Wind River Reservation: Drought Risk and Adaptation in the Interior (DRAI) Report

Prepared by Shannon M. McNeeley and Tyler A. Beeton

Wind River Reservation: Drought Risk and Adaptation in the Interior (DRAI) Report

A report for the
Wind River Indian Reservation's Vulnerability to the Impacts of Drought and the Development of Decision Tools to Support Drought Preparedness *project*

Prepared by:

Shannon M. McNeeley
shannon.mcneeley@colostate.edu

and

Tyler A. Beeton
tyler.beeton@colostate.edu

Suggested Citation:
McNeeley, S.M., Beeton, T.A., 2017. Wind River Reservation: Drought Risk and Adaptation in the Interior (DRAI) report. A report for The Wind River Indian Reservation's Vulnerability to the Impacts of Drought and the Development of Decision Tools to Support Drought Preparedness project. Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO. Available at: https://tinyurl.com/y4cv9zpe

Cover: Wyoming Wind River Mountains. Photo by FLickr user m01229

Table of contents

Executive summary

The Wind River Indian Reservation (WRIR) is located in west-central Wyoming and is home to the Eastern Shoshone and Northern Arapaho tribes. Drought in this region is part of natural variability, as the region experiences frequent, and severe drought events, which have significant impacts on the social and ecological communities on the reservation. In the first 16 years of the 21st century, WRIR has experienced three extreme to exceptional drought periods, and two 'micro-drought' events that have caused water shortages in parts of the reservation and have significantly affected human livelihoods and the ecosystems on which they depend. Climate projections suggest increased warming and evapotranspiration, and although there is no consensus on the directionality of precipitation, the timing and seasonality of precipitation events will be altered. Therefore, there is an urgent need to build tribal capacity to prepare for, and respond to, drought and climate variability now and into the future.

To address this, the WRIR drought preparedness project has developed foundational partnerships with the Eastern Shoshone and Northern Arapaho tribes, the Wind River Office of the Tribal Water Engineer (TWE) and the Water Resources and Control Board, North Central Climate Science Center (NCCSC) at Colorado State University, the High Plains Regional Climate Center and the National Drought Mitigation Center at University of Nebraska-Lincoln, University of Wyoming, National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS), among many other universities and government agencies. The project is multi-disciplinary, and these partners work closely with the TWE and the Wind River water board, who are the leadership and decision-making authority on water management, to co-produce actionable science for drought preparedness. This includes a community-driven, social-climate-ecological vulnerability assessment, among others.

This report describes the progress of in-depth, semi-structured interviews with water and resource managers at WRIR. The purpose is to document and understand local knowledges and observations of drought risk and responses, and demonstrate how these can help inform drought preparedness and planning. This report is informed by a social-ecological systems (SES) framework, and an integrated vulnerability assessment to determine the social and ecological vulnerabilities to drought and climate variability at WRIR.

Results are organized into three thematic sections, and sub-topics. In the first section (3.1), we address three major storylines that emerged from analysis of the interviews. The first storyline illustrates how water availability is a function of interacting and unique biophysical, physical infrastructure, and social drivers that result in system shortages at WRIR (3.1.1). Managers are witnessing changes to historical seasonal trends in climate and weather. They are experiencing less snowpack during critical periods, warmer temperatures, and an earlier transition of precipitation falling as rain versus snow, the combination of which results in accelerated snowmelt and peak runoff to occur two weeks to one month earlier than in the past. The Bighorn General Stream Adjudication determined the water rights at WRIR; water rights at WRIR are tied strictly to agriculture, which limits the 15 equal and beneficial uses defined in the Wind River Water Code, they do not extend to groundwater, and the State of Wyoming has legal responsibility to administer water on tribal and non-tribal lands at WRIR. Although the State generally allows the TWE to administer water in the Bureau of Indian Affairs (BIA)-managed Wind River Irrigation Project in the Little Wind River, a number of barriers limit their ability to do so. Inadequacies in the physical infrastructure (e.g., reservoirs, conveyance systems, monitoring networks) in the Wind River Irrigation Project are significant barriers to effective water management. We demonstrate how these social and ecological factors combine to affect water availability by reviewing three cases of water years that resulted in water shortages.

The second storyline emphasizes spatial variabilities in drought vulnerability within and between watersheds at WRIR (3.1.2). Tribal and non-tribal producers in the BIA-managed Wind River Irrigation Project are generally more vulnerable to drought than the primarily non-tribal producers on the Bureau of Reclamation (BOR)-managed system, though there are differences between upstream and downstream water users in the Little Wind River, for example, and small storage facilities and glacial retreat pose significant risks to those users in the Crowheart region of the Upper Wind River.

The third storyline describes the issues associated with “Futures” water and storage (3.1.3). “Futures” water rights are the “paper” rights awarded to the tribes in the Bighorn General Stream Adjudication. Several drawbacks to these rights were reported: 1) rights are tied to agriculture (as are all water rights at WRIR), which is contrary to Wind River Water Code, and developing the lands to utilize these rights are challenged by complex land tenure arrangements, limited loan opportunities, and increasing lease rates on BIA allotments; 2) conflicts with the BOR as to where to store water for the future; 3) majority of rights and discussions of where to develop infrastructure to use rights do not support the most vulnerable populations at WRIR; and 4) rights only apply to on-stream infrastructure.

