when input becomes limited during drier months. If a hydrologic system has any anthropogenically created water reservoirs, then those who hold out of priority rights can purchase water stored in those reservoirs, in order to meet the consumption demand that can no longer be met by the natural flow (Van Kirk et al. In Press). In many agriculturally dominated watersheds, this scenario occurs to varying degrees each agricultural water year, much to the detriment of the overall health of the aquatic ecosystems and, in particular, prized trout fisheries.

Farming styles that once depended on backbreaking physical labor and the use of animal dependent devices has advanced to a more refined industrial strategy that utilizes millions of dollars worth of machines (Batie & Healy 1984). As the farming community transitioned from small homesteads to large scale agricultural industry, the production, demand, and cost of operation have all increased (Batie & Healy 1984). This agricultural revolution resulted in vast increases in water consumption and demand. This once again triggered the expansion of cutting-edge irrigation technology and water transportation infrastructure. The resulting network of irrigation canals run like veins through the land, connected to a steel skeleton of pivot lines, sprinklers, and central lines that supply the agricultural fields with water. The natural hydrologic system is often stressed by the demand this framework helps to satisfy (Fiege 2009).

The issue of intensive agricultural water usage in southeastern Idaho has the potential to get much worse unless an immediate solution is discovered. Since the doctrine of prior appropriation allocates water to users on the basis of priority water right date, holders of junior water rights may not have access to water in times of water scarcity (Idaho Department of Water Resources). Additionally, as climate change continues to result in extreme climate fluctuations (Van Kirk et al. In Press), it is not unreasonable to expect that this region of Idaho, which already experiences extremely harsh winters and dry summers due to its geographic location, will feel the continuing impacts of climate change acutely (Van Kirk et al. In Press). Climate change has the potential to lead to extreme water scarcity in this region, with large implications for the environment and species that inhabit it. Trout populations and the aquatic ecosystems they inhabit will likely be particularly affected, as historically they have been heavily impacted by increased surface water usage for agricultural irrigation (Fiege 2009).

In an attempt to increase the efficiency of water usage and economic water-based profit, the state of Idaho created a water bank in 1979 (Ghosh et al. 2014). However, water markets are not always the most efficient due to third party impacts, high transaction costs, and historical barriers (Ghosh et al. 2014). Idaho runs the oldest water bank in the west that allows for the buying and trading of water rights and permits (Ghosh et al. 2014). Though it has been in operation for forty years, it has not been utilized to its fullest extent until recent years. For example, the Idaho water bank traded 70.69 million m^3 of water in 2012, up from the 0.16 million m^3 of water traded in 1995 (Clifford et al. 2004). Though use has grown, limitations stemming from the state regulation of water banks, such as the one in place in Idaho, provide a motivation for water marketing, an increasingly popular strategy for addressing excessive agricultural water usage (Ghosh et al. 2014).

A prime example of the development of Water Marketing Programs in southeastern Idaho is the HFF's fledgling Water Marketing Program. The Henry's Fork Watershed contains roughly one quarter of the Snake River Basin agricultural complex, and is economically valued at $2.5 billion USD annually (Idaho Water Resource Board 2009). Within the same watershed are economically valuable Brown Trout (*Salmo trutta*), Rainbow Trout (*Oncorhynchus mykiss*), and Cutthroat Trout (*Oncorhynchus clarkia bouvieri*) fisheries that attract a tourism-based fly-fishing industry (Van Kirk et al. In Press). This industry generates between $29-60 million USD annually, with 82.7% of all persons visiting the watershed each year to fish (Loomis 2006).

Both agriculture and fly-fishing based tourism, the two dominant industries within the Henry's Fork watershed, are heavily water dependent. The fishing industry relies on water conservation to maintain healthy fisheries while agriculture depends on water consumption. Thus, both industries are inherently at odds with the other. HFF has long worked to understand this dynamic through building relationships with persons involved in both industries and by executing cutting edge scientific studies pertaining to the intricacies and idiosyncrasies present. Their collaborative research-based approach has earned HFF a sterling reputation and the respect and trust of the active parties within the watershed. This trust is especially valuable given the historically large divide between the agricultural and scientific communities in the American West. In response to the massive drought in the watershed that spanned from 2011 to 2016 (Figure 1), HFF developed and launched a Water Marketing Program in 2017 to provide a multifaceted economic incentive-based approach to water usage reduction.

1.2 The Water Marketing Program

The HFF Water Marketing Program incentivizes surface water reduction at priority conservation points. The advantage of a private entity like HFF incentivizing the reduction of water usage is that HFF does not have to meet certain government mandates, such as ancillary requirements that typically must be met in addition to water reduction goals before financial payment is distributed (Vig and Kraft 2016). Therefore, HFF can directly incentivize the reduction of water without such additional requests. The ability to target properties and particular points of surface water diversion using economic incentives is a relatively new concept, with a beta version of the program successfully established in the summer of 2017. Ideally, the Water Marketing Program will reduce water usage in the Henry's Fork River watershed, with the goal of preserving critical aquatic habitats for fish without compromising local farm revenues. While the preliminary results are promising, the long-term effects of a program like that established by the HFF have yet to be seen. The work documented in this thesis is intended to aid HFF and the Upper Snake River Collaborative, a group of non-profit organizations dedicated to preserving trout fisheries in the west, in the advancement of their Water Marketing Program.

The HFF Water Marketing Program breaks down its goals into two main categories: fisheries goals and water-management goals. The fisheries goals are designed to help improve, or at least maintain, the trout populations and fisheries within the watershed. The first fisheries goal of the program is to ensure that trout populations meet the objectives that Idaho Fish and Game (IDFG) set for Henry's Lake. The second goal is to maximize migratory fish populations in the Island Park Reservoir (IPR). These populations have declined over time as conditions have changed. The third main fisheries goal is to maintain a Rainbow trout population of at least 3,075 fish per mile within Box Canyon. The installation of a hydroelectric plant, which included fish screens, installed on the IPR dam in 1994, resulted in a decrease from a previous Rainbow Trout density of 4,068 fish per mile to an annual average of 2,989 fish per mile (Van Kirk et al. In Press). Given that there is a fraction of the original, pre-screen Rainbow Trout population inhabiting this region, it is important to ensure that their population does not drop any further. To help maintain population numbers, there is an additional annual recruitment of goal of 3,000 2-year-old juvenile trout per year, at minimum within the Box Canyon stretch.

