IMPACTS OF LOW SUMMER STREAMFLOWS ON WATER RESOURCES IN THE JEFFERSON VALLEY: HISTORICAL RESPONSES AND FUTURE CHALLENGES

by

Alex Michael Leone

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2016

©COPYRIGHT

by

Alex Michael Leone

2016

All Rights Reserved

ACKNOWLEDGEMENTS

I wish to thank my primary advisor, Dr. Julia Haggerty, for her perpetual encouragement and enthusiasm for my research. I also wish to express appreciation for my committee members, Dr. Greg Pederson and Dr. Jamie McEvoy, for their constructive guidance and support. This thesis would not have been possible without the assistance of Gary Nelson, Jefferson Valley rancher; David McKernan, George Grant chapter of Trout Unlimited; Ron Spoon, MT FWP; and the MT DNRC Water Rights Bureau. And finally, most importantly, I would like to thank my exceptional, wonderful family for their support and continual encouragement throughout my education.

TABLE OF CONTENTS

1. INTRODUCTION & LITERATURE REVIEW 1

Introduction 1
Literature Review 8
Water Resources and Policy in the West 8
A Changing Climate 12
Moving Towards and Integrated Approach 15
The Jefferson Valley as a Social-Ecological System 20
The Adaptive Cycle Model 22
Resilience Assessment Approach 24

2. RESILIENCE ASSESSMENT PART 1: DESCRIPTION OF THE JEFFERSON BASIN SES 28

Biophysical Context 28
Topography & Geology 29
Climate 31
Hydrology 35
Aquatic Ecology 44
Terrestrial Ecology 46
Human Settlement & Development 46
Tribes 47
Euro-American History 48
Population Growth 49
Land Use Transition 51
Agriculture 51
Mining 54
Water Rights 55
Sport Fishery 59

3. RESILIENCE ASSESSMENT PART 2: KEY VARIABLES AND DRIVERS OF RESILIENCE OVER TIME 64

Exploitation Phase (r): 1850-1920 65
Water Infrastructure Development 66
Conservation Phase (k): 1920-1988 68

TABLE OF CONTENTS – CONTINUED

Dam Building in the Greater Jefferson 70
Late K Phase: 1970-1988 74
MT Fish, Wildlife and Parks & Instream Flows 74
Coalition Formation 75
Release Phase (Ω): 1988-2001 76
The Drought of 1988 77
Water Leasing and HB 707 80
Instream Flow Recommendations 81
Administrative & Legislative Closures 83
Reorganization Phase (α) mid 1990's-present 83
Formation of the JRWC & Drought Management Plan 85

4. POTENTIAL RESILIECE CONCERNS IN THE JEFFERSON BASIN 90

A Climate in Flux 90
Climate Trends 95
Climate Projections 107
Proliferation of Center Pivot Irrigation 114

5. METHODS TO INCREASE DROUGHT RESILIENCE & CONCLUSIONS 119

Increasing Drought Resilience 119
Expanding Reservoir Storage in the Basin 119
Modify the Current JRWC Drought Management Plan 124
Water Leasing for Instream Flows 127
Tributary Enhancement Projects 127
Irrigation Conversion 129
Conclusions 131

REFERENCES CITED 134

APPENDICES 151

APPENDIX A: Analysis of Water Rights in the Jefferson 152
APPENDIX B: Analysis of Annual Angler Days on Streams in Montana 155
APPENDIX C: Analysis of Temperature Trends 157
APPENDIX D: Downscaled Climate Projections 159
APPENDIX E: Interview Guide 164

LIST OF TABLES

Table Page

1. Overview of methods used....6
2. Climate summary for Trident, MT....32
3. Climate summary for Twin Bridges, MT....32
4. Regional population trends....51
5. Leading agricultural commodities in the Jefferson Basin....52
6. Ownership of the 15 most senior large water rights in Jefferson Basin....56
7. Ownership of the 10 largest water rights sourced from the Jefferson River regardless of priority date....57
8. Summary of major reservoirs in the greater Jefferson Basin....70
9. The 2013 Jefferson River Watershed Council drought management plan....86
10. Summary of drought episodes on the Jefferson since the first implementation of the drought plan in 2000....88
11. Ten lowest mean monthly stream discharge totals on record during the summer months at the Melrose stream gage on the Big Hole River....92
12. Summary of the meteorological stations used in the temperature trend analysis....97
13. Future average maximum temperature projections for the greater Jefferson Basin....111
14. Future summer stream discharge projections for the Jefferson River....112

LIST OF TABLES – CONTINUED

Table Page

15. Future annual stream discharge projections for the Jefferson River 112

16. Future precipitation projections for the greater Jefferson Basin 113

17. Acreage of land irrigated in Montana by method of water distribution 114

18. Breakdown of sprinkler irrigation techniques and the amount of acreage under each method in MT 115

LIST OF FIGURES

Figure Page

1. Mean August stream discharge on the Jefferson River At Three Forks, MT 2
2. Study area map of the Jefferson River Basin in southwest Montana 4
3. The four-phase adaptive cycle model 24
4. Five stages of the resilience assessment framework....25
5. Map of the Jefferson River and its major tributaries 30
6. Map of average annual precipitation in the greater Jefferson Basin....34
7. Basin Creek average annual SWE accumulation....34
8. Albro Lake average annual SWE accumulation 35
9. Annual streamflow hydrograph of the Jefferson River at Twin Bridges, MT....37
10. Annual streamflow hydrograph of the Jefferson River at Three Forks, MT 37
11. Map of USGS stream gage locations and major canals and ditches in the Jefferson Basin....39
12. Recent episodes of low streamflow on the Jefferson River near Twin Bridges, MT....40
13. Recent episodes of low streamflow on the Jefferson River near Silver Star, MT....40
14. Recent episodes of low streamflow on the Jefferson River near Three Forks, MT 41
15. Average annual discharge on the Big Hole River near Melrose, MT 42

LIST OF FIGURES – CONTINUED

Figure Page

16. Average annual discharge on the Jefferson River near Three Forks, MT 43

17. Average annual discharge on the Jefferson River near Twin Bridges, MT....43

18. Comparison of average annual streamflow on the Jefferson River and all of its major tributaries....44

19. Chart showing regional population trends 50

20. Map showing agricultural (top pane) and irrigated lands (bottom pane) in the Jefferson Basin....53

21. Map showing locations of points of use (POU) for water rights in the Jefferson Basin sourced from the Jefferson River/Jefferson Slough....58

22. Map showing locations of major canals/ditches in The Jefferson Basin....59

23. Estimated number of annual fishing days on the Jefferson River 61

24. Estimated number of annual fishing days on the upper Gallatin River....62

25. Estimated number of annual fishing days on the lower Big Hole River 62

26. Maximum volume of all water allocated in the Jefferson Basin by decade of priority date....66

27. Location of the major reservoirs in the greater Jefferson Basin....72

28. Palmer Drought Severity Index for August of 1988....78

29. Average daily discharge on the Jefferson in 1988 78

LIST OF FIGURES – CONTINUED

Figure Page

30. Mean August stream discharge on the Jefferson River near Three Forks, MT 82

31. Drought episodes on the Jefferson that resulted in streamflows dropping below instream flow targets at the Silver Star gage 89

32. Tree-ring reconstructed streamflow volumes at the Toston stream gage on the Missouri River (1579-1996) 93

33. Frequency of drought episodes in the upper Missouri Basin (by length of drought) 93

34. Comparison of monthly temperature and precipitation variables influencing late summer streamflows on the Big Hole and Jefferson Rivers 96

35. Location of U.S. Historical Climatology Network Stations used in the temperature trends analysis....98

36. Annual number of days where maximum temperatures met or exceed 85˚F (very warm days) 100

37. Seasonal window of very warm temperatures (annual tallies)....101

38. Annual number of days were minimum temperatures met or fell below 0˚F (very cold days)....102

39. Seasonal window of very cold temperatures (annual tallies)....103

40. Onset of "fall"—first day of the season (post July 1st) with a minimum temperature ≤32 ˚F 104

41. Average number of frost free days in southwest MT 105

42. Hydrological region selected for the downscaled climate projections 109

LIST OF FIGURES – CONTINUED

Figure Page

43. Comparison of Jefferson River inflows from four sources in 2007 117

44. Map of irrigated lands in the Jefferson with locations of major communities and active USGS gages.....125

45. Map displaying tributaries of the Jefferson River that have been the focus of restoration projects.....129

ABSTRACT

In an attempt to understand the complex interrelationships between climate, water infrastructure regimes, and water governance this thesis examines relationships between drought and water use in the Jefferson River Basin in southwest Montana. The Jefferson River is one of the three great headwater streams of the Missouri River and is itself comprised of the Beaverhead, Big Hole and Ruby Rivers, encompassing a substantial drainage basin of 9,532 sq. miles. The Jefferson's unique hydrological position inherently situates the basin "at the end of the line" of water users and flows at its confluence have plummeted to 200 cubic feet per second (cfs) during extreme drought periods, leaving little water in the river to appease appropriators along the river's remaining 80 miles. The Jefferson River (and all of its important tributaries) is highly utilized for agriculture, resulting in chronic dewatering during peak irrigation demand (typically July through mid-September). Persistent water scarcities over the last 15 years have tested the Basin's ability to sustain historic levels of agricultural production and maintain a commercial sports fishery. This thesis provides a resilience assessment of water resources in Jefferson Basin. RA's attempt to conceptualize dynamic interactions between linked social and ecological systems (SES's). Analysis of complex human use systems (SES's) is inherently interdisciplinary and necessitates a mixed methods approach. The RA completed for this thesis integrated physical analyses of the water use system (utilizing GIS, hydrology, climate and demographic data) with a qualitative survey of water stakeholders with the goal of understanding the processes that drive the Jefferson SES and identifying weaknesses that reduce resilience. Over the last 30 years the Jefferson Basin has benefited from a unique subset of water users and natural resource managers that have successfully worked to improve conditions in the face of extreme environmental challenges. This RA found that although it is highly likely that the Jefferson will be challenged by extreme conditions in the future (related to a changing climate), it is also evident that there is potential for the basin to transition into alternate and more resilient regimes.

CHAPTER 1

INTRODUCTION & LITERATURE REVIEW

Introduction

Montana's landscapes and economic prosperity are inexorably linked with water. As the headwaters of a continent, Montana generates 34 million acre feet of water per year (MAFY) within its borders and provides over 40 MAF of water annually to downstream jurisdictions in the US and Canada (MT Department of Natural Resources and Conservation [MT DNRC], 2015). Water that falls atop Triple Divide Peak in Glacier National Park eventually flows into the Pacific, Atlantic or Arctic oceans (via Hudson Bay). With a population of just 1 million, Montana consumes approximately 2.4 MAFY; a small proportion of its average annual output (MT DNRC, 2015). Montana's water assets support two of the state's largest economic sectors, agriculture and tourism, that combined represented 28% of the state's total economic output from 2012-2014 (University of MT Bureau of Business and Economic Research, 2015). Montana is also regarded to be the premier trout fishing locale in the U.S., offering the most liberal stream access law in the country and thousands of miles of fishable waters (Burke, 2013). In 2013 the state's streams generated over 1.2 million non-resident angler days that contributed an estimated $713 million to the state's economy (MT Fish, Wildlife and Parks [MT FWP], 2014).

Persistent and chronic drought conditions that began in 2000 have severely stressed Montana's water resources, negatively impacting agricultural producers,

commercial fishing outfitters and aquatic and terrestrial ecosystems. According to Dracup et al. drought is defined as, "a condition of insufficient moisture caused by a deficit in precipitation over some time period" (1980). Droughts are typically classified based on two overriding characteristics, the frequency and duration of the events (McKee et al., 1993). This research will focus on single year hydrological drought events impacting summer baseflows (i.e. low streamflows during the July-September period). Sufficient streamflow volumes are crucial during this late-summer period as both agricultural and ecological demands placed on the limited supplies of water are high.

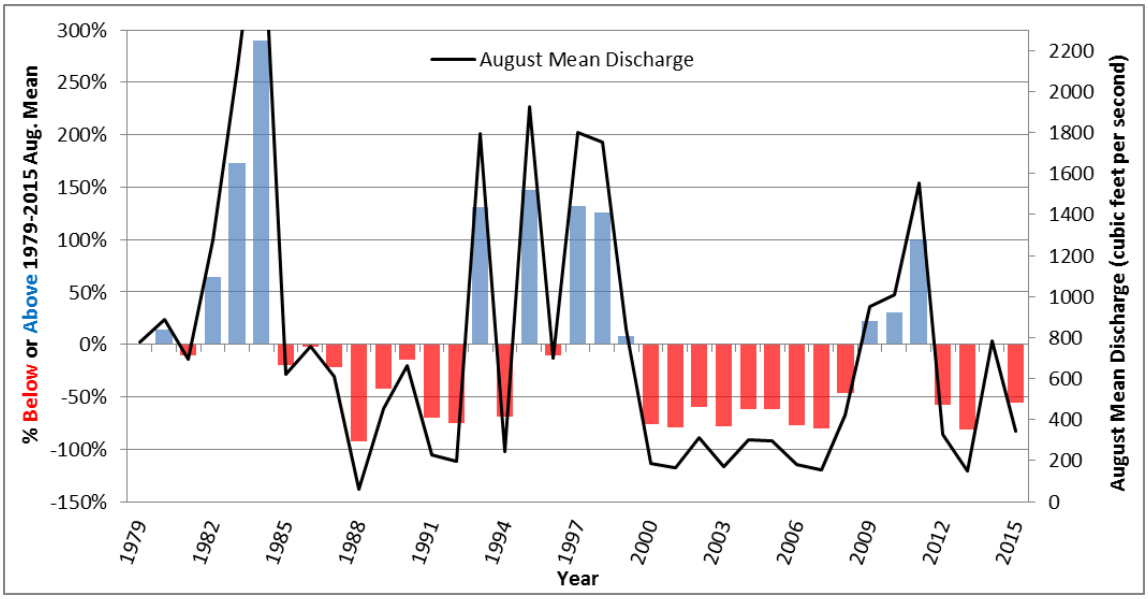


Figure 1. Mean August stream discharge in cubic feet per second (black line) on the Jefferson River near Three Forks (1979-2015). Red and blue bars represent the August discharge anomaly (% above or below the long term average). Data source: USGS *National Water Information System*.

From 2000-2015 mean August stream discharge on the Jefferson River (near Three Forks) in southwestern Montana was at least 50% below the long term (1979-2015) average of 788 cubic feet per second in 11/15 years and more than 75% below the

long term average in 6 of those Augusts (Figure 1). Severe summer streamflow depletions similar to those recently experienced on the Jefferson have impaired water quality on several of Montana's blue ribbon trout streams, inducing mortality in both native and non-native fish species. High water temperatures and low river flows have prompted Montana's state wildlife management agency, Montana Fish Wildlife & Parks, to implement restrictions on angling in eight of the past 16 seasons on the Jefferson River.

The Jefferson is one of the three great headwater streams of the Missouri River (along with the Gallatin and Madison Rivers) and is itself comprised of the Beaverhead, Big Hole and Ruby Rivers, encompassing a substantial drainage basin of 9,532 miles^2 (United States Geological Survey, 2015a; Figure 2). The Jefferson's unique hydrological position inherently situates the basin "at the end of the line" of water users. Flows at the confluence of the Jefferson have plummeted to 200 cfs during extreme drought periods, leaving little water in the river to appease appropriators along the river's remaining 80 miles. The Jefferson River (and all of its important tributaries) is highly utilized for agriculture, resulting in chronic dewatering during peak irrigation demand (typically July through mid-September). The Jefferson has also been coined as the "forgotten fork of the Missouri" and "the river fisherman forgot" among regional anglers due to the stream's relatively fickle status as a fishery. Chronic drought has plagued the Jefferson since the mid 1980's and angler use on the river has declined over that period. The trend on the Jefferson is particularly striking when compared to other streams in the vicinity that have seen significant increases in fishing pressure over the same time frame.

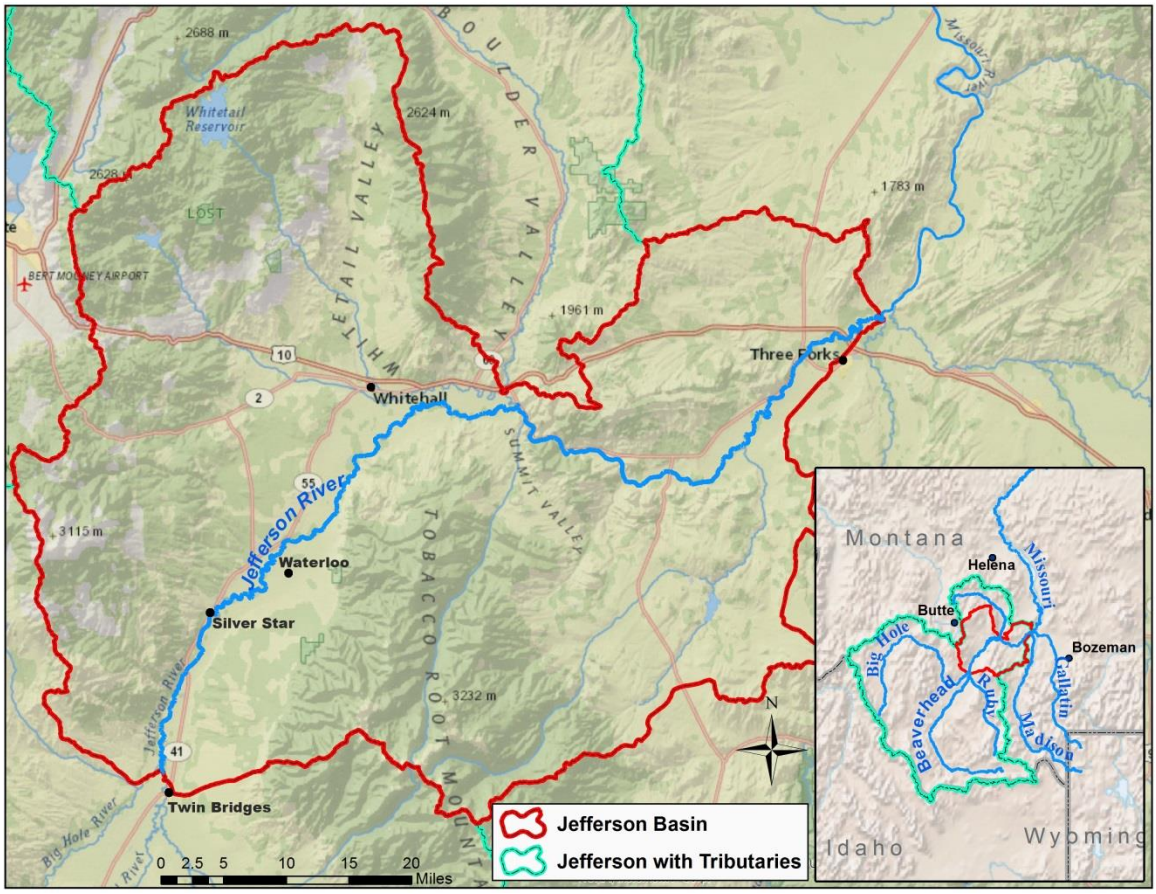


Figure 2. The Jefferson River Basin located in southwest Montana, USA. The Jefferson flows 83 miles from its confluence near Twin Bridges to its mouth at Three Forks. Data Source: National Hydrography Dataset (2014), MT NRIS—GIS Clearinghouse.

In an attempt to understand the complex interrelationships between climate, water infrastructure regimes, and water governance this thesis will examine relationships between drought and water use in the Jefferson River Basin. Although a wealth of research has been devoted to climate change and its hydrological and meteorological implications, little work has investigated the vulnerabilities or resiliencies of current water distribution regimes. The majority of jurisdictions in the western U.S. (including Montana) distribute water rights under an appropriative system (a priority system based

on time of water right establishment). The future effectiveness of the appropriative system in allocating water equitably under shifting climate scenarios is highly uncertain. Current drought management strategies in the Jefferson Basin consist of voluntarily reductions in surface water withdrawals (triggered by low streamflows) and restrictions on angling (triggered by high water temperatures). Persistent water scarcities over the last 15 years have tested the Basin's ability to sustain historic levels of agricultural production and maintain a commercial sports fishery. In the face of extreme drought, the Jefferson's aquatic ecosystem has endured, trout populations have begun to rebound, and irrigated acreage in the basin has increased. How has the Jefferson Basin water use community adapted to these tremendous external and internal stresses and persevered? What is it that makes the Jefferson Basin drought resilient? Is the current drought management regime robust enough to meet the unprecedented challenges associated with a changing climate?

To answer these questions this thesis will provide a resilience assessment of water resources in Jefferson Basin. Resilience assessments (RA's) have been recommended as a method to operationalize the concept of resilience and are now performed worldwide on topics ranging from natural resources management to urban planning (Stockholm Resilience Center, 2015). Although several detailed frameworks have been proposed for developing resilience assessments (Walker et al., 2002; Walker & Salt, 2012; Resilience Alliance, 2010) the application of these approaches has proven empirically challenging. Resilience assessments focus on dynamic interactions between linked social and ecological systems (SES's). Analysis of these systems is inherently interdisciplinary and

necessitates a mixed methods approach. RA's are undertaken with the goal of understanding the processes that drive SES's and identifying weaknesses that reduce resilience. This thesis considers physical and social processes that drive the Jefferson SES, and includes quantitative and qualitative methods. Specific methodological approaches will be discussed at the beginning of each chapter with supplemental details provided in the appendices. Table 1 gives a broad overview of the data analyzed and methods used in this thesis.

Major Thesis Question	**Method of Inquiry and Analysis**	**Data Sources**
What are important biophysical components of the Jefferson Basin SES?	• Maps describing important components of the SES • Regional climate summaries • Average stream discharge hydrographs • Description of aquatic and terrestrial ecosystems	*MT Geographic Information Systems Data Clearinghouse, Western Regional Climate Center, USGS National Water Information System*
What are important human and social components of the Jefferson Basin SES?	• Narrative of human settlement • Description of population trends • Summary of land use, agriculture and water rights • Quantification of the Jefferson sports fishery	*Historical water resources surveys, MT Census and Economic Information Center, National Agricultural Statistical Service—Farm and Ranch Irrigation Surveys, MT DNRC water rights database (see appendix A), Montana Fisheries Information System*
How did water resources in the Jefferson Basin develop over time?	• History of water resources development through the lens of the four phase adaptive cycle…per Gunderson and Holling (2002)	*MT DNRC water rights database (see appendix A), historical water resources surveys, US Bureau of Reclamation/MT DNRC reservoir information*
What historical disturbances have influenced the trajectory of the Jefferson Basin SES?	• Analysis of the impacts of the drought of 1988 • Overview of major governance attempts to mitigate drought impacts	*Regional newspaper articles, MT water rights law review articles, MT Fish Wildlife & Parks Jefferson River fisheries assessment, Jefferson River Watershed Council—Drought Management Plan, informal interviews with key informants*
How has the climate of the Jefferson Basin changed over the last 100 years?	• Analysis of observed temperature trends in the Jefferson Basin region over the instrumental period of record	*U.S. Historical Climatology Network, analysis of climate trends at three local meteorological stations… per Pederson et al., 2010 (see appendix C)*

What are anticipated future impacts to the climate and hydrology of the Jefferson Basin?	• Analysis of downscaled hydrology and climate projections	*CMIP5 hydrology and climate projection ensemble analysis investigating future temperature and streamflow regimes (see appendix D).*
What impacts might the expansion of center pivot irrigation have on water use in the Jefferson?	• Synopsis of center pivot irrigation in Montana and associated impacts	*National Agricultural Statistical Service—Farm and Ranch Irrigation Surveys*
How can the Jefferson SES increase resilience to cope with future drought?	• Suggestions for increasing drought resilience in the Jefferson Basin	*Informal interviews with key informants (see appendix E)*

Table 1. Table summarizing the major questions answered in this thesis, the methods of inquiry/analysis and the corresponding data sources.

The remainder of this chapter reviews relevant literature concerning SES resilience, western resource geography and water policy in Montana. Chapter 2 provides an overview of the Jefferson Basin SES's biophysical and human components. In this chapter the SES is delineated spatially and a detailed summary highlights important physical and human drivers of the system. Chapter 3 analyzes the evolution of the Jefferson's SES through the lens of the adaptive cycle model developed by Gunderson and Holling (2002). This portion of the thesis also delineates the Jefferson SES temporally, beginning with Euro-American settlement in the mid-19th century and continuing through present day. Chapter 4 discusses potential future resilience concerns in the Jefferson SES and includes a detailed analysis of regional trends in climate (1900-present) in addition to providing up-to-date climate projections for the Jefferson Basin. Chapter 5 discusses methods that may be utilized to increase drought resilience in the Jefferson Basin.

Literature Review

Water Resources and Policy in the West

> "Battles over water in the West are always about something more. At their most elemental, they are about survival." – Bettina Boxall, 2007

In the arid western United States, control of freshwater resources is at the heart of the region's history. Water in the West has been a contentious topic since explorer John Wesley Powell authored his famous *Report on the Lands of the Arid Region in the United States* in 1879, suggesting that western settlement be coordinated around watersheds to avoid conflict over the scarce resource (Powell, 1879). Powell's ideas were quickly criticized by powerful railroad interests of the time who hoped to capitalize on the sale of land to homesteaders. The U.S. Congress sided with the railroad lobbyists and developed legislation promoting the agricultural development of the region. Furthermore, late 19th century climatological theories professed that "rain followed the plow" hastening settlement of marginal lands throughout the West. During an irrigation conference in 1883, Powell famously pronounced "Gentlemen, you are piling up a heritage of conflict and litigation over water rights, for there is not sufficient water to supply the land" (Hiltzik, 2010). The heart of Powell's prophetic statement, the inherent discrepancy between water supply and demand in the West, has directed water policy and governance for over 160 years in the region.

To cope with water scarcity issues, western states adopted a legal institution of water distribution that varied greatly from those established east of the 100th Meridian (a line that roughly divides the county between its arid and non-arid regions). This system

of water rights, known as prior appropriation, has influenced the pattern of human development of water resources in much of the West. The prior appropriation doctrine, first established by miners to cope with water scarcity during the California Gold Rush, allocates water supplies based on the productivity of the water's use (Gillilan & Brown, 1997). Water rights are not tied to streamside land possession (as is the case under the riparian doctrine in the East) and may be bought, sold or transferred, unconnected to land ownership. The basic tenets of prior appropriation require that for a water right to be established water must be diverted from a source and put to beneficial use. Subsequent users that divert water from the same source may do so provided they do not encroach on the rights of previous users. Consequently, the general value of a water right is controlled by the priority date of the appropriation (i.e., first in time, first in right) and the water right's relative location on the source—calls for water may only be made to junior users upstream, not downstream. While a water right is limited to the *use* of water for beneficial purposes it is considered real property and may be transferred, purchased or sold (Montana State University [MSU] Water Center, 2014).

Although prior appropriation may arguably result in an equitable distribution of water among users, it encourages complete utilization of a water source for purely human uses. Included in many western state's water laws, "use it or lose it" clauses punish those who use less than their legal entitlement of water by permanently reducing the unused apportionment. Under this provision, a farmer who switches from flood to pivot irrigation must utilize all of the water conserved in the process or risk having their water right diminished. The "use it or lose it" caveat of western water law reinforces late 19th and

early 20th century ideals of water as a resource that should be controlled, managed, and distributed to meet the needs of an industrial society (Reisner, 1993). Several scholars have noted that this imperialistic view of water has resulted in an inequitable distribution of both water infrastructure and invested capital throughout the western United States (Worster, 1985; Reisner, 1993). Massive irrigation projects subsidized by the federal government transformed some regions of the West into lucrative agro-industrial hubs (e.g. Imperial and Central valleys in California) while other areas remain essentially unchanged (e.g. the Jefferson Valley in Montana). Water distribution systems in the Jefferson Basin retain much of their original infrastructure from the 19th century. Collective water user associations operate and maintain the majority of the canals and diversion structures in the Basin, without the assistance of large scale government subsidies. Further discrepancies in government funded domestic water supply projects has also been a contributing factor in regional population growth patterns. The West contains both the most populous (California with ~39 million) and least populous states (Wyoming with ~580,000) in the U.S. ("California", 2015; "Wyoming", 2015).

As the noted western author Charles Wilkinson observes, the "lords of yesterday" (i.e. prior appropriation and the General Mining Law of 1872) represent a "lack of symmetry between nineteenth-century methods and modern values" (1993, p. 22). The laws and policies that comprise the "lords of yesterday" are often held entrenched by overpowering interests that control the resources. Attempting to change the system becomes exceedingly difficult as power structures become ingrained (Wilkinson, 1993). In Montana, instream flow mechanisms (allowing water to legally be retained instream)

were the result of an intense 6-year battle in the Montana Legislature between conservation and agricultural interest groups (McKinney, 1997). A recent water pact signed between the State of Montana and the Confederated Salish and Kootenai Tribes took over 10 years to ratify and continues to be challenged by deep-rooted interests who view the compact as the "Revolutionary War for citizens of Montana" (Sakariassen, 2015). Of Montana's 85 water basins, only 6 have been fully adjudicated (final decree issued) since the Montana Legislature began the process in 1979 (MT DNRC Water Adjudication Bureau, 2015). In non-adjudicated basins, overlapping claims of water ownership creates legal ambiguity that leaves all but the most senior water right holders uncertain of their claims (Kavulla, 2015).

The prior appropriation system's emphasis on water use and resource exploitation has resulted in vastly over allocated watersheds throughout the West. The total amount of surface water appropriated in the Jefferson River (excluding stock water permits) is approximately 5,500 cubic feet per second (cfs) during the peak irrigation season (MT DNRC, 2015 Water Rights Bureau; appendix A). In comparison, the average annual discharge on the Jefferson at its mouth near Three Forks is around 1,900 cfs (USGS, 2015a). Over allocation of water has contributed to several severe dewatering episodes that have negatively impacted the river's aquatic ecosystems and resulted in trout kills that have weakened the Jefferson's recreational economy. In July of 1988 MT FWP recorded a flow of 4.7 cfs at the Waterloo Bridge on the Jefferson River; a drainage area of approximately 7,500 sq. miles (Pierce, 2008; USGS, 2015c). Local newspaper articles from that summer document major fish kills on the Jefferson, Big Hole and Madison

Rivers that severely impacted regional outfitters (Associated Press, 1988; Carter, 1988a; Carter, 1988c). A *Butte Standard* feature chronicling the impact of the 1988 drought on the local economy mentions that business for an outfitter on the Big Hole was "off 70 percent" that season (Carter, 1988b). The article also quotes outfitter, Phil Smith, who details the effect on his business, "People call up and ask us, 'How's the fishin?' What can we tell them? We're in trouble. People don't even stop by the shop. They drive to the river and take a look and drive out of town" (Carter, 1988b). Although the drought of 1988 impacted rivers statewide, the most severe dewatering of the season occurred on the Jefferson and Big Hole Rivers. Subsequent low flow episodes have plagued the Jefferson since 1988, and the river has only recently seen increases in fish populations and angling pressure (Spoon, 2008; appendix B).

A Changing Climate

With a potential to exacerbate water supply problems that have afflicted the Jefferson since the mid-1980's, climate change poses a significant threat to the Basin's future. The link between increased emissions of greenhouse gasses, rising global temperatures and regional scale impacts to hydrologic processes is now indisputable (Barnett et al., 2008; Rosenzweig et al., 2008). Recent comprehensive assessments published by the International Panel on Climate Change (IPCC) and the United States Global Change Research Program (USGCRP) emphasize that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (Qin et al., 2013). The USGRP's 2014 National Climate Assessment presents data documenting rising average annual temperatures throughout the U.S. (1.3-

1.9˚F from 1895-2012) with much of that increase being attributed to the rapid warming experienced over the past 22 years (Melillo et al., 2014).

Rising temperatures over the past 100 years have already influenced a variety of biophysical processes on the earth and have been attributed to the retreat of glaciers and increases in wildfire intensity in the western U.S. (Field et al., 2014). A wealth of literature has been published concerning global climate change and its impacts on snowpack and streamflow in the western United States (Hamlet et al., 2005; Hidalgo et al., 2009; Mote, 2006). It is now fairly evident that future climate warming will result in several drastic and potentially disastrous changes to regional hydrologic patterns in the western United States. Predictions of decreasing snowpack (as more precipitation falls as rain instead of snow) is of vital importance to water management in the region as many streams are entirely snowmelt driven (Knowles et al., 2006; Klos et al., 2014). Winter snowpack acts as a "natural reservoir" of precipitation, slowly releasing water during drier portions of the year sustaining millions of acres of irrigated farmland throughout the West (Pierce et al., 2008; Vano et al., 2010).

Researchers are also predicting that spring runoff of snowmelt will occur increasingly earlier in the water year (Lundquist et al., 2009; Stewart et al., 2004; Stewart et al., 2005). A recent study examining the climatic drivers of snowmelt in the northern Rockies revealed that over the past four decades, records have documented declining snowpack values and earlier snowmelt timing (corresponding to warmer spring temperatures and changing atmospheric circulation patterns) (Pederson et al., 2010). Both empirical studies and climate projections have noted the greater sensitivity the

northern Rockies and inland Pacific Northwest to warming relative to other regions in the West. Research by Regonda and others found that the timing of peak runoff was advancing throughout the West with the trends strongest at low elevations and in the interior Pacific Northwest (2005). In Montana, annual variations in snowmelt dynamics are dominated by winter temperatures and mid-elevation snowpack volumes (Pederson et al., 2011). Modest increases in winter temperatures (which are projected) have the potential to drastically advance the timing of spring runoff and subsequently impact water supplies and reservoir systems (Regonda et al., 2005, Klos et al., 2014).

As well as runoff timing concerns, several studies have investigated climate change's influence on declining summer streamflow volumes in the Rocky Mountain region (Leppi et al., 2012; Rood et al., 2008). Research examining trends in August river discharge values (from 1950-2008) in the central Rocky Mountains (including Montana) indicated that 89% of the 155 stations analyzed exhibited a declining trend in flows (Leppi et al., 2012). General circulation model (GCM) ensemble analyses predict significant decreases in summertime precipitation (for 2071-2099 compared to 1970-1999) in the northern Rocky Mountain region under both low and high emission scenarios (Melillo et al., 2014). Sufficient summer flows are essential to support agricultural, ecological, recreational, municipal and industrial water uses. A reduction in water supplies when water demand is the greatest will increase completion and conflict over water resources in the area.

Moving Towards an Integrated Approach

While water scarcities and a changing climate pose grave threats to the future of water resources in the West, recent changes in governance techniques present an opportunity to break the overarching power arrangements that have guided water decision making in the region for over 100 years. Beginning in the second half of the 20th century general views on natural resources and the meaning of conservation shifted in the United States. Environmental legislation passed in the 1960's and 1970's was a response to the massive environmental degradation wrought by 100 years of unchecked industrialization and overexploitation of natural resources. In Montana a new state constitution (ratified in 1972) embodied many environmental ideals of the time, granting all Montana residents the "right to a clean and healthful environment" (MT Constitution, Article II, Section 3). Before this period, water resources were viewed in primarily utilitarian terms and little value was given to the ecological or cultural significance of the resource. Following the passage of federal legislation such as the Clean Water Act (1972) and Endangered Species Act (1973), water resources gained statutory protections for social and ecosystem services they provide.

Since the 1970's there has been an increasing emphasis on valuing water for a multitude of values, not just the economic maximization of the resource (Blatter & Ingram, 2001; Whiteley et al., 2008). Through both legislative action and rulemaking procedures, western state governments have developed several legal mechanisms that offer protection for contemporary water values. In Montana the list of applicable beneficial uses (which originally included agricultural, municipal and industrial uses) has

grown to include fisheries, wildlife, wildlife habitat, recreation and aquifer recharge (MSU Water Center, 2014). Furthermore, instream flow provisions, enabling existing water rights to be leased and reserved for fish and wildlife, first passed the Montana Legislature in 1989. The tools described above, and others that have been developed to increase the equitable distribution of water, are forced to fit within the legal framework of prior appropriation. Consequently, the overall success of these governance mechanisms has been mixed. For example, in the Jefferson Basin MT FWP's reserved water rights, established to protect instream flows, have a priority date of 1985. While these rights constitute a substantial volume, their extremely junior priority dates render them insignificant.

Although historical governance arrangements (such as prior appropriation) continue to guide water resource policy decisions in Montana and the rest of the West, the last 20 years have seen a significant transformation in watershed management at global, regional and local scales. Beginning in the early-1990's it became recognized that a more integrated approach to water management was necessary to deal with the ever-increasing demands for freshwater resources in the face of dwindling supplies globally (United Nations Department of Economic and Social Affairs [UNDESA], 2014). Both international (United Nations) and national organizations (American Water Resources Association [AWRA]) have recommended that water management and policy be organized around the concept of Integrated Water Resources Management (IWRM) (UNDESA, 2014; AWRA, 2011). IWRM is defined by the Global Water Partnership as:

> "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant

> economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (2010).

IWRM was designed to address shortcomings associated with the hierarchical top down approach to water management that prevailed through most of the 19th and 20th centuries (Engle et al., 2011; GWP, 2010).

Another related organizational paradigm, adaptive management, has attempted to tackle water resource decision making under uncertainty (Engle et al., 2011). While the physical processes that control water resources (i.e. climate) are in a constant state of fluctuation, "Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity" (Milly et al., 2008). In the western U.S. the distribution of water via the prior appropriation doctrine is based on a stationary amount of water. Water compacts between parties (states, tribes, basins, etc.) are often grounded on volumes established at the time of the agreement's signing. Many compacts are decades old and climate and/or land use conditions have changed over that period—typically resulting in diminished water supplies and conflict. This disparity has resulted in numerous highly publicized "water wars" throughout the West (e.g. Colorado River Compact, Republican River Compact, Arkansas River Compact). Adaptive management techniques are characterized by iterative decision making processes that incorporate feedbacks between decision making and system monitoring (Holling, 1978). The iterative process allows for administrative flexibility and has been applied to water resources problems worldwide (Gregory et al., 2006; Pahl-Wostl, 2007; Kallis et al., 2009; Engle et al., 2011).

Recent water stewardship approaches in the Western U.S. incorporate parts of both the IWRM and adaptive management paradigms. Bottom up governance regimes organized at the local level (i.e. watershed groups) now play a substantial role in watershed planning. In Montana over 50 watershed groups have formed since the mid 1980's to conserve and protect both surface and groundwater resources (Montana Watershed Coordination Council, 2015). Many of these groups have also established drought plans that contain monitoring guidelines, weekly update requirements during low flows, and streamflow trigger points that prompt management actions. Over the past 30 years Montana's grassroots watershed organizations, working in cooperation with government and non-government agencies, have successfully organized to keep water in the stream for the benefit of both aquatic ecosystems and residents of Montana. Through the formal establishment of integrated and adaptive management policies and stakeholder driven watershed groups, contemporary water resources management emphasizes a holistic, stakeholder driven approach for solving water resources conflicts.

The human use of surface and groundwater resources has been described as a common pool resource by scholars (Ostrom et al., 1999). Common pool resources (natural or human created) are a type of open access subtractable good in which it is difficult to exclude users (Ostrom et al., 1994). According to Hardin's Tragedy of the Commons Theory, the use of this type of resource should eventually result in a complete breakdown of the system as users of the resource ignore costs imposed on other (i.e. irrigators are only interested in maximizing their operations and deplete all surface and groundwater supplies) (Ostrom,et al., 1999). This complete utilization rarely occurs as

systems become self-organized by the users who depend on the resource and recognize benefits gained from their own restrictions (Ostrom et al., 1999). The prior appropriation doctrine—which creates a property right system for the use of water—functions as set of standardized rules to equitably manage a common pool resource. Alternatively, recent collaborative water management approaches have worked to informally manage scarce water resources.

On the ground management actions, through either aquatic restoration efforts or the establishment of drought plans, constitute the majority of the efforts undertaken by watershed organizations. At this type of operational level, watershed groups (in the form of government-citizen partnerships) have worked to improve aquatic habitats and water quality throughout the United States (Margerum & Robinson, 2015). Watershed groups operate using technical expertise from government agencies and input from NGO's, water users and citizens. Funding of these groups is often sustained through government sponsored grants and direct contributions from NGO's. Successful operation of watershed groups requires an engaged base of volunteer water users and citizens active in management and the decision making process (Margerum & Robinson, 2015).

Research into the collaborative management of water resources (through a watershed group) has identified several keys to effective approaches. A study reviewing 37 papers on conflict resolution in watershed management (at the local level) found that sufficient funding for management activities and engaged leadership are important in creating effective strategies (Leach & Pelkey, 2001). The same study concluded that although local circumstances play an important role there is rarely a "hard formula" for

successful watershed management. Overall, the studies have highlighted the importance of decentralized governance and organizational stability over time (Imperial, 2005). Additionally, there is a common consensus that there is no one size fits all policy for improving aquatic health and addressing watershed problems. Appropriate solutions are almost always sourced locally with engagement and cooperation among the relevant stakeholders (Imperial, 2005).