In the second section (3.2), we provide a discussion of how key informant interviews inform drought risk assessment and drought planning. First, we highlight a number of ways that the interviews can inform physical climate assessment. The key informant interviews help to: 1) document historical drought periods, which are currently being compared to historical averages by the project’s physical climate team; 2) identify indicators and information sources managers use, as well as considerations of the timing and seasonality that is important for making decisions (what is used?; when it is used?; and for what purpose?), which is important to ensure relevant data is used as scales that match managers’ decision context and helps to determine where to locate output material; and 3) identify additional monitoring needs. Second, key informant interviews help to identify the species habitats, and ecosystems of cultural, spiritual, and management concern, and the specific relationships, or important variables, to consider in an ecological impacts assessment. Results indicate that while drought and climate variability can cause devastating impacts to social-ecological systems, impacts were primarily the result of multiple and interacting social and ecological factors and not driven by climate alone.

In the last section (3.3), we offer additional questions for future research that were identified through an in-depth analysis of the interviews.

We hope that this report will help inform drought preparedness planning, and adaptation efforts to respond to increasing climate variability and change at WRIR, while protecting and managing WRIR resources in the ways that the Eastern Shoshone and Northern Arapaho see fit. Although this report relies on information from WRIR water and resource managers, this report does not necessarily represent the views of the Eastern Shoshone or Northern Arapaho government.

List of figures

List of tables

1. Introduction

The Wind River Indian Reservation (WRIR) in west-central Wyoming encompasses 2.2 million acres of semi-arid landscape that includes irrigated agriculture, desert grasslands and high altitude, alpine areas (Figure 1). The reservation is home to the Eastern Shoshone and Northern Arapaho tribes. The population of WRIR is approximately 26,630 (2010 Census), and this includes tribal members, people who identify with one or the other tribe but perhaps do not qualify for tribal membership, and non-Indians. The people, wildlife, and vegetation in the region, depend on glacier- and snow-fed tributaries to the Wind River, a part of the headwaters of the Missouri Basin. The tribes have a Wind River Water Code that outlines their 15 beneficial and equal uses of water throughout the reservation (Wind River Indian Reservation 1991). The major uses of water on the reservation include agricultural and ranching production, and municipal use for several small communities in, and surrounding WRIR (e.g., Ethete, Fort Washakie, Lander, Riverton, among others). Uses also include fisheries management, as the basin is home to several native species, including the rare Yellowstone cutthroat trout (*Oncorhynchus clarkia*), and other species that are culturally important to the tribes including the genetically pure sauger (*Sander canadensis*) (Amadio et al., 2005; Krueger et al., 1997), and Burbot (*Lota lota*), among others (Bergersen et al., 1993; Krueger and Hubert, 1997; Underwood et al., 2016). Finally, the tribes protect water for vegetation and wildlife management for subsistence and ceremonial activities.

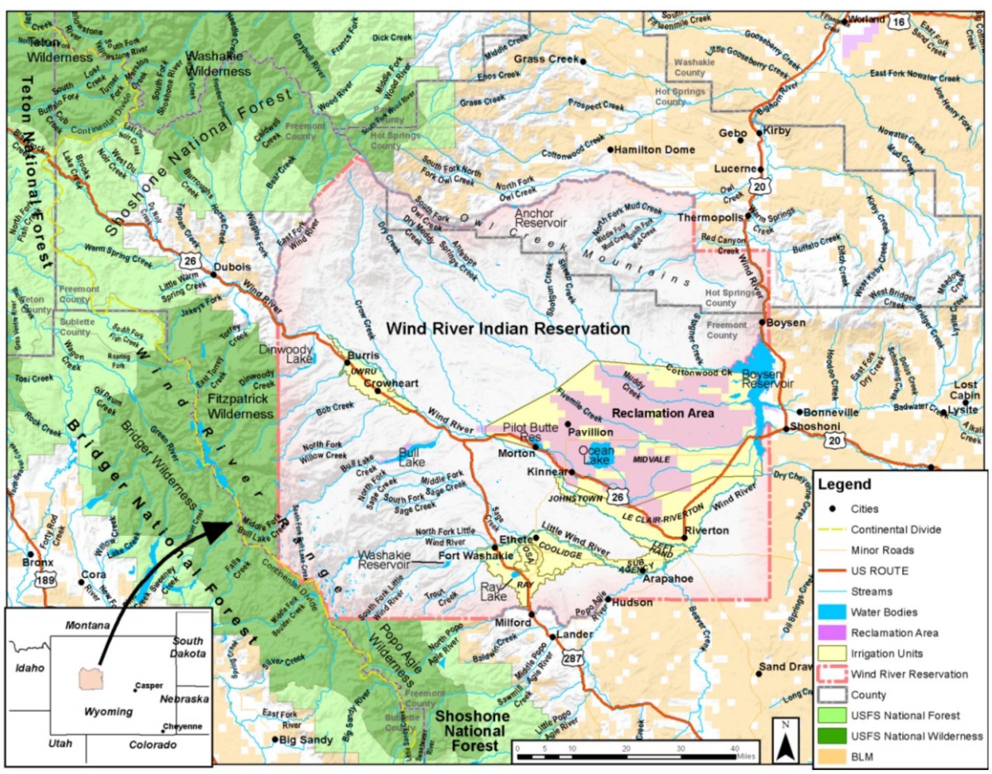


Figure 1: Map of Wind River Indian Reservation in west-central Wyoming.