Because fisheries can be heavily influenced by water temperature, water quality, and water turbidity variations (Eklov 1999; Lessard & Hayes 2003), water management goals can greatly impact the fisheries goals. Fluctuations in such water parameters are directly related to the amount of water present in and released from the reservoirs throughout the year. In order to maintain healthy aquatic ecosystems within the watershed, the HFF outlines four specific water management goals. The first goal is to maintain an average winter flow output from the IPR of 357 cubic feet per second (cfs) per day during from December through February. This flow directly impacts the amount of juvenile trout recruitment during the winter months and maintaining this minimum will help achieve the fisheries goals. Another goal directly related to the mean winter flow goal is to keep the IPR at 44% of its total capacity, at minimum, by the end of the agricultural water year. This is equivalent to ~60,000 acre-feet of water (Water Education Foundation). Another crucial water management goal is to maintain a streamflow of 1,200 cfs or more at the St. Anthony's United States Geologic Survey (USGS) gage year-round. The fourth main water management goal is to make certain that Henry's Lake remains at minimum ~80% of capacity (approximately ~76,000-acre feet).

Though the fisheries and water management goals may be separate in name, these two categories are intertwined because the goals for the fisheries cannot be met without also meeting the water-management goals as well. For instance, studies have shown that poor winter outflow from reservoirs can contribute to a large-scale decrease in juvenile trout recruitment due to the unfavorable conditions and reduction in habitat downstream of the reservoir (Gregory 2000, Mitro et al. 2003, Garren et al. 2006). This was illustrated within in the watershed from 2012 to 2016, when the Henry's Fork Watershed experienced the worst drought since the 1930s and the Dust Bowl years (Figure 1). During the 2012-2016 drought, the overall quality of the Henry's Fork trout fishery suffered harshly and first and second year juvenile trout recruitment declined. The decrease in recruitment contributed to a decrease in overall health of the watershed ecosystem and the quality of the fishing experience. With these impacts in mind, HFF began looking for ways to address water conservation and usage leading to the creation of their Water Marketing Program, a multifaceted, economics incentive-based approach to water use reduction.

1.3 Incentivization Mechanisms

The HFF Water Marketing Program seeks to partner with farmers to reduce the amount of surface water used during the agricultural water year. By reducing the amount of storage water used, the program ensures that more water is held in the IPR. If the IPR can retain at least 44% of its maximum capacity at the end of each agricultural water year, then the reservoir will be able to release adequate winter flows of at least 357 cfs daily. As a result, trout habitats will be positively impacted and overall water quality downstream will be improved, resulting in a healthier ecosystem and increased juvenile trout recruitment. The HFF Water Marketing Program approach builds a strategic “water cushion” for irrigators in the region. If there is more water still available later in the agricultural water year, there is significantly less risk of crop loss in the case of a late season drought or dry spells because there will still be storage water available. Therefore, this program acts as both a drought risk reduction plan as well as an ecosystem conservation plan for the entire watershed.

The program functions by leasing land, promoting alternative agricultural practices, encouraging the alteration of traditional crop regimes, and investing in agricultural infrastructure. For example, the program incentivizes farmers to produce quinoa, which is a non-traditional crop that requires less water than more traditional crops. The altitude and environmental conditions of the watershed are remarkably similar to regions in South America that produce much of the imported quinoa that is consumed in the North America (O’Connell 2019). However, the quinoa industry in southern Idaho is rapidly growing and now is the largest quinoa producer in North America (O’Connell 2019).

The program also incentivizes alterations to traditional crop regimes. In a good summer a productive parcel can produce 3 cuttings of alfalfa throughout the season (Daigger et al. 1970). Because there are typically multiple cuttings in a given growing season, sustained irrigation is needed to maintain the crop (Daigger et al. 1970). If a farmer is incentivized to forgo a third cutting of alfalfa in August, when water is scarce and the farmer’s water right may have transitioned from natural flow to storage flow sourced from the IPR, then the quantity of storage water that would have been used for the final cutting would be conserved and remain in the IPR.

Investment in more efficient irrigation infrastructure is another possible mechanism to reduce water usage. If water is more efficiently applied to crops, then less water will be used to produce the same amount of crops. While this sounds ideal in theory, in practice, irrigation efficiency can reduce incidental groundwater recharge in this region. Reducing incidental recharge will decrease the rate with which the underlying aquifers fill, leading to an overall negative effect on the long-term availability of surface water within the watershed. So, while investing in more efficient infrastructure for irrigation can be done, it must be done carefully and only after the possible impacts have been quantified on a case by case basis R. Van Kirk, personal communication, Nov. 24th 2018) .

Another path to water reduction is leasing land and paying farmers to simply not apply water to the leased land. The second year of the HFF's Water Marketing Program was completed this past summer in 2018. HFF rented 6 parcels of land from local Aston area farmers at $50 an acre (Figure 2). The rentals included a clause stating that the farmers could not use the water that would usually be applied to the rented parcels on the parcels themselves and any other field or land they owned. This amounted to HFF paying $38.50 per acre foot of water that was estimated to be saved. The farmers were allowed to plant a cover crop on the parcels and irrigate it in order to establish the cover crop. The presence of a cover crop reduces soil erosion and compaction. However, most farmers chose to not plant a cover crop, and the one parcel that was planted with grain, Parcel 1, was modified midsummer and the crop was removed using herbicide later in the summer (Figure 2).

It was not until the rentals were solidified and the program was well underway that a serious flaw was identified within the system, and within the overall program: there was no way to prioritize which lands were targeted for potential rental. In the case of the 2018 parcels, 5 of the parcels were land in use for agriculture. However, Parcel 6, was not (Figure 2). Parcel 6 contained a mix of native grasses that are estimated to have been growing for multiple years. This parcel was likely already enrolled in the Conservation Reserve Program (CRP), a federal program initiated by the Regan administration 1985, which incentivizes farmers to seed their ground with native grasses. The program, which is managed by the Farm Service Agency (FSA), enrolls land in the program in various contracts that range from 10 to 15 years in length and is the largest privately based land conservation program in the nation (United States Farm Service Agency). Parcel 6 was likely already unproductive agriculturally, and so its owners had decided to enroll it in the CRP program in order to glean some bit of profit from it. Therefore, the HFF Water Marketing Program did not benefit by paying the owners of Parcel 6 to not apply water to their field, as those owners were already engaging in management practices minimizing water usage. In order to be more effective with the allocation of HFF funding, a mechanism for prioritizing specific parcels, or places of water use, needed to be developed. The focus of this honors thesis is to develop a functioning model and database for the HFF to identify which parcels should be targeted for inclusion into the HFF Water Marketing Program.

2. Methods

2.1 Data Collection

The data for this thesis was collected from a variety of different sources. Some field data documenting the second year of the Water Marketing Program was also collected by the author in the summer of 2018. This data includes, but is not limited to, photographic documentation of the parcels (Figure 2) that participated in the Water Marketing Program for that year as well as weekly status reports regarding the condition of the parcels.

Place of use (POU) and point of diversion (POD) datasets were acquired from the Idaho Department of Water Resources (IDWR). Average monthly precipitation in the form of Parameter-elevation relationships on independent slopes model (PRISM) was sourced from the PRISM Climate Group at Oregon State (Daily et al. 2008). Finally, evapotranspiration (ET) raster data was sourced from EEFlux, a Google Earth based generator which uses Landsat images to produce the spatial distribution of ET for those images.