The Jefferson Valley as a Social-Ecological System

Impending population growth, changing land use patterns and climate induced alterations to the hydrologic cycle present challenges for future water management in the Jefferson. Frequent and recurring drought in the Jefferson Basin has already resulted in undesirable outcomes for ecological communities and economic systems that are dependent on sufficient supplies of freshwater. Understanding the capacity of the Basin's water use community to respond to drought, and its capability to adapt to a shifting climate, is necessary to predict future impacts on the watershed. In addition to understanding the climatic drivers of future drought, historic periods of drought recorded in observations and climate proxies (e.g. tree rings) provide many realizations of drought events (varying in magnitude and duration) that provide valuable insights and test scenarios for water managers.

Water use systems such as the Jefferson function through a complex set of interrelationships between natural and social components. A methodology designed to describe and analyze these components is to view them as a linked social-ecological system (SES). As defined by Glaser et al.,

> "a social-ecological system consists of a bio-geo-physical unit and its associated social actors and institutions. Social-ecological systems are complex and adaptive and delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context" (2008).

A social-ecological systems approach attempts to bridge the traditional divide between the social and natural sciences, maintaining that the systems are intricately linked through feedback mechanisms (Berkes & Folke, 2000).

When social and ecological systems are interconnected, the overall SES is a highly intricate and adaptive arrangement, encompassing multiple subsystems as well as being fixed within larger systems. This nesting of systems across multiple scales is important to recognize when assessing SES's (Walker et al., 2004). Small-scale interactions (e.g. the dewatering of an insignificant tributary on the Jefferson) have the potential to produce much greater effects at larger scales (e.g. dewatering impacts senior hydroelectric water rights 100 miles downstream on the Missouri, raising electrical generation costs). These cross-scale relationships occur through both top down and bottom-up interactions and cover broad ranges of spatial-temporal scales (Gunderson & Holling, 2002).

SES approaches are increasingly being employed to characterize complex systems in terms of their overall social and ecological resilience (Walker et al., 2002; Folke, 2006; Walker & Salt 2012). SES resilience has been defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004). Just as ecosystems are in a constant state of flux with multiple future trajectories, resilience is not a static desired state, but an evolving attribute of a system (Holling,

1973; Gunderson & Holling, 2002). Resilience in a SES may change over time due to internally controlling variables or external shocks to the system.

Social-ecological systems contain important thresholds that if crossed, result in altered system feedbacks and lead to changes in the overall structure and function of the system (Walker et al., 2006). This alteration of a system's state to one with different controls and functions has been described as a regime shift (Holling, 1973; Folke et al., 2004). Previous work on thresholds has documented the varying nature of regime shift responses. Sudden changes in feedbacks to an ecosystem may result in a rapid response of state variables (e.g. trophic transition of a lake) or in other cases, a much slower transition in state variables (e.g. conversion of a fishery from native to non-native species) (Folke et al., 2004; Scheffer & Carpenter, 2003). Regime shifts may be reversible or irreversible (at least on human time scales) and result in a large range of outcomes (both desirable and undesirable) (Folke, 2006). Understanding the dynamics that contributed to previous regime shifts within a SES enables predictions to be made about the potential for future regime shifts within the system.

The Adaptive Cycle Model

The adaptive cycle of complex ecosystems, an important heuristic used to characterize the historical evolution of social-ecological systems, was first termed by Canadian ecologist C.S. Holling (1986). Traditional views on ecosystem dynamics saw succession as linear, static, and predictable (resources accumulate over time resulting in disturbance and renewal). The adaptive cycle integrates the inherent non-linearity present in dynamically coupled systems, viewing ecosystems as being in a constant state of flux

between different basins of attraction (future trajectories) (Gunderson & Holling, 2002). Trajectories are controlled by stabilizing forces (increase resilience of the system) and destabilizing forces (decrease resilience of the system).

The adaptive cycle is composed of four phases (Figure 3) that delineate within the cyclic evolution of complex ecosystem- from birth and exploitation, to growth and maturation, followed by collapse and reorganization (Holling, 2001). The first phase, exploitation/growth (r) is characterized by rapid development and exploitation of natural resources and capital (Gunderson and Holling, 2002). In the second phase, conservation (K), growth slows as the system becomes more interconnected and the availability of natural resources/social capital diminishes (Walker et al., 2006). The third phase, release/collapse (Ω), is marked by chaotic, and potentially rapid change to the system, "accumulated resources are released from their bound, sequestered and controlled, state connections are broken, and feedback regulatory controls weaken" (Gunderson and Holling, 2002). In the final phase of the adaptive cycle, reorganization/renewal (α), a recombination of system variables results in a novel SES arrangement, unhindered by prior combinations or associations (Chaffin et al., 2014). The adaptive cycle is a useful tool for analyzing, understanding, and quantifying changes in complex systems over time. It is a flexible framework that has been utilized by researchers and managers in both social and ecological sciences.

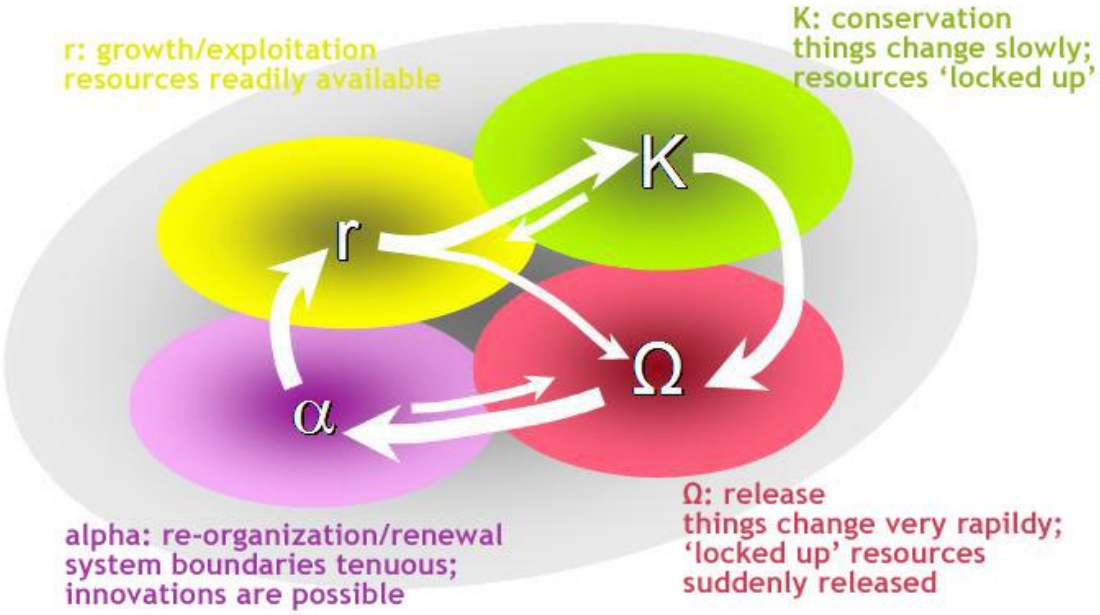


Figure 3. The four-phase adaptive cycle as described by Gunderson and Holling. Figure copied from the Resilience Alliance (2010).

Resilience Assessment Approach

A resilience assessment that identifies significant thresholds and potential regime shifts is a necessary initial step in managing for a resilient socio-ecological system (Resilience Alliance Handbook, 2010). Resilience assessments are completed to understand potential weaknesses in a system and identify areas in which resilience may be improved. As defined by the Resilience Alliance, the resilience assessment framework

> "[is] an approach to managing natural resource systems that takes into account social and ecological influences at multiple scales, incorporates continuous change, and acknowledges a level of uncertainty has the potential to increase a system's resilience to disturbance and its capacity to adapt to change" (Resilience Alliance, 2010, p. 4).

The definition above incorporates many of the same ideals encapsulated in both the IWRM and adaptive management paradigms that have been proposed as models for

contemporary water resources management. The resilience assessment approach has been applied to an array of complex water problems worldwide on topics ranging from water governance in the United States, to ecosystem based management of marine resources in the Great Barrier Reef (Cosens et al., 2014; Maynard et al., 2010).

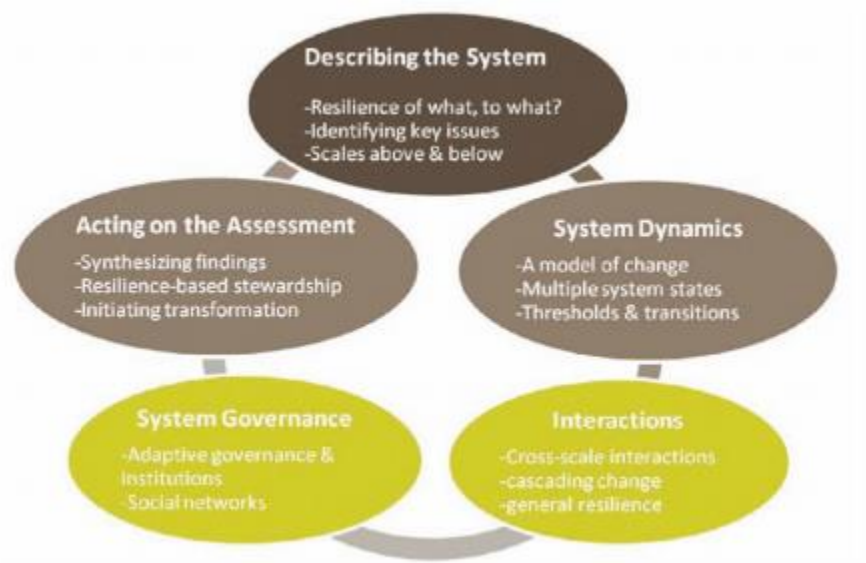


Figure 4. Five stages of the resilience assessment framework. Figure copied from the Resilience Alliance workbook for practitioners. Data Source: http://www.resalliance.org/files/ResilienceAssessmentV2_2.pdf

The Resilience Alliance proposes that there are five broad stages within the assessment framework: "describing the system…understanding system dynamics, probing system interactions, evaluating governance, and finally acting on the assessment" (Resilience Alliance, 2010; Figure 4). This thesis aims to address the first four steps, providing an overall valuation of resilience in the Jefferson River Basin SES. Although several detailed frameworks have been proposed for developing resilience assessments (Walker et al., 2002; Walker & Salt, 2012; Resilience Alliance, 2010) the application of

these approaches has proven empirically challenging. SES's are highly complex and variable in nature and attempting to apply a "one size fits all" valuation is not always appropriate (Chaffin et al., 2014; Nemec et al., 2014). Furthermore, preexisting frameworks for resilience assessments require large quantities of data that may not be feasible or realistic to compile.

A recent comprehensive study termed the "Adaptive Water Governance Project" investigated resilience in heavily regulated and developed river basins throughout the United States (from the Everglades to the Columbia). The project was composed of six basin teams that used a variety of approaches to complete resilience assessments in their respective basins. Two important findings from a synthesis report of that project are worth mentioning here. First, the report identified the importance of a "historical approach to assessment" as a means to understand the "change in resilience and governance attributes through time" (Cosens et al., 2014). Second, the report found that legal mechanisms provide important windows "to sometimes new and collaborative approaches to water governance" (Cosens et al., 2014). The subsequent resilience assessment contained in the next two chapters, and which is at the heart of this thesis, integrates both of these findings.

Following the stepwise approach demonstrated by Chaffin, Gosnell and others in their recent SES resilience assessment of the Klamath River Basin in central Oregon, and part of the Adaptive Water Governance Project, this thesis will adopt the overall methodology presented in the Resilience Alliance's 2010 handbook. In chapter 2, I will characterize the Jefferson Basin SES's boundaries and associated scales, describing both

its physical and human geography. Chapter 3 will analyze SES resilience in the Jefferson Basin over time utilizing the four phase adaptive cycle of complex ecosystems developed by Gunderson & Holling (2002). Acting on recommendations made in the Chaffin et al. Klamath assessment, Chapter 4 of this thesis will integrate downscaled climate prediction data tailored to water users in the Jefferson Basin.

CHAPTER 2

RESILIENCE ASSESSMENT PART 1: DESCRIPTION OFTHE JEFFERSON BASIN SES

An important part of any resilience assessment is to identify and describe the socio-ecological system and its associated boundaries and scales (Resilience Alliance, 2010; Walker & Salt, 2012). Part 1 of this resilience assessment (comprising the remainder of this chapter) will investigate important biophysical, social and economic drivers of the Jefferson Basin SES. This portion of the assessment will also identify and define the main issues of concern within the SES. Utilizing a mixed methods approach, this chapter synthesizes data from a variety of publicly available sources (see methods table from introduction).

Biophysical Context

The Jefferson River Basin is located in southwestern Montana, approximately 15 miles west of the metropolis of Butte, Montana. Over 9,500 square miles in area (approximate in size to the U.S. state of Vermont); the Jefferson Basin contains the most distant headwaters of the Missouri River (USGS, 2015a; "Vermont", 2015). The Jefferson River flows through a complex landscape that supports a robust wildlife population and intact cottonwood (*Populous trichocarpa*) floodplain ecosystem. Although the main-stem of the Jefferson meanders a relatively short distance of 83 miles, it functions as an integral conduit between its headwater tributaries (the Beaverhead, Big Hole and Ruby Rivers) and the Missouri River. For the purposes of this assessment the

83 mile, main-stem portion of the watershed (from approximately Twin Bridges, MT to Three Forks, MT) will be known as the "Jefferson Basin". The larger watershed encompassing the Beaverhead, Big Hole, Boulder and Ruby Rivers will be termed the "greater Jefferson Basin" (Figure 5). The following hydrological analysis of the Jefferson will focus on problems of concern related to low streamflows. Although there are known issues with sedimentation and water temperatures on the Jefferson it is beyond the scope of this thesis to address these topics in detail.

Topography & Geology

The greater Jefferson Basin consists of numerous distinct mountain ranges (Figure 6). The Centennial and Tendoy Mountains constitute the southern boundary of the basin and contain the headwaters of the Beaverhead River (and subsequently the Missouri). The Gravelly Range and Tobacco Root Mountains mark the eastern edge of the watershed separating the Jefferson and Madison drainages. Just west of the Gravelly Range, three distinct but relatively small ranges, the Snowcrest, Ruby and Blacktail Mountains, divide the Ruby and Beaverhead Valleys. On the western margin of the greater Jefferson Basin, the Beaverhead Mountains and Anaconda Range contain the Big Hole River, with the Pioneer Range situated directly east of the Beaverhead Range separating the Big Hole and Jefferson valleys. The Elkhorn and Highland Mountains form the northern border of the basin.

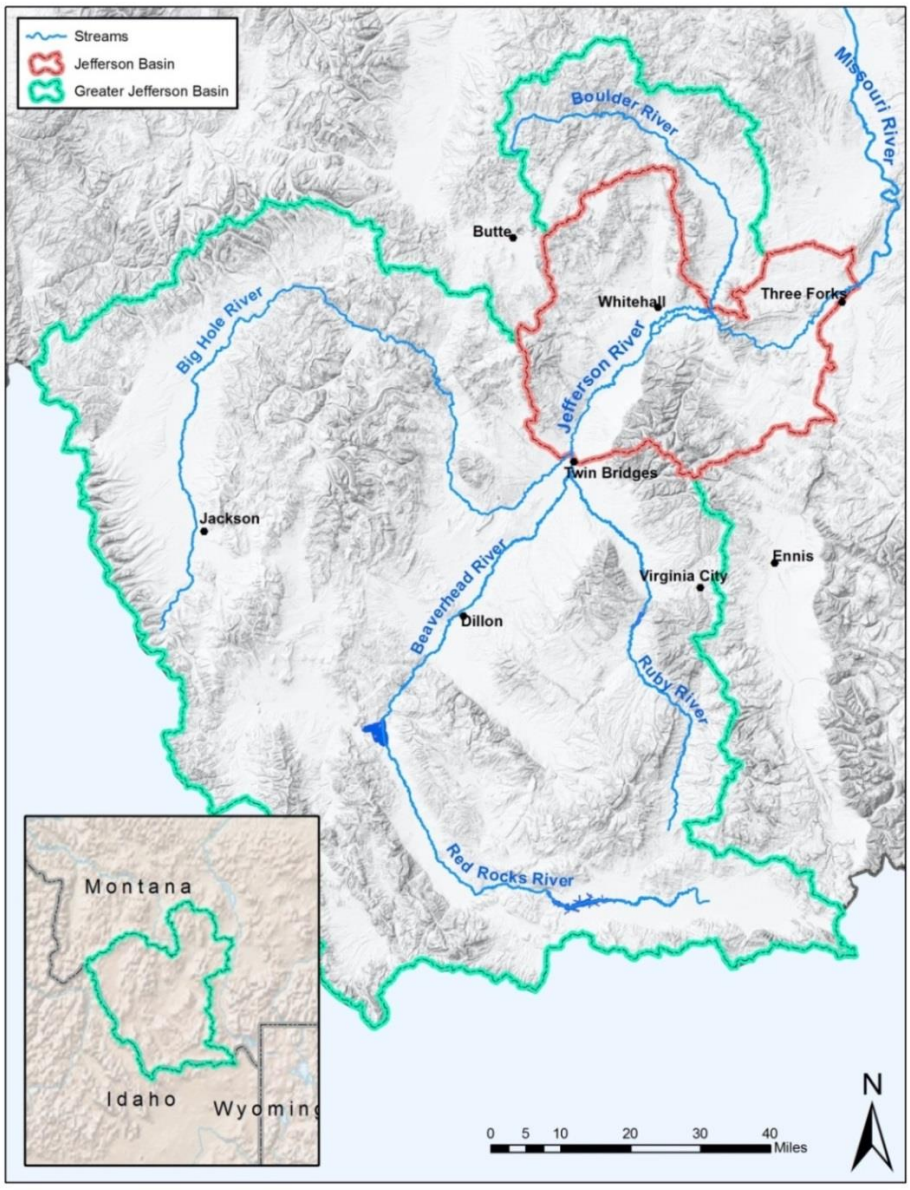


Figure 5. Map of the study area: the (greater) Jefferson River Basin located in southwest Montana, USA. Data Source: National Hydrography Dataset [NHD] (2013), MT NRIS—GIS Clearinghouse.

The Jefferson River flows through a rich geologic landscape flanked by mountain ranges containing some of the oldest rocks found in North America. Metamorphic rocks dating from the Archean (2.7 billion years ago) are present in both the Ruby Range and the Tobacco Root Mountains (James, 1990). As described by Vuke et al., the upper

Jefferson Valley is asymmetrical with steep, west-dipping faults on the east side and smaller east-dipping faults on the western margin. The Jefferson Valley floor is an intermontane basin filled with sediment transported from the surrounding mountains (Brancheau, 2015). A series of alluvial fans and benches are clearly visible on the flanks of the Jefferson Valley and date from the Middle Pleistocene (~120-780 thousand years ago) or younger (Bartholomew et al., 1999). Several of the mountain ranges that constitute the boundary of the Jefferson Basin contain plutons (magmatic intrusions) tied to the Boulder Batholith. The Boulder Batholith is a mass of igneous rock that breached the surface of earth's crust 73-78 million years ago in an area roughly located between Butte and Helena, Montana. Emplacement of the Boulder Batholith in the late Cretaceous is associated with heavy metal ore deposits, including lead, zinc, silver, gold and copper (Johnson, 2004). The historic mining districts in Butte, Helena, Elkhorn and Pony were propelled by mineral rich veins accompanying the Boulder Batholith.

Climate

Temperatures in the Jefferson Basin fluctuate dramatically on annual, seasonal and daily scales. Early 19th century explorers Lewis and Clark described these temperature oscillations while traveling through the Jefferson Valley in early August of 1803, "The tops of these mountains were yet partially covered with snow while we in the valley were suffocated nearly with the intense heat of the midday sun. The nights are so cold that two blankets are not more than sufficient covering" (Lewis et al., 2003). Annual temperatures in the Jefferson Basin exhibit seasonal fluctuations common for mid-latitude continental climates. In valley bottom locations, average temperatures peak

in July and August and reach their minimums in December and January (Tables 1 & 2). The period of frost free days in the Jefferson Basin (number of days when minimum temperatures are above 32 F), ranges from 167 days at Twin Bridges (at the confluence of the Jefferson) to 180 days at Trident (at the mouth of the Jefferson) (Western Regional Climate Center, 2015).

Climate Summary for Trident, MT (Elevation 4,036 ft)													
Base Period 1981-2010	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Average Max. Tem (F)	35.9	41.1	50.1	59.3	68.6	77.3	86.2	85.8	74.7	60.7	43.4	35.1	**60.0**
Average Min. Temp (F)	13.3	17.3	24.8	31.9	40.1	47.2	51.8	50.2	41.4	31.7	21.1	13.5	**32.1**
Average Total Precip (in.)	0.45	0.37	0.75	1.41	2.32	2.43	1.46	1.07	1.20	1.04	0.60	0.53	**13.62**

Table 2. Trident, Montana climate summary. Data source: Western Regional Climate Center. Base period for calculations: 1981-2010.

Climate Summary for Twin Bridges, MT (Elevation 4,625 ft)													
Base Period 1981-2010	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Average Max. Temp (F)	35.8	40.8	49.4	58.0	66.7	75.2	83.6	82.3	72.5	59.9	43.1	34.4	**58.6**
Average Min. Temp (F)	12.4	15.4	22.0	28.2	35.8	42.5	45.9	43.3	35.7	27.5	18.9	11.9	**28.4**
Average Total Precip (in.)	0.22	0.22	0.51	0.91	1.73	2.00	1.13	1.02	0.91	0.69	0.38	0.29	**10.01**

Table 3. Twin Bridges, Montana climate summary. Data source: Western Regional Climate Center. Base period for calculations: 1981-2010.

Precipitation patterns in the region vary depending on elevation and location. Higher elevations within the Anaconda, Beaverhead and Pioneer ranges receive the greatest average annual precipitation accumulations in the greater Jefferson Basin (40-50 inches/year) and effectively function as a rain shadow capturing much of the moisture bound for the rest of the watershed (Figure 6). The Tobacco Root Mountains also accrue

relatively high amounts of precipitation with some locations averaging over 40 inches per year. In contrast, bottomlands in the Jefferson and Big Hole Valleys rank among the lowest annual precipitation averages in the state of Montana, with some locations averaging less than 9 inches per year. As illustrated in Figure 6, much of the lower elevation areas in the greater Jefferson Basin are arid and may technically be classified as desert, receiving less than ten inches of precipitation annually (Köppen climate classification BSk—semi arid steppe climate). Valley bottom locations average between 9-15 inches of precipitation yearly depending on location and aspect, with the wettest period occurring between April and May (Tables 2 & 3).

The extreme disparity in precipitation between the higher and lower regions necessitates an expansive water use infrastructure in the Jefferson. Annual precipitation totals in the valleys are not sufficient to support extensive commercial farming operations and irrigation is necessary. Precipitation in the form of snowfall is accrued at higher elevations from October-March and released as snowmelt in the spring and early summer (April-June). Snowfall usually begins accumulating in mid-October in the Jefferson Basin with snowpack peaking sometime in April or early May (depending on elevation) and typically absent by mid-June. On average, the snowiest months in the mountainous headwaters regions are March & April (Figures 7 & 8).

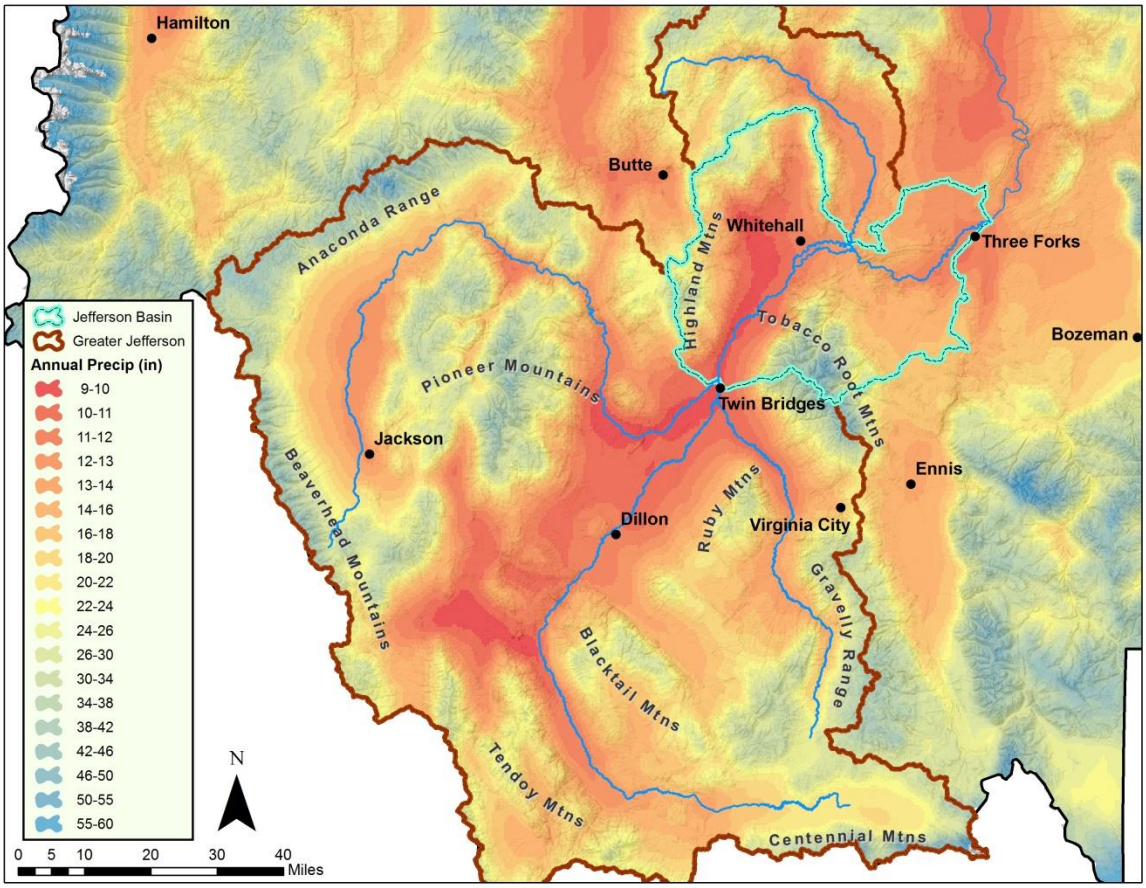


Figure 6. Average annual precipitation totals in the greater Jefferson basin. Annual precipitation based on a base period of 1981-2010. Precipitation layer data source: Montana Climate Office (2015), MT NRIS—GIS Clearinghouse.

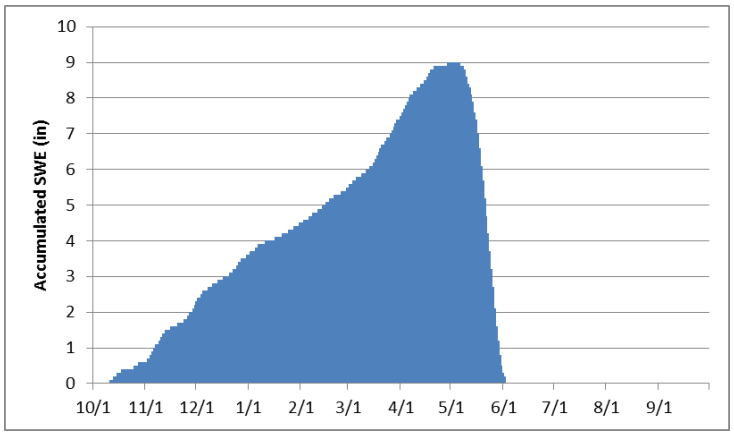


Figure 7. Basin Creek SNOTEL located in the Boulder Mountain Range (7,180 ft) average annual snow water equivalent (SWE) accumulation. Base period for calculations: 1981-2010. Data source: Natural Resources Conservation Service (2015).

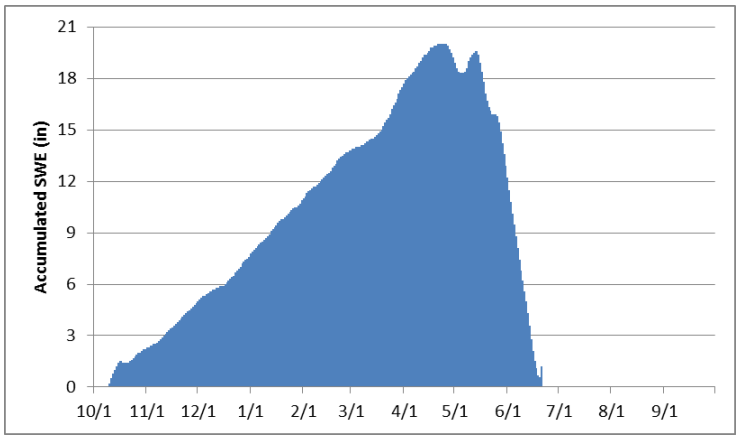


Figure 8. Albro Lake SNOTEL located in the Tobacco Root Mountain Range (8,300 ft) average annual snow water equivalent (SWE) accumulation. Base period for calculations: 1981-2010. Data source: Natural Resources Conservation Service (2015).

Hydrology

Understanding and quantifying the hydrology of the Jefferson Basin is integral in determining the watershed's social, economic and ecologic vulnerability in addition to understanding the potential for social and ecologic resilience. The greater Jefferson River Basin is situated on the flanks of the Continental Divide in southwestern Montana. The most distant of the Jefferson's headwaters, and subsequently the Missouri River, rise 298 miles from the river's mouth in the Centennial Mountains, a sub-range of the Bitterroot Mountains that straddle the Montana-Idaho border (Demetriades, 2005). The streams that drain the north slope of the Centennial Mountains eventually coalesce to form Red Rock Creek which meanders westward through the Centennial Valley before entering Lima Reservoir (where it becomes the Red Rock River). After departing the reservoir, water flows northwest spilling into the Clark Canyon Dam near Dillon, MT. The water that exits the Clark Canyon dam forms the Beaverhead River which flows northeast through a broad intermountain valley known as the Beaverhead Valley. As the Beaverhead courses

through the community of Twin Bridges, Montana it joins the Ruby River, and then subsequently the Big Hole River, officially merging to form the Jefferson River 1.5 miles north of the town (Figure 5).

From the Jefferson's confluence near Twin Bridges, the river flows due north approximately 40 miles through the historic communities of Silver Star and Waterloo before veering east near Whitehall. Whitehall functions as the informal dividing point between the upper and lower portions of the Jefferson Valley. Much of the upper section of the Jefferson is braided and historically—before extensive streambank stabilization efforts—the River migrated within its floodplain inundating adjacent agricultural lands (Jefferson River Watershed Council, 2010). After absorbing the Boulder River (North) 7 miles downstream from Whitehall, the Jefferson turns slightly south as it enters the scenic and limestone dominated, Jefferson River Canyon. Upon exiting the narrow canyon, the Jefferson passes into a broad valley on the east side of the Tobacco Root Mountains as it approaches the town of Three Forks and the confluence of the Missouri River.

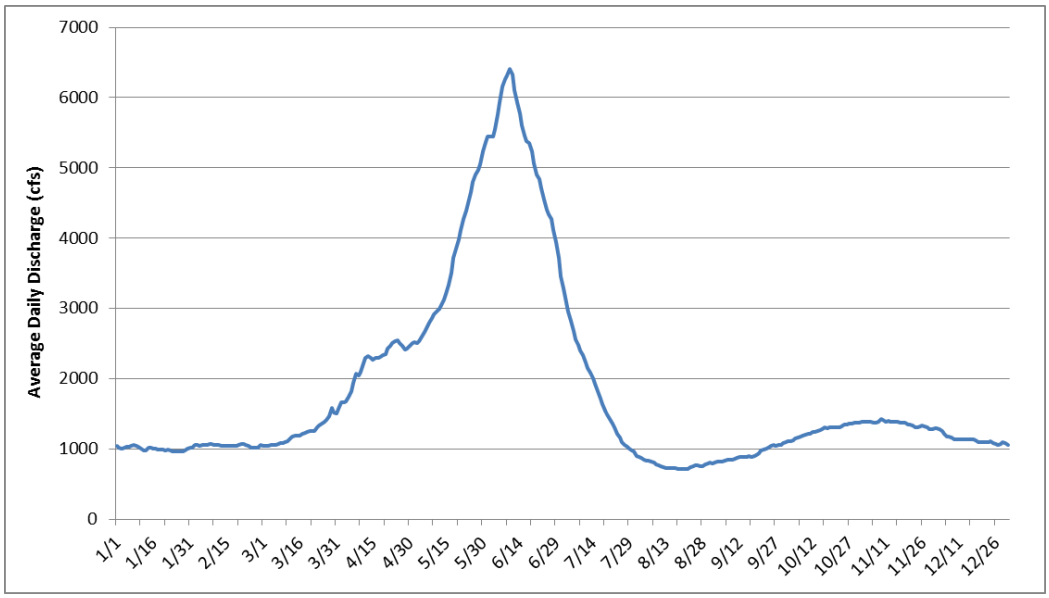


Figure 9. Average daily flows on the Jefferson River at Twin Bridges (USGS Gage 6026500). Base period of calculations: 1941-1943, 1958-1972, 1995-2014. Data source USGS (2015b).

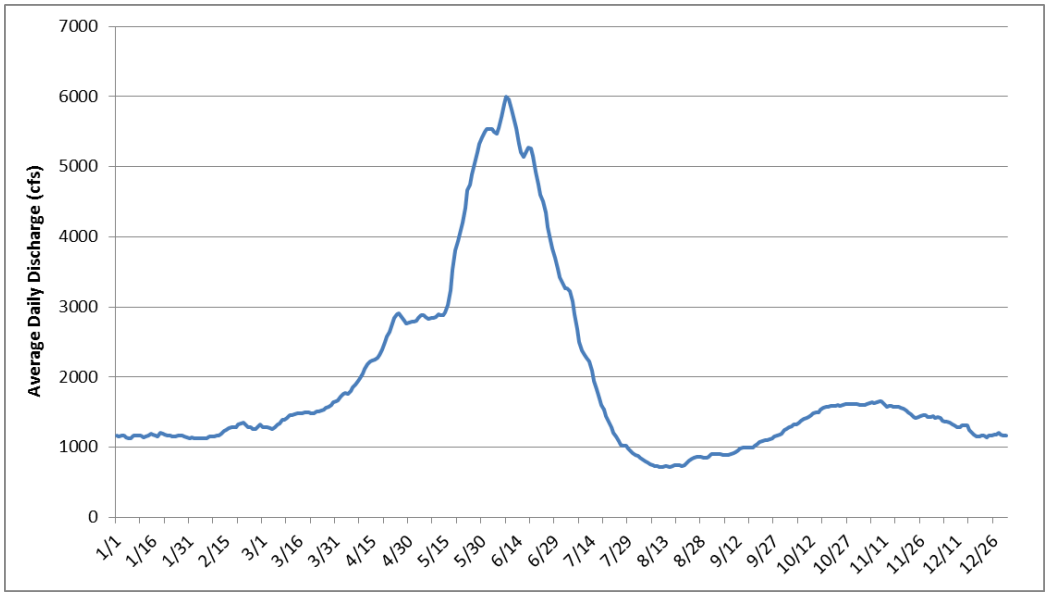


Figure 10. Average daily flows of the Jefferson River at Three Forks (USGS Gage 6036650). Base period for calculations; 1979-2014. Data source USGS (2015a).

Overall patterns of streamflow on unregulated streams within the greater Jefferson Basin are characteristic of other snowmelt-dominated systems in the intermountain West.

On an annual basis, streamflow values typically peak during spring runoff (April-June) and recede to their lowest values during the late summer period of high irrigation demand (August-September), before rebounding slightly as irrigation ceases by the end of September (Figures 9 & 10). Seasonal variations in streamflow within the basin may be dramatic, influencing both agricultural and ecological productivity. In 2013 average daily stream discharge on the Jefferson River at Three Forks peaked at 3,450 cfs on May 30th before plummeting to its lowest point of only 90 cfs on August 22 (USGS, 2015a).

Beginning in 2000, the Jefferson River has experienced a record number of extreme drought years (over the period of record), with streamflows dropping below drought management guidelines in eight out of the last fifteen years. As illustrated in Figures 11-14, extremely low flows have been fairly restricted both spatially and temporally. The Silver Star to Waterloo section of the Jefferson has historically seen the most substantial dewatering on the river, with volumes dropping to 50 cfs as recently as 2013 (USGS, 2015c). Interestingly, the river channel both downstream and upstream from this location typically contains more water (Figures 12-14). Irrigation withdrawals on the reach of the Jefferson between Twin Bridges and Waterloo divert approximately 350 cfs during the growing season and constitute some of the largest water rights on the River (Spoon, 2008). Downstream from Waterloo, groundwater recharge and canal return flow contributes significantly to the increase in surface flow volumes (Spoon, 2008).

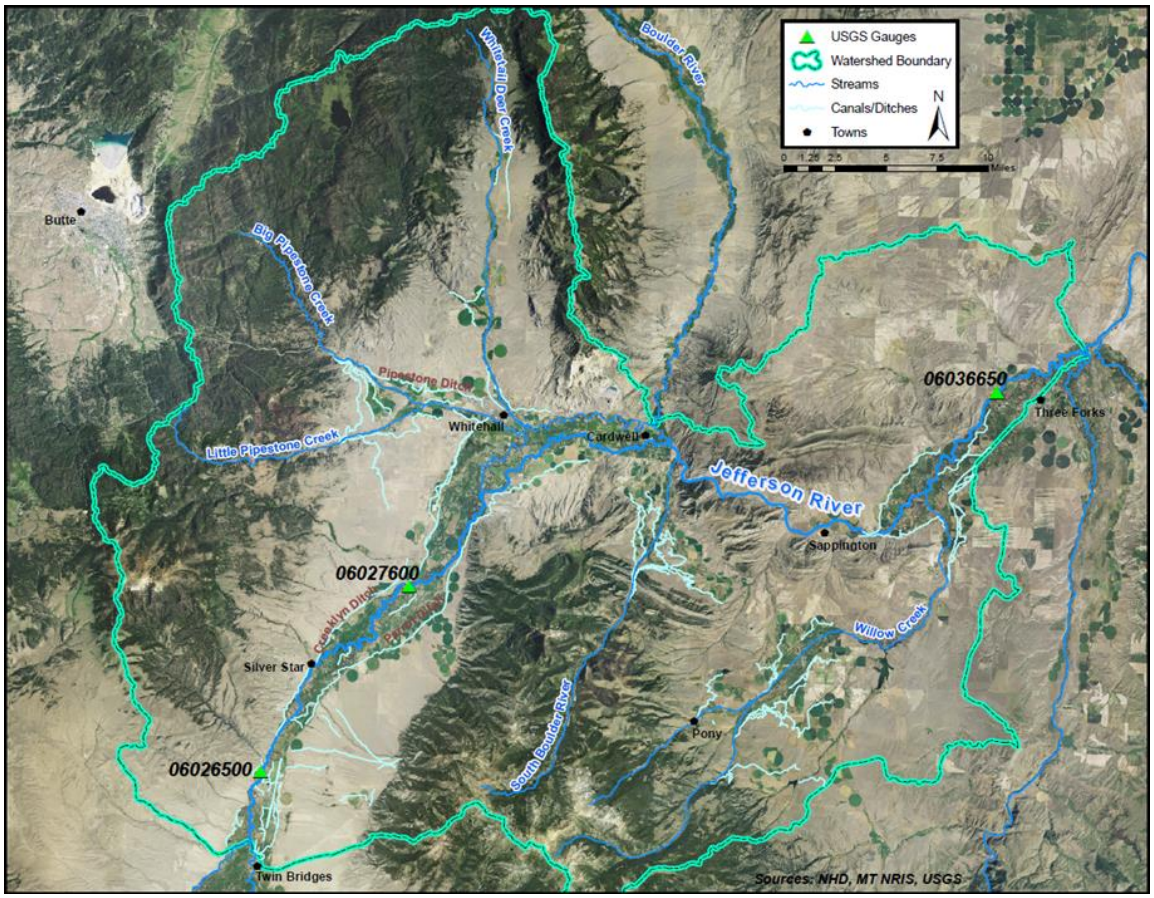


Figure 11. Map of USGS stream gage locations and major canals and ditches in the Jefferson Basin. Creeklyn Ditch was incorporated in 1932; Parrot Ditch was constructed in 1888 and incorporated in 1916. Stream and canal/ditch data layer from National Hydrography data set (2014). Other mapping data: MT NRIS—GIS Clearinghouse.