Drought is part of natural variability at WRIR, as the region experiences frequent, severe drought events, which have significant impacts on the social and ecological communities on the reservation. In the first 16 years of the 21st century, WRIR experienced 3 extreme to exceptional droughts (2002, 2006, 2012-2013) of varying magnitude and duration, and "micro-droughts" in 2015 and again in 2016 that registered as abnormally dry to moderate drought conditions on the US Drought Monitor (Figure 2). These micro-droughts or "system droughts", which we define as a drought very short in duration and localized, can be picked up by the Evaporative Demand Drought Index (EDDI; see http://wwa.colorado.edu/publications/reports/EDDI_2-pager.pdf that illustrates the 2015 micro-drought at WRIR). Therefore, living with, and responding to, drought is part and parcel of living on this landscape. Climate projections suggest increased warming and evapotranspiration, and although there is no consensus whether precipitation will increase or decrease, the seasonal timing and magnitude of precipitation events will be altered (Rice et al., 2012).

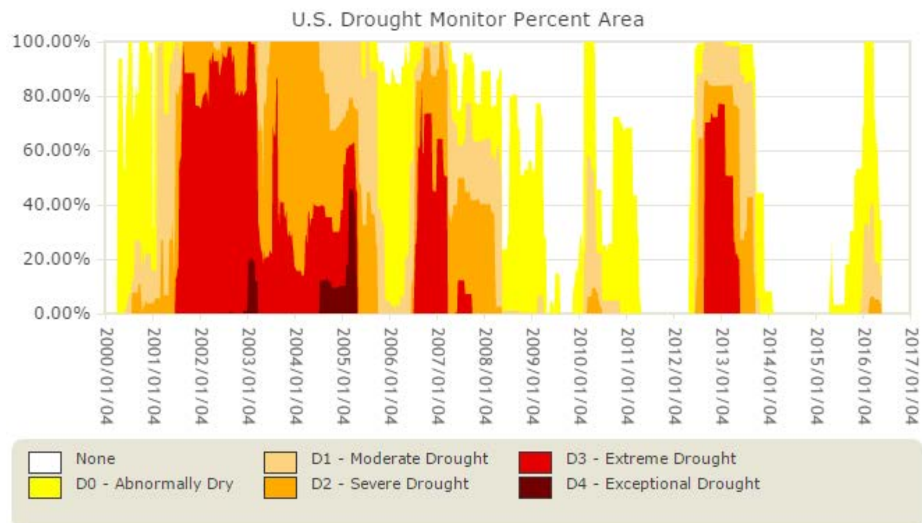


Figure 2: Drought severity at WRIR, 2000-present. Percent area in drought based on HUC6 Bighorn basin. Source: Drought Risk Atlas, http://droughtatlas.unl.edu/.

The purpose of this report is to describe the progress of the drought risk interviews to date with Wind River water and resource managers for the Wind River Indian Reservation Drought Preparedness Project. This report is informed by qualitative data collected as part of a multi-institutional, and multi-disciplinary collaboration between the WRIR tribes, Tribal Water Engineer's (TWE) Office at WRIR, North Central Climate Science Center (NCCSC) at Colorado State University, the High Plains Regional Climate Center and the National Drought Mitigation Center at University of Nebraska-Lincoln, University of Wyoming, National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS), among many other universities and government agencies (See Appendix 1: University and government agency partners on WRIR drought preparedness project for a full list of partners). The collaboration consists of three science teams (Physical Climate, Ecological Impacts, and Social Sciences), the goal of which is to co-produce a drought preparedness plan that integrates social, physical climate/hydro-climate, and ecological sciences with local knowledge to build capacity for WRIR land and water resource managers to respond to, and prepare for, drought impacts on the reservation.

This report is informed by a social-ecological systems (SES) framework, and an integrated vulnerability approach from a social science lens to determine the social and ecological risks and vulnerabilities to drought and climate variability in local contexts. Here, we report on information gleaned from in-depth semi-structured interviews, specifically the local knowledges and observations of drought risks and responses. The results presented here are organized according to three questions:

1. What are the major storylines that emerged from the interviews? These storylines address: the biophysical and social factors that drive water availability, with examples from three drought periods; spatial variability in drought vulnerability; and "Futures" water and storage.
2. What are the ways in which interviews can inform drought risk assessment and planning? Specifically, we address how the interviews can complement and provide inputs for the physical climate assessment team, and the ecological assessment team.
3. What are some additional research questions and/or hypotheses that emerged from the interviews?

1.1. Conceptual framework

Drought is a complex phenomenon, which is driven by biophysical and social processes (Glantz, 1994; Kallis, 2008; Van Loon et al., 2016; Wilhite and Buchanan-Smith, 2005; Wilhite and Glantz, 1985). The factors that combine to impact water availability and contribute to water shortages can be divided into three broad, but interacting factors: 1) biophysical availability includes differences in the timing, amount, form, and effectiveness of precipitation, soil conditions, evapotranspiration, among others (Kallis, 2008; Van Loon et al., 2016; Wagener et al., 2010); 2) legal and management-related factors includes the legal rights to access water, both surface and groundwater abstraction, and legal authority/management decisions to allocated and administer water rights (Barnes, 2017; Chief et al., 2016; Christian-Smith et al., 2015; Hill and Engle, 2013; McNeeley, 2014; Pahl-Wostl, 2007); and 3) physical infrastructure includes the state and capacity of conveyance systems, reservoir facilities, and monitoring networks, among others (AghaKouchak et al., 2015; Barnes, 2017; Kallis, 2008). While biophysical processes are no doubt important drivers of water shortages, water rights and management behavior, and construction of large reservoirs, dam structures, and canal diversions, are as important if not more important (Haddeland et al., 2014; McNeeley, 2014; Orlove and Caton, 2010; Van Loon and Lanen, 2013).