2.2 Modeling & Scoring System

The modeling for this project was done using Esri's ArcGIS Pro. A combination of geoprocessing and spatial analysis was carried out using the various tools within the model builder function. This function was used to isolate errors and create a framework that could be both manipulated and replicated in the future. In addition to ArcGIS, R Statistical software and Microsoft Excel were used to clean data and expedite calculations. Both programs produce files that can easily integrate into ArcGIS. The model was built using 3 main variables: priority date, NID and PODs (Figure 3).

2.2.1 Priority Date

The first variable, priority date, is perhaps the lynchpin of the model. Under the prior appropriation water law that governs water in the State of Idaho, priority dates determine when rights go in and out of priority during any given agricultural water year. A water right transitions from natural flow over to storage flow from reservoirs once there is no longer enough natural flow within the river channel to fulfill all of the rights that have priority over that water right. In the Henry's Fork Watershed, if the owner of that right wants to continue to irrigate, they can purchase storage water from the IPR. That purchased storage water is then shuttled to the out of priority water right's POD for as long as he or she can afford to do so. Given that the HFF's water conservation strategy hinges on the reduction of storage water use and keeping physical water in the IPR, understanding and accounting for when priority water rights typically switch from natural flow to storage flow is essential.

To fully understand the nature of the water rights and historical trends in priority within the watershed, a comprehensive dataset was obtained from the IDWR. This data was then used to calculate a 117-year median trend for when water rights would be fully met over the course of the agricultural water year. Upon analyzing this data, it was found that water rights with priority dates before 1895 are almost always in priority for the duration of any given agricultural water year (Figure 4). Meaning, these water rights rarely transfer from using natural flow to using storage flow. Therefore, only rights from 1985 and younger are of interest for the Water Marketing Program, as it makes little sense to target priority rights that rarely if ever use water from the IPR.

2.2.2 Point of Diversion

The second variable, POD, or simply the location where water is removed from a river or stream for use, is incredibly important for assessing the value of a potential water right within the watershed. A POD can be miles from the POU (the location where the water is actually put to beneficial use under prior appropriation water law). Where water is diverted from a channel can impact its importance to the HFF Water Marketing Program.

The IDWR POD database has over 10,200 entries for the Henry's Fork watershed. To isolate the PODs that are relevant to the HFF, coding in R Statistical software was used to isolate the data of importance. First, all groundwater rights were removed from the dataset; this resulted in a remaining 4,717 entries. These were removed because the HFF Water Marketing Program currently only incentivizes the reduction of surface water usage. From here all surface water rights that were smaller than 1 cfs were removed from the data, as water rights of this size have little to no impact on the overall consumption of surface water. The remaining entries were then filtered to only include sources of importance to the Water Marketing Program demand reduction goals. This step included eliminating all unnamed creeks, springs, drains and ditches because an unnamed location could not be categorized by geographic reach. It also removed the water rights located on South Fork tributary streams that deliver water to the south of Rexburg, outside of the watershed. Additionally, all water rights located on tributary streams in Island Park and some smaller tributaries that are located west of the Henry's Fork River were removed. A further 36 PODS were removed because they filled minimum streamflow, hydroelectric, industrial, storage and conservation organization water demand (R. Van Kirk, personal communication, Nov. 24th, 2018). Lastly, water rights with priority dates older than 1895 were filtered out, creating a finalized database of 788 water right PODs that are relevant to the HFF's Water Marketing Program. These 788 pertinent PODs were then assigned to one of 11 reaches, or geographic sections within the watershed. These reaches and abbreviations for each reach that were used in the modeling are outlined in Table 1.

Table 1: 11 reaches within the Henry's Fork Watershed and corresponding abbreviations (R. Van Kirk, personal communication, Nov. 24th, 2018)

Reach Description	Abbreviation
Henry's Fork River upstream of or at the Chester Dam	"HF.ab.Chester"
The canals that divert water from the Lower Fall River: Fall River, Silkey, Chester Enterprise, Curr, McBee	"Fall.R.Lower"
Any other diversions from the Fall River and its tributaries. All diversions in North Fremont Canals, including Black Spring	"Fall.R.Other"
Chester Dam to St. Anthony gage portion of the Henry's Fork River	"HF.Chester.StA"

The Henry’s Fork River portion that is downstream of the St. Anthony gage	“HF.Below.StA”
The Teton River within Teton Valley	“Teton.Upper”
Teton River tributaries that are located within Teton Valley	“Teton.V.tribs”
Any other Teton River tributaries of importance: Canyon Creek, Moody Creek Milk Creek	“Teton.tribs.other”
The canals on Teton River that divert water between the Crosscut Canal to Rexburg Irrigation on the South Fork and also the Teton Island Feeder on North Fork.	“Teton.Main.Canals
Teton River Pumps, also known as the Canyon Pumpers	” Teton.Pumps”
Lower forks of the Teton River	“Teton.Lower”

2.2.3 Point of Diversion Criteria Ranking

These specific reaches, and the PODs that fell within them, were given rankings on a binary system based on whether the reach fulfills (1) or does not fulfill (0) 5 specific criteria. A simple binary ranking system was used for this thesis as the main goal of this thesis was to develop the model and ensure that it functions as intended, but it should be noted that applying scaled weights for certain criteria may allow for a more accurate end result and should be attempted in future work. The 5 specific criteria by which the 11 reaches and 788 PODs were ranked are as follows: does the reach lie within geographic region of interest (“Geog”), reduce demand on IPR storage water (“IP.reduce”), increase flow at the St. Anthony gage (“StA.increase”), directly benefit the fisheries immediately downstream (“Fisheries”), and increases or maintains traditional rates of incidental groundwater recharge (“Min.rchg.loss”). Thus, the lowest possible score that a reach can receive was 0 and the highest is 5 (Table 2).

Table 2. Prioritization values assigned by reach (R. Van Kirk, personal communication, Nov. 24th 2018).

Reach	**1.Geog**	**2.IP.reduce**	**3.StA.increase**	**4.Fisheries**	**5.Min.rchg.loss**	**Total**
Fall.R.Other	1	1	1	1	1	5
HF.ab.Chester*	1	1	1	0	1	4
Fall.R.Lower	1	1	1	1	0	4
Teton.Upper	1	1	0	1	1	4
Teton.tribs.other	1	1	0	1	1	4
Teton.Pumps	1	1	0	1	1	4

Dewey, LC, Xcut	1	1	1	0	0	3
Teton.V.tribs	1	1	0	1	0	3
HF.Chester.StA	1	0	1	0	0	2
HF.Below.StA	1	0	0	1	0	2
Teton.Main.Canals	1	1	0	0	0	2
Teton.Lower	1	0	0	0	1	2

*Except Dewey, Last Chance and Crosscut to Fall River canals

The geographic prioritization criterion, ("Geog") simply determines if the POD is in a relevant geographic region for the Water Marketing Program. Because all of the PODs were within the boundaries of the watershed, they all were in a relevant geographic region and received a 1. While this criterion may seem irrelevant, it is important to include for future iterations of this model, as HFF may wish to apply the model to different regions.