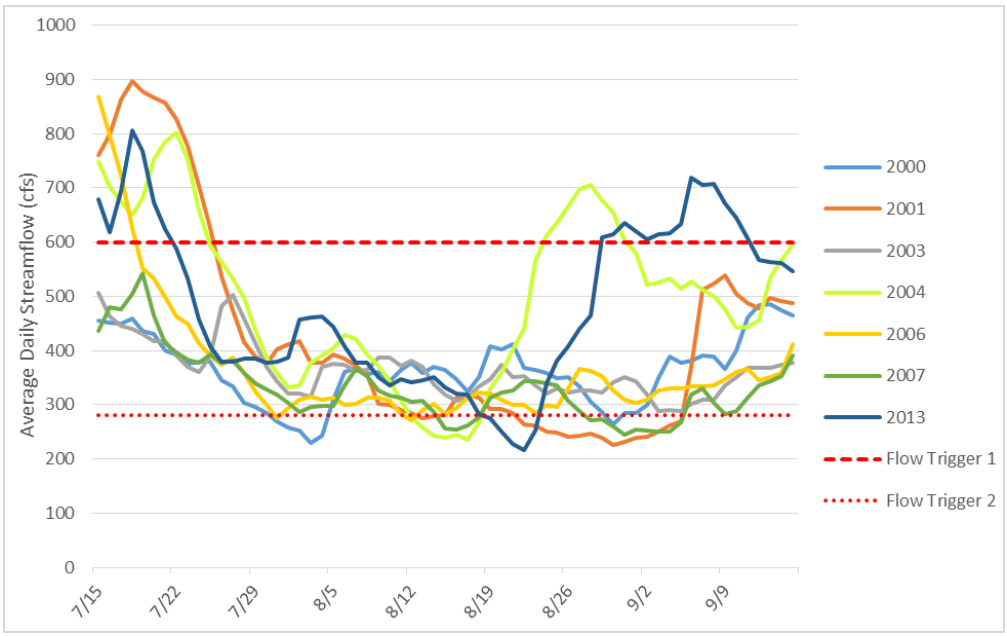


Figure 12. Recent episodes of low streamflow on the Jefferson River near Twin Bridges, MT (USGS gage: 6026500). Period of record: 1941-1943, 1958-1972, 1995-2014. Flow trigger points prompt the Jefferson River Watershed Council (JRWC) to recommend management actions. Data source: USGS (2015b).

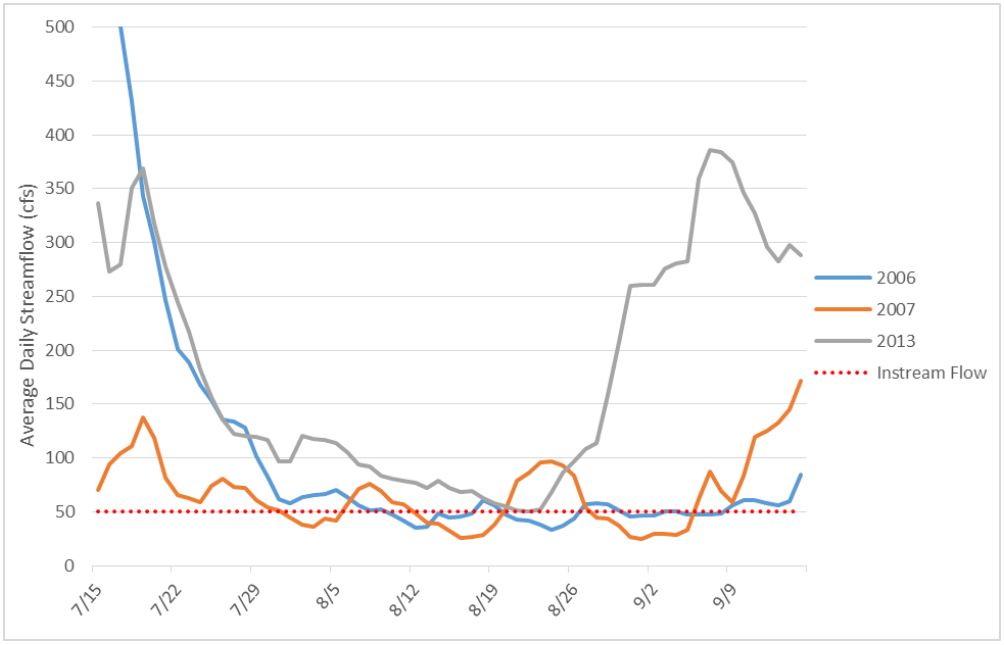


Figure 13. Recent episodes of low streamflow on the Jefferson River near Silver Star, MT (USGS gage: 6027600). Period of record: 2006-2014. The primary goal of the JRWC drought management plan is to retain a streamflow of at least 50 cfs at Silver Star. Data source: USGS (2015c).

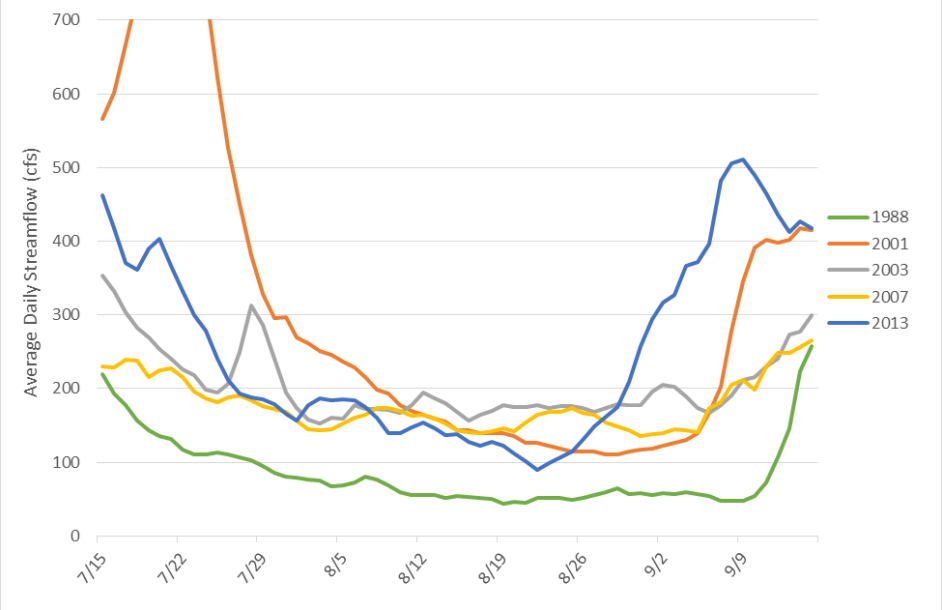


Figure 14. Recent episodes of low streamflow on the Jefferson River near Three Forks, MT (USGS gage: 6036650). Period of record: 1979-2014. Data source: USGS (2015a).

On interannual time scales, average yearly discharge volumes display significant variability (Figures 15-18). Multi-year variability in streamflow in the region is driven partly by large scale atmospheric processes that alter temperature and precipitation patterns. In the northern Rocky Mountains much of the observed year to year variability in snowfall and streamflow volumes has been attributed to changes in synoptic scale drivers of climate (i.e. Pacific Decadal Oscillation [PDO] , El Nino Southern Oscillation [ENSO]) (Pederson et al., 2011). As illustrated in Figures 15-18 streams in the greater Jefferson Basin exhibit similar trends in streamflow on longer, decadal time scales. Two of the gages examined experienced below average streamflow volumes from the mid-1980s to the early-1990's, followed by a relatively shorter period of above average flows in the mid-1990's and a return to negative flow anomalies from 2000-2010 (Figure 15 & 16). The gage with the longest period of record in the greater Jefferson Basin (Big Hole

near Melrose) also exhibits negative streamflow anomalies from approximately the mid-1920's to the mid-1940's and positive anomalies from 1960 to the mid-1980's (Figure 13). Both of these long term streamflow irregularities are weakly associated with phases of the PDO (Pederson et al., 2011) which was in a positive phase from around 1925-1947 and a negative phase from 1947-1976 (Mantua et al., 2002).

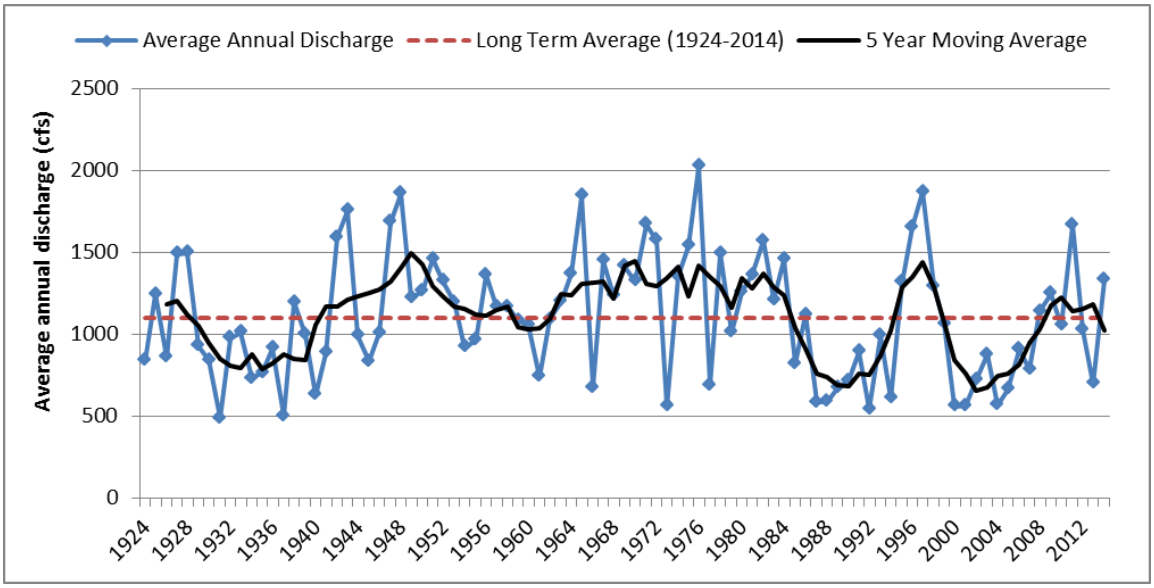


Figure 15. Average annual discharge on the Big Hole River near Melrose (USGS gage 602550). Period of record: 1924-2014. Data source USGS (2015d).

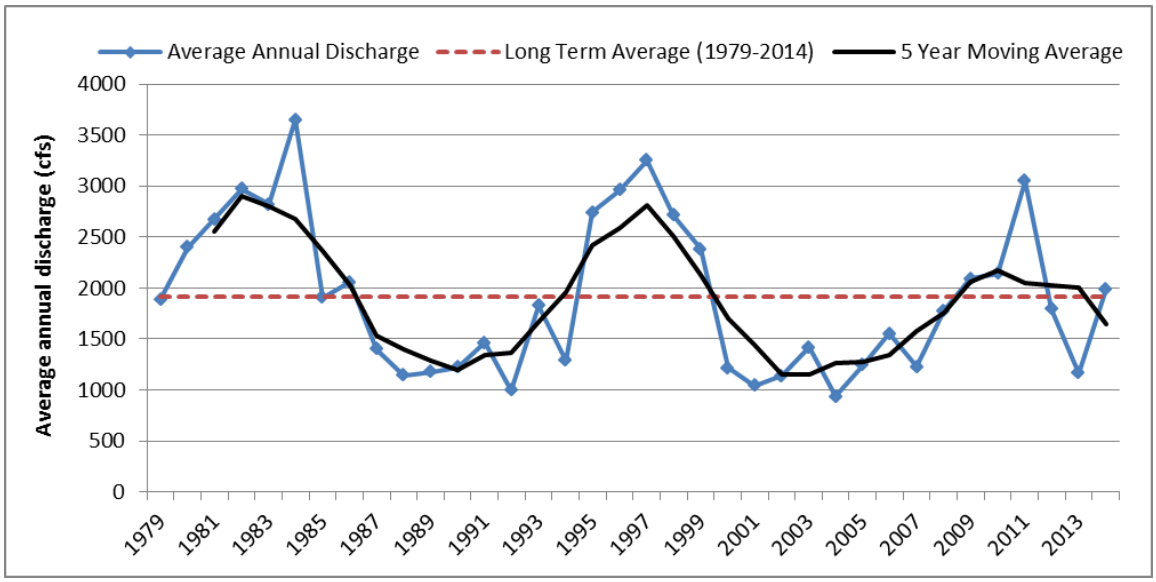


Figure 16. Average annual discharge on the Jefferson River near Three Forks (USGS gage 6036650). Period of record: 1979-2014. Data source USGS (2015a).

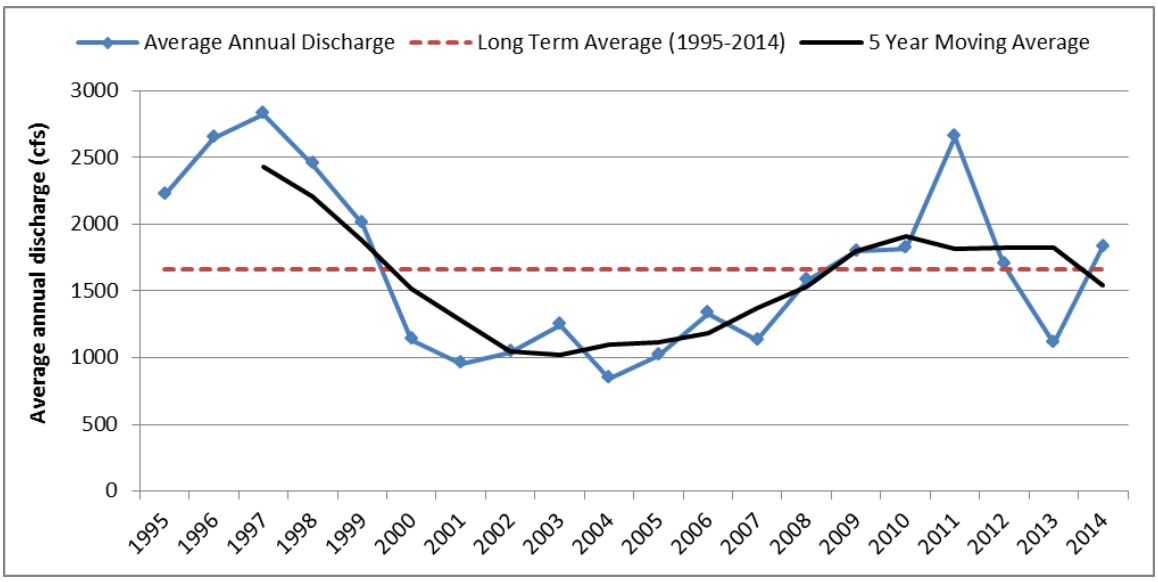


Figure 17. Average annual discharge on the Jefferson River near Twin Bridges (USGS gage 6026500). Period of record: 1995-2014. Data source USGS (2015b).

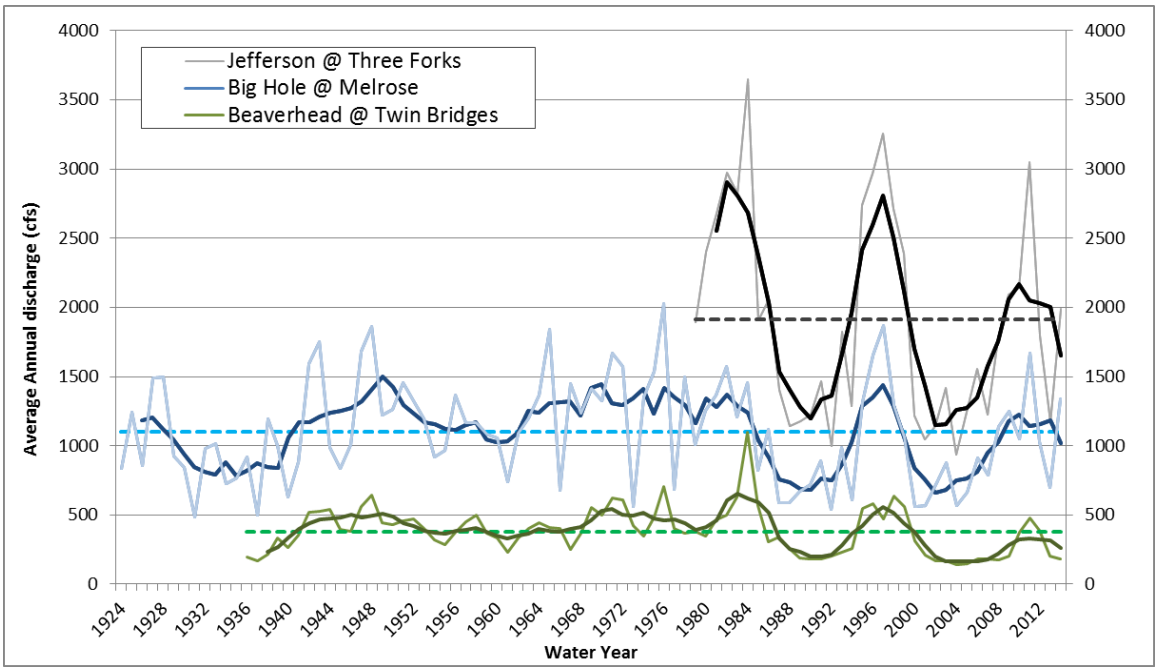


Figure 18. Comparison of average annual streamflows on the Jefferson River and its major tributaries. Clark Canyon Dam regulates flows on the Beaverhead gage (after 1964). Data includes all available annual streamflow means over the period of record for each gage. Gaps represent a break in the data set. Data source: USGS (2015a, 2015d, 2015g).

Aquatic Ecology

The Jefferson River supports numerous native and non-native fish species including: rainbow trout, brown trout, brook trout, hybrid westslope cutthroat trout, westslope cutthroat trout, mountain whitefish, common carp, longnose dace, longnose sucker, Rocky Mountain sculpin, mountain sucker, white sucker and northern pike (MT FWP, 2013). The state of Montana lists the westslope cutthroat trout and the Arctic grayling (only present in the Big Hole, Ruby and Red Rock drainages) as species of concern (JRWC, 2010). The Jefferson River sport fishery has historically been dominated by brown trout, with rainbow trout composing a larger proportion of fishing hauls over the past ten years (Spoon, 2008).

Importantly, the greater Jefferson watershed contains the last remaining habitat in the contiguous United States supporting native fluvial Arctic grayling (*Thymallis arcticus*). Arctic grayling are a cold water salmonidae species (the same family as trout, whitefish and salmon) that are easily identified by their distinct sail-like dorsal fin. Fluvial arctic grayling were historically dispersed throughout the upper Missouri basin and previously inhabited the Beaverhead, Big Hole, Jefferson, Gallatin, Madison, Ruby, Smith, Sun and mainstem Missouri (upstream from Great Falls) river systems (United State Department of the Interior [US DOI], 2014). Populations in these native habitats declined significantly in the second half of the 20th century, eliminating the species from all but Big Hole River basin (MT FWP, 2010). Recent reintroductions on the upper Ruby and Madison drainages (upstream from Ennis Reservoir) have reestablished self-sustaining populations in these systems. Attempted reintroductions of fluvial Arctic grayling on the Jefferson River failed (US DOI, 2014). The upper Missouri River distinct population segment (DPS) of fluvial Arctic grayling was classified as a candidate species under the Endangered Species Act (ESA) from July of 1994-April 2007 and was petitioned for listing under the ESA as early as 1982 (MT FWP, 2010). Initiated in 2006, the Big Hole Grayling Candidate Conservation Agreement with Assurances (CCAA) is a collaborative planning effort among NGO's, governmental organizations and landowners to conserve the grayling and avoid a formal listing of the species under the ESA (DOI, 2014). The CCAA has proven to be an effective tool in conserving grayling populations in the Big Hole and has resulted in similar efforts to conserve sage grouse in eastern Montana.

Terrestrial Ecology

The Jefferson River reach from Twin Bridges to the mouth of the Jefferson Canyon near Cardwell has been identified as a significant wildlife corridor due in large part to the intact riparian cottonwood forests that continue upstream on the Jefferson's three major tributaries. The intact cottonwood stands support numerous avian species including osprey, bald eagles, golden eagles, sandhill cranes, snow geese and swans. River otter, mink and beaver also reside in the Jefferson in significant numbers and are often spotted on float trips. The area around the confluence of the Jefferson and Boulder rivers is recognized as a wildlife corridor between the Tobacco Root and Boulder mountain ranges providing important habitat for moose, deer, antelope, elk, mountain lion and black bear (American Wildlands, 2009).

Human Settlement & Development

The history of human occupation in the Jefferson Basin is rooted in the region's importance as a travel corridor and the area's relative abundance of natural resources. The Jefferson River's contemporary name was designated by the Lewis and Clark Expedition on July 28th, 1805 as the Corps of Discovery arrived at the Missouri River headwaters;

> "Both Capt. C. and myself corresponded in opinion with respect to the impropriety of calling either of these streams the Missouri and accordingly agreed to name them after the President of the United States and Secretaries of the Treasury and the State" (Lewis et al., 2003).

Concluding that the western of the three forks of the Missouri to be the most prominent; the "Jefferson" was named after the third President of the United States and traversed by the Corps during August of 1805 (Lewis et al., 2003).

Tribes

Prior to Euro-American settlement in the middle of the 19th century, the greater Jefferson Basin was inhabited by numerous Native American communities. The earliest evidence for human habitation in the area dates to approximately 12,000 to 13,000 before present, although significant occupation likely occurred relatively recently (Bryan, 1996). Beginning in the 1500's, several Native American tribes ventured into the Jefferson Valley/Missouri River headwaters region including the Salish, Pend d'Oreille, Shoshone, Crow, Blackfeet, Hidatsa, Gros Ventre and Assinboine (Bryan 1996; Headwaters Heritage Museum, n.d.). The abundance of buffalo in the Missouri headwaters drew tribes from west and south of the continental divide (such as the Salish and Shoshone) that ventured into the area as hunting parties (Farr, 2001).

When the Lewis and Clark Expedition traveled up the Jefferson River in early August of 1805 they mentioned the importance of the Jefferson Valley as a travel corridor noting an "old Indian road" near the Big Hole River. The headwaters regions of the Missouri and Yellowstone Rivers had long been recognized as heavily contested hunting grounds. Lewis and Clark documented the lack of permanent Native American populations in the region, attributing in to the unusual abundance of buffalo and other big game (Farr, 2001). According to tribal territories defined by the Fort Laramie Treaty of 1851 and the Flathead and Blackfeet Treaties of 1855, the area encompassing the

Missouri River headwaters (and subsequently the Jefferson Basin) was established as a common buffalo hunting ground by the U.S. Department of the Interior in 1855 (Farr, 2001). The formal creation of such a vast hunting commons was unique in the history of the West and continues to enable native peoples to assert aboriginal hunting and fishing rights in the upper Missouri Basin (Farr, 2001).

Euro-American History.

Although fur trappers and frontiersmen ventured into southwest Montana as early as the 1820's, Euro-American settlement in the Jefferson Basin began in earnest with the establishment of a town site near the present day location of Whitehall, MT in 1863 (MT State Engineer's Office, 1956). As mining camps in the proximate regions exploded throughout the 1860's and 1870's, agricultural communities sprung up along the Jefferson River to supply the growing populations and maintain transportation routes. When Montana was incorporated into a territory in 1865, both Jefferson and Madison Counties, which contain the majority of land in the Jefferson Valley, were instituted as two of the nine original counties. At the time of the 1870 census, populations in both Madison and Jefferson Counties were well established with approximately 4,000 residents combined (Forstall, 1996). As mining activities in the area began to wane after the end of WWI, and a multi-year drought gripped the Missouri headwaters, populations in both counties declined from 1920-1950.

Population Growth

Since the 1950's the Mountain West has been the fastest growing multi-state region in the U.S. (Power and Barrett, 2001). Changing population growth patterns in the western U.S. and Montana have been documented an analyzed in both the media and academic literature (Travis, 2007; Hansen et al., 2002). Climate driven water supply issues have the potential to be intensified by Montana's recent, and anticipated, population growth. With a growth rate of approximately 28% from 1990-2014, and a projected population of 1.2 million in 2050, Montana will experience increasing population pressures in the coming decades (MT Census and Economic Information Center [CEIC], 2014). Recent amenity driven development has contributed to water supply shortages in several Montana basins proximate to the budding urban centers of Missoula, Bozeman and Billings. From July of 2013 to July 2014, Bozeman was classified as the 6th fastest growing micropolitan statistical area in the country by the U.S. Census Bureau (Dietrich, 2015). Exurban development in the lower Bitterroot Valley (Ravalli County) and Gallatin Valley (Gallatin County) has negatively impacted groundwater resources and necessitated the closure of these basins, by order of the State Legislature, to new water appropriations (MT State University Water Center, 2014; ECONorthwest, 2008). Expansion of these urban "bubbles" is anticipated to continue for at least the next 20 years (MT CEIC, 2014).

The community of Three Forks, located near the mouth of the Jefferson and situated 31 miles northwest of Bozeman, has experienced significant growth since 1990. From 1990 to 2014 Three Forks population increased 58% (1,203 to 1,903), nearly

double the state average for the same period (MT CEIC, 2014). Although the extreme lower sections of the Jefferson Basin proximate to the Bozeman growth bubble have—and are projected to continue—experiencing substantial development in the coming decades, much of the rest of the watershed has seen stagnant or declining growth rates over the past 25 years (MT CEIC, 2014) (Figure 17; Table 4). As evidenced in Table 4, both Madison and Jefferson County (which contain the majority of the Jefferson Valley) have seen significant growth since 1950. Bucking this trend, communities in the upper portion of the Jefferson Valley (Whitehall, Twin Bridges and Sheridan) have struggled to maintain populations and have yet to see significant amenity driven growth experienced in other portions of the region (Figure 19; Table 4).

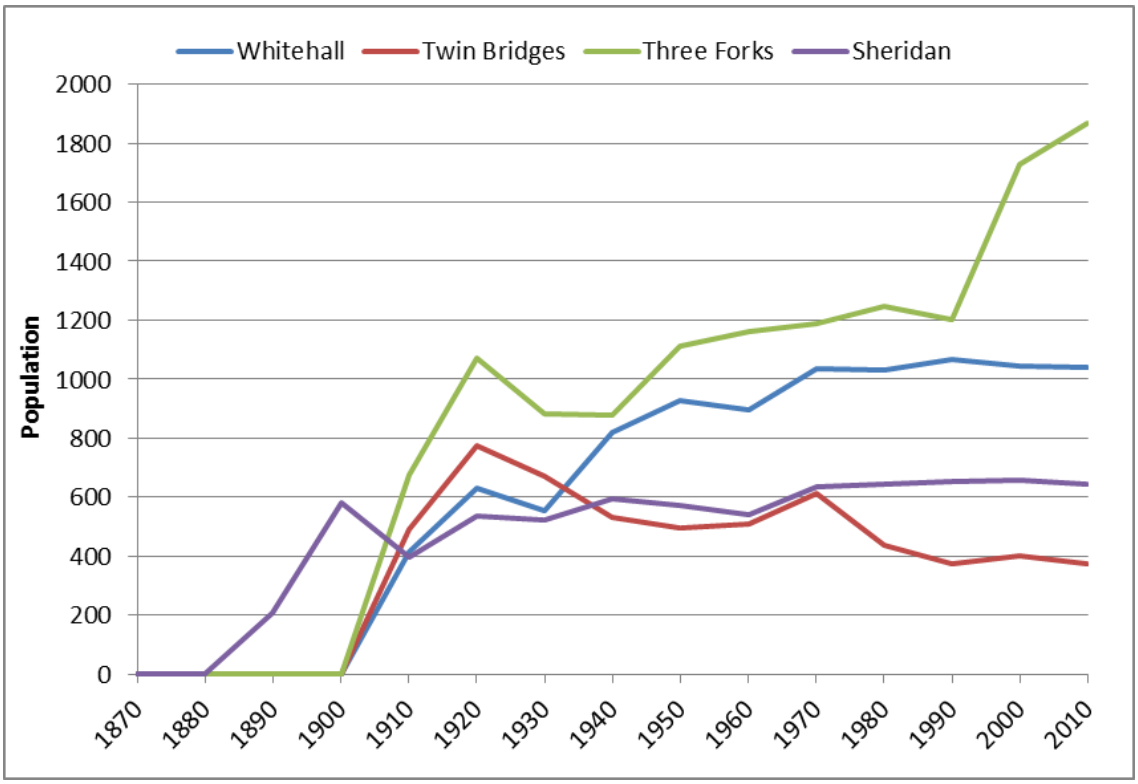


Figure 19. Chart of regional population trends. Data source: MT Census and Economic Information Center (2014).

	Madison County	Jefferson County	Whitehall	Twin Bridges	Three Forks	Sheridan
1870	2,684	1,531	--	--	--	--
1880	3,915	2,464	--	--	--	--
1890	4,692	6,026	--	--	--	207
1900	7,695	5,330	--	--	--	581
1910	7,299	5,601	417	491	674	399
1920	7,495	5,203	629	775	1,071	538
1930	6,323	4,133	553	671	884	521
1940	7,294	4,664	818	534	876	597
1950	5,998	4,014	929	497	1,114	572
1960	5,211	4,297	898	509	1,161	539
1970	5,014	5,238	1,035	613	1,188	636
1980	5,448	7,029	1,030	437	1,247	646
1990	5,989	7,939	1,067	374	1,203	652
2000	6,851	10,049	1,044	400	1,728	659
2010	7,691	11,406	1,038	375	1,869	642

Table 4. Table of regional population trends. Data source: MT Census and Economic Information Center (2014).

Land Use Transition

Development in Montana has also resulted in a relatively rapid land use transition from agricultural to urban uses in some regions, while others have seen little change over the past 80 years. The amount of acreage in farmland in Gallatin and Ravalli counties, historically considered some of the most fertile land in the state, decreased substantially from 2007 to 2012 [Gallatin from 776,868 ac. to 702,713 ac. (-10%) and Ravalli from 262,872 ac. to 234,782 ac. (-11%)]. Additionally, high-value irrigated acreage decreased in both counties over the same time period [Gallatin 81,651 ac. to 79,100 ac. (-3%) and Ravalli 72,235 ac. to 61,574 ac. (-17%)]. Comparatively, Jefferson and Madison counties, which contain a majority of Jefferson valley agricultural land area, saw modest declines or increases in the amount of acreage in farmland [Madison 1,060,833 ac. to 1,085,291

ac. (+2%) , Jefferson 391,248 ac. to 371,205 ac. (-5%)]. Significantly, both counties also experienced growth in the amount of irrigated acreage within each county [Madison 104,948 ac. to 111,891 ac. (+ 7%), Jefferson 26,722 ac. to 29,215 ac. (+9%)] (National Agricultural Statistical Service [NASS], 2007; NASS, 2012).

Agriculture

Describing the agricultural productivity of the Jefferson Valley is difficult due to the split county-level jurisdictions within the basin. Although the majority of the Jefferson Valley is contained within Madison and Jefferson counties, portions of the basin reside in Silver Bow, Gallatin and Broadwater Counties (Figure 20). Agricultural statistics are typically computed at the county level, limiting the effectiveness of this level analysis for the Jefferson Valley. Despite the restrictions, Table 5 displays the major agricultural commodities produced in the Jefferson Valley (alfalfa, hay and cattle) and the relative importance of each statewide.

	Land in Farms 2012 (acres)	Alfalfa Hay 2013 (acres harvested)	Alfalfa State Rank	Other Hay 2013 (acres harvested)	Hay State Rank	Cattle & Calves 2013 (head)	Cattle State Rank	Sheep & Lambs (2013) head	Sheep State Rank
Jefferson County	371,205	12,000	44	7,000	22	21,500	44	900	40
Madison County	1,085,291	43,000	3	30,000	3	77,000	11	3,100	23

Table 5. Leading agricultural commodities in the Jefferson Basin. State rankings out of 56 MT counties. Data source NASS (2014).

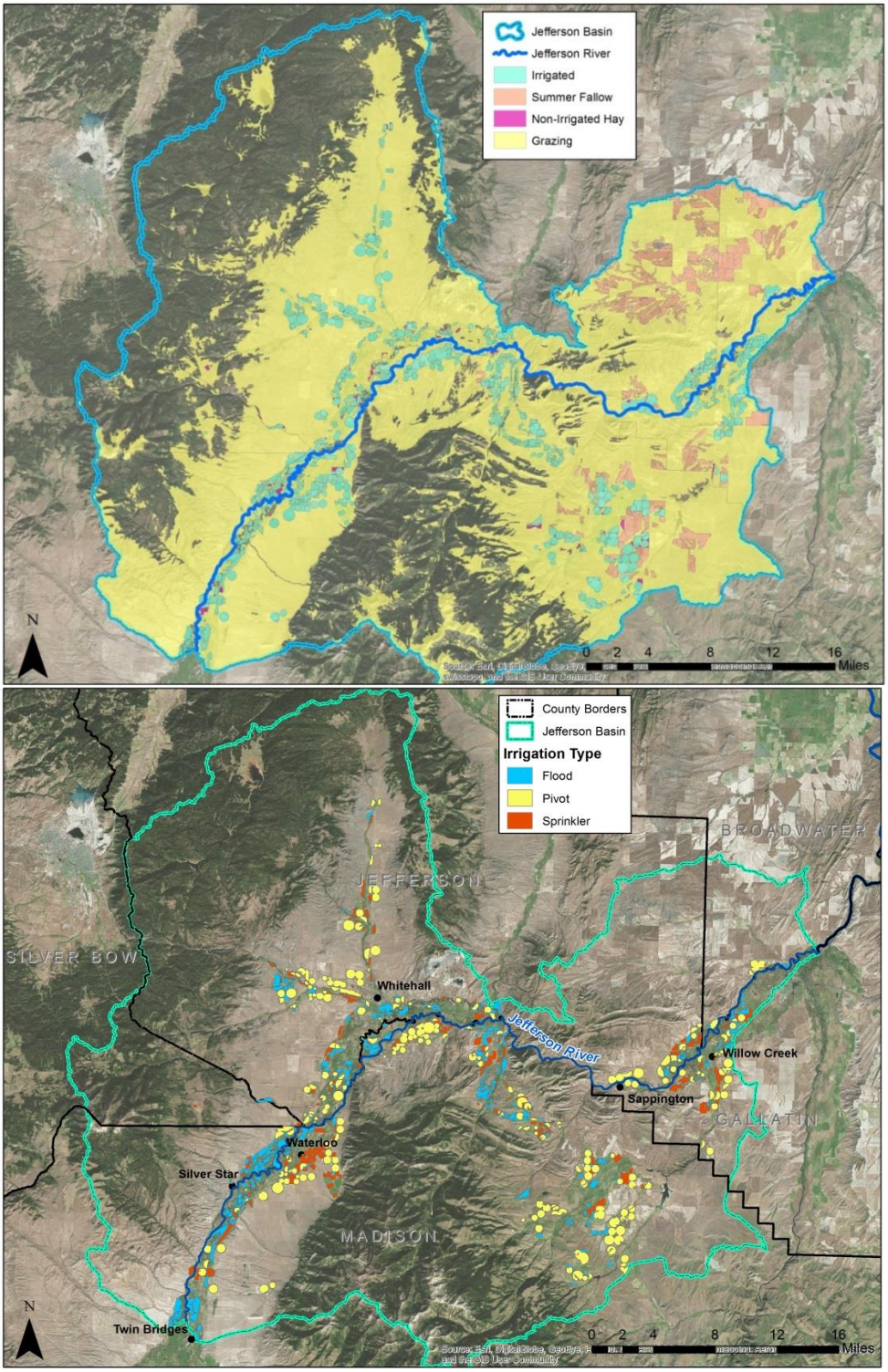


Figure 20. Maps showing agricultural (top pane) and irrigated lands (bottom pane) in the Jefferson Basin by method of agricultural use or irrigation. See legend for agricultural/irrigation land use classification. Data source: MT Department of Revenue (2014), MT NRIS—GIS Clearinghouse.

According to GIS data analyzed from the Montana Department of Revenue (2014), there are approximately 43,000 acres of irrigated farmland within the Jefferson River Basin. The majority of the irrigated acreage within the Jefferson boundary is identified as being under center pivot (~24,000 acres) with other forms of sprinkler irrigation comprising a smaller component (~8,000 acres). There is also a significant amount of land under flood irrigation (~11,500 acres); with much of it concentrated between Twin Bridges and Waterloo (Figure 20; MT DOR, 2014).

Mining

Throughout the 19th and early 20th centuries, mining was the primary economic driver within the greater Jefferson Basin. As will be discussed in further detail in chapter 3, early mining activities in the region guided patterns of settlement and agricultural development from the 1860's through the 1910's. Although most major mining operations had ceased by the 1950's, in 1982 the Golden Sunlight Mine opened 5 miles northeast of Whitehall, MT (Bryan, 2015). The open pit mine is owned by Barrick Gold Corporation and in October of 2015 was the only active major gold mine operating in Montana. In 2014 the Golden Sunlight was the largest single taxpayer in Jefferson County, employing approximately 150 people. Due to a global slump in gold prices, Barrick Gold closed open pit operations at the mine in November of 2015 laying off 140 workers (Bryan, 2015). The Golden Sunlight continues to operate on a small scale mining underground in tunnels (with most of the work performed by contractors).

Water Rights

As stated earlier in this thesis, water governance in the Jefferson Basin is organized around the legal framework of prior appropriation. Under prior appropriation, senior water rights are those with the earliest priority dates (time of water right establishment) that have continually been put toward a beneficial use. The state of Montana's Water Rights Bureau has recently digitized the entire state's water rights data in a spatially explicit GIS format. Utilizing that database it was possible to approximate the most powerful senior water rights in the Jefferson Basin (Table 6). Within the top senior quartile of ownership (water rights established before approximately 1895) the largest owners are summarized by the maximum volume of water allocated per year in Table 6. As displayed in Tables 6 & 7 many of the senior rights are comprised of ditch and canal companies which continue to operate as a consolidated group of users (Parrot Ditch Company, Old Hale Ditch Company).

	Owner	Priority Date Year	Source Name	Maximum Flow Rate (cfs)	Maximum Volume (acre feet/year)
1	LOWER JEFFERSON CANAL CO	1884	JEFFERSON RIVER	106.8	32130
2	PARROT DITCH CO	1881	JEFFERSON RIVER	50.0	21186
3	JOHN D KOUNTZ	1880	BIG PIPESTONE CREEK	37.5	20493
4	PARROT DITCH CO	1880	JEFFERSON RIVER	37.5	15890
5	FISH CREEK IRRIGATING DITCH CO; PLEASANT VALLEY DITCH CO	1882	JEFFERSON RIVER	30.0	14434
6	MICHELLE TEBAY; NORMAN E TEBAY	1883	JEFFERSON RIVER	25.0	9257
7	SHARON M TURNER; WAYNE L TURNER	1871	JEFFERSON SLOUGH	25.0	7722
8	SAPPINGTON JEFFERSON S RANCHES INC	1884	JEFFERSON RIVER	19.2	7557
9	FLATTOP RANCH LLC	1860	JEFFERSON RIVER	9.3	6710
10	CARLEEN G CLARK; JIM F CLARK	1871	JEFFERSON RIVER	12.5	5396
11	GIDEON WATER USER ASSN INC	1882	N. WILLOW CREEK	10.0	4910
12	GIDEON WATER USER ASSN INC	1882	N. WILLOW CREEK	7.5	3683
13	SITZ ANGUS FARMS LP	1875	S. WILLOW CREEK	11.8	3645
14	BUTTE-SILVER BOW COUNTY	1866	MAMMOTH CREEK	5.0	3604
15	JODY L SANDRU; RICK R SANDRU	1871	JEFFERSON RIVER	7.5	3237

Table 6. Ownership of the 15 most senior large water rights (within the top quartile of ownership-priority dates before 1895) in the Jefferson Basin. Data source: DNRC water rights database (2015). For water right quantification methodology see appendix A.

The water rights data reveal that the Jefferson River is a highly over-allocated system with a maximum allocated volume of approximately 2.6 million acre feet annually—twice the actual average output of 1.4 million acre feet. Furthermore, the combined total maximum flow rate of all the water rights in the basin totals approximately 5,500 cfs. Mean daily flows on the Jefferson River peak around 6,000 cfs in early June (Figure 9 & 10) and average 1,900 cfs daily on an annual basis.

	Owner	Priority Date Year	Maximum Flow Rate (cfs)	Maximum Volume (AF/year)	Percent of Total
1	PARROT DITCH CO	1894	500.0	211860	8.02%
2	PARROT DITCH CO	1891	231.2	97964	3.71%
3	LOWER JEFFERSON CANAL CO	1884	106.8	32130	1.22%
4	PARROT DITCH CO	1881	50.0	21186	0.80%
5	OLD HALE DITCH CO	1895	50.0	18117	0.69%
6	JEFFERSON ISLAND RANCH LLC	1889	49.8	18026	0.68%
7	VALLEY CATTLE CO	1888	25.0	18018	0.68%
8	JEFFERSON ISLAND RANCH LLC	1913	45.6	16530	0.63%
9	PARROT DITCH CO	1880	37.5	15890	0.60%
10	SAPPINGTON JEFFERSON S RANCHES INC	1935	40.0	15761	0.60%

Table 7. Ownership of the 10 largest water rights (by maximum volume) sourced from the Jefferson River regardless of priority date. Percent of total represents the total volume allocated for the entire Jefferson Basin. As noted above, the Parrot Ditch Company controls a large portion of water rights sourced from the Jefferson River—constituting a substantial portion of the total volume allocated in the Basin. For water rights analysis quantification methodology see appendix A.