Therefore, this study was framed by a social-ecological systems (SES) framework using an integrated vulnerability assessment approach (Berkes et al., 2003; Berkes and Folke, 1998; Ford et al., 2010; Smit and Wandel, 2006; Westley et al., 2002). An SES framework (also referred to as coupled human-natural systems) emphasizes the inextricable linkages between social and ecological system components (Berkes and Folke, 1998). In this vein, humans directly impact ecosystems through land use decisions, land tenure arrangements, and management objectives and mandates, for example. In turn, humans directly depend on the quality and quantity of the services that are provided by ecosystems. Therefore, the distinction between social and ecological system components is artificial and neither can be fully understood when studied in isolation (Chapin III et al., 2009).

The biophysical and social factors that impact water availability are heterogeneous in space and time. Consequently, vulnerability to drought is context-specific and disprorportionately affects marginalized groups and communities (Hayes et al., 2004; Wandel et al., 2016). Vulnerability can be defined as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt" (Adger, 2006: 268). As the definition implies, vulnerability consists of three interdependent components. Exposure is the degree to which the system (in this case could refer to species, communities, groups, populations, ecosystems) experiences a stressor such as drought, sensitivity refers the possibility that the stressor will cause harm, and adaptive capacity is the ability to prepare for change, and/or to respond to change (Adger, 2006; Smit and Wandel, 2006).

The social science of risk and vulnerability considers how people perceive drought, the social and ecological factors that enable or constrain responses to drought, and the role of humans as actors in complex SES that can actively exacerbate or attenuate drought impacts (McNeeley et al., 2017; McNeeley and Lazrus, 2014; O'Brien et al., 2007; Renn, 2011). For instance, the sensitivity to a stressor and the capacity to respond are the product of land use and land tenure arrangements, livelihood practices and dependencies, which can be limited by a set of social, cultural, economic and institutional barriers (Adger et al., 2007; Bierbaum et al., 2013; McNeeley, 2012; Moser and Ekstrom, 2010; Smit and Wandel, 2006). Further, the risk and vulnerabilities of drought are framed and interpreted in very different ways due to different knowledges and experiences, and management objectives or priorities. These factors ultimately shape perspectives of how to respond, under what circumstances to respond, and the specific response options that are considered appropriate to deal with drought (Adger et al., 2013; McNeeley and Lazrus, 2014; Renn, 2011).

Therefore, the factors that determine vulnerability are the product of place-based social and ecological contexts, and responses considered to deal with change and the capacity to do so is limited by a host of barriers and dependent upon diverse framings of risk and capacity. Rather than assume the drivers of vulnerability *a priori,* we use a determinants approach which relies on local knowledge and observations to document and understand what determines or causes vulnerability to drought (Ford et al., 2010; Füssel and Klein, 2006; Grothmann and Patt, 2005; Smit and Pilifosova, 2003; Smit and Wandel, 2006).

2. Methods

2.1. Data collection

Semi-structured, in-depth interviews (n= 22) were conducted with land and resource managers at WRIR. Interviewees included water managers from the Tribal Water Engineer's Office and State Water Engineer's Office, members of water users associations on the reservation, ranchers and crop agricultural producers, and staff from the United States Fish and Wildlife Service (USFWS) and Bureau of Indian Affairs (BIA). Informants were identified using purposive sampling, which is a non-random sampling technique that is useful to identify informants who have knowledge that aligns with the research objectives (Bernard, 2006; Patton, 2002). The interview protocol consisted of questions that addressed: how managers frame and interpret drought and drought risks; the indicators that are used to determine drought progression and impacts; the management decisions that are affected by drought; the capacities and barriers to respond to drought; and the impacts to key management issues and livelihoods (See Appendix 2: Drought Risk and Adaptation in the Interior (DRAI) interview questions and Appendix 3: Context for overarching research questions for DRAI project for tabular and network view output from the overarching research questions which informed the analysis below).

2.2. Data analysis

Semi-structured interviews were analyzed using a modified grounded theory method. Grounded theory is a set of prescriptive guidelines for determining meaning, and ultimately building theory, from analysis of textual data (Bryant, A and Charmaz, K, 2007; Glaser, B and Strauss, A, 1967). The approach is intended to be an iterative and inductive process of open coding (segmenting data and assigning concepts to raw data) and axial coding (relating concepts to one another) to identify concepts and higher order categories of relationships and themes in the data, , which are refined, modified, and expanded by constantly comparing across cases (in this case individual transcripts) (Charmaz, 2011; Corbin and Strauss, 2008). The modified approach used here acknowledges the influence of the researcher's experience and knowledge-base on data interpretation and analysis, and emphasizes the utility of situating the analysis within relevant theoretical frameworks (Corbin and Strauss, 2008; Strübing, 2007). For example, we used a determinants approach to understand what determines or causes drought vulnerability in local contexts (Ford et al., 2010; Füssel and Klein, 2006; Smit and Wandel, 2006). General determinants and decision contexts identified in the vulnerability literature informed the development of the interview protocol and provided structure to the analysis, however context specific concepts and categories discussed by the managers were coded as such.