The second criterion, "IP.reduce," analyzes a POD's potential to reduce delivery from the IPR in order to meet the demand of the Crosscut Canal diversion in the middle of the summer (Figure 5). The Crosscut Canal diversion experiences specific demands due to complications arising from the Teton Dam, originally proposed in the 1970s to create a new reservoir. Construction began and water rights to the reservoir water that it would create were issued. However, in 1976 before the dam was fully completed, the dam burst and the project was abandoned (United States Bureau of Reclamation). This left junior rights to a non-existent dam in the Teton Canyon. Under the 1987 to 2014 Snake River Basin Adjudication, these rights are allowed to stand today and are allowed to source natural flow from the Teton River to satisfy their rights long into the agricultural water year, despite having junior rights to many older rights downstream (Vonde et al. 2016). Because of this anomaly, a large amount of water must be shuttled from the IPR through the Crosscut Canal in order fill the older rights downstream. If water usage can be reduced upstream of the Crosscut Canal on both the Henry's Fork River and the Teton River, more water will be available in the river channel, which can then fulfill the older priority rights downstream of the Crosscut Canal with a lowered need for storage water from IPR (R. Van Kirk, personal communication, Nov. 24th 2018). If a POD is located in a reach that satisfies this criterion it receives a 1 and if it is not it receives a 0.

One of the Water Marketing Program's main water management goals is keeping 1,200 cfs of water moving through the channel at the St. Anthony's USGS gage. This goal is addressed by "StA.Increase." 1,200 cfs is the lowest possible amount that can maintain healthy ecosystems and water quality throughout the reaches downstream of the IPR by reducing turbidity and decreasing water temperature (Van Kirk et al. In Press). The St. Anthony's USGS gage is located near the bottom of the watershed, therefore any natural flow saved upstream of it reduces the need to remove water from the IPR. Therefore, any PODs that are located in reaches above the St. Anthony's gage receive a 1 while those below receive a 0 (R. Van Kirk, personal communication, Nov. 24th, 2018).

The fourth criterion, "Fisheries," concerns downstream fisheries. If water from the IPR reservoir is being used, and the aforementioned St. Anthony's gage flow target is met, any water saved at a given POD benefits the fisheries directly downstream of that POD. If a POD meets this goal it receives a 1, if it does not, it receives a 0.

Finally, the last criterion in question, "Min.rchg.loss," concerns incidental recharge. In this case a 1 score for this criterion indicates that a POD has a minimal, if any, impact on incidental groundwater recharge. A 0 score for this criterion indicates that the POD decreases incidental recharge. Determining this parameter is somewhat subjective, taking into account relative seepage, hydrogeology, and if the water is moved in a pipe, pump, or canal (R. Van Kirk, personal communication, Nov. 24th, 2018).

2.2.4 Net Irrigation Demand

The third variable, NID, accounts for temporal trends for the evapotanspiriation (ET) of different crops during the agricultural water year. The four main crops grown within the watershed are winter grain, spring grain, potatoes, and alfalfa. Of these four crops, potatoes are considered the cash crop. Each of these crops have different growing seasons within the agricultural water year and thus require more or less irrrigation in accordance with their relative growth seasons. During temporal periods when these growing seasons overlap the demand for irrigation, and thus demand for water, vastly increases. These different growing seasons are represented by the 30 year average crop evapotrainspiration data for the Ashton, Idaho agricultural region (Figure 6).

Though it is possible to extrapolate possible trends in overall irrigation demand using this ET data, it does not provide empirical data to support those patterns. Thus, Equation 1 was used to assess net irrigation demand as follows:

$$NID = ET - precip \tag{Eq. 1}$$

where "NID" is net irrigation demand, "ET" is evapotranspiration, and "precip" is precipitation. By understanding how irrigation demand varies throughout the agricultural water year and throughout the watershed both spatially and temporally, HFF can better tailor their Water Marketing Program to the needs of the watershed.

The NID portion of the model was created using ET data sourced from EEFlux, which is a tool that utilizes the Google Earth engine. EEFlux converts raw Landsat data into actual and real ET floating-point based rasters (Personal communication with Jason Kelley, 2/12/2019). Landsat images for each month of the 2018 agricultural water year were obtained. The ET rasters were taken for one day during each month, with the selection of the day based on a combination of lower percent cloud cover and the location of the cloud cover within the watershed. If the Landsat image had significant cloud cover over the lower part of the watershed, which contains the main agricultural regions, it was not utilized. None of the available Landsat images for October of the 2018 had a clear, low cloud image for the main agricultural regions. If a substantially cloud covered image were used it would impact the accuracy of ET calculations within the EEFLUX software and decrease the accuracy of the overall model. Accordingly, Landsat images were used from the 20th of April, 6th of May, 7th of June, 9th of July, 10th of August, and 11th of September of 2018. These images all overlapped with the main areas of interests and had the least cloud cover over these regions. Unfortunately, these images did not cover the northern portion of the watershed and thus NID values were unable to be calculated for 8 water rights that are of relevant ages and water sources located north of the IPR. However, all remaining 780 water rights of concern were located within the scope of the selected images. The ET rasters were then imported in ArcGIS Pro and used in model calculations.

In order to calculate the "precip" portion of the NID equation, PRISM rasters were used. PRISM rasters geospatially display precipitation averages over a specified period of time and were sourced from Oregon State's PRISM download center. The data was 4km in resolution, however 800m data is also available for purchase. For the purpose of this thesis, 4km resolution data was downloaded for each month in the 2018 agricultural water year, excluding October. This data displayed the average precipitation distribution over the watershed in a point-based raster form.

Once both PRISM and ET rasters were acquired, they were limited to the watershed using the ArcGIS clipping tool. After this, the tool raster calculator was used to execute Equation 1 for each month in question. This produced a range of NID values, which helped to further identify important temporal periods for irrigation demands. If a month produces only negative NID values, precipitation exceeds ET and therefore there was likely no need for irrigation. If a month produces a combination of positive and negative values across the raster it indicates that ET exceeded precipitation in the regions where the NID value was positive. Therefore, additional water through irrigation was likely applied to the land with these positive NID values. The higher the positive value, the larger the amount of water that likely had been applied to the field, and thus the higher the NID. Using this reasoning the months that had only negative NID values were discounted from further calculations. Thus, only the NIDs for the months of July, August and September were used to calculate a total overall NID for the watershed during the 2018 agricultural water year. It should also be noted that August had a marginally negative overall NID scoring range. August is one of the drier months of agricultural water year and therefore it can be assumed that ET during August typically exceeds precipitation; the single day ET raster that was used is therefore likely not representative of the overall trends during August. Finally, NID rasters for the months of July, August and September were averaged together using the ArcGIS raster calculator. This produced a total average NID raster for the 2018 agricultural water year, which had values ranging from negative values up to 4.