A GIS based examination of water rights sourced exclusively from the Jefferson River and Jefferson Slough reveals the spatially explicit nature of the water rights. As seen in Figure 21, many of the water right points of use (POU) for rights sourced from the Jefferson River/Jefferson Slough are located directly downstream from Silver Star. Not surprisingly, this is the most vulnerable stretch of river during drought and has been the focus of recent drought management efforts. Four major canals/ditches draw water from this stretch of river (Parrot, Creeklyn, Jefferson and Fish Creek) comprising a significant volume of water (Spoon, 2008; Figure 22).

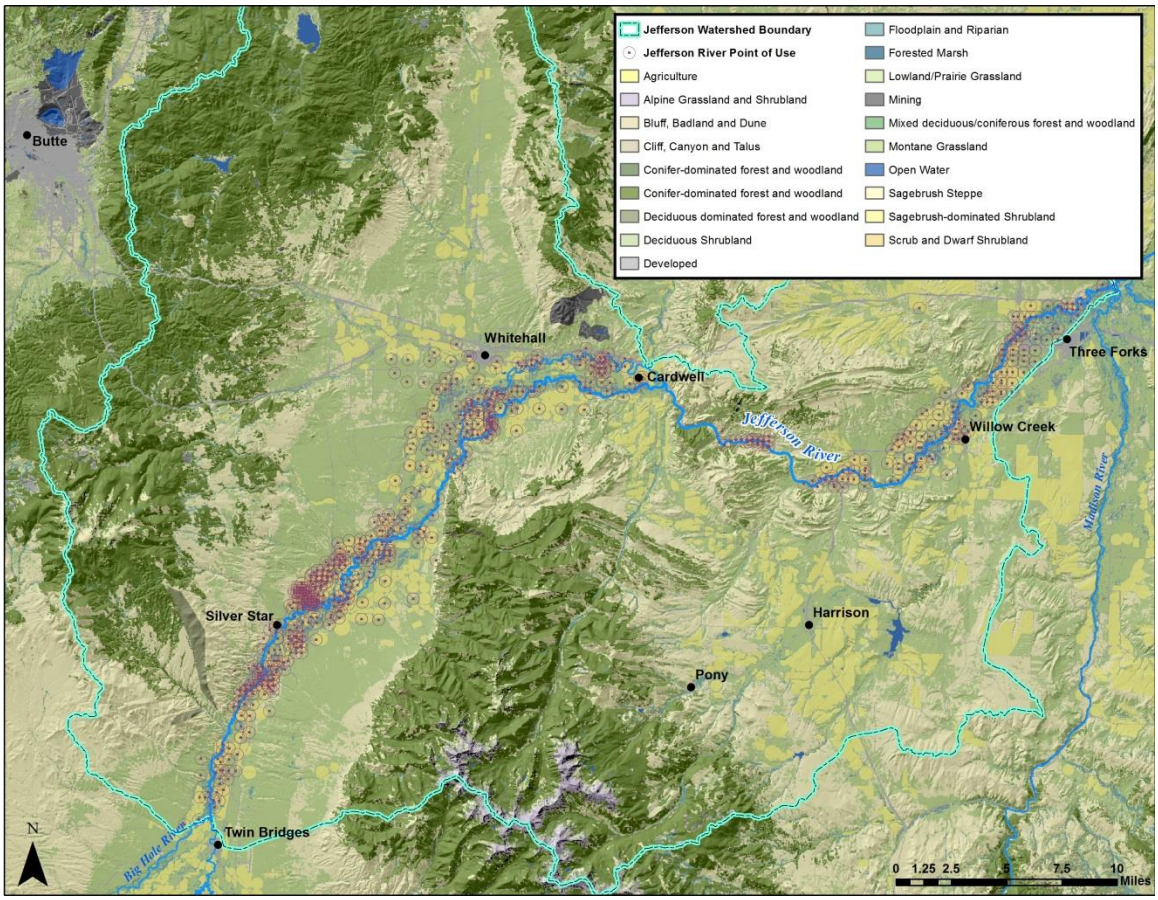


Figure 21. Map showing locations of points of use (POU) for water rights in the Jefferson Basin sourced from the Jefferson River/Jefferson Slough. See appendix for water rights analysis methodology. Data source: MT NRIS—GIS Clearinghouse.

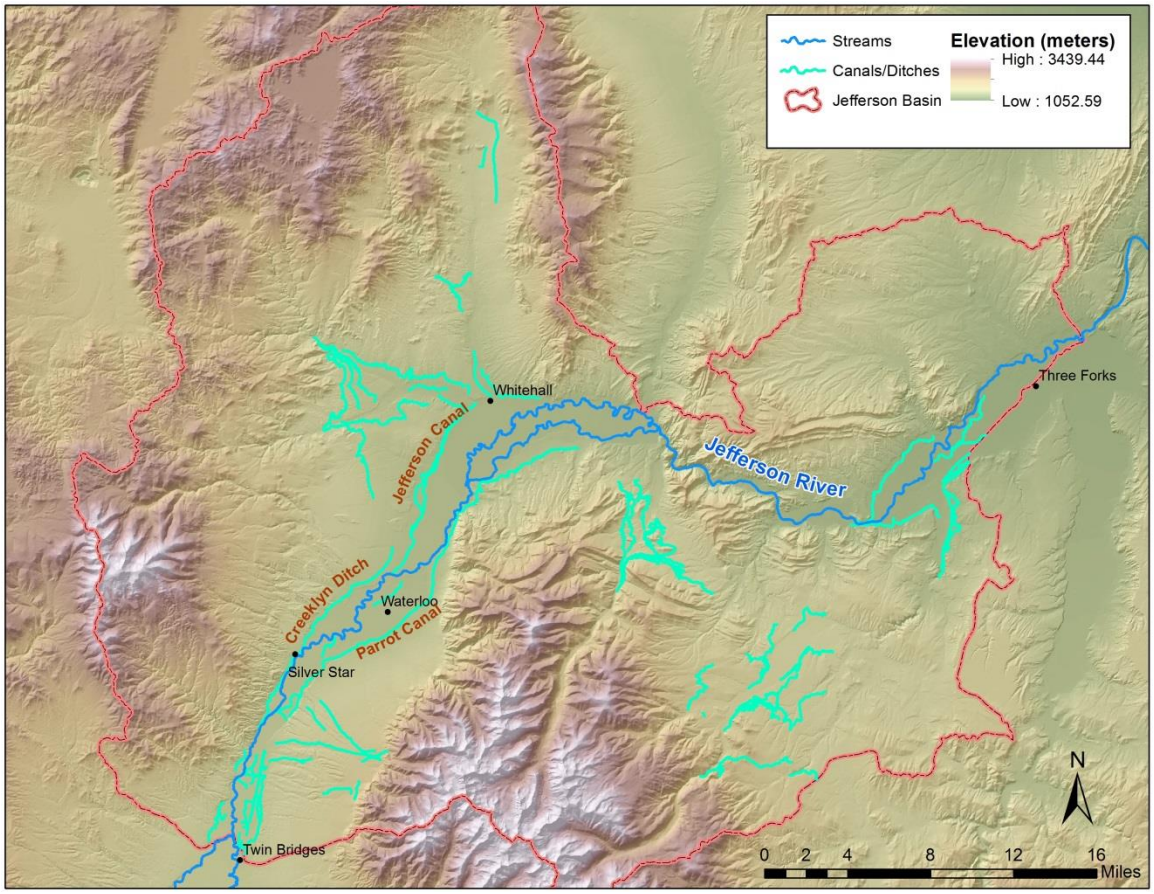


Figure 22. Map showing locations of major canals/ditches in the Jefferson Basin. The three canals/ditches labeled on the map voluntarily contribute water under the JRWC drought management plan. Data source: MT NRIS—GIS Clearinghouse.

Sport Fishery

The Jefferson River's colloquial reputation as the "forgotten fork" of the Missouri and the "river that fishermen forgot" may be attributed to the stream's fickle status as a fishery. Jefferson River trout populations have experienced dramatic fluctuations since electrofishing surveys began in the late 1970's. Research by Ron Spoon, a fisheries biologist for MT FWP, revealed a direct link between streamflow levels and fish populations on the Jefferson (2008). A portion of the study investigated population estimates for brown trout on two sections of the Jefferson (Hells Canyon and Three

Forks) conducted over the period 1979-2007. The results of the analysis showed dramatic declines in both stretches; with estimates of over 600 fish per mile in the mid-1980's dropping to fewer than 200 fish per mile by the mid-2000's (Spoon, 2008). Although populations of both rainbow and brown trout have recovered significantly as of 2015, brown trout densities are still well below the historical highs logged in the mid-1980's.

In the past, the Jefferson River supported a more vibrant commercial fishery than present. A period of relatively stable flows in the 1970's and early 1980's resulted in an increase in trout populations and recognition of the Jefferson's potential as a world class fishery. A 1984 article from Outdoor Life magazine optimistically describes the "river that fisherman forgot" as an underappreciated stream that seasonally "yields several trout weighing between eight and 11 pounds" (Law, 1984). Surveys of angler pressure conducted by MT FWP reflect the importance of streamflow on angler demand over time on the Jefferson. As illustrated in Figure 21 angling pressure peaked on the Jefferson in 1983 with approximately 27,500 anger days recorded. Following the devastating 1988 drought-induced fish kills, trout populations declined drastically river wide (Spoon, 2008). Correspondingly, fishing pressure receded and has yet to recover to the peak levels recorded in 1983.

Comparing the Jefferson River (Figure 23) to other regional fisheries reveals the unique nature of the fishery. Both the Jefferson's major tributary systems (Figure 25), and neighboring Missouri headwater streams (Figure 24), have seen significant increases in fishing pressure over time with non-residents comprising the majority of the recent growth. In comparison, the estimated number of annual angling days on the Jefferson has

declined fairly steadily from 1983 to the mid-2000's. Furthermore, the majority of those who fish the Jefferson are Montana residents while nonresident days comprise the bulk on the Big Hole and Gallatin Rivers. Unfortunately, the data included in the angler day analysis doesn't include totals for the last two years. The Jefferson River has seen a significant increase in non-resident guided fishing pressure since 2013. A local fisherman recalled seeing substantial numbers of guided trips on the upper Jefferson River the last two seasons—describing the pressure as unprecedented in his experiences (Mike Richter, personal communication, 2015).

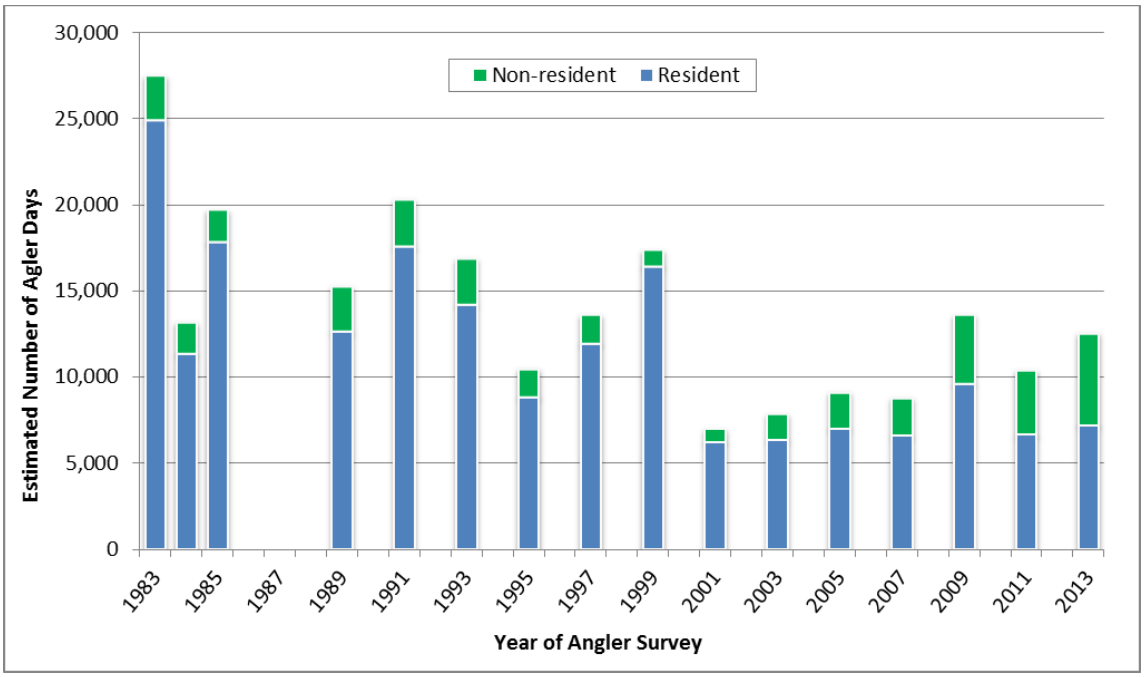


Figure 23. Estimated number of annual fishing days on the Jefferson River (entire river). Data compiled from MT FWP surveys: http://fwp.mt.gov/fishing/mFish/

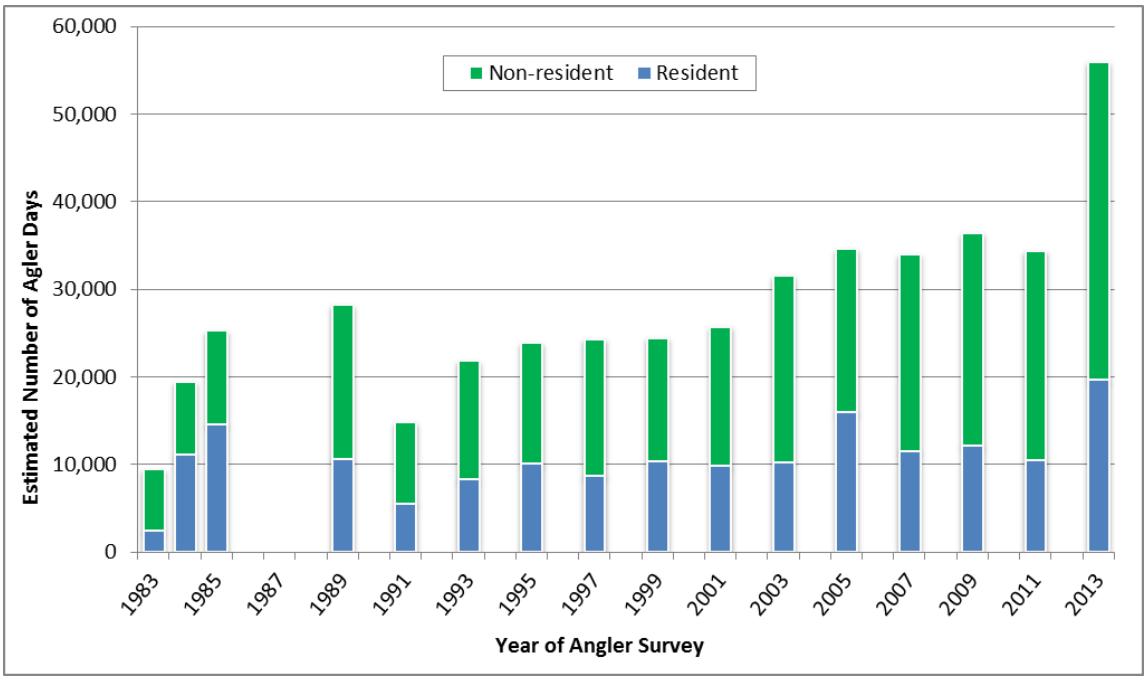


Figure 24. Estimated number of annual fishing days on the upper Gallatin River (river mile 68-95). Data compiled from MT FWP surveys: http://fwp.mt.gov/fishing/mFish/

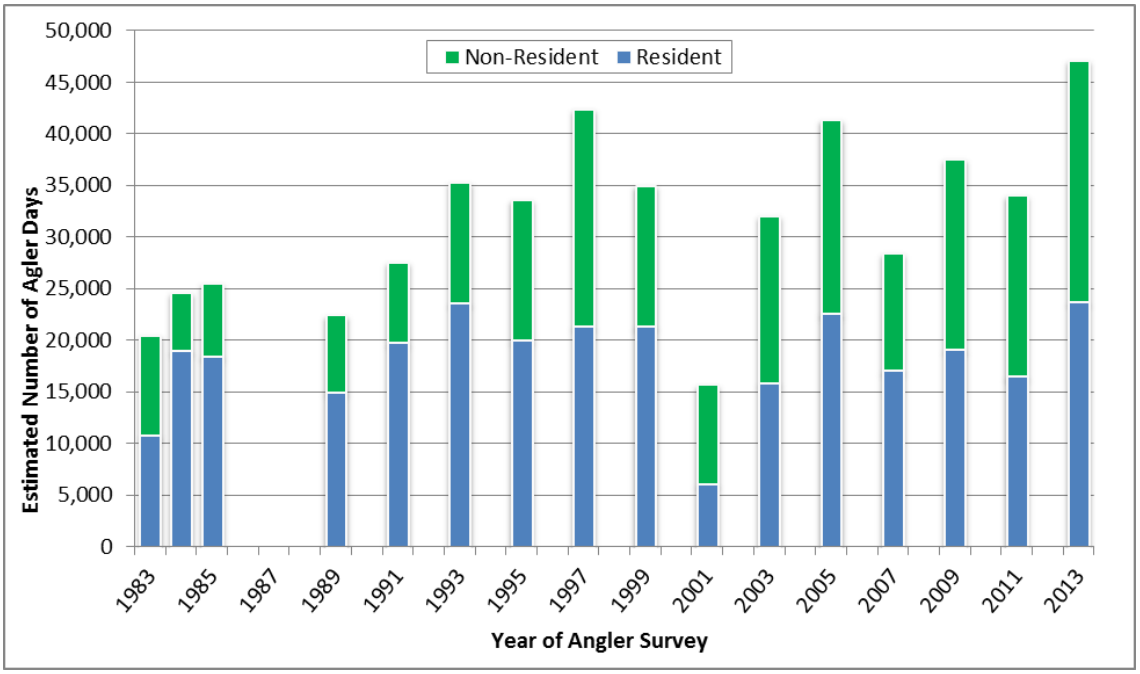


Figure 25. Estimated number of annual fishing days on the lower Big Hole River (river mile 0-49). Data compiled from MT FWP surveys: http://fwp.mt.gov/fishing/mFish/

As evidenced in the first portion of this resilience assessment, the Jefferson Basin SES is comprised of a complex set of biophysical and social components that operate at varied scales to control the overall trajectory of the system. The primary controlling variables of the Jefferson Basin SES over the last 150 years—the underlying hydrology, appropriative water rights, population growth, land use and irrigation policies—have interacted dynamically, resulting in a reduction in the overall resilience of the system to external disturbance. Part 2 of this assessment (contained within the next chapter) will review the Jefferson Basin's "trajectory of resilience" over time in order to conceptualize the system components most responsible for modifying the underlying characteristics of the SES (Chaffin et al., 2014).

CHAPTER 3

RESILIENCE ASSESSMENT PART 2: KEY VARIABLES AND DRIVERS OF RESILIENCE OVER TIME

As described in chapter 2, the Jefferson Valley SES is comprised of both biophysical processes and social mechanisms that function in concert to guide the system's overall trajectory. Over the past 150 years, a combination of these variables has controlled the Jefferson Basin's resilience to disturbances. Examining the historic trajectory of the system reveals the internal driving mechanisms and external shocks that act to control the current state of the SES. It also enables researchers to forecast future scenarios and perturbations to the system stemming from processes such as climate change and population growth (which have already occurred and are likely to continue).

The four phase adaptive cycle, as developed by Gunderson and Holling (2002), has been prescribed as a means by which to describe the evolution of coupled SES's over time (Folke, 2006). The adaptive cycle model attempts to capture the dynamic, and inherently non-linear, pattern of succession within SES's. A previous study investigating water resources in central Oregon successfully employed the adaptive cycle model to trace the evolution of the Klamath Basin SES and found that the framework "adequately describes the trajectory of the basin SES and helps situate the dynamic role of resilience within the timeline of change" (Chaffin et al., 2014). In the remainder of this section, the narrative of water use and development in the Jefferson Basin (beginning with Euro-American settlement) will be explored through the lens of the adaptive cycle.

Exploitation Phase (r): 1850-1920

The first phase of the adaptive cycle (r) is marked by the rapid consumption of natural resources and accumulation of capital. In the late 1850's Euro-American homesteaders began trickling into the extreme lower portion of the Jefferson Valley near the headwaters of the Missouri. As the Montana gold rush began in earnest with discoveries along Grasshopper Creek near present day Dillon in 1862, white settlers flooded into the area. Subsequent strikes in Virginia City and Elkhorn (located within 40 miles of the Jefferson) hastened the rapid pace of development in the region and by 1870 several permanent communities had been established in the Jefferson Basin and Madison and Jefferson counties boasted populations of over 4,000 residents combined (Forstall, 1996). Federal policies such as the Homestead Acts of 1862 and 1909 and the General Mining Law of 1872 facilitated the rapid exploitation of the region's natural capital allowing virtually any US citizen the opportunity to homestead, log or mine on public lands ("Homestead Acts", 2015).

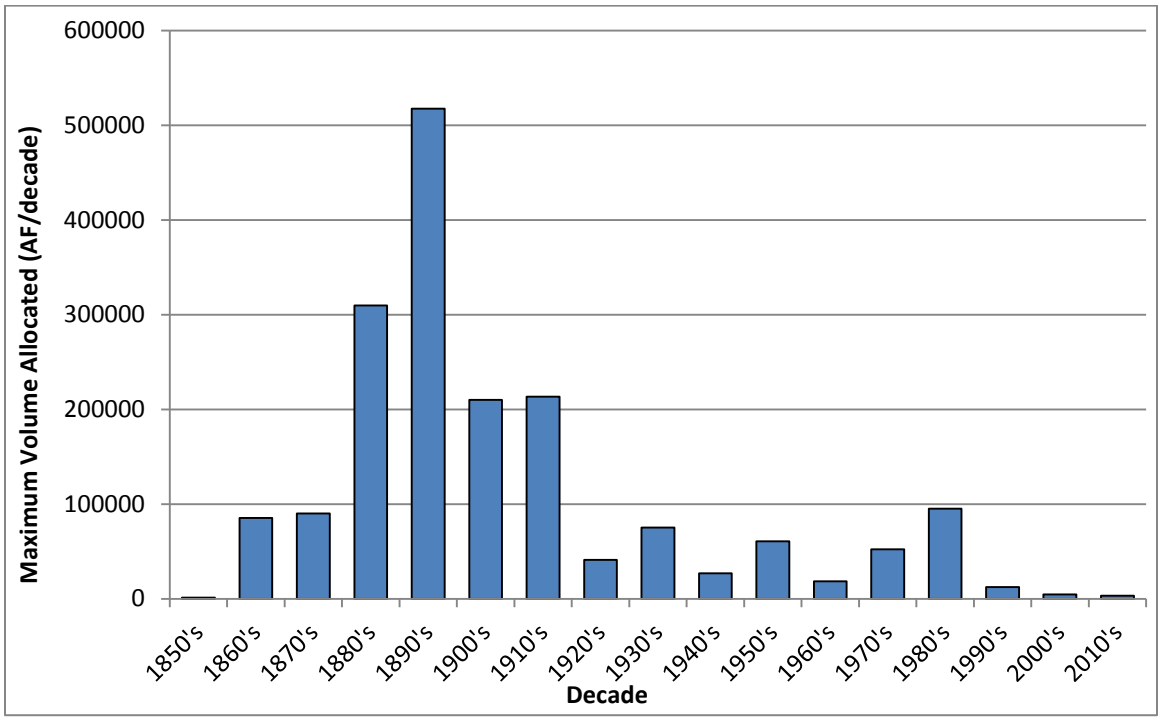


Figure 26. Maximum volume of all water allocated in the Jefferson Basin (Montana DNRC basin code 41G) by decade of priority date (excludes instream flow rights for fisheries). Data source: DNRC water rights database (2015). See appendix A for water rights quantification methods.

Water Infrastructure Development

A histogram of water right establishment dates in the Jefferson Basin (Figure 26) illustrates the correlation between water appropriations and regional economic development. The earliest recorded water rights in the Jefferson Basin have priority dates of 1855-1860 and are located near the mouth of the Jefferson between Three Forks and Harrison, Montana. Identified in the MT DNRC water rights database as groundwater rights from developed springs, these initial appropriations were used by homesteaders for small scale stock watering. As mining districts in Bannack, Virginia City, Boulder and Helena exploded in the 1860's and 1870's, water distribution systems (i.e. canals, ditches and reservoirs) in the Jefferson quickly expanded to supply the camps (MT State

Engineer's Office, 1956; MT State Engineer's Office, 1965). The volume of water appropriated during this period expanded to include larger quantity surface diversions extracted from perennial tributaries throughout the basin for flood irrigation.

The period from approximately 1880-1920 marks the beginning of large scale irrigation in the Jefferson Valley. Irrigated agriculture grew dramatically throughout this era to meet the needs of booming populations in the neighboring Butte and Anaconda mining camps. As a report to the Secretary of the Interior notes from 1888, "[t]he city of Butte….is already the largest and most populous city west of Denver, between the Mississippi River and the Pacific coast, and is the largest mining camp in the world" (Secretary of the Interior, 1888). Water resources development during this time was characterized by the establishment of ditch companies and the diversion of relatively large volumes of water (>20 cubic feet per second) from more technically challenging sources such as the main stem of the Jefferson River (MT State Engineer's Office, 1956; MT State Engineer's Office, 1965; Montana Department of Natural Resources and Conservation [MT DNRC] Water Resources Division, 2015). Many of the ditch companies established during this period are still in existence today (e.g., Parrot Ditch Company, Old Hale Ditch Company, Pipestone Water Users Association). These institutions hold some of the most powerful senior water rights in the Jefferson Basin.

Butte's population peaked during WWI with approximately 91,000 residents in 1917 (Kemmick, 2006). Consequently, the decade from 1910-1920 saw the last significant volume of water appropriated in the Jefferson Basin and signified the end of the initial water extraction boom (Figure 26). Several cross-scale interactions facilitated

the end of the initial exploitive phase in the Jefferson. Correlated with a decline in the Butte mining districts following the end of WWI (and a lack of easily divertible water), new appropriations in the Jefferson steadily declined after 1920. Furthermore, severe drought that began in 1918 and extended until the early 1940's severely impacted Montana's agricultural economy (Malone et al., 1991). The drought combined with a crash in wheat prices at the end of WWI quickly ended Montana's homesteading boom and between 1920 and 1930 Montana was the only state in the U.S. to lose population (Holmes et al., 2008).

Conservation Phase (k): 1920-1988

During the conservation phase (k) of the adaptive cycle there is less rapid exploitation than the previous phase as the variables that control the SES's trajectory become more protracted and predictable (Gunderson & Holling, 2002). The conservation stage is marked by the shift from rapid growth and exploitation to an increasing focus on specialization and efficiency. During this stage, connections between variables within the SES strengthen, helping to regulate the system's internal state. Although the conservation phase results in increased efficiency within the SES, redundancies are often eliminated and the system may become less resilient and more vulnerable to disturbances (Walker et al., 2004). The conservation period in the Jefferson basin is marked by the incremental consolidation of hydrologic infrastructures (through the creation of ditch companies and reservoirs) and an increasing focus on SES maintenance as opposed to resource exploitation.

This conservation period in the Jefferson saw the continued exploitation of natural resources, albeit at a much slower pace. Early gold rushes in the region were sustained by easily extracted placer deposits that quickly became exploited. The mining districts of Virginia City, Bannack, and Elkhorn that 50 years earlier had been the most prominent communities in the state of Montana were ghost towns by the 1940's. A government report from 1928 notes, "to-day mining has ceased to be a material factor in the economic affairs of the region [Jefferson Valley] and agriculture is the principal industry" (United States Geological Survey [USGS], 1928). While significant mining activities continued in southwest Montana as late as the 1970's, they tended to focus on lode deposits and required large amounts of processed ore and invested capital to yield profits.

As ditch companies became thoroughly established in the Jefferson Basin in the late 19th to mid-20th centuries, water users became increasingly dependent on their services and worked to consolidate water rights and conveyance infrastructures. While consolidation undoubtedly increased water delivery efficiency it also may have resulted in a less resilient system. Before the formation of ditch companies, disturbances to the water use system (i.e. extreme drought, washed-out diversions, bankruptcy) would have impacted a set of users differently, based on the resilience of the individual user. During low streamflow conditions for instance, a farmer with access to a perennial spring would be more resilient than one dependent on surface water supplies from a minor tributary. Under a consolidated system of users, impacts from disturbance are not irregularly dispersed (i.e. a failed head gate or ditch company bankruptcy) would result in severe consequences for an entire group of users.

By the early 1920's the Jefferson Basin had entered a new stage in the development of its water use infrastructures. A combination of economic, social and environmental factors severely impacted the Jefferson SES's productivity. From 1920-1950 relatively few new water rights were filed in the Jefferson Basin (Figure 26). Over this same period the populations of both Madison and Jefferson counties declined approximately 20% as drought forced many homesteaders to abandon their operations (Table 4). From 1950-1985 new water rights filed in the Basin were characterized by an increasing reliance on appropriations of groundwater for domestic purposes (MT DNRC Water Resources Division, 2015; appendix A).

	Ruby Dam	**Clark Canyon Reservoir**	**Lima Reservoir**	**Willow Creek Reservoir**
Date completed	1938	1964	1909	1938
Impounds	Ruby River	Beaverhead River	Red Rock River	Willow, Dry Hollow, & Norwegian Creeks
Dam type	Earthfill	Earthfill	Earthfill	Earthfill
Owner	Montana DNRC	US BOR	US BOR	Montana DNRC
Operator	Ruby Water Users Assoc.	US BOR	Red Rock Water Users Assoc.	Willow Creek Water Users Assoc.
Full pool storage	37,642 af	325,324 af	75,180 af	18,000 af
Surface area	970 acres	5,903 acres	2,460 acres	868 acres
Primary water use	Irrigation	Irrigation	Irrigation	Irrigation
Secondary water use(s)	Recreation, flood control	Flood control, recreation	Flood control, recreation, wildlife	Recreation

Table 8. Summary of major reservoirs in the greater Jefferson Basin. Data sources: United States Bureau of Reclamation (USBOR), MT DNRC State-Owned Water Projects, MT Water Resources Surveys for Madison and Jefferson Counties.

Dam Building in the Greater Jefferson.

Following the initial period of rapid hydrologic hybridization of the Jefferson SES detailed in the exploitation phase, a series of reservoirs was constructed from 1909-1964 that gradually increased water supplies for local agricultural users (Figure 27; Table 8).

The nature of this brief dam building phase in the greater Jefferson Basin is characteristic of a SES in the conservation phase of the adaptive cycle. The reservoirs provided water that both sustained existing operations through low flow years and brought new land under irrigation (MT State Engineer's Office, 1965).

The first major irrigation project in the greater Jefferson Basin was the construction of Lima Reservoir on the Red Rock River (the major headwater tributary of the Beaverhead) which was erected in 1889, washed out in 1890 or 1891, and rebuilt in 1909 (USGS, 1928). The reservoir was initially designed to supply water to an area of "raw lands" in the area but following a period of chronic water shortages in late 1910's was purchased by a consolidation of existing water users in the lower Red Rock and Beaverhead Valleys to buffer their diminished water supplies (USGS, 1928). The water ownership change at Lima Reservoir in 1919 highlights the transition of the water use system in the greater Jefferson Basin from a phase of exploitation (r) to conservation (k). External disturbances (extreme drought) effectively stopped the expansion of irrigation in the region as existing water users struggled to sustain their operations.

Lima Reservoir is currently owned by the U.S. Bureau of Reclamation and operated by a local association of water users (USBOR, n.d.). Water rights connected to the reservoir are senior to those downstream in Clark Canyon and its users are given priority during drought years. Lima Reservoir also plays an important ecological role, functioning as an effective fish barrier and protecting one of the last known endemic populations of lake dwelling (adfluvial) Arctic grayling in the contiguous U.S. (French,

2014). Non-native brown trout prey on other fish (such as grayling) and have decimated populations of native fish in watersheds downstream from the reservoir.

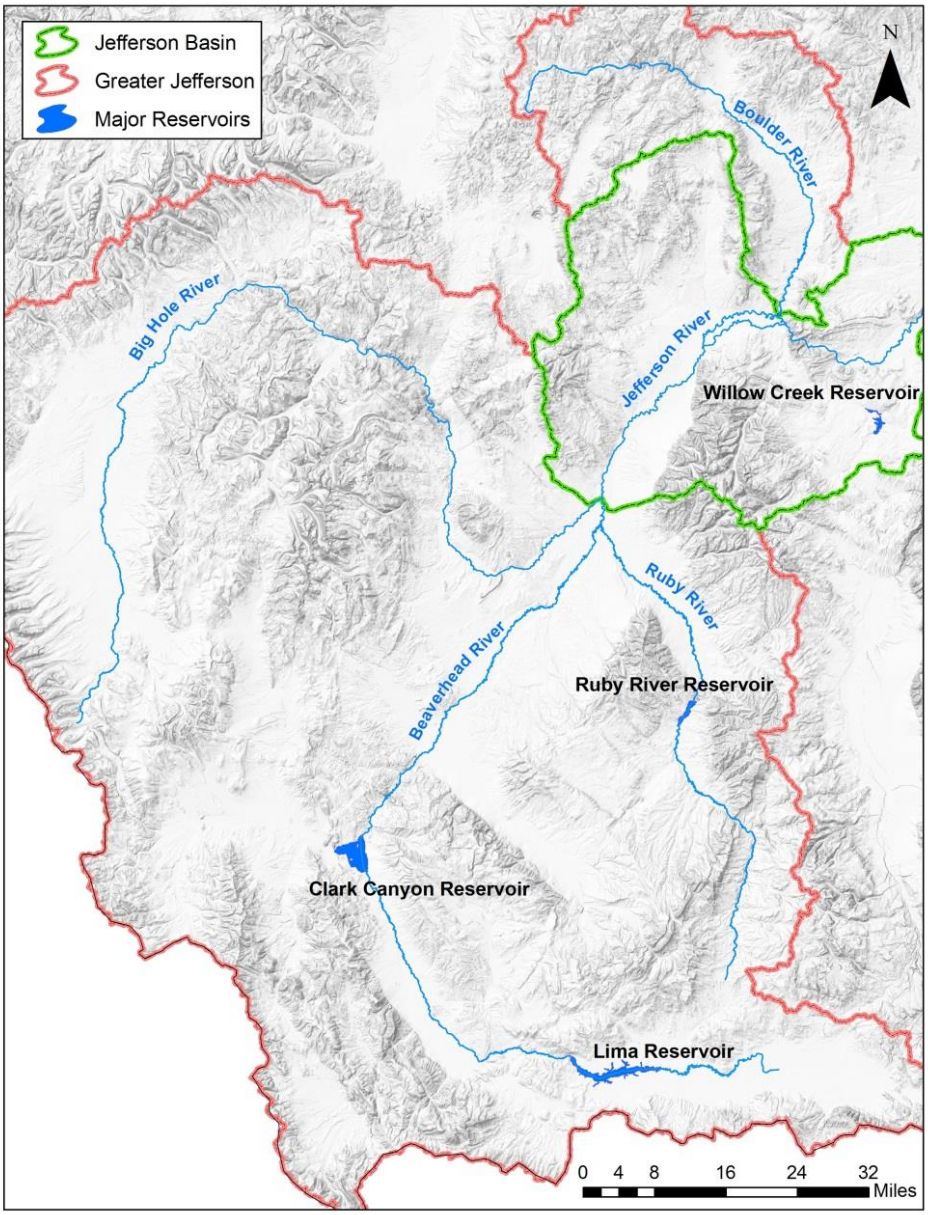


Figure 27. Location of the major reservoirs in the greater Jefferson Basin. Reservoir data source MT FWP (2014b). Mapping data source: MT NRIS—GIS Clearinghouse.

Both the Ruby River and Willow Creek Reservoirs were commissioned for construction by the Montana State Water Conservation Board in the mid-1930's and funded through loans provided by the federal Public Works Administration (PWA) (MT State Engineer's Office, 1965). The PWA was crafted in 1933 by the FDR administration as a response to the Great Depression with a goal of stimulating the economy through the construction of large-scale public works such as dams. Many of the smaller irrigation dams funded through the PWA required the establishment of water users associations. In the greater Jefferson these groups (such as the Willow Creek and Ruby Water Users' Associations) were required to enter into water marketing contracts with the State Water Conservation Board and pay annual fees to recompense the cost of reservoir construction (MT State Engineer's Office, 1965). Both of the PWA-era reservoirs in the basin are now owned by the state of Montana and are operated by local water users.

The largest reservoir in the basin, Clark Canyon, was completed at the end of the USBOR's great dam building era (1930's-1960's) under the authority of the 1944 Pick-Sloan Flood Control Act (USBOR, 2006; "Bureau of Reclamation", 2015). The project provides supplemental irrigation service to approximately 50,000 acres that was previously non-irrigated and is managed by the Clark Canyon Water Supply Company (CCWSC) and the East Bend Irrigation District (EBID) (Beaverhead Watershed Committee, 2004). The CCWSC/EBID purchases water from the BOR under a contract that was re-negotiated in 2006 and distributes water to its users through shares of stock (USBOR, 2006). As a portion of the 2006 contract re-negotiations, a minimum instream flow of 25 cfs was agreed upon to protect fisheries. Extreme drought conditions in the

Beaverhead drainage beginning in the late 1980's have severely impacted the reservoirs ability to protect aquatic species, provide consistent water deliveries for the irrigation community and meet state water quality standards (Montana Department of Environmental Quality, 2014).

Late K Phase: 1970-1988

The late K phase of the adaptive cycle is the point at which "efficient systems start to show signs of weakness and vulnerability" (Chaffin et al., 2014). As the conservation phase progresses, resources become increasingly sequestered and the system becomes less flexible (Walker et al., 2004). Overall SES resilience is reduced and small shocks to the system may initiate a collapse. By the late 1970's it was apparent that the overutilization of Montana's natural resources had severely impacted aquatic resources throughout the state. Through efforts initiated by both grassroots organizations and state government agencies, Montanans attempted to prevent the collapse of the state's vulnerable water communities.

MT Fish Wildlife and Parks & Instream Flows.

In 1969, the Montana legislature began to address concerns related to chronic low streamflow when it authorized the MT Department of Fish and Game (now known as MT Fish Wildlife and Parks) to obtain new water rights on 12 select streams throughout the state for fish and wildlife purposes (known as Murphy Rights and named after the bill's sponsor) (Ferguson et al., 2006). The Murphy Rights contain priority dates of 1970 or 1971 and have limited value due to their junior priority dates. In 1973, the Montana

Water Use Act (passed by the MT Legislature) expanded the ability of federal and state agencies to make instream flow reservations on any stream in the state (Ferguson et al., 2006). These mechanisms, although relatively insignificant as a conservation tool, were important because they legally recognized instream flows for fish and wildlife as a beneficial use under MT water law.

Coalition Formation

Beginning in earnest in the late 1970's groups of Montana irrigators, recreationists, and conservationists began forming coalitions to address water management concerns at the local level. These innovative, bottom-up approaches have proven to be highly successful in some watersheds (such as the Blackfoot and upper Clark Fork) and these coalitions have effectively worked with government agencies to mitigate chronic dewatering issues (Blackfoot Challenge, n.d.; Clark Fork Coalition, 2014). Drought management plans, like those developed on the Big Hole and Blackfoot Rivers, include predetermined streamflow trigger points that prompt voluntary actions by landowners that reduce surface water withdrawals during low flows.

Currently, most of the major watersheds in the state are protected by an array of coalitions and many have developed drought management plans. The Jefferson River Wikipedia page notes that "advocates" for the river include Trout Unlimited, the Jefferson River Watershed Council, the Jefferson River Canoe Trail, the Western Watersheds Project and Montana River Action ("Jefferson River", 2015). Although at present, most basins in Montana have formed coalitions and created drought strategies, the overall effectiveness of these attempts has been mixed from a conservation

standpoint. The Jefferson and Big Hole Rivers experienced severe collapses of their aquatic ecosystems in the late 1980's, before the formation of watershed organizations or drought management plans in their respective basins. Low streamflows continue to plague rivers systems statewide and as of 2011, Montana Fish Wildlife and Parks had labeled over 2,900 miles of watercourses in Montana as chronically dewatered (Montana Fish Wildlife and Parks [MT FWP], 2011).