Interviews were analyzed using Atlas.ti (http://atlasti.com/), a qualitative data analysis software program that supports analysis of textual data using a grounded theory methodology (Hwang, 2007). We used a series of analytical functions to link concepts and categories across cases. For instance, we used code groundedness, which refers to the number of times a code was applied to segments of text to characterize major management issues and storylines. We also used code co-occurrence, or the number of times a codes occurs alongside another code in the same segment of text, to understand how managers discussed drought risk and vulnerability across the different sub-basins at WRIR, for example. Finally, we used network analyses to characterize the biophysical and social factors and the relationships between those variables that affect water availability (See Appendix 4: Complex network analysis of interacting and unique biophysical, physical infrastructure, and social drivers that result in system shortages at Wind River Reservation). The results are framed by comments made by key informants, which are illustrated using exemplar quotes.

3. Results

The results presented below are organized into three thematic sections, and sub-topics. We first address three major storylines that emerged from the interviews, followed by a discussion of how key informant interviews can provide critical inputs for the physical climate and ecological impacts assessment teams and inform drought planning. In the last section, we offer additional questions for future research that were identified through an in-depth analysis of the interview transcripts. At the beginning of each section we provide brief summary points, referred to as the 'section at a glance'

3.1. Major storylines that emerged from analysis of interviews

3.1.1. Water availability is a function of interacting and unique biophysical, physical infrastructure, and social drivers that result in system shortages at Wind River Reservation

Water availability, or water shortage, during times of drought is contingent upon physical and biophysical availability (e.g., climate/weather, topography), legal availability (e.g., water rights), management behavior and use (e.g., water stored or released), and physical infrastructure (e.g., dams, reservoirs, canals). Figure 3 is a simplified conceptual diagram of the biophysical and social factors that affect water availability and lead to water shortages at WRIR (See also Appendix 4: Complex network analysis of interacting and unique biophysical, physical infrastructure, and social drivers that result in system shortages at Wind River Reservation). Note that the codes and categories are not mutually exclusive, meaning that the many of the codes and categories capture a variety of concepts. Therefore, an iterative, inductive discovery process was warranted to better understand the ways in which local informants interpret drought, drought risks, and the impacts to water availability on their landscapes. We describe first the biophysical factors that drive water availability and how these processes are undergoing change, followed by a discussion of the legal and management-related factors, and then the physical infrastructure factors that affect water availability at WRIR. It is important to note that these factors play out in different ways across the various sub-basins, and even within sub-basins, at WRIR (e.g., Little Wind, Big Wind [including Upper and Lower Wind], Crowheart, Owl Creeks [Upper Bighorn]), and across key management sectors of concern, such as irrigation for ranching and grazing and agricultural food crops, traditional and/or cultural uses, riparian ecosystems and fisheries, and various wildlife species. We discuss this spatial heterogeneity in the section below as well as in the spatial vulnerabilities section (Spatial variability in drought vulnerabilities within and between watersheds). Finally, we highlight case examples from three drought periods at WRIR to illustrate how interacting biophysical and social factors combine to impact water availability at WRIR.

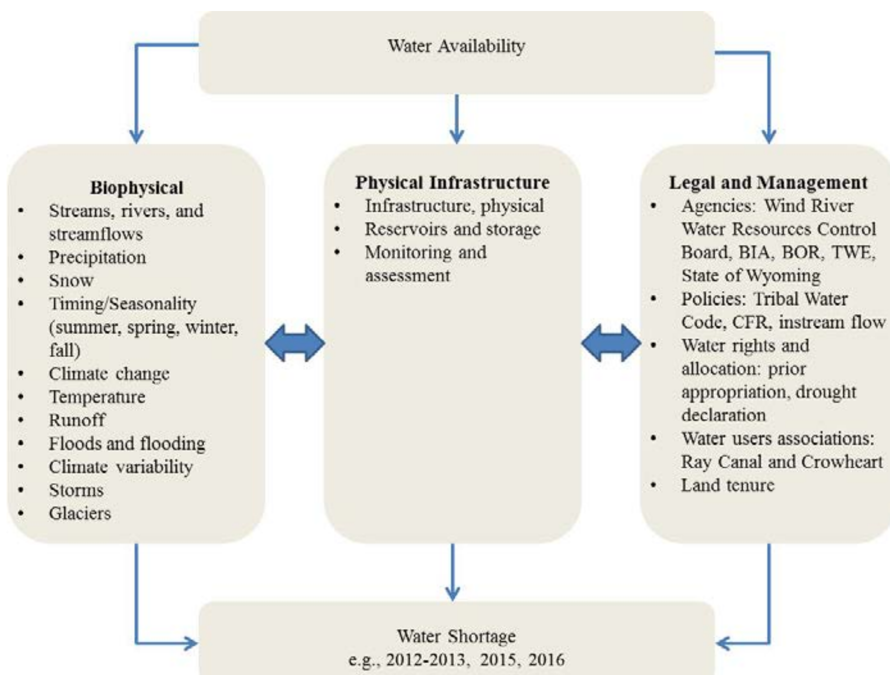


Figure 3: Conceptual diagram of interacting social and ecological factors that affect water availability at WRIR. Water availability is a function of biophysical, physical infrastructure, and legal and management related factors. These can combine to create water shortages in a given year.