The total average NID from 2018 raster was produced as floating-point rasters, which are used to represent continuous data (Esri). Therefore, in order to calculate averages for each POU shapefile of interest, the raster was converted from a floating-point raster to an integer-based raster, which was accomplished using the lnt tool. The raster to polygon tool was then used to create unique polygons for each value and its location over the watershed. These NID polygons were then associated with the POU shapefiles using the spatial join tool. In the process of spatially joining the two, the gridcode value field (or value associated with each NID polygon) was averaged in order to calculate the unique average NID value for each POU shapefile. This created a new shapefile layer that was comprised of all of the POUs that had overlapped spatially with the NID polygons. This new shapefile layer was then joined with the cleaned POD database using the add join tool. This further reduced the shapefiles of interest to ones that corresponded with the specific PODs of relevance. The attribute table for this new shapefile was exported to Excel where the averaged NID was broken down into their weighted rankings on a 0 to 5 scale. This scale was designed in order to account for the unimportance of negative values as well as the increasing importance of positive values as they become larger (Table 3).

Table 3: NID shapefile values and their associated ranking value

NID Value	Assigned Ranking Value
All negative values	0
0	1
1	2
2	3
3	4
4	5

Once both the NID values and the POD values were scaled and ranked on individual 0-5 scales they were then combined in equal weight for a combined scale of 0-10. The database with these calculations was then reimported into ArcGIS in table format. They were then merged with the POU shapefiles again using the add join tool. Once the rankings and values that were stored in the new NID database were associated with the POU shapefiles the symbology function was used. The symbology of the final prioritization layer was set to unique values and then the values associated with the total combined ranking was displayed. This created a layer of shapefiles that displayed the total overall prioritization value for each shapefile of interest within the agricultural region of the watershed.

3. Results & Discussion

3.1 Prioritization Ranking

The results of the modeling and applied scoring system of this thesis produced an interactive layer file that contains the cumulative ranking, model arm rankings, water right number, owners, PODs, and all other pertinent information for each of the 350 relevant POU shapefiles. This layer file was also expressed in a map that geospatially illustrates the distribution of the POUs that are colored coded by their cumulative ranking values (Figure 7) and databases for both POUs and PODs and all associated information. Though the cumulative ranking scale was from 0 to 10, all of the parcels within the watershed had a value between 2 and 8 (Figure 7). The final product layer and databases will be instrumental in ensuring the efficient allocation of funds for HFF's Water Marketing Program. It will allow HFF to target higher priority parcels and to easily identify land owners and water right holders of priority parcels to contact as potential candidates for the HFF Water Marketing Program. Accounting for priority date, location of PODs by their associated reach, and for irrigation intensity allows HFF to avoid selecting parcels like Parcel 6 (Figure 2) in the future and will effectively allow them to save the most water at the least cost each year.

It should be noted that there are 4 POUs that have null values, all located in the northern portion of the watershed (Figure 7), as these parcels are the POUs for the 8 water rights that were not covered by the ET Landsat images and therefore do not have associated NID ranking values. However, all of the linked POD ranking values remain associated with these 8 parcels and thus are still informative. However, the water allocated towards these 8 parcels may not be relevant for the Water Marketing Program, as the northern part of the watershed (in which these parcels are located) has historically been used to seasonally run cattle and is not a hot bed of irrigation-based agriculture.

3.2 Observed Trends

Overall, the highest valued parcels in the watershed are located along a transect east of the Henry's Fork River (Figure 7). That region encompasses much of the dominant agriculture within the watershed. With agriculture comes an advanced irrigation network and infrastructure, resulting in higher cumulative rankings associated with these lands. This region also includes the parcels located near the bigger population centers of St. Anthony, Rexburg, and Ashton.

In contrast, substantially lower cumulative rankings are associated with the majority of parcels located near the towns in the Teton Valley, in the southeastern portion of the watershed (Figure 7). The Teton Valley has considerably less agriculture than the other regions, thus these lower cumulative rankings reflect less desirable parcels for the Water Marketing Program. Agriculture has diminished in this region as the population has increased in recent years. The Teton Valley area offers affordable housing near Jackson Hole, WY, resulting in increased housing developments in the area, with the southeastern side of the Valley near Driggs and Victor now dotted with houses and developments (City of Driggs).

While the Teton Valley is a region characterized by low cumulative rankings, the lowest values in the Henry's Fork Watershed are predominately located to the west of the Henry's Fork River between St. Anthony and Rexburg (Figure 7). These parcels all have a total ranking value of 2. The parcels in this region have negative NID values and thus received 0 out of 5 for their NID values. This information suggests that these parcels to the west of Henry's Fork River between St. Anthony and Rexburg may have had little to no need to irrigate crops in 2018 and therefore likely do not draw on the IPR in typical years. For their POD ranking values, these parcels only received 1s for "Geog" and "Fisheries," having minimal impact on incidental groundwater recharge, IPR levels, and of course the discharge from St. Anthony's gage, as these parcels are located downstream of St. Anthony. HFF can use this information to focus their efforts on other regions of interest, keeping in mind that if NID values for these parcels change in the future(e.g., as a result from climate change or shift in crops grown), that they may be of more importance than they are currently.

3.3 Limitations

There are some limitations to the work of this thesis; almost all of them are data related. The work described here uses the 2018 agricultural water year as a case study. However, it is important to note that the year 2018 may not be representative of all agricultural water years. Furthermore, the years 2011 to 2016 were significant drought years and therefore not at all indicative of any long-term trends or averages in the data that this thesis uses. Because of this most of the recent data averages are skewed due to these abnormal drought conditions and cannot be used to accurately represent average normal conditions within the watershed. However, the accuracy of calculations produced in this thesis would benefit from data averaged over a longer time scale.

Another data-based limitation of this thesis is the resolution of the PRISM precipitation data rasters. The 4 km resolution rasters are available for download for free and are what was used in the NID calculations. However, there are 800 m resolution rasters that are available for purchase. These higher resolution rasters would allow for more accurate average NID calculations for each POU shapefile and would be worthwhile to incorporate into future iterations of the model once funding is secured.

Additionally, when calculating NID, soil moisture was not accounted for because there is a lack of available soil moisture data in raster format. Given the recent debut of ECOSTRESS on the International Space Station hopefully such data will become available on a global scale and can be incorporated into future NID calculations following Equation 2 (American Society of Agronomy 2019),

$$NID = ET - precip - SM \qquad \text{(Eqn. 2)}$$

where "NID" is net irrigation demand, "ET" is evapotranspiration, "precip" is precipitation, and "SM" is soil moisture. If soil moisture is accounted for, then NID can be more accurately predicted. Including preexisting soil moisture content in the NID calculation will be of increasing importance as the watershed faces a potential increase in water stress due to altered timing of melting snowpack, climate change, and changing population dynamics.