Release Phase (Ω): 1988-2001

When a disturbance pushes a SES beyond its internal capacity to recover, the system collapses and enters a period of chaotic release. During the release phase of the adaptive cycle; "accumulated resources are released from their bound, sequestered, and controlled state, connections are broken and feedback regulatory controls weaken" (Gunderson & Holling, 2002). As historic connections and feedback mechanism break apart, uncertainty reigns and the SES enters a new period that may allow for a novel rearrangement of system variables (Folke, 2006). During this subsequent phase of reorganization (which will be discussed in detail in the following section) the SES is highly vulnerable to external disturbances and may reenter a phase of "creative destruction" (Folke, 2006). As noted by Gunderson and Holling, this phase of the adaptive cycle often results in "loops" between collapse and reorganization (2002). It is apparent that the drought of 1988 initiated a collapse of the Jefferson SES that resulted in an unstable period of subsequent drought related "releases" that continued into the early 2000's. Although a variety of mechanisms were proposed in response to the devastating

drought of 1988, as this section and the next will show, the attempts have been only marginally effective on the Jefferson.

The Drought of 1988.

The North American drought of 1988 ranks among the worst episodes of drought recorded in the United States. With damages estimated at $40 billion, the drought of 1988 was the 4th most costly natural disaster in the US from 1980-2014, ranking behind Hurricanes Katrina, Sandy and Andrew (National Centers for Environmental Information, 2014). The large areal extent of the drought contributed to the massive monetary losses incurred. At the height of the drought over 48% of the US continental landmass was impacted including prime grain production regions of the northern Great Plains and Midwest (Trenberth et al., 1988). In the Northern Rockies, the Great Yellowstone Fires of 1988 charred over 750,000 acres of timber and received massive national media coverage, burning the droughts impacts into the public consciousness ("Yellowstone fires of 1988", 2015). Although several causes of the drought have been proposed (meteorologically), the drought that impacted the northwestern U.S. was likely initiated by a lingering 1986-1987 El Nino event in the tropical Pacific Ocean (Trenberth & Grant, 1992).

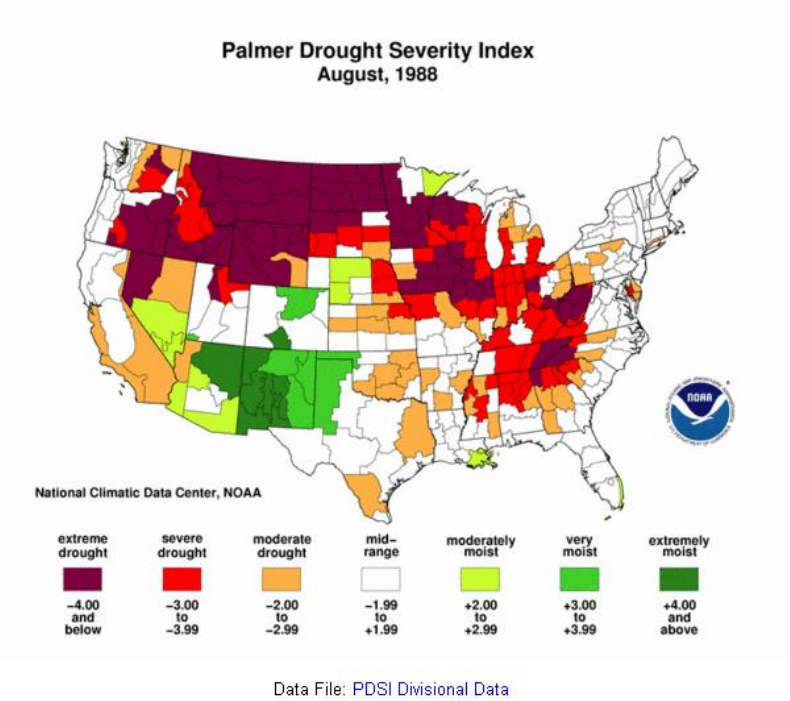


Figure 28. Palmer Drought Severity Index for August of 1988. Data Source: National Centers for Environmental Information, Historical Palmer Drought Indices. Retrieved from http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/

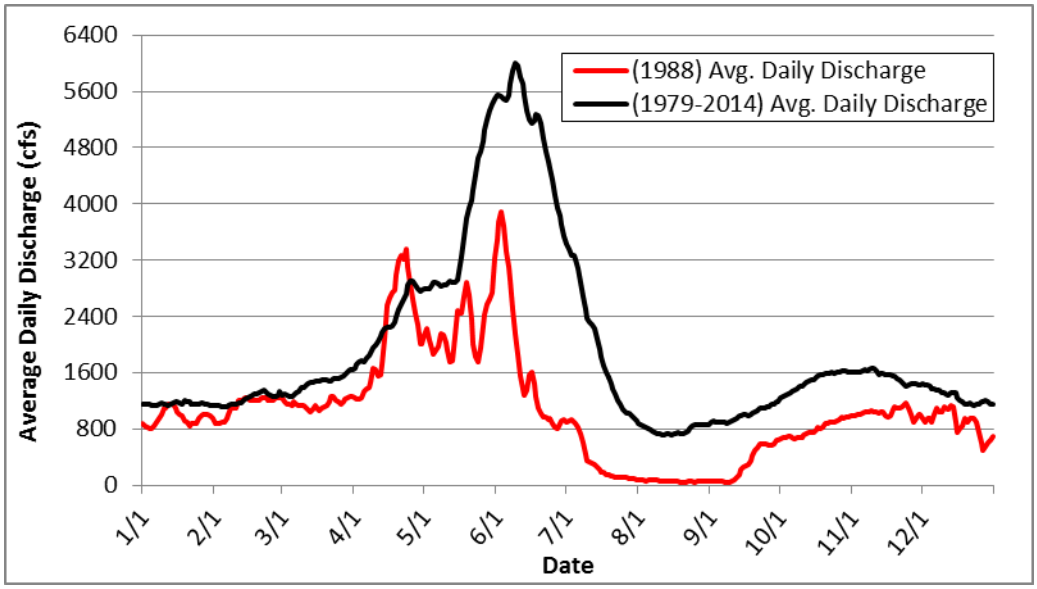


Figure 29- Average daily discharge values on the Jefferson River near Three Forks (black line) compared to steam discharge during the drought of 1988 (red line). Data source: USGS (2015a).

On the Jefferson River, the 1988 drought resulted in the most drastic dewatering episode in the stream's recorded history. The drought was particularly devastating due to the prolonged nature of its impacts. Newspaper articles document drought induced fish kills (localized mortality in fish populations) beginning as early as mid-July (Associated Press, 1988). By August all of Montana was rated as being under extreme drought conditions (Figure 28). For over 45 days (July 29-September 11) flows recorded at the Three Forks USGS stream gage on the Jefferson River (a drainage area of over 9,500 square miles) dropped below 100 cfs (Figure 29; USGS, 2015a). A one-time USGS measurement at the Waterloo Bridge in August, recorded a streamflow of only 4.7 cfs (Pierce, 2008). Montana conservation advocate Joe Gutkoski describes the power of the 1988 drought on his Montana River Action website:

> I remember standing on the bank at Al Anderson's Canoe House, a few miles above the town of Three Forks. With me was Al's father and we were looking at the [Jefferson] river. There was no flow between pools. Looking across the river at the end of August, a farmer was overhead irrigating his third cutting of alfalfa (Gutkoski, n.d.).

Before the unprecedented dewatering of 1988, water users in the Jefferson had been able to maintain the agricultural water use system and retain water instream. The 1988 drought resulted in a scramble for the last drop of water as ditch companies struggled to shore up diversion structures and capture the Jefferson's dwindling flows. As a Silver Star grocer noted in a local newspaper article from the summer of 1988, "the irrigators have the right to dry up the river, and they're exercising that right" (Associated Press, 1988).

Drought induced fish kills in the greater Jefferson Basin during 1988 severely impacted populations of both native fish (especially whitefish) and non-native brown and

rainbow trout. As noted in Ron Spoon's 2008 fisheries assessment of the Jefferson, brown trout population densities have yet to recover to levels seen before 1988. Montana fly fishing legend and conservationist George Grant summarized the long term impact of the drought, "It will take years to get it [the Jefferson] back to a good fishing stream" (Carter, 1988c). Substantial fish kills were also recorded on the lower Big Hole and Beaverhead River during the summer of 1988 (Richardson et al., 1990). In an attempt to alleviate drought related stresses to the regional fishery, MT FWP introduced emergency changes to fishing regulations for the first time in the agencies history in mid-August of 1988. Creel limits for trout on streams within the greater Jefferson Basin were reduced from five to two fish with hopes of protecting wild adult stocks and improving recruitment (Richardson et al., 1990).

Water Leasing and HB 707

In response to the 1988 drought, the 51st Montana Legislature passed HB 707 (otherwise known as the Water Leasing Bill) in 1989. The bill created a four year pilot program under MT FWP that allowed water rights to be leased from willing individuals for the purposes fish and wildlife habitat (Ferguson et al., 2006). The measure was supported by recreation and conservation interests and strongly opposed by agricultural groups, resulting in a highly publicized battle during March and April of 1989. A legislative report on the Water Leasing Program from 1998 noted that HB 707, "was probably the most controversial natural resources issue that came before that body" (MT FWP, 1998). The impact of the initial program was hindered by a lack of funding and limitations placed on it by the legislature. Furthermore, MT FWP elected to proceed with

caution following the controversy HB 707 spurred and the agency conducted several studies before implementation of the program (MT FWP, 1998).

In 1995 a coalition of agricultural and environmental groups helped pass legislation that enabled private organizations or individuals to lease water rights for instream flows to benefit fisheries in Montana, expanding the scope of the initial leasing program (Ferguson et al., 2006). The legislation offered two avenues for water right holders to convert their water right from a consumptive to instream use. The right could be leased to a private group or individual or be converted to an instream use altogether. Under both options, the conversion was originally limited to a 20 year period. In 2005 the legislature removed the leasing term limits, permitting private water leasing permanently (Ferguson et al., 2006).

Instream Flow Recommendations.

In 1989, MT FWP established recommendations for the quantity of water needed to sustain a healthy aquatic ecosystem and vibrant sport fishery for streams in the Missouri Basin (MT FWP, 1989). A recommended quantity of 1,100 cfs for the Jefferson River was calculated using the wetted perimeter method (MT FWP, 1989). The wetted perimeter method utilizes cross sectional streambed measurements and flow rates to determine relationships between streamflow and the proportion of a river channel covered with water. The FWP study identified two important thresholds on the Jefferson that result in a relatively rapid increase in streambed exposure with declining flows (1,100 cfs and 550 cfs at the Twin Bridges USGS gage). Streamflow below 1,100 cfs results in amplified channel exposure, with flows less than 550 cfs resulting in a rapid

degradation of aquatic habitat (MT FWP, 1989). As evidenced in Figure 30, since 2000 mean August steamflows have dropped well below the established instream flow recommendations during the summer irrigation season.

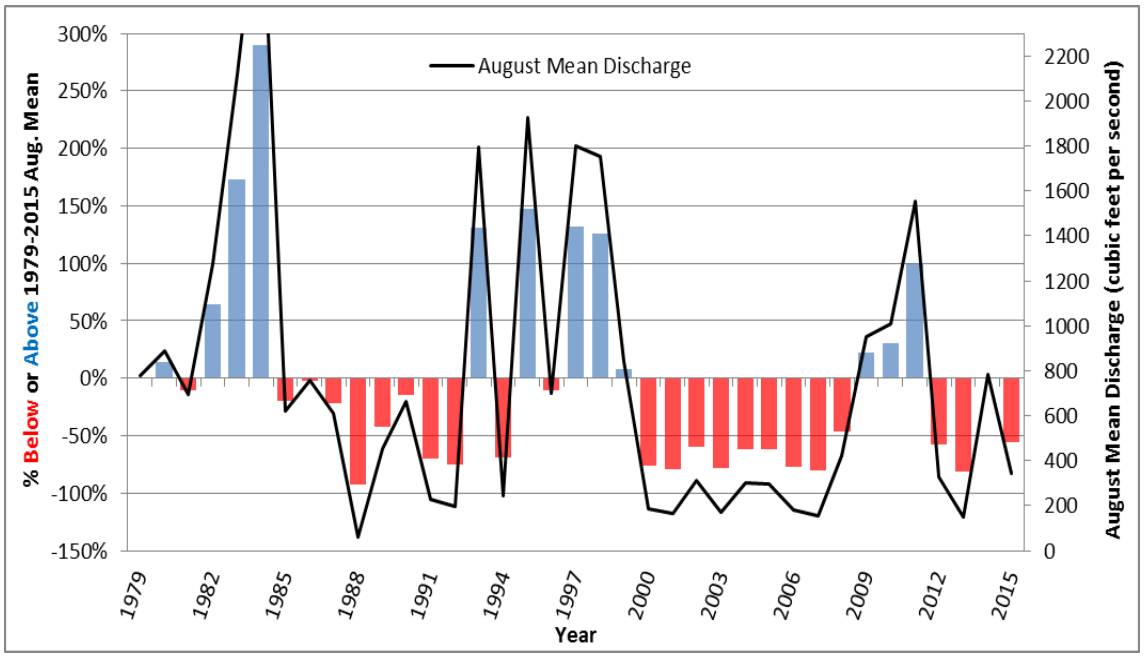


Figure 30- Mean August stream discharge in cubic feet per second (black line) on the Jefferson River near Three Forks (1979-2015). Red and blue bars represent the August discharge anomaly (% above or below the long term average).

In 1992 the Montana Department of Fish Wildlife and Parks (utilizing data from the report discussed above) reserved a huge volume of instream flow rights for fisheries in the upper Missouri River Basin above Fort Peck Dam (Montana State University Water Center, 2014). The water rights reserved instream within the Jefferson Basin constitute a massive volume of over 1,100 cfs with a priority date of July 1, 1985 (MT DNRC Water Resources Bureau, 2015). Despite being exceptionally junior and ineffective in preventing low streamflows, these instream rights essentially closed the Jefferson River (and others) to new surface water appropriations.

Administrative & Legislative Closures

Montana Code Annotated 85-2-319 gives both the DNRC and the MT Legislature authority to close over utilized basins to new water appropriations. The law was first utilized by the DNRC to close the mainstem of the Milk River in 1983.The statute is intended to protect existing water rights and maintain water quality standards on streams that could be adversely affected by future appropriations (Montana Water Resources Division [MTWRD], 2003). In the 1990's the DNRC closed 10 basins through administrative rule closures and the state legislature used its authority to stop applications for new appropriations in 6 major river basins (MTWRD, 2003). On April 1, 1993 the Montana Legislature officially closed the Jefferson and Madison River Basins to new surface water appropriations (MTWRD, 2003).

Reorganization Phase (α) mid 1990's-present

It is important to remember that the transition of a SES from a state of release (Ω) to one of reorganization (α) is often "messy, incremental and uncertain" (Chaffin et al., 2014; Gunderson and Holling, 2002). The boundaries between these phases are not easily defined and a system may oscillate between the two during the reorganization phase (Walker et al., 2006). The reorganization phase of the adaptive cycle model is characterized by the formation of novel SES arrangements that are unhindered by previous connections and feedbacks. As the SES moves forward, it adjusts to changes brought on by the previous phases of collapse and reorganization, increasing overall resilience in the system (Walker et al., 2006).

In the Jefferson, the drought of 1988 resulted in a complete dewatering of streambeds throughout the basin for the first time in Euro-American history. The drought also garnered substantial media attention (both statewide and national) that propagated perceptions that low streamflows were the result of inefficient agricultural practices and a lack of action by the state of MT (Carter, 1988a). The idea that farmers "could care less" if they dried up the river became a rallying cry for recreationists and conservationists throughout the state. A quote from a local outfitter on the Big Hole during the summer of 1988 summarizes this mentality "I care about the ranchers, but I want them to care a little about me too. If each of them gives just a little bit of a trickle all the way down to Twin Bridges than we'll survive too" (Carter, 1988b).

The drought induced collapse of the system provided a "window of opportunity" for a novel recombination of system variables within the Jefferson SES (Osslon et al., 2006). In an interview with Ron Spoon, long-time MT FWP fisheries biologist for the Jefferson, he stated that the drought of 1988 "jolted folks" in addition to being an important "catalyst for change" in the Jefferson Basin (Ron Spoon, personal communication, November 11, 2015). Although some water users felt that it was well within their rights to dewater streams in the face of exceptional conditions, a separate and equally powerful contingent was dismayed by the dry streambeds. Many water users in Montana consider themselves to be stewards of Montana's most valuable resource and the drought of 1988 sparked a call to action within that community.

Formation of the JRWC & Drought Management Plan

Beginning with the establishment of watershed conservation strategies in the mid-1990's the Jefferson SES entered a period of reorganization (α) that has continued until present. The watershed coalition formed in the Jefferson was a unique grassroots effort initiated by a handful of agriculturalists and conservationists motivated by a sense of stewardship of the water resource. The JRWC was formed in 1999 by a group of local irrigators from the upper Jefferson Basin and local FWP and NGO representatives. The effort was spearheaded by water users Gary Nelson (Creeklyn ditch), Joe Schlemer, John Kountz, Dean Hunt (all on the Parrot Canal), Bob Lombardi (Jefferson Canal), Dean Hansen (Fish Creek Canal) and local Trout Unlimited advocate Bruce Rehwinkel (Ron Spoon, personal communication, November 11, 2015).

Prior to the formal establishment of the JRWC, MT FWP and several of the major canal groups began early efforts to understand low flows on the Jefferson by installing monitoring gages on several of the major ditches/canals that draw water from the mainstem of the River in the critical Twin Bridges to Waterloo stretch (Ron Spoon, personal communication, November 11, 2015). This flow data was gathered to both characterize the true volume of water withdrawn and provide the flow data to local water users. In 1999, the JRWC developed its first drought management plan, modeled after the successful plan developed in the neighboring Big Hole Watershed. The drought plan (detailed in Table 9) establishes streamflow trigger points that prompt voluntary reductions in surface water withdrawals from irrigators (JRWC, 2012). The overarching goal of the drought plan is to maintain a minimum of 50 cfs at the Parsons Bridge USGS

gage near Silver Star on the Jefferson. The plan also contains water temperature thresholds that if crossed, prompt MT FWP to implement restrictions on angling (JRWC, 2012).

Jefferson River Watershed Council Drought Management Plan Triggers (2013)				
Drought management triggers	**Trigger Level**	**Gage Site**	**Binding**	**Description**
Streamflow Trigger 1	600 cfs	Twin Bridges	No	*Serves to alert water users of declining flow conditions and requests voluntary conservation measures (also prompts a press release informing the public of low flow conditions).*
Streamflow Trigger 2	280 cfs	Twin Bridges & Silver Star	No	*Prompts an evaluation by MT Department of Fish Wildlife and Parks (FWP) to determine if a mandatory fishing closure on the river is necessary. Also initiates voluntary reductions in irrigation and municipal water use and invokes the JRWC to update water users weekly. Weekly meeting informs water users on inflows, ditch withdrawals, and flow status at the Parsons Bridge gage. Goal is to maintain a minimum flow of 50 cfs at Parsons.*
Water Temperature Trigger	73° F	Twin Bridges	Yes	*Implemented independent of streamflow levels. Applied when maximum daily water temperatures equal or exceed 73° F for three consecutive days. Prompts MT FWP to implement mandatory time of day closure to prohibit angling between 2:00 PM to 12:00 AM.*

Table 9. The 2013 Jefferson River Watershed Council drought management plan. Data source: http://www.jeffersonriverwc.org/files/Plans/Drought_Management_Plan/JRWC_Drought_Mgt_Plan_2012.pdf

Angling restrictions typically begin with what are known as “hoot owl closures" that prohibit fishing from 2 p.m. to midnight (the period of peak water temperatures). If water temperature or streamflow conditions deteriorate further, FWP may mandate a total

closure of the stream to angling. Since first being put into action in 2000, the Jefferson has experienced eight seasons with mandatory fishing restrictions (either hoot owl or full) (Table 10). From 2000-2015, the combined fishing closures restricted 360 days of fishing on the Jefferson (for methods see Table 10). As evidenced by the fishing closure start and end dates displayed in Table 10, the closures typically impact the river during the height of the summer season for commercial fishing outfitters. Statewide in 2013, nonresident angler days peaked from July-September, with August recording the highest number of nonresident angler days of any one month period (MT FWP, 2015).

The JRWC drought plan was crafted to sustain the sport fishery and retain water instream on the heavily dewatered Silver Star to Waterloo reach of the river. Although streamflows have dropped below management criteria three times since the gage at Parsons Bridge near Silver Star was installed in 2006, voluntary water reductions have kept the stream from completely dewatering as it did during 1988 (Figure 31). Furthermore, despite an extended period of extreme drought conditions from 2000-2007, fish populations have rebounded on the Jefferson. Correspondingly, angling pressure has steadily increased since the implementation of the drought plan. In 2001, approximately 7,000 angler days were reported for the Jefferson; by 2013 that number had nearly doubled to an estimated 12,500 total angler days (for methods see appendix B).

Comparisons of Recent Drought Episodes on the Jefferson (2000-present)										
	2000	**2001**	**2003**	**2004**	**2005**	**2006**	**2007**	**2012**	**2013**	**2015**
*Basin snowpack as of April 1st (percent of normal SWE for base period 1981-2010)**	98%	75%	110%	90%	79%	119%	83%	104%	90%	75%
*Average May temperature anomaly (in degrees Fahrenheit for base period 1981-2010)***	+0.7˚	+2.9˚	+0.5˚	-1.2˚	-0.6˚	+2.2˚	+1.8˚	-0.8˚	+1.6˚	+0.7˚
Stream flow rate at lowest point of season (measured in cfs at Three Forks USGS gauge)	120	110	152	141	238	156	136	278	90	229
Date lowest flow recorded	8/3	8/28	8/3	8/16	8/27	8/15	8/31	8/10	8/22	9/4
*Fishing closure type (voluntary "V", partial "P", full "F")****	F	P, F	V, P	V	P	P, F	P, F	V	P, F	P
Fishing closure start and end date	8/5-9/17	8/15-9/13	7/30-9/16		7/25-9/16	7/21-9/13	7/11-9/16		7/25-9/4	7/3-7/30
Length of fishing restrictions and/or closure (total days)	43	29	48		53	54	67		38	28

Table 10. Summary of drought episodes on the Jefferson since the first implementation of the drought plan in 2000. *Basin snowpack as of April 1st is used because it is the average date of peak snowpack in Montana. **Average May temperature anomaly for MT climate division 2. ***Initiated by MT FWP. Voluntary closures are the first step 'V'. A partial closure 'P' prohibits fishing during the heat of the day. Full restrictions 'F' result in a complete closure of the fishery. Sources: NRCS Snotel (Jefferson Basin), NCDC (Climate at a glance), USGS National Water Information System, newspaper articles (for fishing closure start and stop dates).

The adaptive cycle narrative of exploitation, conservation, collapse and reorganization utilized in this chapter appropriately describes the historical trajectory of the Jefferson Basin SES over the last 150 years. Although somewhat arbitrary and subjective, the "adaptive cycle metaphor also has some explanatory power", helping to conceptualize the transformation of a complex SES (Chaffin et al., 2014). As this chapter

has shown, forces of adaptation and transformation have guided the Jefferson SES since the collapse of the system in 1988 and have worked to increase drought resilience in the basin. Positioning the Jefferson SES within the adaptive cycle model also offers a systematic approach with which to predict future perturbations to the system. How will the Jefferson SES respond to continued climate induced alterations to the physical system? What impacts might the expansion of center pivot irrigation have on the water use system? Chapter 4 will discuss potential regime shifts related to changes such as these in the Jefferson SES in addition to proposing methods for increasing overall resilience in the Basin.

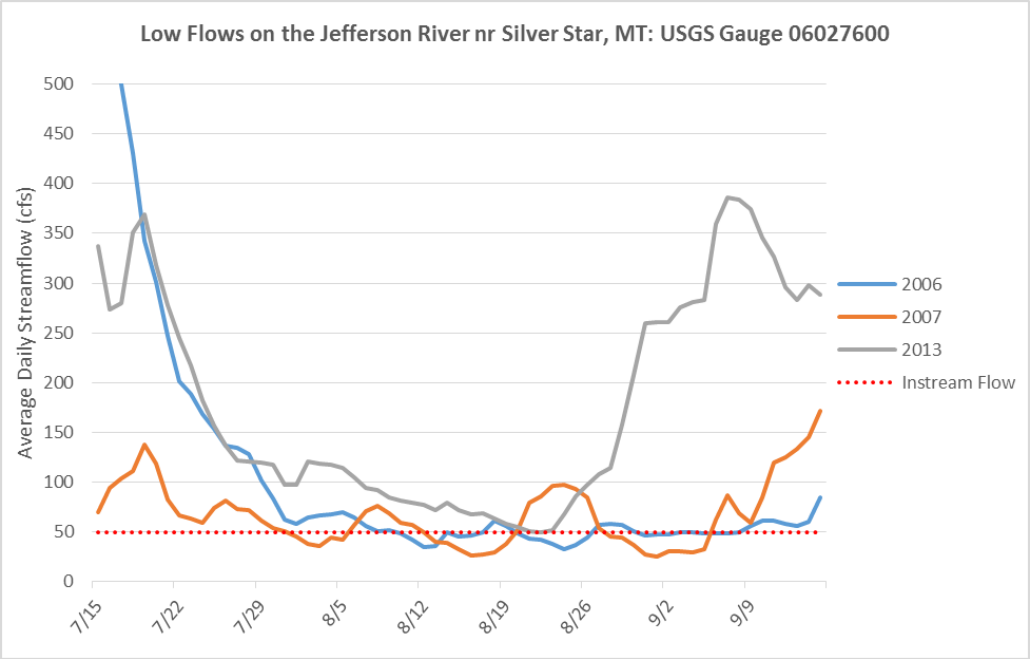


Figure 31. Drought episodes on the Jefferson that resulted in streamflows dropping below instream flow targets at the Parsons Bridge USGS gage near Silver Star. Period of record: (2006-2015). Data source USGS (2015c).

CHAPTER 4

POTENTIAL RESILIENCE CONCERNS IN THE JEFFERSON BASIN

The previous three chapters have described the Jefferson Basin as a dynamic socio-ecological system that has only recently entered into a new governance regime. This novel period may be considered a "window of opportunity" to boost drought resilience in the Basin. Although internal mechanisms such as water leasing projects and drought management plans have worked to retain instream flows on streams throughout Montana, a warming climate and changing land use patterns will continue to pose challenges for both irrigators and cold water fisheries. This chapter considers two disparate dynamics with the capacity to move the Jefferson SES "toward and perhaps across particular social and/or ecological thresholds" negatively influencing the system and "potentially transforming the SES into alternate regimes" (Chaffin et al., 2014, p. 44). Climate change poses the greatest threat to the future of the Jefferson Basin SES and will be examined in the first portion of this chapter. Changing irrigation practices and the ongoing conversion from gravity-flood systems to center pivot irrigation will be discussed in the remainder of the chapter.

A Climate in Flux

Since the late 1980's, prolonged periods of drought in the Jefferson Basin have directly impacted aquatic ecosystems, the local economy and downstream water users. Although recent droughts have been severe, the region experienced extreme conditions

prior to the 1980's. The closest steam gage with an uninterrupted long-term record (1924-2015) is the Melrose, MT station on the Big Hole River (approximately 20 miles from Twin Bridges and the confluence of the Jefferson). As illustrated in Table 11, the Dust Bowl Drought of the 1930's was likely the most significant multi-year episode of drought that impacted streamflow over the period of record in the greater Jefferson Basin. The drought caused widespread environmental and economic devastation throughout the U.S. and was unique in its intensity and length—lingering for close to a decade in parts of MT. Evidence from paleoclimate studies (primarily tree ring chronologies) suggests that the Dust Bowl Drought was the most severe in Montana over the last 200 years (Figure 32). A recent paper by Benjamin Cook theorizes that expansive precipitation deficits throughout western North America in 1934 rank that year as the single driest during the last 1000 years (2014). Drought and periods of anomalously warm temperatures are anticipated to expand in both intensity and duration in the future threatening to surpass the severity of droughts experienced in the 1930's. Since the Dust Bowl Drought of 1930's Montana communities and water infrastructures have become increasingly developed. Furthermore, the state's population has doubled since that period.

In Montana, reliable observations of streamflow and temperature records go back to the early 20th century. Temperature and streamflow reconstructions generated from tree-ring records offer important insights into long-term regional hydrologic patterns before the period of recorded observations (albeit at coarse scales). Although the precipitation and streamflow deficits experienced in the 1930's were severe, evidence from tree-ring studies suggests that previous episodes of drought may have been even

more intense. A study that reconstructed streamflows on the Missouri River at the Toston streamgage (1579-1996) illustrates the cyclic nature of decadal-scale drought in the region and the frequency at which the episodes recur. As displayed in Figures 32 and 33, long-term droughts (consistent years of below average flows) have occurred fairly frequently from the 16th century to present. It is also important to note the relationship between the length of a multi-year drought and the frequency at which these events occur—the more extreme the drought the less frequent it occurs and vice versa (Figure 33). Understanding historical patterns of drought frequency, duration and intensity is essential when considering the range of future drought scenarios.

Rank	Year	Month	Mean Monthly Discharge (cfs)
1	1988	*Aug*	88
2	1988	*Sept*	115
3	**1931**	*Aug*	124
4	**1940**	*Aug*	127
5	**1937**	*Sept*	137
6	**1935**	*Sept*	139
7	**1931**	*Sept*	141
8	1966	*Aug*	150
9	2000	*Aug*	150
10	1994	*Sept*	164

Table 11. Ten lowest mean monthly discharge totals on record during summer months (June-October) at the Melrose stream gage on the Big Hole River (USGS, 2015d). Years highlighted in red indicate Dust Bowl Drought Years. See Figure 31 for steam gage location.

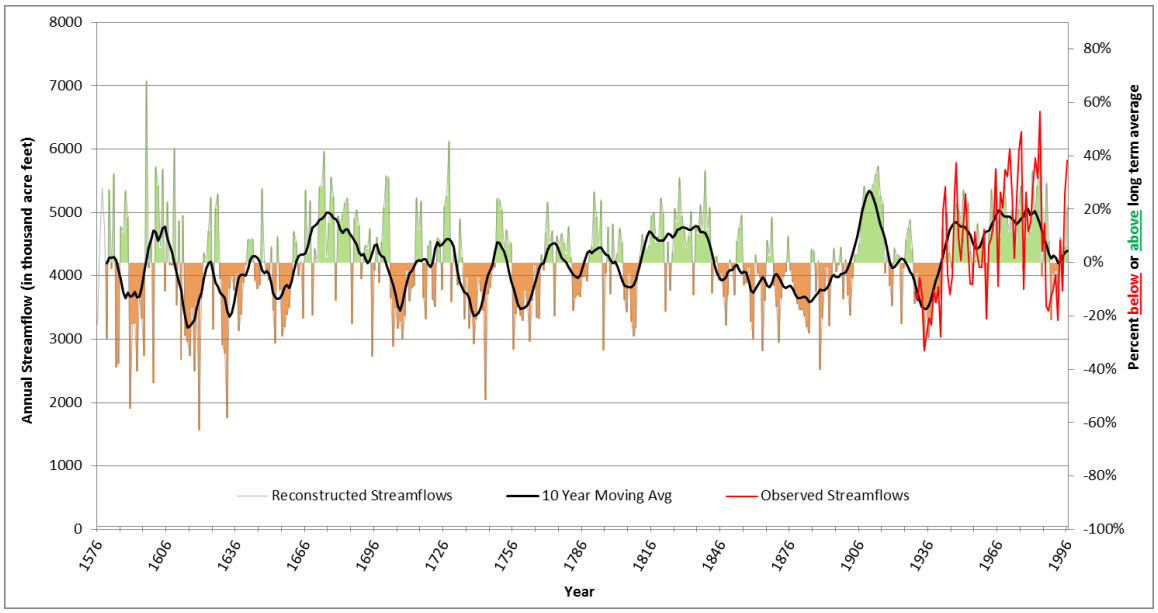


Figure 32. Tree-ring reconstructed streamflow volumes at the Toston stream gage on the Missouri River (1579-1996). The black line represents a 10 year moving average. Red and green bars shows annual discharge as a percent above (green) or below (orange) the long term average. The red line represents observed values at the Toston USGS streamgage (1930-1996). Data source: U.S. Department of Interior, Bureau of Reclamation (2009).

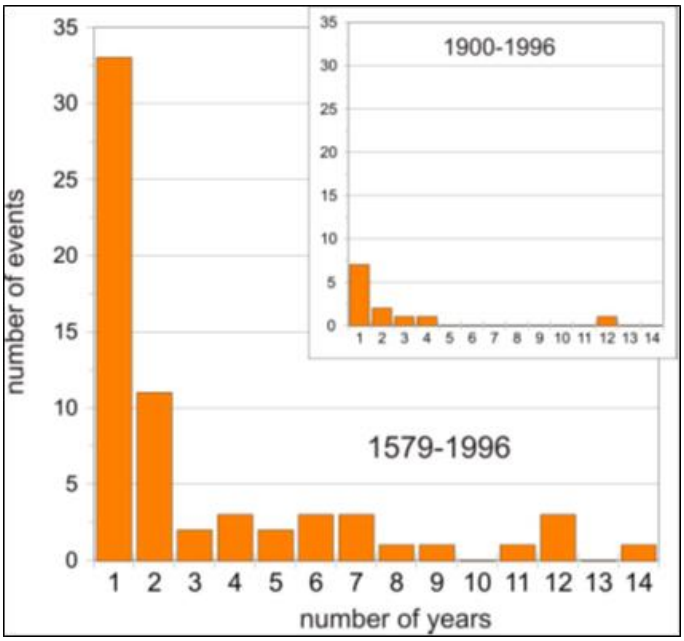


Figure 33. Frequency of drought episodes in the upper Missouri Basin (by length of drought). Drought defined as annual discharge below the long term average. Figure copied from U.S. Department of Interior, Bureau of Reclamation (2009).

Combining climate projections from general circulation models (GCMs) with locally observed climate trends has been proposed as a framework for future land use planning decisions (Hayhoe et al., 2007; Groves et al., 2008). Investigating recent trends in climate enables managers to predict future "climate trajectories". Using a similar approach, this section examines both recent trends in climate (1900-present) at a regional scale and projects future climate and hydrologic scenarios (2020-2080) utilizing an ensemble of publicly available GCMs. Understanding the range of potential perturbations to the future climate system within the Jefferson SES is necessary when considering adaptive management strategies and planning for future drought resilience.

As described in a recent paper on climate change indicators in Vermont, many global markers of ongoing global climate change (such as an increase in atmospheric CO2 concentrations and the melting of Arctic sea) are vague to local communities and don't represent regional and local scale climate responses to anthropogenic change (Betts, 2011). Conversely, climate change data describing smaller scale impacts "can be directly perceived and easily understood by local communities" (Betts, 2011, p. 106). When determining appropriate hydrological and climatological indices to investigate and report, this research focused on data considered meaningful to regional water users in southwest Montana. The following climatological trend analysis investigates local patterns in extreme temperatures and shifting periods of seasonality within the greater Jefferson Basin (from 1900-present). Conventional wisdom proclaims that contemporary winters "aren't as bad as they used to be" and that summers "didn't used to last so long". The

subsequent investigation of temperature trends in the Jefferson region will provide evidence illustrating that these observations are confirmed by climate data.

Climate Trends

To understand the historic drivers of single-year summer streamflow droughts in the greater Jefferson Basin this portion of the climate assessment first investigated links between seasonal temperature, precipitation and their influence on streamflow. Monthly temperature and precipitation data was compiled for the upper Missouri Basin hydrologic unit (Gallatin, Madison and Jefferson Basins) using the Western Regional Climate Center's WestWide Drought Tracker. This data was then compared (using a Pearson's r correlation) to average summer (July-Sept) monthly stream discharge at the USGS stream gage on the Big Hole River at Melrose, MT and naturalized flow data calculated for the Jefferson River by the U.S. Bureau of Reclamation (Figure 34).

Analysis of the correlated variables showed the relationships and linkages between seasonal temperature/precipitation and their relative impact on summer streamflows (average flows for July-September). As illustrated in Figure 34, spring and early summer temperatures are inversely related to summer discharge with the individual months of May and June impacting streamflows the most. Furthermore, early summer (May-July) average temperatures appear to have the largest impact on stream discharge during the summer. Although monthly and seasonal precipitation totals also influences summer discharge, the relationship is not as strong as the temperature variables investigated. Of the precipitation variables analyzed, December (previous year) and January had the greatest impact on summer streamflow during the winter months with the

May-July average precipitation values influencing flows the greatest (Figure 34). Overall, both the temperature and precipitation variables investigated revealed the May-July period to be the most important "season" influencing summer flows.

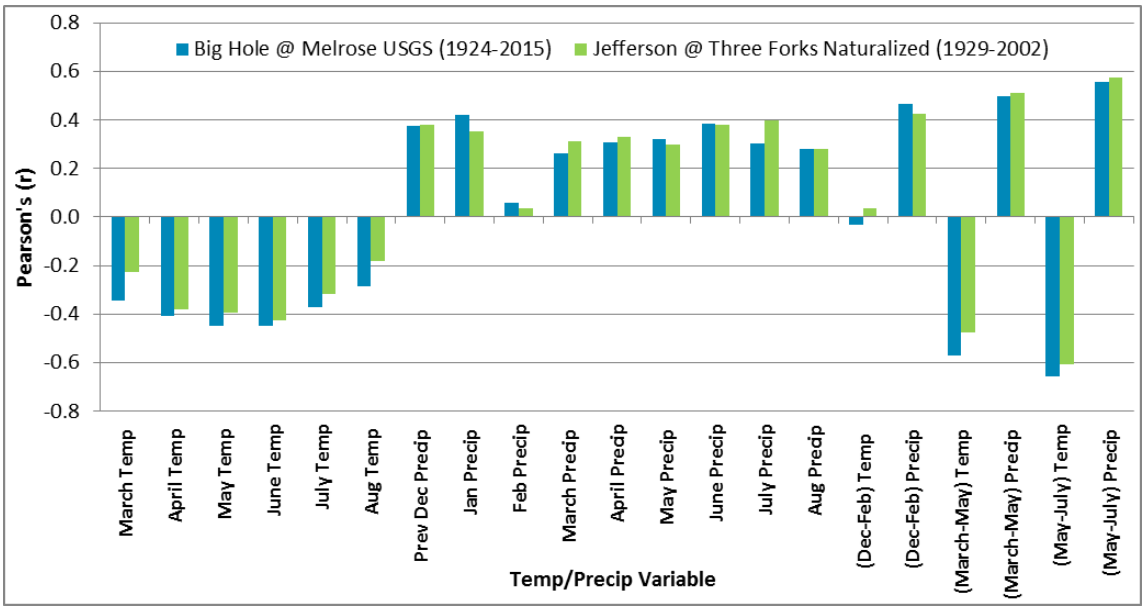


Figure 34- Comparison of monthly temperature and precipitation variables influencing late summer streamflows (July-Sept average discharge) on the Big Hole (blue columns) and Jefferson (green columns) Rivers. Data sources: *Streamflows*—USGS (2015a); *Naturalized flows*—U.S. Department of Interior, Bureau of Reclamation (2009), *Monthly climate averages*—Western Regional Climate Center, West Wide Drought Tracker http://www.wrcc.dri.edu/wwdt/time/

Temperature Trends

Employing the methods presented by Greg Pederson and colleagues in their study examining 100 years of climate in western Montana, temperature data at three long-term meteorological stations proximate to the greater Jefferson Basin were analyzed (2010). Trends in temperature were evaluated at U.S. Historical Climatology Network (USHCN) stations located in Dillon, Ennis and Virginia City, Montana (Menne et al., 2010). USHCN data retrieved from the Carbon Dioxide Information Analysis Center (CDIAC)

consisted of daily maximum, daily minimum and daily average temperatures at each station (T_{max}, T_{min}, T_{avg}). The datasets used in the analysis contained high-quality, long-term records (~100 years) that are relatively free of missing observations (>98% complete). The stations were chosen due to their proximity to the Jefferson Basin and completeness of record. Although data from individual stations should not be used to characterize regional scale climate patterns, comparing multiple stations across climatically similar regions reduces uncertainty (weather 'noise') associated with single station records and provides a coarse overview of regional trends (Pederson et al., 2010). Figure 35 displays the location of the climate stations relative to the Jefferson watershed boundary. Table 12 summarizes the elevation, and percent of record present for the stations used in this analysis.

Weather Station	Elevation (ft)	Latitude	Longitude	Record Present (%) (days of complete record)
Dillon WMCE	5228	45.2128	-112.6447	99.23 (1900-2014)
Virginia City	5773	45.2925	-111.9481	98.74 (1917-2014)
Ennis	4953	45.3394	-111.7111	99.40 (1918-2014)

Table 12. Location, elevation and percent of record for the meteorological stations used in the temperature trend analysis. Record present (%) represents the number of complete days on record (days containing T_{max}, T_{min}, T_{avg}).