3.1.1.1. Biophysical factors affecting water availability

Water availability at WRIR is, in large part, dependent upon runoff from snowpack and glacial melt. Snow accumulates in the western, mountainous areas during winter snow storms, most of which occur in December and January, along with heavy spring snows in March to early-April. Additionally, plant communities at WRIR are predominantly cool-season communities that depend on spring precipitation for plant production that wildlife and livestock depend on, the importance of which cannot be underestimated in this ecosystem. As one informant described, even if annual precipitation was relatively low, impacts were not as great as when spring precipitation was below normal: "there were a few years there where spring moisture was really low… even if we got moisture later in the year…[i]t didn't make up for the lack of water that we had in the spring."[1] Additionally, the interaction between precipitation and temperature can determine physical water availability during the year. For instance, warmer winter temperatures can affect the extent to which snow can crystallize and mature which can have significant impacts on the timing and extent of runoff through the season.[2]

Section at a glance

- Historical seasonal trends
  - Water availability dependent on snow- and glacier-fed tributaries
  - Winter snowpack (December/January), with heavy, wet snows in spring (March/April)
  - Spring (April/May) rain for forage and crop production
  - Runoff has historically occurred in two pulses—one in early spring, with peak runoff occurring in mid-June
- Climate change and variability
  - Less snowpack during critical periods in winter months, combined with warmer temperatures
  - Earlier transition of precipitation falling as rain versus snow
  - Accelerated snowmelt
  - Runoff now occurs 2 weeks to 1 month earlier than in the past
- These changes to water cycle challenge management practices and necessitate innovative actions to prepare for and respond to drought and climate variability.

Conditions typically transition to a dry period in mid- to late-June and persists throughout the summer. The summer dry period is the primary point at which drought becomes most problematic. However, drought can manifest at different points throughout the year, and have differential impacts across sectors. For instance, insufficient snowpack during the winter months can have requisite impacts on forage production and water availability for all uses throughout the year. If drought manifests in the spring season (after April), impacts are not seen as much on the hydrography, however plant communities never fully mature, go dormant early, and result in reduced annual production.[3] These differences in drought onset leads to differences in impacts to ranchers and farmers as one member of the Wind River water board mentioned,

> "When there's not adequate snowpack and stuff from the winter, then we experience drought on irrigated land. When there's inadequate water in the spring…then we

[1] WR28
[2] WR39
[3] WR27 [27:3]

experience drought, kind of a high desert drought, which affects people differently. The rancher is affected by that spring water; the farmer is affected more by the winter." [4]

A lack of precipitation in the fall can have significant impacts on ranching and grazing as fall green-up can help to carry production into the next spring. Importantly, this fall season dry period can have the most lasting impacts on fish populations because populations are set in the fall and drought can reduce the number of juveniles that survive into their first winter.[5]

Stream runoff from snowpack and glacier melt has historically occurred in two pulses. The first pulse typically occurred in March as temperatures warm up in February and early March, and as a result snowpack in the lower elevation zones shed water. Melt season occurs in April, May, and June, and the peak runoff has historically occurred in a second pulse around the second to third week of June.[6] Peak flows that occur early or too late can have significant impacts on plant production. For instance, if peak flows occur too early, plants are not yet mature and cannot utilize the water properly. Conversely, peak flows that occur too late in the season may result in plant communities that are burnt up, which results in reduced productivity. [7]

WRIR is witnessing changes to the timing and seasonality of climate and weather patterns. For instance, informants observed that when there are consistently warmer temperatures during winter and spring months along with altered timing and intensity of winter snows. This can lead to an earlier transition of precipitation falling as rain versus snow, which alters snow conditions on the ground, and contributes to earlier snowmelt and causes peak runoff to occur earlier in the year.[8] Peak runoff now occurs on average two weeks to one month earlier than historically (~Mid-late May). In addition to changes to the timing of runoff, informants reported changes in the magnitude of stream runoff, where runoff occurred more gradually throughout the season instead of in two distinct pulses.[9] Further, the warmer temperatures observed have contributed to glacial retreat in the Wind River Range, which provides a critical source for late-season streamflow, especially among water users in the Crowheart area and Upper Wind River (see section Spatial variability in drought vulnerabilities within and between watersheds). Informants also described an increase in the annual and inter-annual variability in flood and drought trends: "the point is [we are] really getting wild swings in the water cycle here on the reservation that goes from flood to drought to flood to drought again within a four year span."[10]

The combination of these factors challenges management decisions on the ground, and as one manager mentioned past management activities cannot be used today, "we can't use the water management practices of the 80's and the 90's because the water cycle is not that way anymore."[11] The changes occurring to the water cycle at WRIR are difficult to plan for and respond to as managers constantly deal with uncertainty, surprise, and novelty. The changes are also variable in space and time, thus requiring decisions on the order of seasonal, annual, and

[4] WR31 [31:1]
[5] WR37
[6] WR27 [27:5]
[7] WR22
[8] WR27
[9] WR25 [25:5] WR27 [27:5]
[10] WR20 [20:6]
[11] WR36 [36:4]

decadal times scales, and at spatial scales (e.g., sub-basins) that are typically more refined that that which is used in climate modeling. .