3.4 The Importance of Water Marketing Programs in the Context of Future Water Stress

The melting of snowpack that accumulates in the mountains each winter is an important source of water for agricultural water use in the West, and the Henry's Fork Watershed is no exception (Cayan et al. 2001; Stewart et al. 2005; Bales et al. 2006). This source of water is expected to become more variable as the increasing impacts of climate change are felt (Xu et al. 2014). Climate change will impact the crops that farmers choose to plant and that future volatility in water supply and temperature are predicted to lead to extensive agricultural losses (Xu et al. 2014). Xu et al. (2014) suggested that an increase in the number of water transactions can help mitigate the impact of climate change on water availability, however, they also noted the short-comings of the State of Idaho's Water Bank. Given that water marketing programs like HFF's can operate more freely than the State of Idaho's Water Bank, such water marketing programs provide a promising mechanism for reducing agricultural water usage and also for mitigating the additional implications of climate change on agriculture.

Projected increases in global population are accompanied by a projected increase in global demand for food (Boserup 2017). This is not an insignificant factor when considering the future of the Henry's Fork Watershed. The Henry's Fork Watershed produces raw agricultural products for global companies such as Clif Bar, General Mills, Anheuser-Busch, Chobani and Miller-Coors (Van Kirk et al. In Press). The projected increase in food demand will create an increase in demand for agricultural production, which will in turn increase demand on water sources for agricultural irrigation (Pimentel et al. 1992). Given that Idaho is projected to experience an increase in water stress due to climate change and potential population demands, HFF's Water Marketing Program holds significant importance in the context of reducing surface water consumption (Schlosser et al. 2014).

4. Conclusions

There is substantial room for future work that pertains to the products of this thesis. The first involves current data-based limitations of the available average precipitation and ET data, as well as the lack of adequate soil moisture data rasters. Once those are addressed, it is possible that the work flow and modeling described here could be modified and used in similar watersheds throughout the west. Secondly, given the recent development of the Snake River Collaborative, a nonprofit group that is dedicated to addressing agricultural water usage in the west and consists of Trout Unlimited, The Nature Conservancy, Friends of the Teton River, and the HFF, it is the hope of the author that this thesis becomes a baseline starting point for water conservation prioritization work in the future. The work and modeling produced by this thesis will directly impact the health of aquatic ecosystems and marquee trout populations. Furthermore, it also has the potential to mitigate the impacts of population growth, increased food demand, and increased agricultural water usage in the face of global climate change within the watershed, and any watersheds that is applied to in the future.

Figures

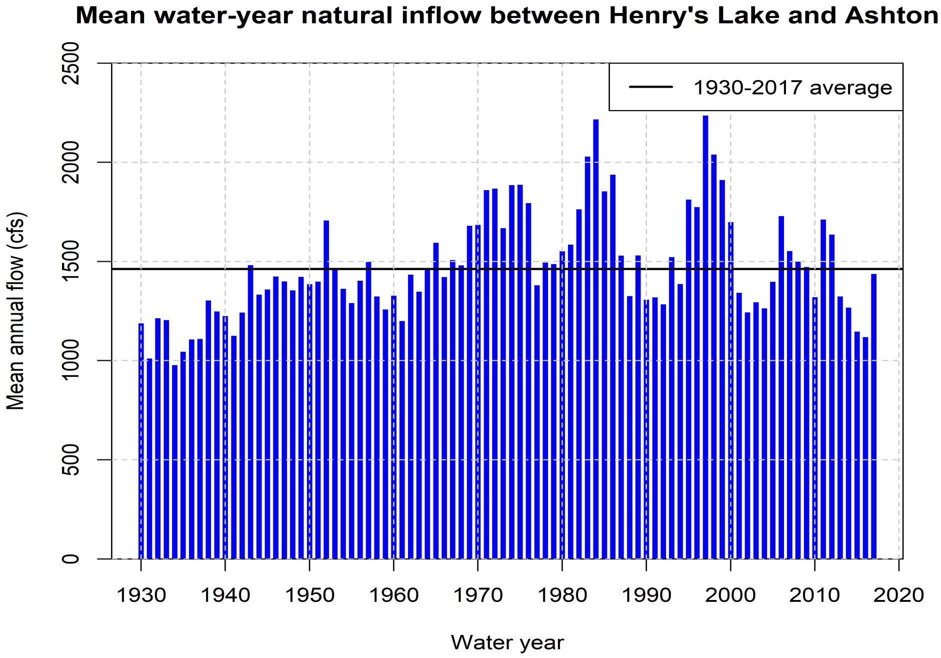

Figure 1: The mean water-year natural inflow between Henry's Lake and Ashton. This can be used to interpret the relative abundance of water in the watershed and stands as a proxy for a drought record. This figure was modified from a figure produced by R. Van Kirk (Van Kirk 2018) using data sourced from the Idaho Department of Water Resources (IDWR).

Parcel 1
Parcel 2
Parcel 3
Parcel 4
Parcel 5
Parcel 6

Figure 2: Photos of the parcels rented for the 2018 Water Marketing Program. The location of the parcels in each photo is indicated by the red arrows.

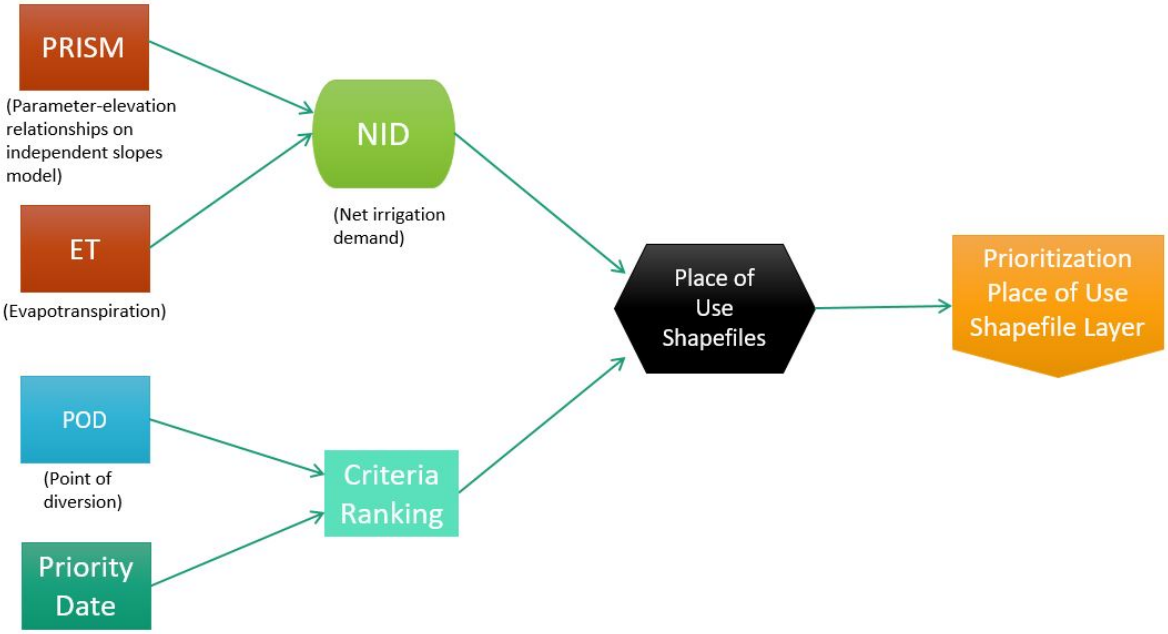

Figure 3: The general model flow and variables utilized in this thesis.