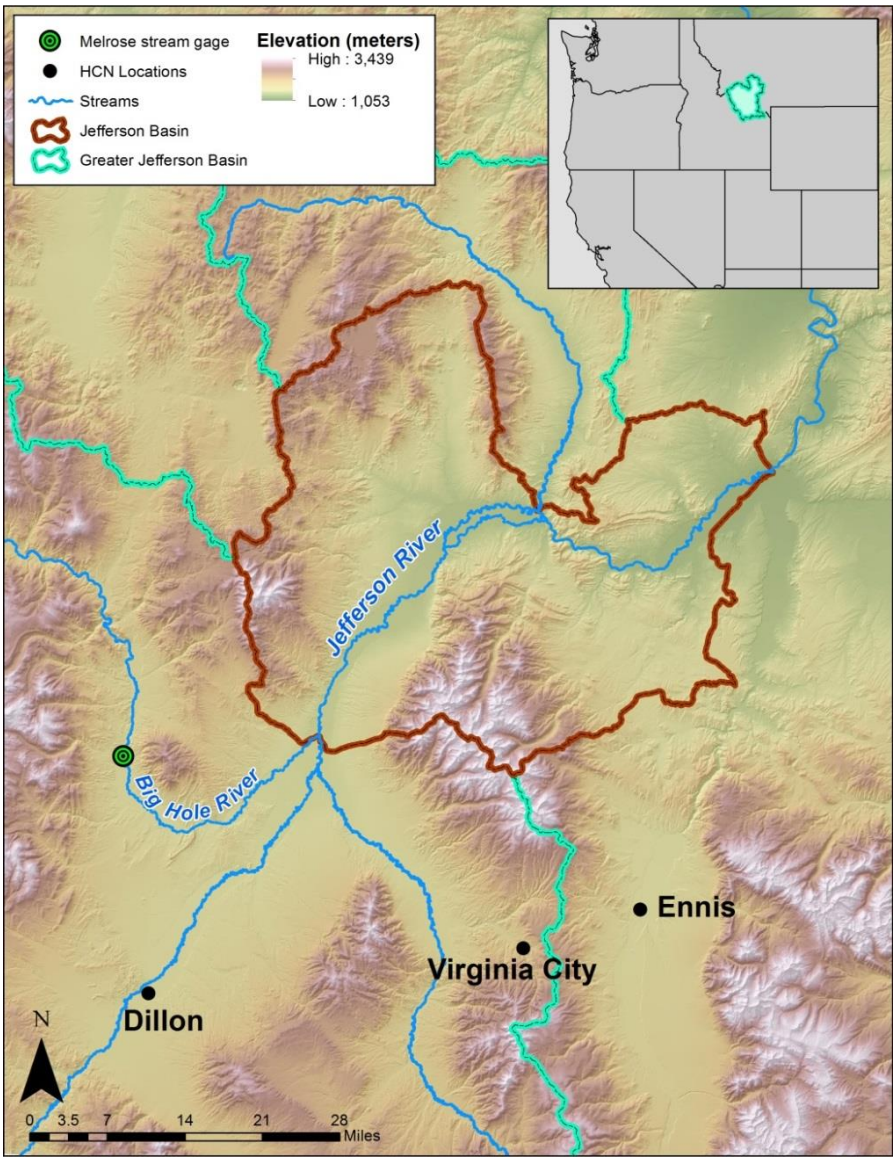


Figure 35. Location of United States Historical Climatology Network (USHCN) stations used in the temperature trend analysis relative to the Jefferson Basin. The location of the Melrose USGS stream gage is also included. Mapping data source: MT NRIS—GIS Clearinghouse.

Utilizing the R statistical software program and code modified from the Pederson et al. study (2010) this portion of the research investigated several markers of a warming climate in the Jefferson Basin region. To determine whether significant change had occurred to the climate system over the period of record, three temperature thresholds (0

˚F, 32˚F, and 85 ˚F) were used as reference points for analysis. These values were chosen due to important ecological and social processes that may be altered by long-term changes in the average timing and duration of temperatures above or below the thresholds (Pederson et al., 2010). For this research, the annual number of "very warm" days (T_{max} ≥85 ˚F) and "very cold" days (T_{min} ≤0 ˚F) was calculated (Figure 36 & 38) for each station as well as the seasonal window in which those temperatures occurred (Figure 37 & 39). The onset of "fall" was determined for each calendar year by tallying the first day of summer (post July 1st) that minimum temperatures dropped ≤ 32 ˚F (Figure 40). Annual numbers of "frost-free days" were defined by tallying the number of days per year with minimum temperatures above 32 ˚F (Figure 41).

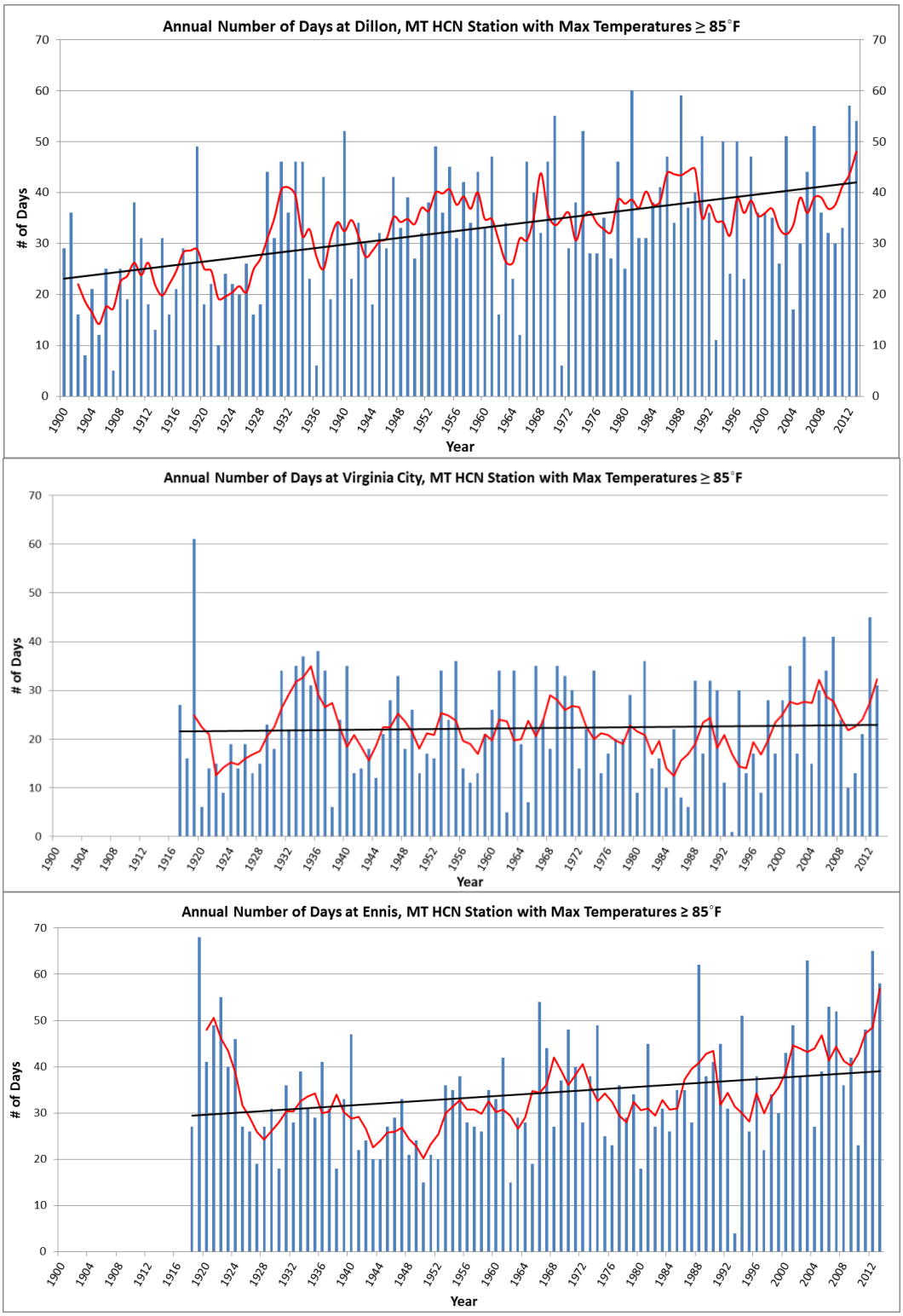


Figure 36. Annual tally (blue bars) of the number of days where maximum temperatures met or exceeded 85˚F (very warm days). A 5-year moving average (red line) highlights overall trends and variability. Straight black lines depict a simple linear regression.

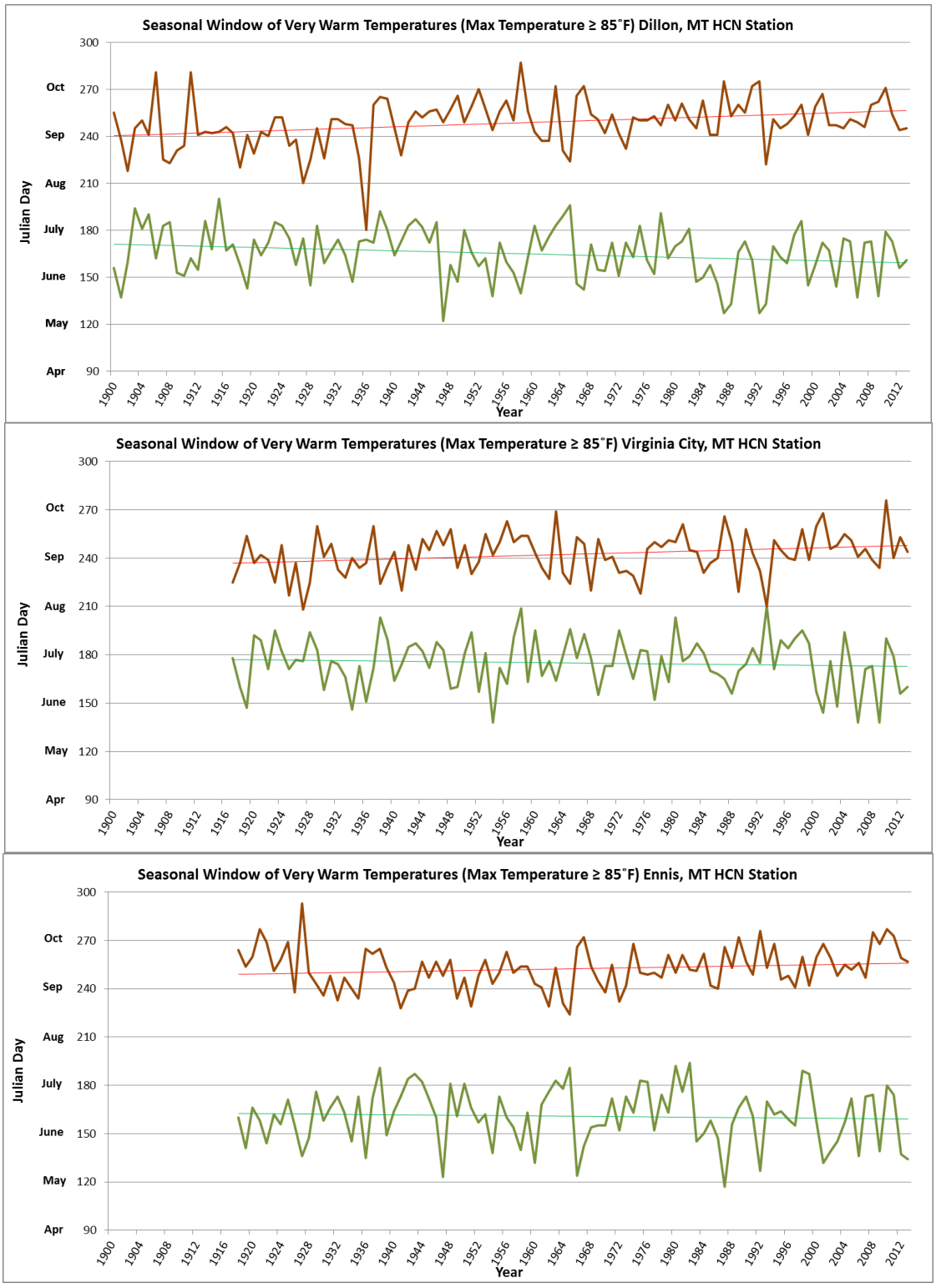


Figure 37. Seasonal window of very warm temperatures (days with maximum temperatures ≥ 85˚F). Annual trends in the first day (green line) and last day (red line) of the year maximum temperatures exceeded the threshold are plotted.

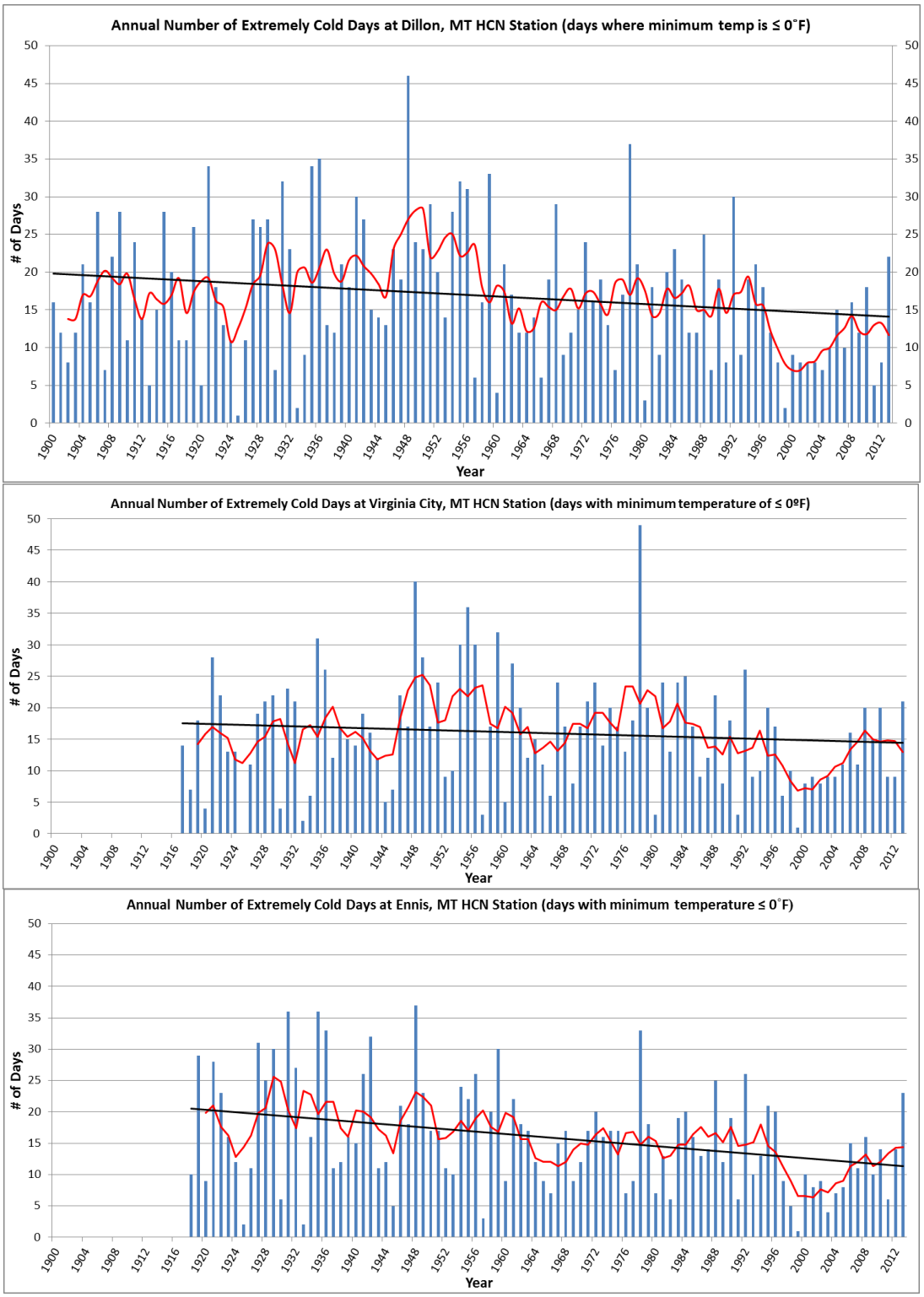


Figure 38. Annual tally (blue bars) of the number of days where minimum temperatures met or fell below 0˚F. A 5-year moving average (red line) highlights overall trends and variability. Straight black lines depict a simple linear regression.

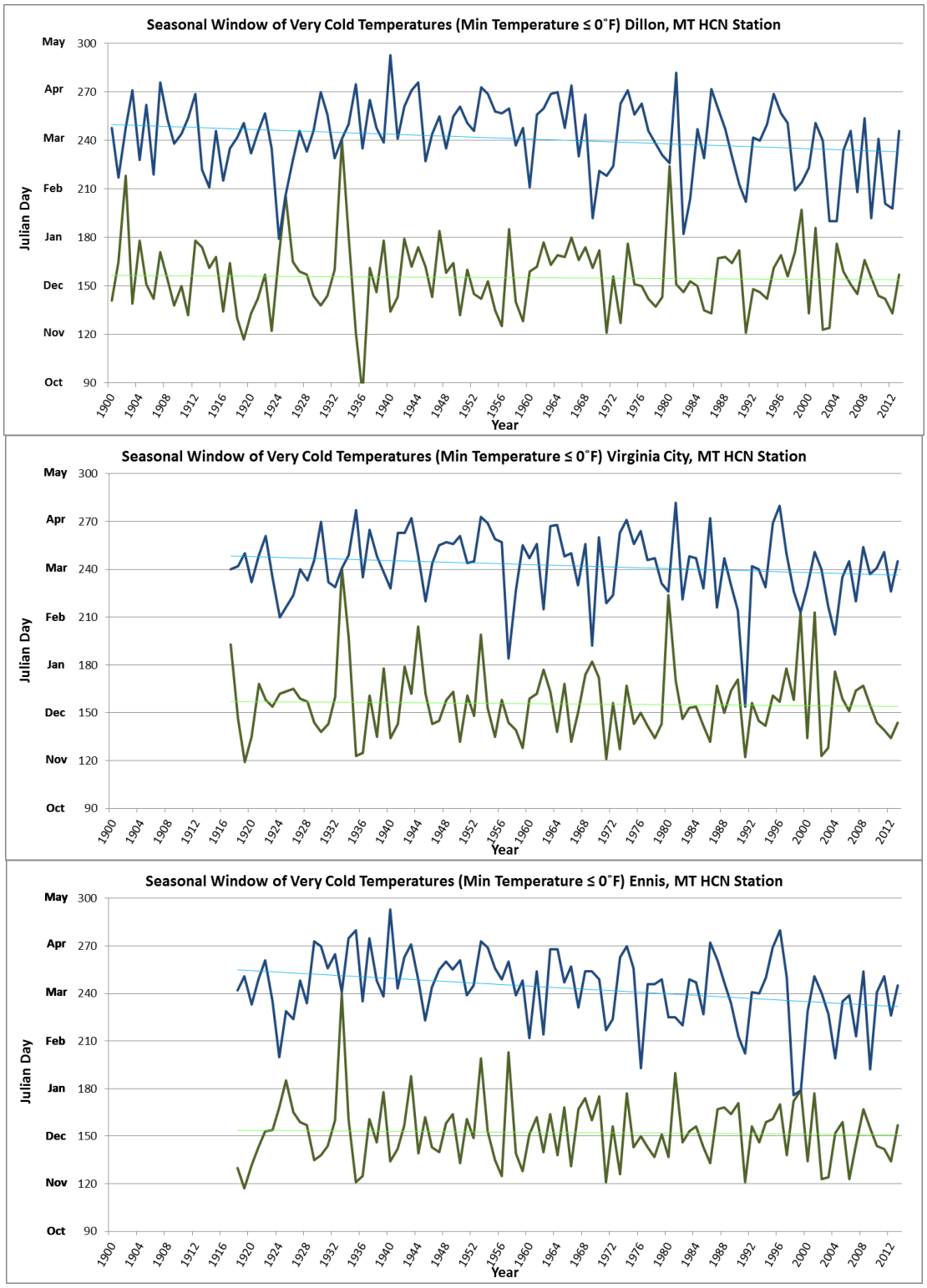


Figure 39. Seasonal window of very cold temperatures (days with minimum temperatures ≤ 0˚F). Annual trends in the first day of seasonal cold (green line) and last day (blue line) minimum temperatures met or dropped below the threshold are plotted.

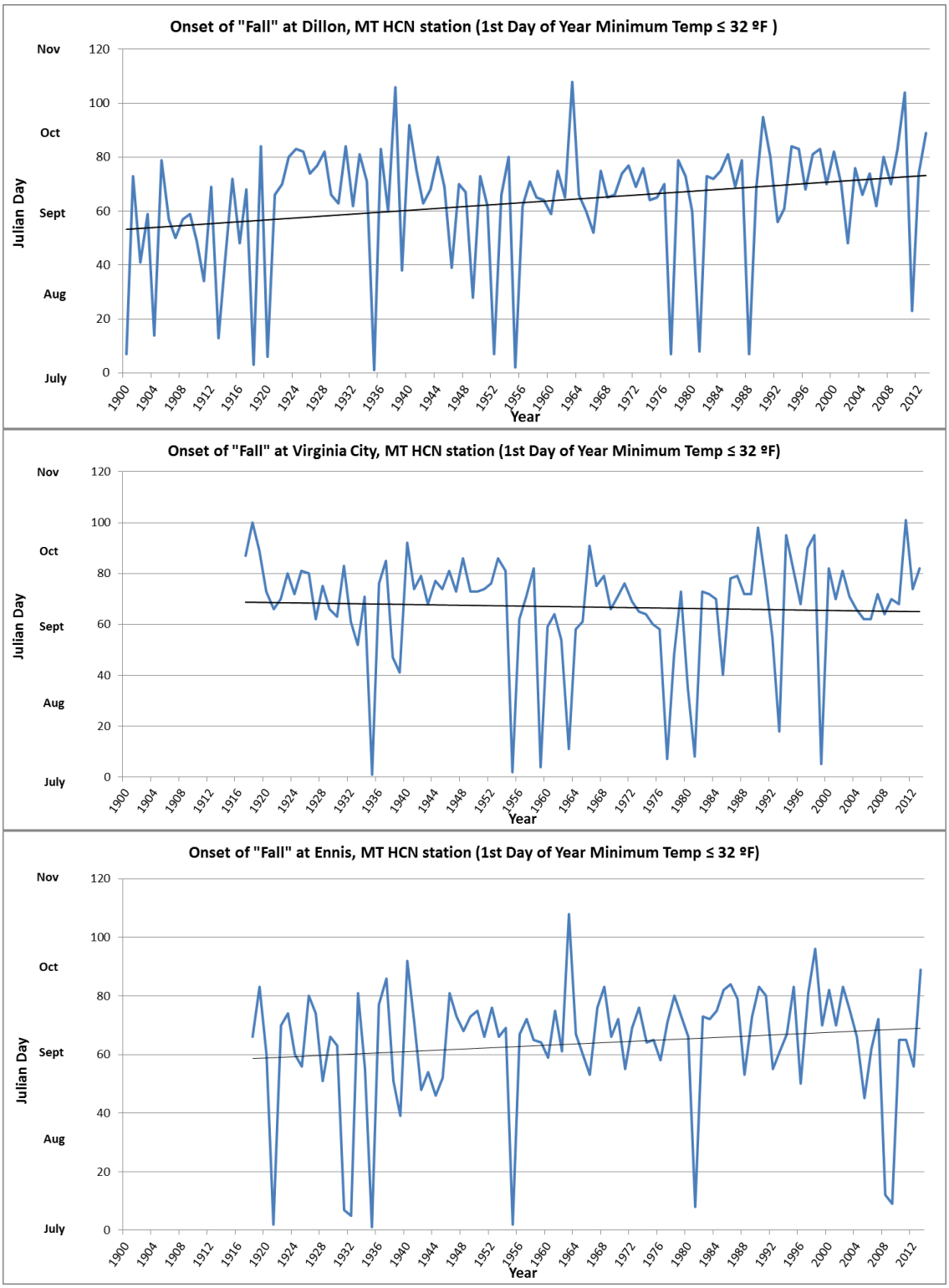


Figure 40. Onset of "fall"—first day of the season (post July 1st) with a minimum temperature ≤ 32 ˚F. Straight black lines depict a simple linear regression.

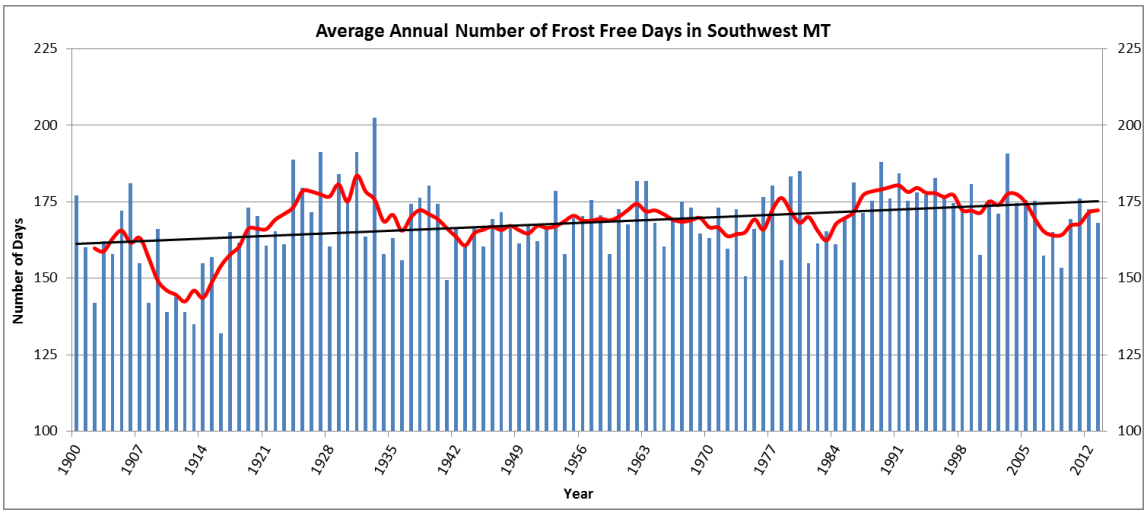


Figure 41. Average number of frost free days in SW MT. Frost free days defined as days with minimum temperatures ≥ 32˚F. A 5-year moving average (red line) highlights overall trends and variability. Straight black lines depict a simple linear regression.

Analysis of the temperature indices described above revealed that over the past century the climate of the greater Jefferson Basin has changed significantly. As Figure 36 illustrates, the average annual number of very warm days ($T_{max} \geq 85$˚F) in the region has increased over the last 100 years at all three of the stations analyzed. The trend is most pronounced at the lower elevation, valley bottom stations located in Dillon and Ennis. The Dillion HCN station saw a substantial increase in the average annual number of very warm days ($T_{max} \geq 85$˚F), from approximately 20 days/year in 1900 to over 40 days/year in 2013. Importantly, the seasonal window in which very warm temperatures occur has also grown at all three stations (Figure 37). In 1900 the season of very warm temperatures in Dillon typically lasted from the end of June to the beginning of September (~65 days). By 2013 that season had grown by over three weeks, with very warm temperatures now beginning on average in the first half of June and lingering until mid-September (~90 days).

While the average annual tally of warm days has been on the rise over the last 100 years in the region, the number of very cold days has declined (as well as the seasonal window in which cold temperatures occur). As with the previous assessment of warm temperatures, this trend is most evident in the lower elevation sites located in Ennis and Dillon (Figures 38 &39). In 1918 Ennis averaged approximately 21 days per year with minimum temperatures ≤ 0 ˚F; by 2013 the station averaged 12 days of very cold temperatures (Figure 38). Interestingly, all three stations show a marked decrease in the seasonal window of very cold temperatures ($T_{min} \leq 0$ ˚F); with the downward trend only evident in the spring. In the 1910's, the average window of very cold temperatures typically lasted from early December to mid-March at all locations; by 2013 that date had shifted almost three weeks earlier in the season to late February (Figure 39).

The temperature analysis also revealed that the onset of "fall" (defined here as the first date of minimum temperatures ≤ 32 ˚F) is occurring increasingly later in the season at the Dillon and Ennis stations. Over the last 100 years, the average "fall" season has been delayed by approximately 20 days in Dillon and 10 days in Ennis (Figure 40). Correspondingly, the average annual number of frost fee days has increased. Taking an average of all three stations showed that the mean annual number of frost-free days has expanded by 17 days over the period of record (Figure 41).

The patterns present in the indices discussed above point to a warming climate in the region that has been characterized by an increase in very warm temperatures during the summer and a decrease in very cold temperatures during the winter. The data shows that winters are not as cold as they used to be and summer temperatures have expanded

their range. Seasonal patterns in temperature have shifted over the last 100 years impacting both biological and physical processes within socio-ecological systems. In southwest Montana, an increasing window of extreme summer heat has resulted in earlier snowmelt timing and correspondingly, an advance in spring runoff. Warm temperatures also increase evapotranspirative demand in terrestrial ecosystems (including planted crops); boosting potential plant growth while at the same time increasing the amount of water needed for growth. The temperature trends discussed in this section may be used to conceptualize the current trajectory of temperature, and the temperature driven portions of the Jefferson Basin's hydrology (i.e. snow accumulation, timing of runoff, evaporative losses). The following analysis will provide a coarse overview of predicted future climate conditions in the region.

Climate Projections

Although a large body of research has been devoted to quantifying and projecting climate change at a global or continental scale, researchers have more recently began to investigate impacts at finer regional and local scales. Changing precipitation and temperature regimes exhibit large spatial variations in the severity of projected impacts (Melillo et al., 2014). Advances in computing and GCM downscaling techniques in the last 20 years have reduced model resolutions from 100 km to less than 1 km (Hall, 2014). This high-resolution data is now readily available through open access web based platforms and for the first time is being integrated in long-term regional planning processes (Barsugli et al., 2013).

This study integrates data from one of these web-based platforms, and utilizes climate and hydrology projections sourced from the International Panel on Climate Change's (IPCC's) Coupled Model Intercomparison Project Phase 5 (CMIP5). Developed by the World Climate Research Program, the CMIP

> "provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze GCMs in a systematic fashion, a process which serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception in 1995" (World Climate Research Program, 2015).

A recently released collaborative climate projection web archive, hosted by the Lawrence Livermore National Laboratory, includes CMIP 5 model output for around 30 GCM's that may be downscaled to fit multiple spatial scales (from watersheds to towns) (U.S. Bureau of Reclamation [USBOR] et al., 2014). The web archive contains access to both hydrology and climate projects and includes tutorials enabling tabletop climate assessments to be performed. Custom data-retrieval features allow users to modify the climate and hydrological indices investigated as well as the spatial and temporal scale of the projections. The archive produces output based on four future greenhouse gas (GHG) emissions scenarios—termed Representative Concentration Pathways or RCPs. The RCPs range from scenarios in which global GHG emissions peak by 2020 and decline substantially thereafter (RCP 2.6), to situations in which emissions continue to rise throughout the 21st century (RCP 8.5).



Figure 42. Hydrological region selected for the downscaled climate projections. See appendix D for a description of the methodology and GCMs used in the analysis. Data source: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

The climate projection web archive allows users to spatially delineate model output based on watershed boundaries (through the selection of pour points). After defining the greater Jefferson Basin as the geographic extent (Figure 42), three variables were chosen for future climate analysis (precipitation, maximum air temperature, and total runoff). A monthly time step was selected for the period of January 1950 through December 2099 and following the methodology detailed in the hydrology projection tutorial, output data retrieved from the web archive (csv format) was analyzed in Microsoft Excel. Model output for each of the three variables examined consisted of monthly averages (for the period 1950-2099) computed from 97 individual climate projections (split among 4 emissions scenarios). Monthly average values represent a spatial mean over all of the contributing grid cells upstream from the selected pour point

(the greater Jefferson). To quantify the projected change in each of the three variables a decadal average was computed for the period of (1990-1999) and compared to three future decades (2020's, 2050's and 2070's). Median values of percent change within the four emission scenarios were used to make comparisons. For a detailed explanation of the steps followed to process the data and the models utilized in the downscaled projections see appendix D.

It is important to remember that climate projection data is essentially a series of model-based predictions with increasing uncertainty over time. This information provides workable future climate scenarios for use in resource planning (although the projection's limitations must be acknowledged). The data presented in the following discussion is comprised of averages sourced from 97 different climate models and contains large amounts of variability (see appendix D for a list of the models used). Uncertainty in projecting future precipitation regimes (also the basis for streamflow modeling) is evident in the variance among model output for the runoff and precipitation parameters investigated. Temperature projections on the other hand, contained significantly less variance and may be considered more reliable predictions. The values presented in the summaries represent basin wide decadal medians and should not be used to quantify warming at finer spatiotemporal scales. Although there are large amounts of variability within the individual model predictions, the data as a whole offers a coarse overview of the range of expected future climate outcomes in southwest MT.

The data reveals that climate change may result in several drastic changes to the hydrologic cycle of the greater Jefferson Basin. Summer maximum temperatures are

anticipated to be significantly warmer in the future. Average maximum temperatures for the months of June, July and August are anticipated to be around 5˚F warmer in the 2020's and over 10 ˚F warmer by the 2070's (Table 13). This projection correlates with the rising trend in very warm maximum temperatures observed over the last 100 years in the region and discussed earlier in this assessment. Warming temperatures will lengthen the growing season and increase evapotranspiration altering biophysical processes and contributing to reductions in summer streamflows.

Projected Mean June-August Max Temperatures for the Greater Jefferson						
1990-1999 Average of 71˚F for MT Climate Division 2	**2020's**		**2050's**		**2070's**	
	Temp	**Increase**	**Temp**	**Increase**	**Temp**	**Increase**
RCP2.6	75.8	4.8	77.0	6.0	75.7	4.8
RCP4.5	75.0	4.1	79.2	8.2	81.5	10.5
RCP6.0	75.7	4.7	78.4	7.4	81.9	10.9
RCP8.5	76.2	5.3	82.6	11.6	87.3	16.3
Combined	**75.7**	**4.7 (6.6%)**	**79.5**	**8.5 (12.0%)**	**81.7**	**10.7 (15.1%)**

Table 13. Future average maximum temperature projections for the greater Jefferson Basin. Projected change was calculated using a base period of 1990-1999. Values represent a decadal average maximum temperature over June, July and August. For a detailed methodology and list of the GCMs used in the analysis see appendix D.

Under all four emission scenarios future summer stream discharge volumes are anticipated to be well below the 1990's decadal average (Table 14). Mean streamflow on the Jefferson River during June, July and August is predicted to be reduced on average between 12-16 % in the 2020's (reductions from 1990's decadal average). By the 2070's, average reductions under the highest emission scenario approach 35%. Persistent drought and low river levels, similar to conditions experienced in the Jefferson Basin over the last 15 years, are predicted to be more common in future summers. It is important to note that although average summer discharge volumes are anticipated to diminish, total annual

runoff is projected to increase under the majority of the emission scenarios (Table 15). Future precipitation predictions mirror this pattern, with a reduction in summer season precipitation but an increase in the annual totals anticipated (Table 16).

Projected Average June-August Stream Discharge for the Jefferson River at Three Forks, MT						
1990-1999 Average of 9,318 cfs (June-August)	**2020's**		**2050's**		**2070's**	
	projected discharge	**discharge change (%)**	**projected discharge**	**discharge change (%)**	**projected discharge**	**discharge change (%)**
RCP2.6	7,915	-1,403 (-15.1)	7,528	-1,790 (-19.2)	8,047	-1,272 (-13.6)
RCP4.5	7,820	-1,498 (-16.1)	7,512	-1,806 (-19.4)	6,664	-2,655 (-28.5)
RCP6.0	7,975	-1,344 (-14.4)	7,303	-2,015 (-21.6)	7,057	-2,261 (-24.3)
RCP8.5	8,209	-1,109 (-11.9)	6,756	-2,562 (-27.5)	6,072	-3,247 (-34.8)
Combined	**7,933**	**-1,385 (-15%)**	**7,194**	**-2,124 (-23%)**	**7,001**	**-2,318 (-25%)**

Table 14. Future summer streamflow projections for the Jefferson River. Projected change was calculated using a base period of 1990-1999. All discharge vales in cubic feet per second "cfs" represent decadal averages. For a detailed methodology and list of the GCMs used in the analysis see appendix D.

Projected Change in Average Annual Discharge on the Jefferson River at Three Forks, MT			
	2020's	**2050's**	**2070's**
RCP2.6	6.87	4.44	14.81
RCP4.5	1.59	6.38	3.21
RCP6.0	5.22	-2.25	6.33
RCP8.5	8.04	7.30	14.07
Combined	**3.81**	**4.90**	**8.06**

Table 15. Future annual streamflow projections for the Jefferson River (in % change). Projected change was calculated using a base period of 1990-1999. For a detailed methodology and list of the GCMs used in the analysis see appendix D.

Projected Change in Precipitation for the Greater Jefferson Basin						
	2020's		**2050's**		**2070's**	
	Annual	Summer	Annual	Summer	Annual	Summer
RCP2.6	4.7	1.7	6.5	0.1	8.7	7.6
RCP4.5	3.7	-2.9	7.4	-3.2	5.3	-8.3
RCP6.0	2.3	-0.4	5.0	-4.9	8.5	-5.0
RCP8.5	5.2	1.0	6.5	-7.5	11.3	-9.8
Combined	**4.2**	**-0.3**	**6.6**	**-4.1**	**8.4**	**-4.7**

Table 16. Future precipitation projections for the greater Jefferson Basin (in % change). Summer values represent a decadal average change in precipitation over June, July and August. Projected change was calculated using a base period of 1990-1999. For a detailed methodology and list of the GCMs used in the analysis see appendix D.

The projections discussed above are useful when considering the range of future climate scenarios in Jefferson Basin. Despite the limitations of the data, the analysis as a whole illustrates that summer droughts will likely expand in frequency and severity in the future. The climate trends observed over the last 100 years in region (and detailed in the first portion of this climate assessment) correlate with many of the future climate impacts predicted by the climate models. This association is essential to consider when planning for future drought resilience in the Jefferson Basin. The projection data also offers important insights into anticipated changes to seasonal weather and streamflow patterns in the Jefferson Basin. For example, predictions of decreasing water availability in the summer are expected occur despite an increase in annual precipitation and stream discharge volumes. By taking advantage of additional surpluses of water in the fall, winter and spring (through either natural or artificial storage infrastructures) additional supplies of water may be available to buffer predicted summer deficits and increase drought resilience.

Proliferation of Center Pivot Irrigation

With the potential to exacerbate current water supply challenges facing Montana, the use of center pivot irrigation has exploded in the past 30 years. Advanced center pivot irrigation systems operate with satellite accuracy and have replaced more traditional water delivery methods such as gravity-fed surface techniques (i.e. flood irrigation). Conversion from flood to sprinkler irrigation has been lauded as a progressive water conservation practice since the 1990's. Both leading environmental non-profit groups (Trout Unlimited, Alliance for Water Efficiency) and governmental entities (US Bureau of Recreation, Montana Conservation Districts, Natural Resources Conservation Service, MT DNRC) continue to subsidize conversion efforts. According to data from U.S. Department of Agriculture Farm and Ranch Irrigation Surveys, the acreage of center pivot irrigation in Montana increased significantly from 241,287 acres in 1998 to 595,590 acres in 2013 (Table 17). As discussed in Chapter 2 of this thesis, the Jefferson Basin currently has approximately 43,000 acres of irrigated farmland with 24,000 acres under center pivot irrigation and 11,500 acres flood irrigated.