3.1.1.2. Legal and management factors affecting water availability

> *Section at a glance*
>
> - The Bighorn General Stream Adjudication determined the amount and use of tribal reserved water rights at Wind River Reservation
>   - Bighorn I—Afforded WRIR approximately 500 thousand acre-feet of tribal reserved water to be used and administered on tribal land. Tribal reserved water has a "senior" priority date of 1868
>   - Bighorn III—Ruled that tribal reserved water was tied to agriculture purposes, the tribes could not use water rights for instream flows, rights did not extend to groundwater, and the State would assume legal responsibility in administrating tribal and non-tribal water rights at WRIR
> - The State allow the Tribal Water Engineers' Office (TWE) to administer water in the BIA-managed Wind River Irrigation Project on the Little Wind River—each irrigation season the TWE determines hydrological conditions, and during drought can deliver water according to prior appropriation
> - A number of barriers limit water administration on the Little Wind River (e.g., the Bureau of Indian Affairs ultimately determines when to release water form storage facilities)
> - Responses—Producers have developed water user's associations to take great control of, and better manage, the BIA-managed system, and are working towards formally enacting public law 638 from the 1975 Self-Determination Act to gain even more authority in allocation and delivery across WRIR.

The legal factors that affect water rights and administration of those rights at WRIR are complex; here we highlight the major rulings of the Bighorn Adjudication, which was initiated in 1977 to determine water rights for all users in the Bighorn basin, to provide the context for water management on the reservation. Prior to the adjudication, all water on tribal and non-tribal lands at WRIR was administered according to a 1905 state water right. However, following the adjudication water would be allocated according to a prior appropriation, or "first in time, first in right", system whereby "senior" water rights holders have priority in use over "junior" water rights holders during times of water shortage. The decision of Bighorn I afforded WRIR 499,862 acre-fee per year of tribal reserved water to be used and administered on tribal land. These tribal reserved water rights were considered senior water rights with a priority date of 1868 (Robison, 2015). Additionally, Bighorn I established rulings with regard to managing derivative (alottee) water at WRIR. In this case, tribal allotments purchased from tribal members were given an 1868 Walton right, the same priority date of the tribal reserved water right, and can include non-tribal members (referred to as successors) (Robison, 2015). Tribal reserved rights and Walton rights characterize the majority of water rights at WRIR.[12] A third type of water right, referred to as state-based rights, are water rights applied to fee patent lands that are non-trust, non-allotted lands. These state-based water rights are considered junior water rights to the 1868 tribal reserved and Walton rights, and have priority dates ranging from 1905 to as current as 2012, depending on when the land was purchased.[13] Administration of water per the water rights

[12] WR26 [26:7]
[13] WR26 [26:7]

rulings of the Bighorn Adjudication are challenging, in part, because land tenure is patchy across WRIR, and the majority of the canals include a mix of tribal, Walton, and state-based rights.[14]

The tribes completed their tribal water code (TWC) after the final ruling on Bighorn I in June 1989 the purpose of which was to: determine appropriate ways to administer and protect 1868 tribal and Walton water (allotee) along with state derived water; ensure water for 15 beneficial uses (domestic; municipal; agricultural; stock water; industrial; instream flow for fisheries, wildlife, and pollution control, aesthetic and cultural purposes; mineral resource development; water storage, marketing, and transfer; groundwater recharge and supply enhancement; recreational; cultural; religious; hydropower generation; pollution control; and resource development); and to protect water for future use (Wind River Indian Reservation, 1991). According to the TWC, all of the beneficial uses are considered equally important and administered as such. The TWC also established the Tribal Water Resources Control Board and the Office of the Tribal Water Engineer (TWE) to enforce and manage water resources at WRIR (Wind River Indian Reservation, 1991). In 1990 the Wind River Water Resources Control Board granted the tribes a tribal instream flow permit for maintaining and restoring fisheries, recreational uses, and groundwater recharge (Robison, 2015). During the 1990 water year, the tribes submitted a formal complaint to the Wyoming State Engineer's office documenting the impacts of diversions on instream flow levels on the reservation, and requested restrictions on "junior", appropriative water rights held by Midvale Irrigation District to satisfy their instream flow permit, to which the State Water Engineer refused to uphold (Kinney, 1993; Robison, 2015). This set the stage for Bighorn III, which ultimately ruled that tribal reserved water cannot be used for instream flows, and can only be used for agricultural purposes. Bighorn III also ruled that tribal water rights do not extend to groundwater, and the State Engineer would assume legal responsibility for administering all water rights (tribal and non-tribal) at WRIR (Kinney, 1993; Robison, 2015).

As such, the State has ultimate authority over administration of water rights at WRIR. Yet, two DOI agencies own and operate reservoirs within the reservation, which adds to the complex water management regime at WRIR. The Bureau of Reclamation (BOR) own and operate the largest reservoirs in the Wind River Basin (including Bull Lake and Boysen Reservoir among others) that feed irrigation districts downstream and off WRIR. A smaller reservoir in the Upper Bighorn sub-basin (Anchor Dam) was also constructed by the BOR, but is managed by the state Division Engineer. The BIA is responsible for the operation and allocation of water from Washakie Reservoir and Ray Lake in the Little Wind River sub-basin, and from Dinwoody Lake in the Upper Wind River sub-basin. The BIA-managed system is collectively referred to as the Wind River Irrigation Project.