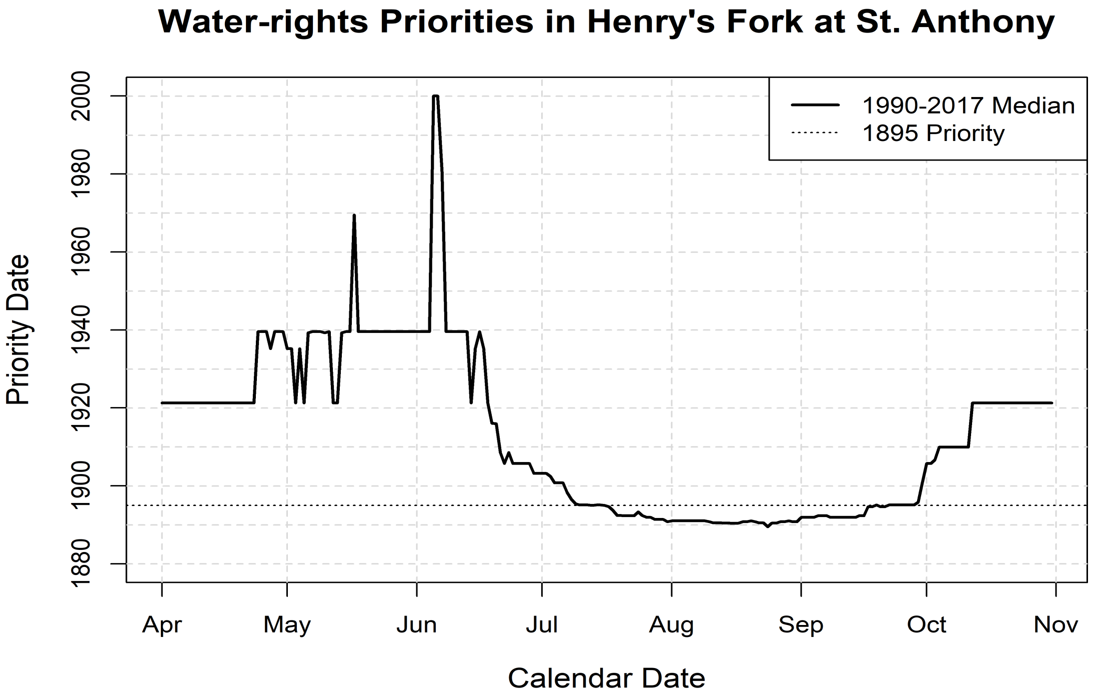

Figure 4: The month that water rights go out of priority at St. Anthony based on a 27-year average. The dotted line illustrates the 1895 and junior priority rights that on average go out of priority every July. This figure was created by R. Van Kirk for the author.

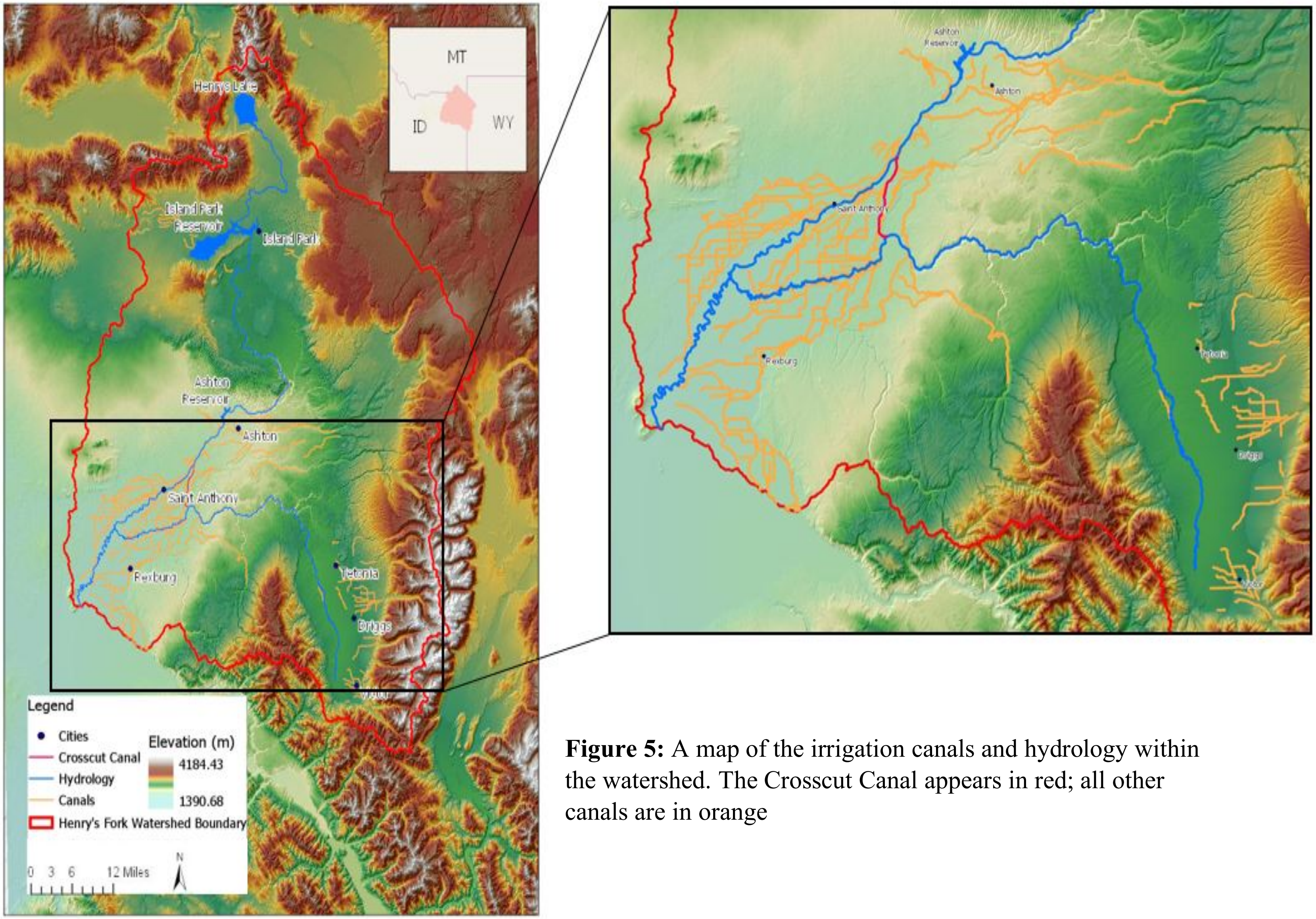

Figure 5: A map of the irrigation canals and hydrology within the watershed. The Crosscut Canal appears in red; all other canals are in orange