Land Irrigated in Montana by Method of Water Distribution					
	Total	**Gravity Fed**		**Sprinkler**	
	Acres	*Acres*	*% of Total*	*Acres*	*% of Total*
1998	1,740,873	1,171,807	67.3%	570,550	32.8%
2003	2,131,955	1,361,731	63.9%	773,008	36.3%
2008	1,947,159	1,102,878	56.6%	881,591	45.3%
2013	1,872,389	1,144,584	61.1%	849,322	45.4%
1998-2013	**+131,516**	**-27,223**	**-6.2%**	**+278,772**	**+12.6%**

Table 17. Acreage of land irrigated in Montana by method of water distribution. Data compiled from U.S. Department of Agriculture Farm and Ranch Irrigation Surveys: available at http://www.agcensus.usda.gov/Publications/Irrigation_Survey/

Montana Sprinkler Irrigation Field Delivery Methods									
	Total Sprinkler	**Center Pivot**		**Side roll, wheel move**		**Hand move**		**Other**	
	Acres	*Acres*	*% of Total*	*Acres*	*% of Total*	*Acres*	*% of Total*	*Acres*	*% of Total*
1998	570,550	241,287	42.3%	231,547	40.6%	86,555	15.2%	11,161	2.0%
2003	773,008	495,051	64.0%	196,136	25.4%	61,341	7.9%	20,480	2.6%
2008	881,591	583,795	66.2%	234,472	26.6%	48,106	5.5%	15,218	1.7%
2013	849,322	595,590	70.1%	164,267	19.3%	44,766	5.3%	26,345	3.1%
1998-2013	**+278,772**	**+354,303**	**+27.8%**	**-67,280**	**-21.2%**	**-41,789**	**-9.9%**	**+15,184**	**+1.1%**

Table 18. Breakdown of sprinkler irrigation techniques and the amount of acreage under each method in Montana. Data compiled from U.S. Department of Agriculture Farm and Ranch Irrigation Surveys: available at http://www.agcensus.usda.gov/Publications/Irrigation_Survey/

Although conversion to center pivot irrigation has been shown to increase water delivery efficiency and boost crop productivity, little research has investigated the impacts to historic surface-water/groundwater interactions. Flood irrigation typically results in a crop consumptive use of approximately 25%, with much of the remaining 75% of water returning to the watershed through surface and groundwater recharge. In comparison, center pivot methods may operate with crop consumption ratios of 85%, resulting in little water returning to the system (Roberts, 2012). Increased crop productivity associated with center pivot systems has made them highly desirable to agricultural producers throughout the United States. Due in part to the large initial costs associated with conversion, the widespread proliferation of center pivot systems has been confined to the Montana's most fertile agricultural lands.

Many hydrologic systems in Montana have been heavily influenced by over 100 years of traditional flood irrigation practices. The conversion of large amounts of acreage from flood to center pivot irrigation has far reaching consequences that are difficult to

predict. In just the last 15 years the acreage under center pivot irrigation in Montana has more than doubled, while the land irrigated with gravity fed flood methods has declined slightly (Table 17 & 18). In 1998, center pivot systems accounted for 14% of all the irrigated acreage in Montana; by 2013 that number had grown to 31%. Temporal lags in surface water/groundwater exchanges suggest that the consequences of these modifications may not be fully understood until years after the conversion is completed. Several studies have stressed the importance of late season irrigation return flows in regional watersheds and documented declining groundwater levels and reduced groundwater recharge associated with changing irrigation practices (Fernald et al., 2010; Kendy & Bredehoeft, 2006; Venn et al., 2004). A reduction in groundwater storage/supply may change the hydrologic system and diminish or eliminate critically important return flows that sustain riverine ecosystems during periods of low flow (Peck et al., 2001).

A significant portion of the Jefferson Basin continues to irrigate using traditional gravity fed surface flooding methods (11,500 acres representing 25% of the irrigated area). Consequently, the Jefferson River—as are many rivers in Montana—is dependent on late season (August-October) irrigation return flows to sustain streamflow volumes necessary to support both agriculture and aquatic plant and animal communities. Included in a 2008 fisheries report, MT FWP fisheries biologist Ron Spoon monitored and compared sources of Jefferson River inflow during the 2007 irrigation season (2008). Figure 43 copied from that report, illustrates the importance of return flows on the Jefferson late in the irrigation season. As discharge from the Jefferson's largest tributary

(the Big Hole River) dwindled by early August in 2007, irrigation return flows contributed a relatively larger proportion of total Jefferson River streamflow volume during the late summer period.

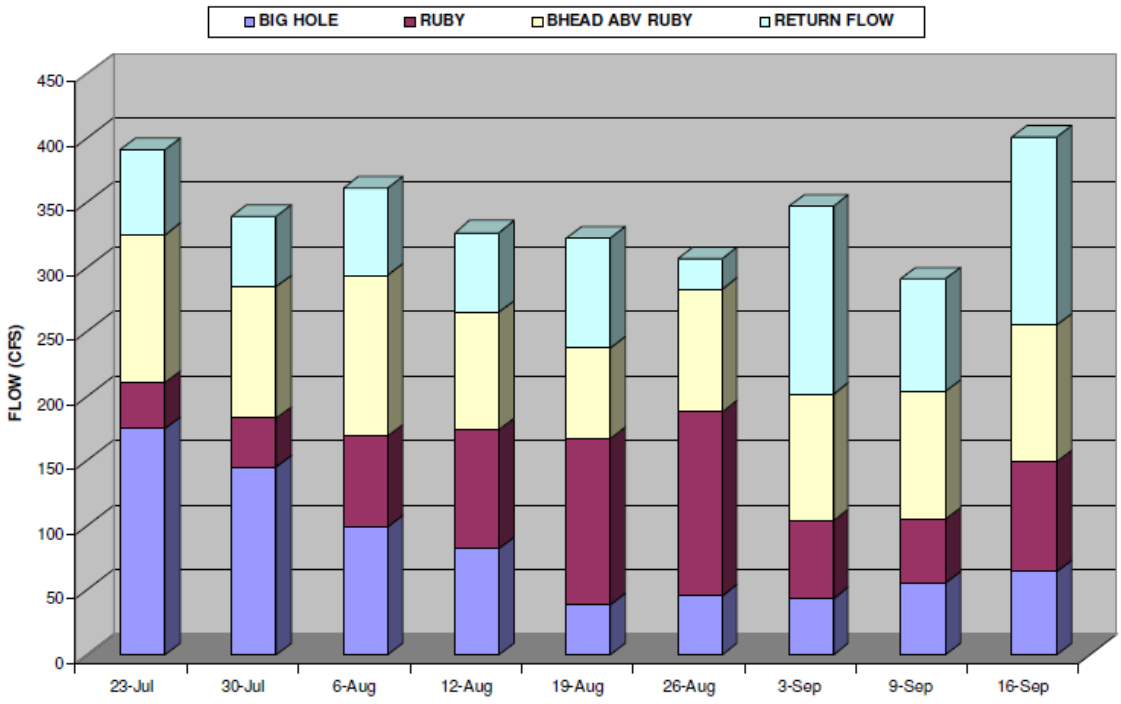


Figure 43. Comparison of Jefferson River inflows from four sources in 2007. Figure copied from MT FWP fisheries report (Spoon, 2008, p. 53).

Changing irrigation practices in the Jefferson and its tributaries have the potential to reduce groundwater levels and late season base flow levels. Irrigation conversion from flood to pivot in the areas surrounding Poindexter Slough in the Beaverhead Valley contributed to a significant decline in the fishery and a reduction of the resource's local economic impact (Beaverhead Watershed Committee, 2014). Pivot conversion was also a factor in the well-publicized dewatering issues on the Smith River (located in central MT) in the early 2000's (Ziemer et al., 2006). The dewatering on the Smith prompted a

MT Supreme Court case in 2006 that forced state agencies within Montana to legally recognize the "connectivity" between surface-water and groundwater (Herring, 2006). The Court's landmark decision was grounded in the prior appropriation doctrine. Groundwater pumping associated with the establishment and conversion to center pivot irrigation had negatively impacted senior surface water rights on the Smith River. The overall impacts of center pivot conversion on surface-water and groundwater cycles are not yet fully understood. Future research must consider the tradeoffs associated with conversion in the context of anticipated near term changes to historical hydro-climate regimes.

This chapter described two different mechanisms that will complicate efforts to manage future periods of drought in the region. Climate change poses the gravest threat to stability of the Jefferson Basin water use system as future periods of drought may exceed the severity of those experienced in the 1930's and late 1980's. Shifting irrigation practices also threaten to upset historical groundwater/surface water interactions and may function to reduce overall drought resilience in some Montana watersheds. Despite these challenges, as the next chapter will show, there are methods that may be implemented to increase resilience and reduce drought related stresses in the Jefferson Basin.

CHAPTER FIVE

METHODS TO INCREASE DROUGHT RESILIENCE & CONCLUSIONS

Increasing Drought Resilience

While development, changing land use patterns and a shifting climate pose threats to the Basin, there are mechanisms (both prospective and currently in place) that may function to increase resilience and lessen impacts from future periods of severe drought. The ideas discussed in the remainder of this section were recommended by Jefferson water stakeholders as means to increase drought resilience in the Basin. Informal stakeholder interviews were conducted between November of 2014 and December 2015 using the interview guide outlined in appendix E. A total of 5 interviews were completed with stakeholders involved in the Jefferson River Watershed Council, the local Trout Unlimited chapter and government agencies responsible for water and wildlife management (Montana Fish Wildlife and Parks). The goals of the following proposals are to maintain flows during drought that are sufficient to allow for continued agricultural use, sustain aquatic ecosystems and maintain/enhance the sports fishery.

Expanding Reservoir Storage in the Basin

As described in chapter 4, climate models are predicting that a decrease in summer-season precipitation and stream discharge will correspond with an increase in annual precipitation and streamflow values in the Jefferson Basin. The models are also predicting that mean summer maximum temperatures may rise significantly (4-5˚F) by as early as the 2020's. Capturing augmented supplies of water during fall, winter and spring

may buffer against the projected decreases in growing season water availability. Expanding reservoir storage capacity has been proposed as a method to improve drought resilience and the Jefferson River's fishery. Plans to increase basin storage have broad appeal among stakeholders and have been touted by some as a "win-win" solution.

Of the Jefferson's three major tributaries, the Big Hole is currently the only basin that lacks a large-scale reservoir. An attempt by the Bureau of Reclamation to dam the Big Hole in the 1960's was met with fierce opposition from local ranchers, state government agencies and conservationists ("Dam on River Seen as Threat", 1964). The Big Hole River currently supports a robust commercial fishery and it is unlikely that a substantial drainage project will be permitted in the drainage in the near future. It is also improbable that a new large capacity reservoir would be constructed in either the Ruby or Beaverhead drainages (both basins currently contain large reservoirs). Expanding Ruby or Clark Canyon Reservoirs is the most realistic scenario to increase water supplies that would sufficiently maintain Jefferson River summer baseflows during drought. Instream flows destined for the Jefferson would also benefit either of the respective lower Ruby or Beaverhead Basins which also suffer from late-summer dewatering issues.

Recent proposals to increase Ruby Reservoir storage capacity were mired by resistance from local landowners and a lack of sufficient funding. In June of 2014 the state of Montana completed a $17 million, four year renovation of the Ruby Dam replacing aging infrastructure on the 75 year old dam (Lundquist, 2014). The much needed renovations included replacement of the reservoirs impaired spillway and outflow channel. An initial plan for the dam's overhaul crafted in 2009 called for a seven foot rise

in the spillway height that would have resulted in a substantial increase in water storage at the reservoir. The plan was touted as a "win-win arrangement" between groups that have historically been at odds over water management; agriculturists and angling groups. Water generated from the increased storage was to be used to supplement downstream flows on the Jefferson River, protecting aquatic populations that have historically experienced drought induced fish kills (Person, 2010).

Although local groups such as the Jefferson River Watershed Council (JRWC), the Ruby River Water Users Association and the George Grant Chapter of Trout Unlimited supported the 2009 plan, local landowners adjacent to the reservoir opposed expansion fearing a loss of acreage resulting from the heightened water level. Well known Montana landowner and late-night talk show host David Letterman wrote a letter to former Governor Brian Schweitzer in April of 2009 advising the state to reconsider its plans stressing "potential environmental consequences" resulting from heightened water levels (Person, 2010). In May 2010 the Montana DNRC (the owner of the dam) officially shelved the expansion plans citing financial concerns. Increasing the size of the reservoir was anticipated to raise costs by $2.5 million, a portion of which would reimburse landowners and purchase the required water rights (Person, 2010). The project would have stored 2,665 acre feet of augmented water designated for instream flows on the Jefferson—enough to increase Jefferson flows by approximately 40 cfs over a 30 day period. Trout Unlimited agreed to contribute to the project financially, offering $900,000 (mostly through grants) to be used for a prorated share of the water and corresponding construction costs (JRWC, 2010).

According to a 2014 report by the DNRC, Ruby reservoir currently contributes over $830,000 in annual angling based economic benefits for the region (MT DNRC, 2014a). That value was computed using a 2006 US Fish and Wildlife report that estimates economic benefits based on annual number of angler days (2006). Angler day numbers are determined through biennial fishing surveys conducted by MT DNRC (see appendix B). The economic value calculated for the Ruby includes both flat water (resulting from the reservoir itself) and downstream benefits. Economic benefits derived from recreational sport fishing are substantial in Montana. The 2014 DNRC report calculated that resident and nonresident angler expenditures contributed over $900 million to Montana's economy (MT FWP, 2014a). The Bureau of Economic Analysis estimates that in 2014 Montana's total economic output was $44.1 billion. Therefore, angler expenditures statewide alone represented over 2% of Montana's total economic output in 2014 (U.S. Department of Commerce Bureau of Economic Analysis, 2015).

A unique agreement between agricultural water users, government agencies and conservationists on Painted Rocks Reservoir (West Fork of the Bitterroot) allows MT FWP to reserve 15,000 acre-feet of water per year as instream flows for fisheries (MT DNRC 2014b). Painted Rocks reservoir is owned my MT DNRC and operated by a local water users association. Agricultural rights total 10,000 acre-feet per year and MT DNRC lists both irrigation and fisheries as primary water uses for the reservoir (MT DNRC, 2014b). Costs for repair and maintenance are split between DNRC and the local water users association. As a portion of the operating agreement, MT FWP pays the salary of a water commissioner who manages the Painted Rocks Reservoir and assures water

deliveries reach their targets (Grassy, 2015). The DNRC releases flows for fisheries during late summer based on streamflow trigger points established downstream on the mainstem of the Bitterroot. The cooperative agreement has buffered water supplies and improved the fishery's economic resource value on one of Montana's most heavily fished streams. Over the last 15 year period of prolonged drought, portions of the Bitterroot have remained open to fishing despite FWP initiated closures on other regional rivers (Grassy, 2015).

Former MT FWP Jefferson River fisheries biologist Bruce Rehwinkel and current biologist Ron Spoon have proposed establishing a cooperative agreement on the Jefferson similar to the one currently in place in the Bitterroot at Painted Rocks (Ron Spoon, personal communication, November 11, 2015). Through either reservoir expansion at Ruby Reservoir or the purchase of existing water rights (upstream from Ruby Reservoir), a sufficient quantity of water might be stored and made available for fisheries during late summer baseflow recessions. As with the Painted Rocks arrangement, the appointment of a water commissioner on the Jefferson would function to ensure proper implementation of the agreement and reduce conflict. The state appointment of a water commissioner in Montana watersheds is controversial and requires approval of the local district court. Furthermore, the commissioner's salary is typically funded by local water users or irrigation districts (the process is detailed under Montana Code Annotated 85-5-101).

Augmenting late summer flows would likely reduce drought related fish mortality and improve fish recruitment (thereby stimulating recreational use and increasing the Jefferson fishery's value). As described in chapter 3, the Jefferson River suffered over

350 days of fishing restrictions between 2000 and 2015. These closures negatively impact recreational outfitters and intensify angling pressure on nearby unrestricted streams. A cost-benefit analysis comparing costs of Ruby Reservoir expansion (or the purchase of existing water rights) versus the benefits derived from heightened downstream recreational use on the Ruby and Jefferson Rivers should be performed to determine the viability of future plans.

Modify the Current JRWC Drought Management Plan

Although the existing drought management plan on the Jefferson has contributed to increased drought resilience since its implementation (see chapter 3), there are concerns related to its future effectiveness in the face of extreme and prolonged periods of drought. The primary goal of the JRWC drought plan is to maintain a minimum streamflow of 50 cfs in the dewatered Silver Star to Waterloo stretch of the upper Jefferson. In both 2006 and 2007 flows dropped well under the 50 cfs level at the stream gage near Silver Star (as low as 25 cfs on 9/1/2007) (USGS, 2015c). The Silver Star gage location represents a relatively large drainage area of 7,759 square miles and both individuals and conservation groups have suggested that the 50 cfs emergency flow volume is insufficient to protect aquatic ecosystems (Dave McKernan, personal communication, January 11, 2016). Despite the limitations of the current plan, there is potential to broaden the scope, impact and effectiveness of future management actions.

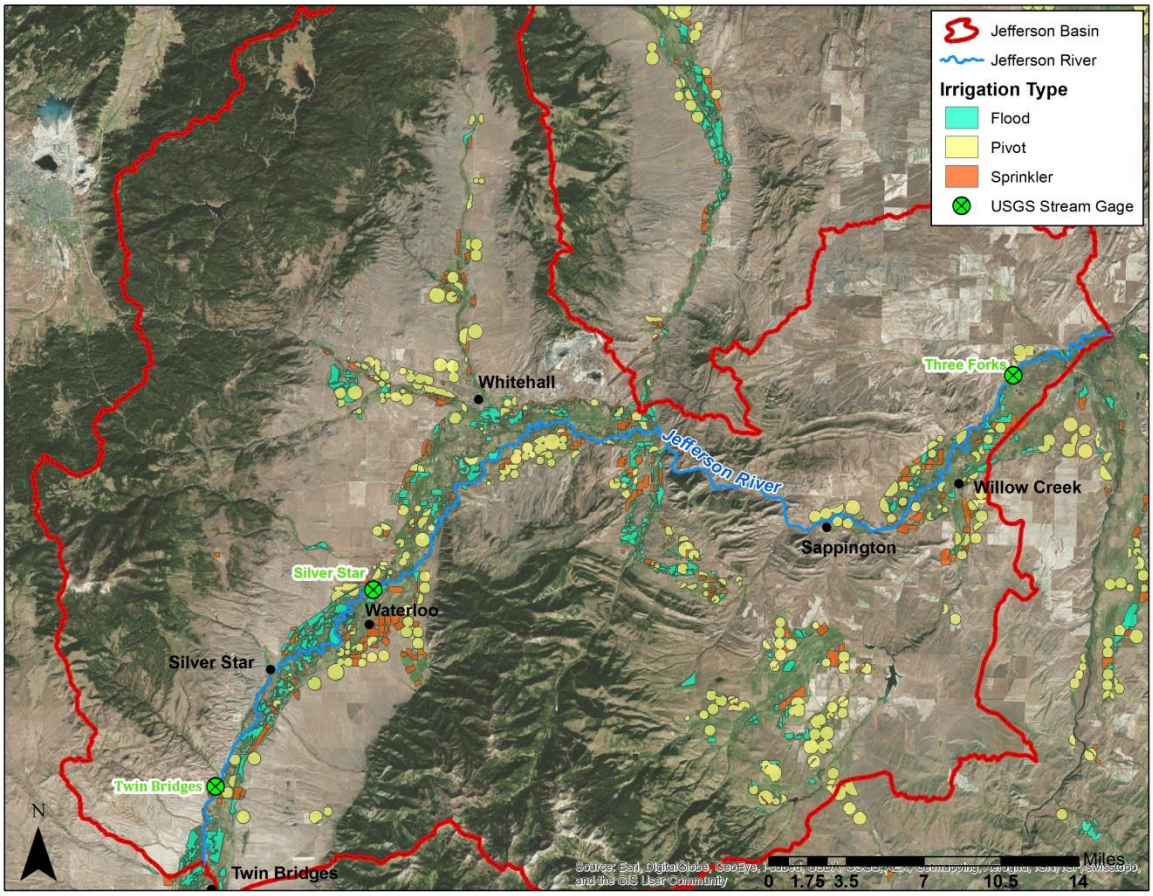


Figure 44. Map of irrigated lands in the Jefferson (according to the MT Department of Revenue) with locations of major communities and currently active stream gages included. Data sources: MT NRIS—GIS Clearinghouse [USGS –gage locations, MT Department of Revenue –land use classification/irrigation type)].

One method to enhance the future viability of the existing drought plan is to expand the buy-in from local water users. At present, a relatively small subset of water users in the upper Jefferson voluntarily reduce surface water withdrawals during low flows. Furthermore, the Jefferson River Watershed Council represents irrigators in only the upper half of the Jefferson Basin (upstream from Whitehall). Broadening the scope of plan to include new users from the lower basin may increase watershed-wide collaboration and enhance the river's fishery.

As evidenced in archived magazine articles and data from Ron Spoon's fisheries assessment, the lower Jefferson supported a more vibrant fishery before the droughts (and subsequent fish kills) of the late 1980's (Law, 1984; Spoon, 2008). Water users in the lower portion of the watershed also benefit from groundwater return flows partially sourced from flood irrigated fields in the upper basin (Brancheau, 2015). During late summer streamflow depressions, stream gages typically record three times greater flows at the Three Forks location than those measured at the Silver Star gage 63 miles upstream (despite limited surface water inputs between the gages) (Figure 44). Convincing additional users throughout the Jefferson Basin to contribute water for instream flows during drought is a necessary, albeit challenging proposition.

It is important to consider the negative economic consequences for irrigators that donate water under the JRWC drought plan. MT FWP fisheries biologist Ron Spoon recalled a farmer giving him a tour of a fallowed field during a drought in the mid-2000's. The point of the exercise was to demonstrate the tangible, on the ground impacts of their management actions. Contributing water users, some of which have economically marginal farming operations, are essentially donating water (resulting in a net loss financially). Plans to compensate irrigators for their water have been proposed by MT FWP and Trout Unlimited but have been met with resistance (Ron Spoon, personal communication, November 11, 2015). Users have voiced concerns that the acceptance of money for instream flows might eventually result in a binding, long-term agreement. The positive ecological impacts of establishing higher instream flow goals for the JRWC drought plan (two to three times the current 50 cfs minimum at Parsons Bridge) must be

compared with the negative economic consequences for agricultural users who may have to fallow fields to meet targets. The next section will discuss methods that might expand the scope of the current Montana water leasing program (and make leasing more palatable to Jefferson Bain irrigators).

Water Leasing for Instream Flows

Creating a temporary and non-binding water leasing program in the Jefferson may potentially increase the amount of water available for instream flows. As discussed in chapter 3, water leasing statutes in Montana were initially met with fierce opposition from the agricultural community. The program that emerged allows for existing water rights to be leased—or converted all together—to instream flows for fisheries. The current process involves an abundance of due diligence and may take years to complete (Bradshaw & Ziemer, 2007). The intricacies of the prior appropriation doctrine require that for a water right to be leased it must first be clearly established that the change in use won't adversely impact rights of senior users. By streamlining a water leasing process for those with recognized senior water rights and enabling them to lease water on a temporary basis (e.g.. when flows at the Twin Bridges gage drop below established trigger points) a dry-year water leasing option could be established in the Jefferson Basin that would benefit both irrigators and anglers.

Tributary Enhancement Projects

A 2007 paper by Trout Unlimited legal experts Stan Bradshaw and Laura Ziemer discusses lessons learned after 10 years of implementing leasing projects in Montana. They observed that water leases were most effective when established on tributaries (as

opposed to mainstems) and used in conjunction with other habitat restoration techniques. Tributary restoration projects on the Jefferson have largely contributed to the increase in fish densities recorded over the last 10 years (Spoon, 2008; Trout Unlimited, 2014; Dave McKernan, personal communication, January 12, 2016).

Beginning in the late 1980's, MT FWP began a collaborative project with Trout Unlimited to improve Jefferson River tributaries for enhancement of the rainbow trout fishery (Trout Unlimited, 2014). Rainbow numbers plummeted in the Jefferson following the droughts of the late 1980's and early 2000's (Spoon, 2008). In the early 2000's the drought-critical Waterloo stretch of the Jefferson hosted approximately 288 fish per mile. In 2007 that number rebounded to 1,214 fish per mile—929 rainbows and 285 browns (Trout Unlimited, 2014). Much of the early tributary restoration occurred on Hells Canyon Creek which responded quickly to the management activities. Willow Springs Creek, Parson Slough, Jefferson Slough and Big Pipestone Creek have been the focus of recent restoration efforts (JRWC, 2010; Christensen, 2014). Figure 45 displays the tributaries that have received restoration work since the mid-1980's. The restoration projects range from the installation of fish screens to streambank stabilization and invasive species management. Restoration has been funded and carried out contributions from government agencies (NRCS, DNRC) conservation groups (Trout Unlimited), and the JRWC. Further tributary restoration efforts will only work to improve the Jefferson River fishery and buffer against extreme summer water temperatures.

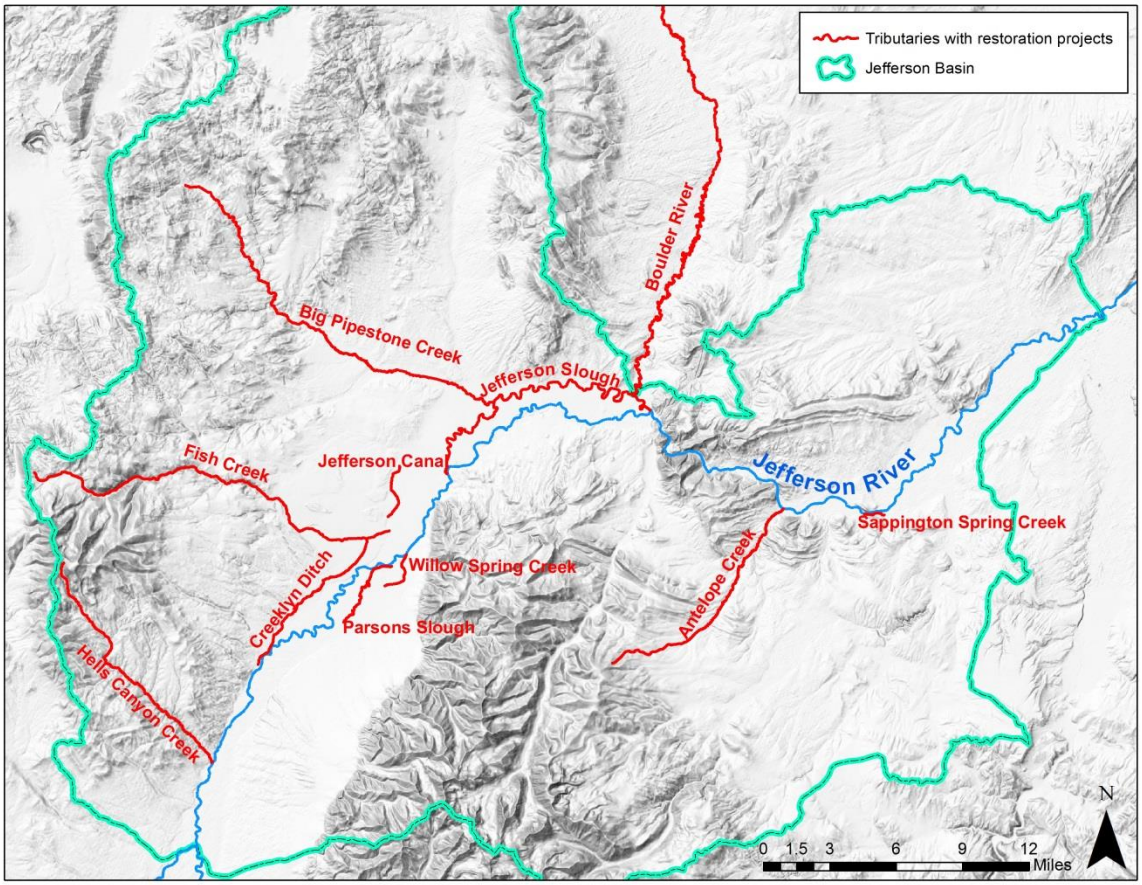


Figure 45. Map displaying tributaries of the Jefferson River (red lines) that have had some type of restoration project completed (1990's-present). Data source: MT NRIS—GIS Clearinghouse.

Irrigation Conversion

The Jefferson Valley (and many other agriculturally dominated regions in Montana) has seen a large scale conversion of irrigation practices over the last 30 years from gravity fed flood systems to sprinkler and center pivot methods (Tables 17 & 18). As described in detail in chapter 4, the upgrade in irrigation efficiencies has resulted in unforeseen consequences for some basins. The Jefferson River currently benefits from irrigation return flows during late-summer surface flow depressions (Spoon, 2008; JRWC, 2010). Floating the middle stretches of the Jefferson in August or September

demonstrates the influence of these return flows—seepage from steep banks and "artificial" waterfalls are evident. Utilizing groundwater data from the Montana Bureau of Mines and Geology Upper Jefferson River Project and a recent Master's thesis investigating groundwater in the Waterloo area, it may be possible to identify portions of the Basin that would result in net overall benefits from the application of flood irrigation (Montana Bureau of Mines and Geology, 2016; Brancheau, 2015, Michael Richter, personal communication, 2016). Harnessing this data and targeting important groundwater sink areas, Jefferson Basin managers might incentivize water users to flood irrigate when surface water supplies are plentiful (April-June). Groundwater returns often result in delayed flows that are reduced in temperature (relative to stream temperatures).

The recommendations laid out in this chapter are not meant to be viewed as "silver bullets" that will solve the Jefferson Basin's drought problems singlehandedly. A combination of methods will be the most impactful and generate the potential to significantly boost drought resilience. Tributary restoration projects that increase trout reproduction and recruitment must be partnered with methods to sustain instream flows during drought that reduces fish mortality. The Jefferson's recent attempts to boost resilience are only possible due to what may be termed "Montana style" cooperation between irrigators, resource management agencies and conservation groups. This conservation strategy has been successfully applied to a broad array of natural resource issues throughout the state—from Montana's recreational stream access provisions to the preservation of bull trout on the Blackfoot River and sage grouse on the eastern Montana prairies.

Conclusions

The desktop resilience assessment (RA) that was performed methodology on the Jefferson Basin SES properly described the dynamics of the system and helps place its current state within the context of historical conditions. Resilience assessments are performed to understand weaknesses in social ecological systems and the biological and social processes that rely on them. Although there are strengths associated with tailoring resilience assessments to individual problem statements or geographical areas, a lack of consistent methodologies also poses challenges. The existing framework that encourages varied approaches makes it difficult to quantitatively compare RA's—even if the areas studied or topics investigated are comparable.

Future attempts to perform a RA similar to the one utilized in this study should narrow its focus unless multiple researchers are involved. The synthesis of physical and social sciences required to complete a RA of drought related issues necessitates a broad and diverse research background. To appropriately and effectively analyze the drivers of a water use SES it would be beneficial to include researchers with backgrounds in environmental policy, hydrology, climatology, social sciences and sustainable natural resources management. As a single researcher with no background in the social sciences it was difficult to integrate the stakeholder interview portion of the thesis into the overall resilience assessment.

For this thesis it would have been more productive to investigate a specific aspect of the Jefferson SES as opposed to the cursory overview performed. Further research into historical streamflow levels and resultant impacts to land use patterns and agricultural

productivity in the Jefferson Basin would benefit from a more comprehensive assessment of the drought plan. Utilizing the water rights and climate projection data compiled in this thesis (appendices A & D) it may be possible to roughly estimate drought vulnerable water rights under future climate and streamflow conditions. An understanding of the physical connectivity between water rights, stream discharge and drought would also benefit water users—helping to clarify conflicts under prior appropriation.

The plight of the Jefferson described in this thesis is a harbinger of what might play out on other vulnerable streams in Montana as climate change increases drought frequency and severity. The droughts weathered in 1988 and the early 2000's brought many streams in MT to the brink of total system collapse (from both an ecological and agricultural water use standpoint). Although it is highly likely that the Jefferson will be challenged by extreme conditions in the future, it is also evident that there is potential for the basin to transition into alternate and more resilient regimes. As recent fish and angler surveys illustrate, the productivity of the Jefferson River (from a sports fishery standpoint) has improved over the past 15 in the face of extreme drought and shifting agricultural demands. A variety of internally controlled system variables (i.e. the JRWC drought plan, restoration efforts) have functioned to reduce stresses on the fishery and protect limited summer baseflows. Despite this, the reality is that water supplies in the Jefferson Basin are scarce and demands placed on the system are high. Future changes to the hydrology and climate of the Jefferson Basin—which are externally controlled—may be beyond the scope of current internal management mechanisms.

The Jefferson River is unique in many aspects when compared to the Missouri River's other more renowned headwaters (the Gallatin and Madison). The Jefferson is still dominated by agricultural uses and has yet to see the influence of amenity migration experienced in proximate watersheds. Although the extreme lower portions of the Jefferson Basin have started to see new residential development—stemming from the frenzied growth in the Bozeman bubble—the rest of the basin has seen stagnant or declining populations (see chapter 3). This relatively minor amount of development in the Jefferson presents an opportunity for the watershed to avoid groundwater depletions triggered by the proliferation of residential wells in the neighboring Gallatin Valley (MT DNRC Water Management Bureau, 2008). Furthermore, a 2014 ruling by a MT District Court judge closing the exempt well loophole that plagued MT watersheds for over 10 years may function to encourage sustainable groundwater development in the Jefferson. The Basin also benefits from a unique subset of water users and natural resource managers that have successfully worked to improve conditions in the face of extreme environmental challenges.

The Jefferson River is on the brink of an aquatic ecosystem recovery to a state not seen in 30 years and commercial fishing outfitters are beginning to take note. It is important to reiterate that this success would not have been possible without the efforts of irrigators that have relied on the Jefferson's water for generations. By planning for inevitable climate inducted changes to the hydrology of the Basin, and continuing the successful Montana-style conservations strategies that have been implemented, the Jefferson may soon lose its status as the "river that fisherman forgot".

REFERENCES CITED

American Water Resources Association [AWRA]. 2011. *AWRA Policy Statements: Integrated Water Resources Management in the US*. Retrieved from http://www.awra.org/policy/policy-statements-IWRM.html

American Wildlands. (2009). *Priority Linkage Assessment: The High Divide Conservation Area*. Technical Report: Version 1. Retrieved from http://www.brainerd.org/downloads/HighDivide_PLA_AWL_2009.pdf

Associated Press. (1988, July 24). Arid conditions killing area fish. *Butte Standard*.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., ... &

Barsugli, J. J., Guentchev, G., Horton, R. M., Wood, A., Mearns, L. O., Liang, X. Z., ... & Goddard, L. (2013). The practitioner's dilemma: how to assess the credibility of downscaled climate projections. *Eos, Transactions American Geophysical Union*, *94*(46), 424-425.

Bartholomew, M. J., Lewis, S. E., Russell, G. S., Stickney, M. C., Wilde, E. M., & Kish, S. A. (1999). Late Quaternary history of the Beaverhead River canyon, southwestern montana. *Guidebook to the Geology of Eastern Idaho*, 237-250.

Beaverhead Watershed Committee. (2004). *Clark Canyon Water Supply Company: Watershed Conservation Plan*. Retrieved from http://www.beaverheadwatershed.org/wp-content/uploads/2015/09/CCWSC-Draft-Water-Conservation-Plan-2004.pdf

Beaverhead Watershed Committee. (2014). *Poindexter Slough Project Summary*. Retrieved from http://www.beaverheadwatershed.org/wp-content/uploads/2012/03/Poindexter-Project-Sumamry.docx

Berkes, F., & Folke, C. (2000). Linking social and ecological systems for resilience and sustainability. *Linking social and ecological systems: management practices and social mechanisms for building resilience*, *1*, 13-20. Cambridge University Press.

Betts, A. K. (2011). Vermont climate change indicators. *Weather, Climate, and Society*, *3*(2), 106-115.

Blackfoot Challenge. (n.d.). *What We Are, What Is Special About The Blackfoot Valley*. Retrieved from http://biz170.inmotionhosting.com/~blackf22/Clone/?p=9

Blatter, J., & Ingram, H. M. (2001). *Reflections on water: New approaches to transboundary conflicts and cooperation*. MIT Press.

Bradshaw, S., & Ziemer, L. (2007). Water leasing in Montana through Trout Unlimited's Eyes. PERC Report, 25(2). Retrieved from http://www.perc.org/articles/water-leasing-montana-through-trout-unlimiteds-eyes

Brancheau, N. (2015). *A Hydrogeologic Evaluation of the Waterloo Area in the Upper Jefferson River Valley, Montana* (master's thesis). Retrieved from http://digitalcommons.mtech.edu/grad_rsch/11/

Bryan, W.L. (1996). *Montana's Indians: Yesterday and Today*. Unknown: American & World Geographic Publishing. Retrieved from https://books.google.com/books?id=kTX_SsG7M10C

Bryan, K.J. (2015, September 20). Golden Sunlight cutback mirrors global gold trend. *Montana Standard*. Retrieved from http://mtstandard.com/news/local/golden-sunlight-cutback-mirrors-global-gold-trend/article_9a08597f-c64a-59a0-8050-b4c1a9b32fcd.html

Burke, M. (2013, April 1). America's Top 10 Flyfishing States. *Forbes*. Retrieved from http://www.forbes.com/sites/monteburke/2013/04/01/americas-top-10-flyfishing-states/

California. (n.d.) From *Wikipedia*. Retrieved November 19, 2015 from https://en.wikipedia.org/wiki/California

Carter, D. (1988a, August 13). Fish going down the Big Hole drain. *Montana Standard*.

Carter, D. (1988b, August 14). Rocky times for rivers: Three perspectives. *Montana Standard.*

Carter, D. (1988c, August 27). Fish lose bout with drought. *Montana Standard.*

Cayan, D. R. (2008). Human-induced changes in the hydrology of the western United States. *Science*, *319*(5866), 1080-1083.

Chaffin, B. C., Craig, R. K., & Gosnell, H. (2014). Resilience, Adaptation, and Transformation in the Klamath River Basin Socio-Ecological System. Idaho Law Review, 2015.

Christensen, K. (2014, June 13). $1.8 million in creek rehabilitation approved by Legislature; work starts this summer. *Montana Standard*. Retrieved from http://mtstandard.com/million-in-creek-rehabilitation-approved-by-legislature-work-starts-this/image_e1474926-f2b2-11e3-9c0a-001a4bcf887a.html

Clark Fork Coalition. (2014). *Our Accomplishments.* Retrieved from http://clarkfork.org/why-were-here/accomplishments/

Cook, B. I., Seager, R., & Smerdon, J. E. (2014). The worst North American drought year of the last millennium: 1934. *Geophysical Research Letters*, *41*(20), 7298-7305.

Cosens, B. A., Gunderson, L., & Chaffin, B. C. (2014). The Adaptive Water Governance Project: Assessing Law, Resilience and Governance in Regional Socio-Ecological

Water Systems Facing a Changing Climate. *Natural Resources and Environmental Law Edition of the Idaho Law Review*.

Dam on River Seen as Threat. (1964, November 26). *Spokane Daily Chronicle*. Retrieved from https://news.google.com/newspapers?nid=1338&dat=19641126&id=81tYAAAAIBAJ&sjid=lvcDAAAAIBAJ&pg=3509,6988382&hl=en

Demetriades, A. (2005). The True Utmost Reaches of the Missouri. *Montana Outdoors, July-August*. Retrieved from http://fwp.mt.gov/mtoutdoors/HTML/articles/2005/MissouriSource.htm

Dietrich, E. (2015, March 30). Galltain County among fastest growing in nation. *Bozeman Chronicle*. Retrieved from http://www.bozemandailychronicle.com/news/city/gallatin-county-among-fastest-growing-in-nation/article_63b13f02-c08b-53eb-932d-98de3bda2e6c.html

Dracup, J. A., Lee, K. S., & Paulson, E. G. (1980). On the definition of droughts. *Water resources research*, *16*(2), 297-302.

ECONorthwest. (2008). *Irrigation in Montana: A Program Overview and Economic Analysis*. Retrieved from http://dnrc.mt.gov/divisions/cardd/docs/publications/AnEconomicAnalysisofIrrigationinMontana.pdf

Engle, N. L., Johns, O. R., Lemos, M. C., & Nelson, D. R. (2011). Integrated and adaptive management of water resources: tensions, legacies, and the next best thing. *Ecology and society*, *16*(1), 19.

Farr, W.E. (2001). When we were first paid: The Blackfoot Treaty, the western tribes, and the creation of the common hunting ground, 1855. *Great Plains Quarterly*, 21(2), 131-154.

Ferguson, J. J., Hall, B. C., & Randall, B. (2006). Keeping Fish Wet in Montana: Private Water Leasing: Working Within the Prior Appropriation System to Restore Streamflows. *Pub. Land & Resources L. Rev.*, 27, 1.

Fernald, A. G., Cevik, S. Y., Ochoa, C. G., Tidwell, V. C., King, J. P., & Guldan, S. J. (2010). River Hydrograph Retransmission Functions of Irrigated Valley Surface Water–Groundwater Interactions. *Journal of Irrigation and Drainage Engineering*, *136*(12), 823-835.

Field, C. B., Barros, V. R., Mastrandrea, M. D., Mach, K. J., Abdrabo, M. K., Adger, N., ... & Burkett, V. R. (2014). Summary for policymakers. *Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*, 1-32.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, 557-581.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global environmental change*, 16(3), 253-267.