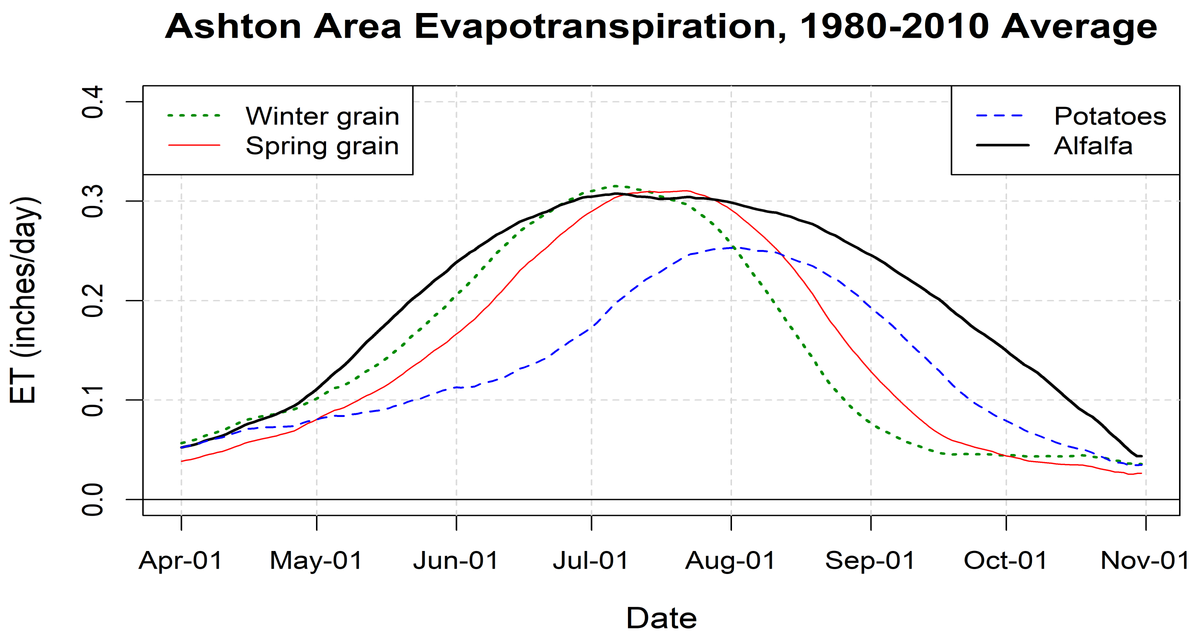

Figure 6: The average Ashton area ET by crop over a 30-year period. This figure was created by R. Van Kirk for the author.

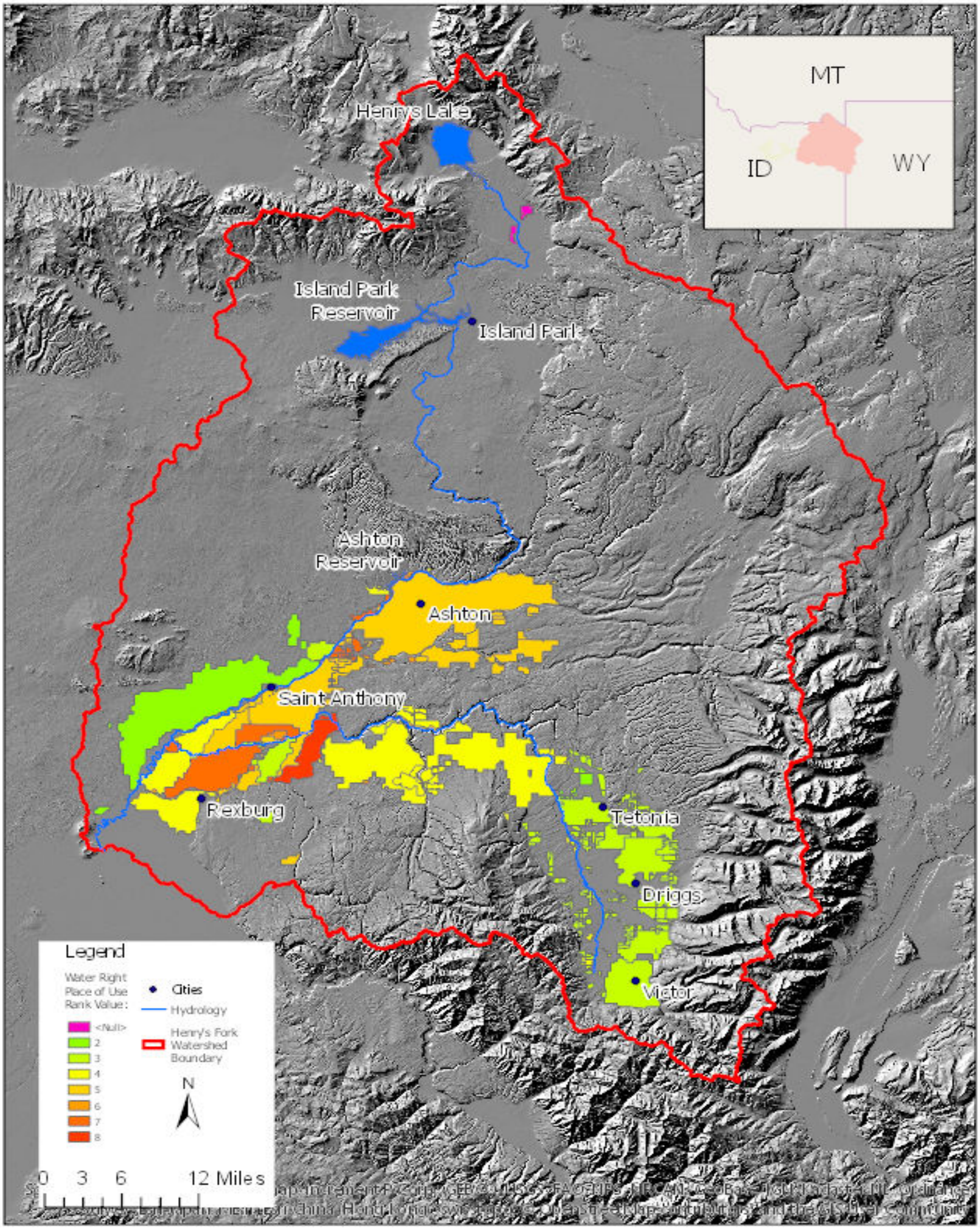

Figure 7: The geospatial distribution of POU shapefiles with their cumulative prioritization ranking.

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