Forstall, R.L. (1996). *Population of States and Counties of the United States: 1790 to 1990: From the Twenty-one Decennial Censuses.* Retrieved from http://www.census.gov/population/www/censusdata/PopulationofStatesandCountiesoftheUnitedStates1790-1990.pdf

French, B. (2014, May 29). Arctic grayling refuge: study works to boost scarce fish in Red Rocks Lakes NWR. *Billings Gazette*. Retrieved from http://billingsgazette.com/lifestyles/recreation/study-works-to-boost-scarce-arctic-grayling-in-red-rock/article_e82166c3-0ba7-5b45-acee-726b9de77670.html

Gillilan, D., & Brown, T. (1997). *Instream flow protection: seeking a balance in western water use*. Island Press.

Glaser, M., Krause, G., Ratter, B., & Welp, M. (2008, May). Human-Nature-Interaction in the Anthropocene. Potential of Social-Ecological Systems Analysis. *Human-Nature-Interactions in the Anthropocene: Potentials of Social-Ecological Systems Analysis.* Preparation Paper for the DGH-Symposium, Sommerhausen, 29th–31st May.

Global Water Partnership. (2010). *What is Integrated Water Resources Management?* Retrieved from http://www.gwp.org/The-Challenge/What-is-IWRM/

Gregory, R., Failing, L., & Higgins, P. (2006). Adaptive management and environmental decision making: a case study application to water use planning. *Ecological economics*, *58*(2), 434-447.

Grassy, J. (2015, May-June). Enough For All: Cooperation among irrigators, angler, and state agencies ensures that Painted Rocks Reservoir provides the Bitterroot River with enough water for both trout and crops each summer. *Montana Outdoors*. Retrieved from http://fwp.mt.gov/mtoutdoors/HTML/articles/2015/Painted Rocks.htm#.VpFSiFIgt-8

Groves, D. G., Yates, D., & Tebaldi, C. (2008). Developing and applying uncertain global climate change projections for regional water management planning. *Water Resources Research*, *44*(12).

Gunderson, L., & Holling, C. S. (2002). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press.

Gutkoski, J. (n.d.). *Montana River Action: Jefferson River*. Retrieved from http://www.montanariveraction.org/jefferson.river.html

Hall, A. (2014). Projecting regional change. *Science, 346*(6216), 1461-1462.

Hamlet, A. F., Mote, P. W., Clark, M. P., & Lettenmaier, D. P. (2005). Effects of temperature and precipitation variability on snowpack trends in the western United States. *Journal of Climate*, 18(21).

Hansen, A. J., Rasker, R., Maxwell, B., & Rotella, J. J. (2002). Ecological causes and consequences of demographic change in the New West. *Bioscience*, 52(2), 151.

Hayhoe, K., Wake, C. P., Huntington, T. G., Luo, L., Schwartz, M. D., Sheffield, J., ... & Troy, T. J. (2007). Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dynamics*, *28*(4), 381-407.

Headwaters Heritage Museum. (n.d.). *Headwater History Page One: 1350 BC to 1860s.* Retrieved from http://www.tfhistory.org/history%20Area%2001.html

Herring, H. (2006, April 15). Montana Supreme Court's Smith River Decision Could Set Precedent. *Newwest.net*. Retrieved from http://newwest.net/main/article/montana_supreme_courts_smith_river_decision_could_set_precedent/

Hidalgo, H. G., Das, T., Dettinger, M. D., Cayan, D. R., Pierce, D. W., Barnett, T. P., ... & Nozawa, T. (2009). Detection and attribution of streamflow timing changes to Climate Change in the Western United States. *Journal of Climate*,22(13).

Hiltzik, M. (2010, July 5). The false promise of Hoover Dam. *Los Angeles Times*. Retrieved from http://articles.latimes.com/2010/jul/05/opinion/la-oe-hiltzik-hoover-dam-20100705

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 1-23.

Holling, C. S. (1978). *Adaptive environmental assessment and management*. Chichester, UK: John Wiley and Sons.

Holling, C. S. (1986). The resilience of terrestrial ecosystems: local surprise and global change. *Sustainable development of the biosphere*, 292-317.

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, *4*(5), 390-405.

Holling, C. S., & Gunderson, L. H. (2002). Resilience and adaptive cycles. *Panarchy: Understanding transformations in human and natural systems*, 25-62.

Holmes, K., Dailey, S. C., & Walter, D. (2008). Montana: Stories of the Land: Montana Historical Society Press.

Holmes, K.., Dailey, S., Walter, D. (2008). *Montana: Stories of the Land*. Montana Historical Society Press. Retrieved from https://books.google.com/books?id=-FahazPXm3YC

Homestead Acts. (n.d.). In *Wikipedia*. Retrieved December 10, 2015 from http://en.wikipedia.org/wiki/Homestead_Acts

Imperial, M. T. (2005). Using collaboration as a governance strategy lessons from six watershed management programs. Administration & Society, 37(3), 281-320.

James, H. L. (1990). Precambrian geology and bedded iron deposits of the southwestern Ruby Range, Montana. *United States Geological Survey, Professional Paper;(USA), 1495*.

Jefferson River. (n.d.). In *Wikipedia*. Retrieved December 10, 2015 from https://en.wikipedia.org/wiki/Jefferson_River

Jefferson River Watershed Council. (2010). *JRWC Watershed Restoration Plan*. Retrieved from http://www.jeffersonriverwc.org/files/Plans/Restoration_Plan/JRWC_Watershed_Plan.pdf

Jefferson River Watershed Council. (2012). *2013 Drought Management Plan*. Retrieved from http://www.jeffersonriverwc.org/files/Plans/Drought_Management_Plan/JRWC_Drought_Mgt_Plan_2012.pdf

Johnson, B. (2004). Reexamining the geochemistry and geochronology of the Late Cretaceous Boulder Batholith, MT. *2004 Denver Annual Meeting of the GSA*. Retrieved from https://gsa.confex.com/gsa/2004AM/finalprogram/abstract_79593.htm

Kallis, G., Kiparsky, M., & Norgaard, R. (2009). Collaborative governance and adaptive management: Lessons from California's CALFED Water Program. *Environmental Science & Policy*, *12*(6), 631-643.

Kavulla, T. (2015, June 26). For Water Rights in Montana, It's Still the Wild West. *Wall Street Journal*. Retrieved from http://www.wsj.com/articles/SB10104187675579354294504581044301233247710

Kemmick, E. (2006, March 15). Billings reaches population milestone of 100,000. *Billings Gazette.* Retrieved from http://billingsgazette.com/news/local/billings-reaches-population-milestone-of/article_3e4a294a-7606-53a6-b6ce-7766f0f28136.html

Kendy, E., & Bredehoeft, J. D. (2006). Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. *Water Resources Research*, *42*(8).

Klos, P. Z., Link, T. E., & Abatzoglou, J. T. (2014). Extent of the rain-snow transition zone in the western US under historic and projected climate. *Geophysical Research Letters*, *41*(13), 4560-4568.

Knowles, N., Dettinger, M. D., & Cayan, D. R. (2006). Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, 19(18), 4545-4559.

Law, G. (1984). The river that fishermen forgot. *Outdoor Life, January* (173), 54-55.

Leach, W. D., & Pelkey, N. W. (2001). Making watershed partnerships work: a review of the empirical literature. Journal of water resources planning and management, 127(6), 378-385.

Leppi, J. C., DeLuca, T. H., Harrar, S. W., & Running, S. W. (2012). Impacts of climate change on August stream discharge in the Central-Rocky Mountains. *Climatic Change*, 112(3-4), 997-1014.

Lewis, M., Clark, W., & Moulton, G. E. (Eds.). (2003). *The Lewis and Clark journals: An American epic of discovery: The abridgment of the definitive Nebraska edition*. U of Nebraska Press.

Lundquist, J. D., Dettinger, M. D., Stewart, I. T., & Cayan, D. R. (2009). *Variability and trends in spring runoff in the western United States. Climate warming in western North America—evidence and environmental effects.* University of Utah Press, Salt Lake City, 63-76.

Lundquist, L. (2014, June 18). Repaired Ruby Dam to provide decades of water. *Bozeman Daily Chronicle*. Retrieved from http://www.bozemandailychronicle.com/news/environment/repaired-ruby-dam-to-provide-decades-of-water/article_39beef96-f67d-11e3-960c-001a4bcf887a.html

Malone, M. P., Roeder, R. B., & Lang, W. L. (1991). Montana: A history of two centuries: University of Washington Press.

Mantua, N. J., & Hare, S. R. (2002). The Pacific decadal oscillation. *Journal of oceanography*, *58*(1), 35-44.

Margerum, R. D., & Robinson, C. J. (2015). Collaborative partnerships and the challenges for sustainable water management. Current Opinion in Environmental Sustainability, 12, 53-58.

Maynard, J. A., Marshall, P. A., Johnson, J. E., & Harman, S. (2010). Building resilience into practical conservation: identifying local management responses to global climate change in the southern Great Barrier Reef. *Coral Reefs*, *29*(2), 381-391.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993, January). The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on*

Applied Climatology (Vol. 17, No. 22, pp. 179-183). Boston, MA, USA: American Meteorological Society.

Melillo, J. M., Richmond, T. C., & Yohe, G. W. (2014). Climate change impacts in the United States: the third national climate assessment. *US Global change research program, 841*. Retrieved from http://nca2014.globalchange.gov/downloads

Menne, M. J., Williams Jr, C. N., & Vose, R. S. (2010). *Long-term daily and monthly climate records from stations across the contiguous United States*. Retrieved from http://cdiac.ornl.gov/epubs/ndp/ushcn/access.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: whither water management?. *Science, 319*(5863), 573-574.

Montana Census & Economic Information Center. (2014). *Montana Population Projections*. Retrieved from http://ceic.mt.gov/population/popprojection stitlepage.aspx

Montana Climate Office. (2015). *Precipitation Yearly Normal for 1981-2010 from PRISM* [GIS data set]. Retrieved from http://mslapps.mt.gov/Geographic_Information/Data/DataList/datalist_Details?did={4C4B11BC-0853-47E1-A630-3924A6F0ED72}

Montana Department of Environmental Quality. (2014). *Lower Beaverhead River and Upper Jefferson River Temperature TMDLs*. Retrieved from http://ofmpub.epa.gov/ waters10/attains_impaired_waters.show_tmdl_document?p_tmdl_doc_blobs_id=67242

Montana Department of Fish, Wildlife and Parks. (1989). *Application for Reservations of Water in the Missouri River Basin above Fort Peck Dam*. (Volume 2: Reservation Requests for Waters above Canyon Ferry Dam). Retrieved from https://archive.org/stream/applicationforre02montrich#page/n1/mode/2up

Montana Department of Fish, Wildlife and Parks. (1998). *Environmental Quality Council Final Report to the 56th Legislature on Water Leasing*. Retrieved from http://fwp.mt.gov/fwpDoc.html?id=50300.

Montana Department of Fish, Wildlife and Parks. (2010). *Candidate conservation agreement with assurances for fluvial arctic grayling in the upper Big Hole River: 2010 Annual Report.* Retrieved from http://fwp.mt.gov/fwpDoc.html?id=33208

Montana Department of Fish, Wildlife and Parks. (2011). *Dewatered streams in Montana* [GIS data set]. Retrieved from http://fwp.mt.gov/gisData/shapefiles/ dewateredStreams.zip

Montana Department of Fish, Wildlife and Parks. (2013). *Statewide Fisheries Management Plan: Jefferson River Drainage.* (SWFMP Part IID, pp 231-236). Retrieved from http://fwp.mt.gov/fwpDoc.html?id=59176

Montana Department of Fish Wildlife & Parks. (2014a). *Summary of Research: Statewide Estimates of Resident and Nonresident Hunter & Angler Expenditures in Montana (2014)*. Retrieved from http://fwp.mt.gov/doingBusiness/reference/surveys/socialEconomic/hunting.html

Montana Department of Fish, Wildlife and Parks. (2014b). *Montana Lakes* [GIS database]. Retrieved from http://fwp.mt.gov/gisData/shapefiles/fwpLakes.zip

Montana Department of Fish, Wildlife and Parks. (2015). *Montana Statewide Angling Pressure, 2013: Summary Report.* Retrieved from http://fwp.mt.gov/fwpDoc.html?id=69030

Montana Department of Military Affairs. (2007). *2007 Update: State of Montana Mulit-Hazard Mitigation Plan and Statewide Hazard Assessment.* Retrieved from https://archive.org/stream/2007updatestateo2007tetr#page/n13/mode/2up

Montana Department of Natural Resources and Conservation. (n.d.). *State-Owned Water Projects*. Retrieved from http://dnrc.mt.gov/divisions/water/projects

Montana Department of Natural Resources and Conservation. (2014a). *The DNRC Economy: A Report for Montana 2014.* Retrieved from http://dnrc.mt.gov/dnrceconomy.pdf/view

Montana Department of Natural Resources and Conservation. (2014b). *Painted Rocks Dam: Fact Sheet*. Retrieved from http://dnrc.mt.gov/divisions/water/projects/docs/factsheets/paintedrocks_factsheet.pdf

Montana Department of Natural Resources and Conservation. (2015). *Montana State Water Plan*. Retrieved from http://dnrc.mt.gov/divisions/water/management/docs/state-water-plan/2015_mt_water_plan.pdf

Montana Department of Natural Resources and Conservation, Water Management Bureau. (2008). *Effects of Exempt Wells on Existing Water Rights*. Retrieved from http://leg.mt.gov/content/committees/interim/2007_2008/water_policy/meetings/minutes/wpic01152008_ex07.pdf

Montana Department of Natural Resources and Conservation, Water Resources Division. (2015). *Montana Water Rights* [GIS data set]. Retrieved from ftp://nris.mt.gov/public/dnrc/

Montana Department of Natural Resources and Conservation, Water Adjudication Bureau (2015). *Adjudication Status: Sorted by Drainage Basin Number*. Retrieved from http://dnrc.mt.gov/divisions/water/adjudication

Montana Department of Revenue. (2015). *Department of Revenue Final Land Unit Classification* [GIS database]. Retrieved from http://mslapps.mt.gov/Geographic_Information/Data/DataList/datalist_Details?did={4754A734-303D-4920-8CAA-F027D5F3EE58}

Montana State Engineer's Office. (1956). *Water Resources Survey: Jefferson County, Montana*. Retrieved from http://dnrc.mt.gov/divisions/water/water-rights/docs/survey-books/jeffersonwrs_1956.pdf

Montana State Engineer's Office. (1965). *Water Resources Survey: Madison County, Montana*. Retrieved from http://dnrc.mt.gov/divisions/water/water-rights/docs/survey-books/madisonwrs_1965.pdf

Montana State University Water Center. (2014). Water Rights in Montana. Retrieved from http://leg.mt.gov/content/publications/environmental/2014-water-rights-handbook.pdf

Montana Water Resources Division, Water Rights Bureau. (2003). *Montana's Basin Closures and Controlled Groundwater Areas*. Retrieved from http://dnrc.mt.gov/divisions/water/water-rights/docs/new-appropriations/basinclose-cgw_areas.pdf

Montana Watershed Coordination Council. (2015). *Watersheds Directory*. Retrieved from http://www.mtwatersheds.org/watershed-groups/

Mote, P. W. (2006). Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. *Journal of Climate*, 19(23), 6209-6220.

National Agricultural Statistics Service. (1998). *1998 Farm and Ranch Irrigation Survey*. Retrieved from http://www.agcensus.usda.gov/Publications/1997/Farm_and_Ranch_Irrigation_Survey/

National Agricultural Statistics Service. (2003). *2003 Farm and Ranch Irrigation Survey*. Retrieved from http://www.agcensus.usda.gov/Publications/2002/FRIS/

National Agricultural Statistics Service. (2008). *2008 Farm and Ranch Irrigation Survey*. Retrieved from http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/

National Agricultural Statistics Service. (2013). *2013 Farm and Ranch Irrigation Survey*. Retrieved from http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/

National Agricultural Statistics Service. (2014). *Montana 2014 Annual Statistical Bulletin*. Retrieved from http://www.nass.usda.gov/Statistics_by_State/Montana/Publications/Annual_Statistical_Bulletin/2014/Montana_Annual_Bulletin_2014.pdf

National Centers for Environmental Information. (2014). *Billion-Dollar Weather and Climate Disasters: Table of Events*. Retrieved from https://www.ncdc.noaa.gov /billions/events

National Centers for Environmental Information. (2015). *Climate at a Glance*. Retrieved from http://www.ncdc.noaa.gov/cag/

National Hydrography Dataset. (2013). *HU-4 Subregions 1002 & 1003*. Retrieved from http://nhd.usgs.gov/data.html

Natural Resources Conservation Service. (2015). *Snotel 30-Year Climatic and Hydrologic Normals (1981-2010) Reports*. Retrieved from http://www.wcc.nrcs.usda.gov/normals/30year_normals_landing.htm

Nemec, K. T., Chan, J., Hoffman, C., Spanbauer, T. L., Hamm, J. A., Allen, C. R., ... & Shrestha, P. (2014). Assessing Resilience in Stressed Watersheds. *Ecology and Society*, *19*(1), 34.

Ostrom, E., Gardner, R., & Walker, J. (1994). Rules, games, and common-pool resources. University of Michigan Press.

Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., & Policansky, D. (1999). Revisiting the commons: local lessons, global challenges. science, 284(5412), 278-282.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water resources management*, *21*(1), 49-62.

Pederson, G. T., Graumlich, L. J., Fagre, D. B., Kipfer, T., & Muhlfeld, C. C. (2010). A century of climate and ecosystem change in Western Montana: what do temperature trends portend? *Climatic Change*, *98*(1-2), 133-154.

Pederson, G. T., Gray, S. T., Ault, T., Marsh, W., Fagre, D. B., Bunn, A. G., ... & Graumlich, L. J. (2011). Climatic controls on the snowmelt hydrology of the northern Rocky Mountains. *Journal of Climate*, 24(6), 1666-1687.

Person, D. (2010, May 24). Plan to make Jefferson River better for fishing halted due to budget woes. *Bozeman Daily Chronicle*. Retrieved from http://www.bozemandailychronicle.com/news/plan-to-make-jefferson-river-better-for-fishing-halted-due/article_9bcf0712-66ca-11df-9210-001cc4c002e0.html

Pierce, B. (2008, June 19). Protecting the Jefferson River. *Bozeman Daily Chronicle*. http://www.jeffersonriver.org/Articles/Watershed_Council.htm

Pierce, D. W., Barnett, T. P., Hidalgo, H. G., Das, T., Bonfils, C., Santer, B. D., ... & Nozawa, T. (2008). Attribution of declining western US snowpack to human effects. *Journal of Climate*, 21(23).

Policy Consensus Initiative. (1997). *Protecting Instream Flows in Montana*. Retrieved from http://www.policyconsensus.org/casestudies/docs/MT_streams.pdf

Powell, J. W., Gilbert, G. K., Dutton, C. E., Drummond, W., & Thompson, A. H. (1879). *Report on the Lands of the Arid Region of the United States: With a More Detailed Account of the Lands of Utah.* (Vol. 3). Government Print Office.

Power, T. M., & Barrett, R. (2001). *Post-cowboy economics: Pay and prosperity in the new American West*. Island Press.

Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., ... & Midgley, P. M. (2014). *Climate change 2013: The physical science basis* (p. 1535). T. Stocker (Ed.). Cambridge, UK, and New York: Cambridge University Press.

Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate*, *18*(2), 372-384.

Reisner, M. (1993). *Cadillac desert: The American West and its disappearing water*. Penguin.

Resilience Alliance. (2010). *Assessing resilience in social-ecological systems: Workbook for practitioners*. Retrieved from http://www.resalliance.org/files/Resilience AssessmentV2_2.pdf

Richardson, F., Hamre, R. H., Service, United States Forest Service, United States Department of the Interior. (1990). *Wild Trout IV: proceedings of the Symposium, Yellowstone National Park, September 18-19, 1989*: U.S. Dept. of Agriculture, Forest Service.

Roberts, M. (2012). *Conversion from Flood to Sprinkler Water Supply Impacts* [PowerPoint slides]. Retrieved from http://dnrc.mt.gov/divisions/water/water-rights/docs/new-appropriations/presentations/flood_sprinkler_conversion.pdf

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., ... & Tryjanowski, P. (2008). Attributing physical and biological impacts to anthropogenic climate change. *Nature*, *453*(7193), 353-357.

Rood, S. B., Pan, J., Gill, K. M., Franks, C. G., Samuelson, G. M., & Shepherd, A. (2008). Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, *349*(3), 397-410.

Sakariassen, A. (2015, September 17). Endless opposition: “Anti-Indian” group puts water compact on conference agenda. *Missoula Independent*. http://missoulanews.bigskypress.com/missoula/endless-opposition/Content?oid=2457623

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in ecology & evolution*, *18*(12), 648-656.

Spoon, R. (2008). *Evaluation of fishery trends in the Jefferson River drainage related to changes in streamflow pattern and habitat restoration activities*. Retrieved from https://archive.org/details/FA1BBD5A-A2E6-4F1E-8283-7711D8AE1E25

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change*, 62(1-3), 217-232.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18(8), 1136-1155.

Stockholm Resilience Center. (2015). *Research at Stockholm Resilience Center.* Retrieved from http://www.stockholmresilience.org/21/research.html

Travis, W. R. (2007). New geographies of the American West. Island Press.

Trenberth, K. E., Branstator, G. W., & Arkin, P. A. (1988). Origins of the 1988 North American drought. *Science*, 242(4886), 1640-1645.

Trenberth, K. E., & Branstator, G. W. (1992). Issues in Establishing Causes of the 1988 Drought over North America. *Journal of Climate*, 5(2), 159-172. doi:10.1175/1520-0442(1992)005<0159:IIECOT>2.0.CO;2

Trout Unlimited. (2014). Partners revive Jefferson River fishery. *Trout Line: Newsletter from the Montana Council of Trout Unlimited, summer 2014*. Retrieved from http://montanatu.org/wp-content/uploads/2012/11/Trout-Line-Summer-2014-pdf-.pdf

United Nations Department of Economic and Social Affairs. (2014). *Water for Life Decade: Integrated Water Resources Management*. Retrieved from http://www.un.org/waterforlifedecade/iwrm.shtml

United States Bureau of Reclamation. (n.d.). *Current Data for Lima Reservoir, MT*. Retrieved from http://www.usbr.gov/gp-bin/arcweb_limr.pl

United States Bureau of Reclamation. (n.d.). From *Wikipedia*. Retrieved December 10, 2015 from http://en.wikipedia.org/wiki/United_States_Bureau_of_Reclamation

United States Bureau of Reclamation. (2006). *Finding of no significant impact: conversion of long term water service contracts to repayment contracts (Clark Canyon Water Supply Company, East Bench Irrigation District).* (FONSI Reference Number: MT231-07-01F). Retrieved from http://www.usbr.gov/gp/mtao/clarkcanyon/fea/ ea_fonsi_entire.pdf

United States Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, National Center for Atmospheric Research, Santa Clara University,… & U.S. Geological Survey. (2014). *Downscaled CMIP3 and CMIP5 Hydrology Projections: Release of Hydrology Projections, Comparison with preceding Information, and Summary of User Needs*. Retrieved from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf

United States Department of Commerce, Bureau of Economic Analysis. (2015). *Regional Economic Accounts*. Retrieved from http://www.bea.gov/regional/

United States Department of the Interior. (1888). *Annual Report to the Secretary of the Interior*. (Volume 2). Washington, DC: Government Printing Office.

United States Department of the Interior, Fish and Wildlife Service. (2006). *2006 National Survey of Fishing, Hunting, and Wildlife Associated Recreation*. Retrieved from https://www.census.gov/prod/2008pubs/fhw06-nat.pdf

United States Department of the Interior, Fish and Wildlife Service. (2014). *Endangered and Threatened Wildlife and Plants; Revised 12-Month Finding on a Petition to List the Upper Missouri River Distinct Population Segment of Arctic Grayling as an Endangered or Threatened Species*. (Docket No. FWS-R6-ES-2013-0120; 4500030113). Retrieved from http://www.gpo.gov/fdsys/granule/FR-2014-08-20/2014-19353

U.S. Department of Interior, Bureau of Reclamation. (2009). *Long-Term Planning Hydrology based on Various Blends of Instrumental Records, Paleoclimate, and Projected Climate Information*, technical report prepared by the Bureau of Reclamation, U.S. Department of Interior, 139pp.

United States Geological Survey. (1928). *Power Capacity and Production in the United States*. (Water Supply Paper 579). Retrieved from http://books.google.com/books?id=p_XUAAAAMAAJ

United States Geological Survey. (2015a). *National Water Information System, Jefferson River near Three Fork MT*. Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06036650&agency_cd=USGS

United States Geological Survey. (2015b). *National Water Information System, Jefferson River near Twin Bridges MT.* Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06026500&agency_cd=USGS

United States Geological Survey. (2015c). *National Water Information System, Jefferson River near Silver Star MT.* Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06027600&agency_cd=USGS

United States Geological Survey. (2015d). *National Water Information System, Big Hole River near Melrose MT*. Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06025500&agency_cd=USGS

United States Geological Survey. (2015e). *National Water Information System, Ruby River above Ruby Reservoir.* Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06019500&agency_cd=USGS

United States Geological Survey. (2015f). *National Water Information System, Boulder River near Boulder MT.* Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06033000&agency_cd=USGS

United States Geological Survey. (2015g). *National Water Information System, Beaverhead River near Twin Bridges MT.* Retrieved from http://waterdata.usgs.gov/nwis/inventory/?site_no=06018500&agency_cd=USGS

University of Montana Bureau of Business and Economic Research. (2015). *Montana 2015 Economic Outlook.* Retrieved from http://www.bber.umt.edu/pubs/econ/CountyOutlooks/15MT.pdf

Vano, J. A., Scott, M. J., Voisin, N., Stöckle, C. O., Hamlet, A. F., Mickelson, K. E., ... & Lettenmaier, D. P. (2010). Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. *Climatic Change*, 102(1-2), 287-317.

Venn, B. J., Johnson, D. W., & Pochop, L. O. (2004). Hydrologic impacts due to changes in conveyance and conversion from flood to sprinkler irrigation practices. *Journal of irrigation and drainage engineering*, *130*(3), 192-200.

Vermont. (n.d.). From *Wikipedia*. Retrieved December 10, 2015 from https://en.wikipedia.org/wiki/Vermont

Vuke, S. M., Coppinger, W. W., & Cox, B. E. (2004). Geologic map of the Cenozoic deposits of the upper Jefferson valley. *Montana Bureau of Mines and Geology Open File Report*, *505*, 1-38.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., ... & Pritchard, R. (2002). Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conservation ecology*, *6*(1), 14.

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social--ecological systems. *Ecology and Society*, 9(2), 5.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, 11(1), 13.

Walker, B., & Salt, D. (2012). *Resilience practice: building capacity to absorb disturbance and maintain function*: Island Press.

Western Regional Climate Center. (2015). *Northern Idaho/Western Montana Climate Summaries*. Retrieved from http://www.wrcc.dri.edu/summary/Climsmnidwmt.html

Whiteley, J. M., Ingram, H. M., & Perry, R. W. (Eds.). (2008). *Water, place, and equity*. Cambridge, MA: MIT Press.

Wilkinson, Charles F. *Crossing the next meridian: Land, water, and the future of the West*. Island Press, 1993.

World Climate Research Program. (2015). *Coupled Model Intercomparison Project Overview*. Retrieved from http://cmip-pcmdi.llnl.gov/

Worster, D. (1985). *Rivers of empire: Water, aridity, and the growth of the American West*. Oxford University Press.

Wyoming. (n.d.). From *Wikipedia*. Retrieved December 11, 2015 from https://en.wikipedia.org/wiki/Wyoming

Yellowstone fires of 1988. (n.d.). From *Wikipedia*. Retrieved December 10, 2015 from https://en.wikipedia.org/wiki/Yellowstone_fires_of_1988

Ziemer, L. S., Kendy, E., & Wilson, J. (2006). Ground Water Management in Montana: On the Road from Beleaguered Law to Science-Based Policy. *Pub. Land & Resources L. Rev.*, *27*, 75.

APPENDICES

APPENDIX A

ANALYSIS OF WATER RIGHTS IN THE JEFFERSON

WATER RIGHTS DATASET INFORMATION/EXPLANATIONS

Water Right Selection- The MT water rights database contains separate point of use (POU) and point of diversion (POD) datasets for each water right registered with the MT DNRC. For the purposes of this study I received additional POD attribute data from the MT DNRC Water Rights Bureau (including ownership and period of use information). Water rights (POD and POU) were queried using GIS software within MT DNRC Basin ID 41G (representing the Jefferson Basin). Each water right may contain multiple POD and multiple POU (many to many relationship). Furthermore, specific attribute information necessary for analysis was contained within both layers. To consolidate the datasets, a merge function was used in ArcMap(v10.2)—the merge was based on the water right ID field (WRNUMER). The merged dataset still contained multiple POD's (representing different locations of water diversions for individual rights) and was condensed to eliminate redundant records. The resultant database contained 4,192 water rights. Water rights were analyzed based on water right identification numbers (WRNUMBER). The subsequent analysis was performed on the merged POD database for DNRC Basin 41G. The data was further filtered using Microsoft Excel.

Water Right Status- Only included only active (surface/groundwater) water rights in the analysis.

Livestock, direct from source water rights- Identified under the MEANSOFDIV field. This type of water right constitutes a substantial amount of the water rights filed in the Jefferson Basin. MT DNRC states this right represents a water volume of around 30 gal/day. According to the DNRC, if challenged in court, the organization uses a standard of 15 gal/day unless the applicant claims otherwise. 15 gallons/day is equivalent to 0.2 acre feet/year. These rights were not included in the water rights analysis due to the relatively low annual totals and the difficulty in quantifying actual use.

Water right flow rates- Identified by MAXFLWRT field in POD (point of diversion dataset). Flow rates are given in either cubic feet per second or gallons per minute. All flows were converted to cubic feet per second (cfs) for the data analysis. Range of flows on the Jefferson varied from 0-1095 cfs.

Priority Dates- Identified by the ENFPRIDATE field in the POD dataset. Converted from *yyyy-mm-dd* format to a 4 digit number format, *nnnn* for the purposes of the data analysis. Excel doesn't recognize dates prior to 1900. http://en.wikipedia.org/wiki/Year_1900_problem. Priority dates are important to determine relative seniority of individual water rights.

Period of Use- Within the POD database period of use is identified as a text string "04/15 to 10/19". Used "text to columns" in Excel to parse data into two separate dates and then calculated number of days between.

Water right volumes- Determined by multiplying the maximum flow rate of a water right (cfs) by its period of use (days). Multiplying subsequent value by a correction factor of 1.98 produces a volume of water in acre feet (AF) per year (MAXFLWRT*Period of Use*1.98= AF/year).

Instream flow water rights- Instream flow rights were not included in the analysis of water rights in the Jefferson. Although instream flow rights comprise a substantial volume of water allocated in the Jefferson watershed, the vast majority of those associated water rights have relatively junior enforceable priority dates (post 1975).

Classification of "senior" water rights- For the purposes of this study the most senior (oldest) quartile (25%) of rights were classified as senior (Figure X). This value was chosen arbitrarily. To calculate this, a histogram was created that tallied the total amount of acre feet allocated per year within the basin. The priority date of 1894 represented the approximate cutoff for the oldest 25% of water rights (by volume allocated per year).

GIS DATASETS USED FOR ANALYSIS

Source for all layers used in analysis are available on the MT GIS Clearinghouse (hosted by the MT State Library). Retrieved from http://geoinfo.msl.mt.gov/

Water Rights- Point of Diversion (with ownership attributes)
Source- MT Water Rights Bureau-DNRC
ftp://nris.mt.gov/public/dnrc

Watershed Boundaries
Source- National Hydrography Dataset
http://nhd.usgs.gov/

Stream Datasets
Source- National Hydrography Dataset
http://nhd.usgs.gov/

Elevation Datasets- 1 arc second horizontal resolution (~10 m)
Source-National Elevation Dataset
http://ned.usgs.gov/

Montana Place Name Dataset
Source- Montana Names from GNIS
ftp://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/GeographicNames/

APPENDIX B

ANALYSIS OF ANNUAL ANGLER DAYS ON STREAMS IN MONTANA

ANNUAL ANGLER DAY ANALYSIS

Angler Pressure Surveys- Have been completed on rivers statewide since the 1980's. The surveys are compiled via mailing questionnaires to resident and nonresident angler. An angler day represents one fisherman fishing one body of water for any amount of time on a given day. Surveys were completed annually from 1982-1985 and then biennially from 1989-2013. The methodological approach used in conducting the surveys has changed slightly over time.

Data Retrieval for surveys from 1982-2009- Data for this period was accessed through the online MT FWP Montana Fisheries Information System (MFISH) database—waterbody name search. Data source: http://fwp.mt.gov/fishing/mFish/

- **Angler Day Survey Methodology**- included within each individual survey summary report is the methods used to complete the surveys. Data source: http://fwp.mt.gov/fishing/anglingData/anglingPressureSurveys/
- **2011 survey-** available through MT FWP's Angling Pressure Survey webpage. Data source: http://fwp.mt.gov/doingBusiness/reference/surveys/anglerPressure.html
- **2013 survey**- available at the following MT FWP website: http://fwp.mt.gov/fishing/anglingData/anglingPressureSurveys/2013.html

Data Uncertainty- The angler day data surveys contain considerable margins of error due to the extrapolation process. Standard deviation values are included in the FWP angler day data (including on the MFISH data server).

APPENDIX C

ANALYSIS OF TEMPERATURE TRENDS

TEMPERATURE TREND ANALYSIS

USHCN Data- United States Historical Climatology Network (USHCN) contains long-term meteorological station data that are used to quantify national and regional scale temperature change in the CONUS. It is a designated subset of the NOAA Cooperative Observer Program (COOP) Network with sites selected according to their spatial coverage, record length, data completeness, and historical stability (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-historical-climatology-network-ushcn).

Data Source- Long-term daily climate records used in this analysis were retrieved from the Carbon Dioxide Information Analysis Center (CDIAC) through the web interface data retrieval system available at http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn_map_interface.html. The following three USHCN sites were used in the temperature trend analysis.

- Ennis, MT (242793)
- Dillon, MT (242409)
- Virginia City, MT (248597)

Temperature Trend Analysis Methodology- Climate trend analysis was calculated in R (the R Project for Statistical Computing) using climate analysis tools developed by Greg Pederson and others in their temperature trend analysis research published in *Climatic Change* (2009). Dr. Pederson gives an overview of the climate analysis tools on his webpage at http://nrmsc.usgs.gov /MTclimate. R-code used in this thesis was modified from the code used in the Pederson et al., research available for public use at http://nrmsc.usgs.gov/files/norock/research/MTclimate/HCNtempAnalysis.r.

Graphical Interpretation- The data acquired from the R-code temperature analysis was transferred to Microsoft Excel to create Figures 32-37 in chapter 4 of this thesis.

APPENDIX D

DOWNSCALED CLIMATE PROJECTIONS

CLIMATE PROJECTION METHODOOGY

Platform Used- The CMIP5 climate and hydrology projections are made available through a collaborative effort between the United States Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, National Center for Atmospheric Research, Santa Clara University, United States Army Corps of Engineers, Scripps Institution of Oceanography and the U.S. Geological Survey. Data source: http://gdo-dcp.ucllnl.org/ downscaled_cmip_projections/dcpInterface.html#Welcome

BCSD Hydrological Projections- Bias-correction spatial digression (BCSD) downscaling techniques are utilized in these projections. BCSD (a statistical downscaling technique) has been used extensively in hydrologic impact analysis and is a proven technique. The analysis methodology used in the projections performed on the Jefferson followed the tutorial available on the CMIP5 model output website. The tutorial details the how to perform runoff change calculation in addition to the climate index calculations used in this thesis and is available at the following website: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html #Tutorials

Selection of the Jefferson Basin- For the hydrological projections, a spatial boundary was established that represents the greater Jefferson Basin. Under the "Projections: Subset Request" tab. The following was selected for each of the "Steps"

1.1—Time step "monthly"
1.2—Domain "Basin Specific"
1.3---Spatial extent selection method "Tributary Area" (45.9254, -111.5111). Selecting this point as the pour point establishes the greater Jefferson Basin's extent.

Attributes of the BCSD Climate Projection- Data source: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#About

Each BCSD climate projection has the following attributes:

- Variables:
  - precipitation, mean daily rate during each month, mm/day
  - surface air temperature, monthly mean, °C
  - missing value flag: 1E+20
- Time:
  - coverage: 1950-2099
  - resolution: monthly
- Space:
  - coverage: North American Land-Data Assimilation System domain (i.e. contiguous U.S. plus portions of southern Canada and northern Mexico, spanning 25.125° N to 52.875° N and - 124.625° E to -67.000° E)
  - resolution: 1/8° latitude-longitude (~12km by 12 km)

Data for the data used for the Tables- For the temperature and streamflow climate projection data in Tables 13-16 median values are represented (medians of the population of climate model monthly output values). The precipitation projection (Table 18) is comprised of mean values due to the high variability in the output. See attached dataset for variance (StDev's).

CLIMATE MODELS USED IN THE ANALYSIS

CMIP5 Modeling Groups- I acknowledge the World Climate Research Program's Working Group on Coupled Modeling and the climate modeling groups listed in the table below and would like to thank the groups for producing and making their output publically available. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The following table was modifiend from the one posted on the CMIP5 modeling website and contains the climate projections used in my analysis. Data source: http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research)	INPE	BESM OA 2.31
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2 CanCM4 CanAM4
University of Miami - RSMAS	RSMAS	CCSM4(RSMAS)*
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5) CESM1(CAM5.1,FV2) CESM1(FASTCHEM) CESM1(WACCM)

Center for Ocean-Land-Atmosphere Studies and National Centers for Environmental Prediction	COLA and NCEP	CFSv2-2011
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CESM CMCC-CM CMCC-CMS
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
		CNRM-CM5-2
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-EARTH consortium	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University	LASG-CESS	FGOALS-g2
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-gl FGOALS-s2
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM
NASA Global Modeling and Assimilation Office	NASA GMAO	GEOS-5
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadCM3 HadGEM2-CC HadGEM2-ES HadGEM2-A
Institute for Numerical Mathematics	INM	INM-CM4
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR

Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR MPI-ESM-P
Meteorological Research Institute	MRI	MRI-AGCM3.2H MRI-AGCM3.2S MRI-CGCM3 MRI-ESM1
Nonhydrostatic Icosahedral Atmospheric Model Group	NICAM	NICAM.09
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME

APPENDIX E

INTERVIEW GUIDE

JEFFERSON WATER STAKEHOLDER ANALYSIS

Method:

To identify the strengths and weaknesses of current management and governance regimes in the Jefferson basin a series of informal interviews was conducted in November 2015 and January 2016. Interview participants were chosen selectively to represent key water stakeholder groups impacted by chronic drought in the Jefferson basin. The key informants that participated represented interests in agriculture, fisheries management, wildlife conservation and drought management. The semi-structured interviews were performed in person by the author of this paper and tape-recorded; responses were coded to maintain confidentiality. In accordance with MSU's policies, this research was approved by the Institutional Review Board and all persons interviewed read and authorized a subject consent form.

Interview Guide:

- <u>The Jefferson River has experienced frequent drought episodes over the past 25 years</u>.
    - What droughts do you feel impacted the ecology and agricultural productivity of the valley the most?
        - What were the impacts?
    - How did water users respond to these episodes before the establishment of the Jefferson River Watershed Committee/drought plan?
        - Were informal agreements in place or did prior appropriation guide decision making?
    - What role (if any) did the State/NGO's play in water conservation efforts in the Jefferson before 2000?
    - What physical process is contributing the most to the ongoing drought (temperature/precipitation/snowfall)?
    - Why is the river reach between Silver Star and Waterloo so vulnerable to drought?
    - How has the increase in acreage under center pivot irrigation impacted water resources?
    - What makes the Jefferson Basin unique from other drainages in the region?

- <u>Establishment of the JRWC/Drought Plan</u>
    - What was the impetus for establishing the JRWC/Drought Plan?

        - Did one actor (Gary Nelson) play the primary role in forming the JRWC?
        - Were there any incentives for ag users?
        - Was there any opposition to establishment?
        - What role did the State/NGO's play?
        - How were the threshold streamflow values and action triggers agreed upon?

- <u>By many measures the voluntary drought plan has been a success.</u>
    - Are there incentives for the stakeholders that reduce diversions?
    - Is it a collective effort involving multiple users or a unique group of users?
    - What happened in 2013?
        - Would the drought plan be impactful if there were climactic conditions more severe than 2013?
        - Could anything have been done (under the current voluntary drought agreement) to meet the flow guidelines during 2013?
    - Does the plan do enough to protect aquatic ecosystems?

- <u>Future scenarios and thoughts about increasing resilience.</u>
    - Climate models are predicting that in the Jefferson Basin: runoff will occur earlier in the year, late summer streamflow volumes will diminish, ET demands will increase, the growing season has and will continue to lengthen.
        - Realistically, what modifications could be made to the water use system in the Jefferson to meet these potential challenges?
            - Upstream reservoir storage expansion?
            - Mandatory drought agreement?
            - Changing agricultural practices?
            - Tributary enhancements