The state generally allows the TWE to administer water in the Little Wind River where the majority of tribal communities and ranchers reside (Figure 4). The BIA Wind River Irrigation Project supports irrigators in the Little Wind River system and in the Crowheart area. In the Little Wind, the project supplies water for approximately 30,000 acres (intended for 40,000 acres, but 10,000 acres is idle land) of land that is watered from Washakie Reservoir, which has an estimated storage capacity of 7,940 acre-feet, and from Ray Lake, which has an estimated storage capacity of 6,980 (Figure 4: MWH Americas, Inc. et al., 2010). The TWE monitors

[14] WR39 [39:6]

snowpack and reservoir levels each irrigation season, and makes determinations on the current year's hydrological conditions (e.g., surplus, normal, or drought per the Wind River Tribal Water Code).[15] If a drought is declared during the season, then the TWE administers water delivery according to a prior appropriation system. In this case, the TWE could restrict "junior" water rights (state right of 1905 or later) in order to ensure that water is available for "senior" water (1868 tribal reserved water).

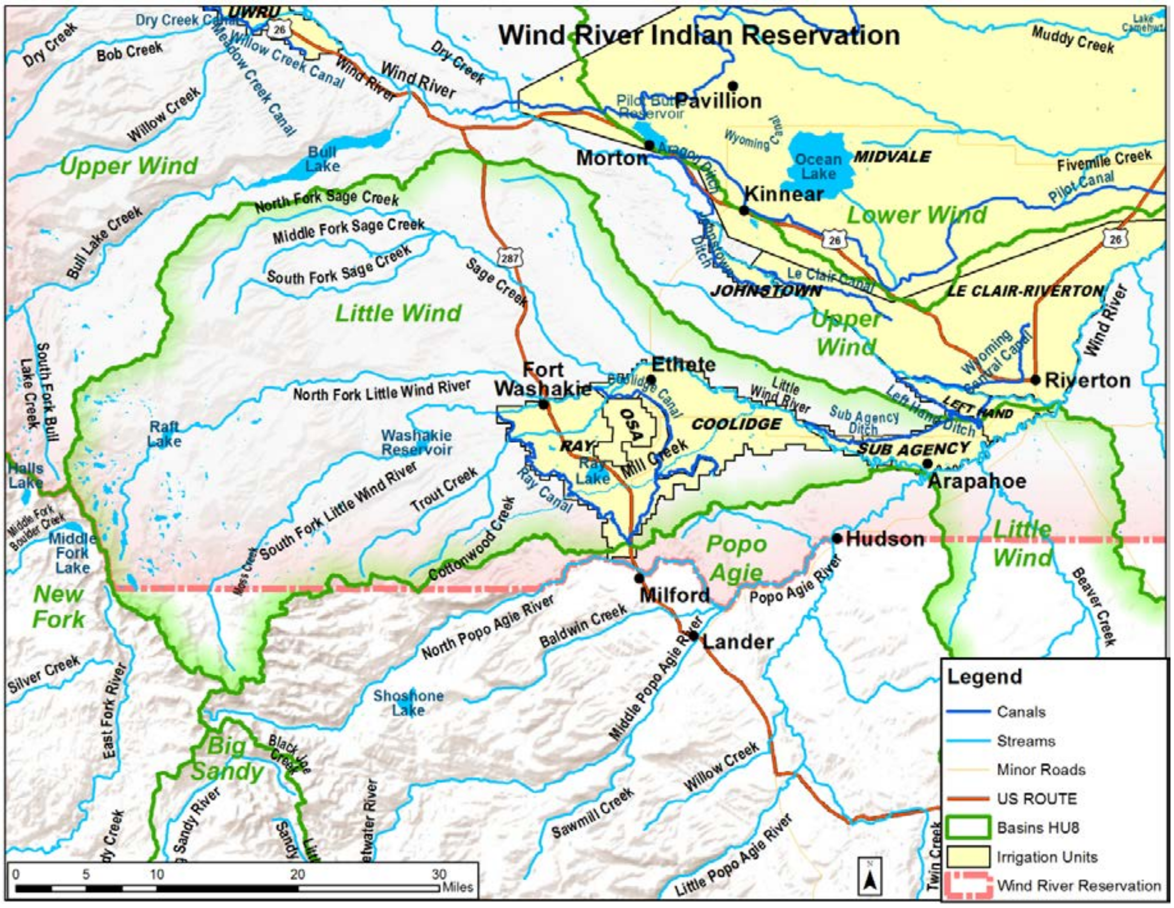


Figure 4: Little Wind River sub-basin, including irrigation units and canals.

The TWE was described by several informants as an organization that has been very critical in developing the capacity of tribes to take more control of water administration at WRIR and to prepare for and respond to drought. The TWE have been instrumental in securing funds to repair dilapidated infrastructure. They also procured funding to install state-of-the-art fish screens and liners in the Wind River Irrigation project (they have constructed diversion structures with an attached fish ladder on Ray Canal, Coolidge, and Sub-Agency, and there are plans in place to install a structure up at Dinwoody in the Upper Wind River sometime in 2017; Figure 4), and co-developed (with USFWS) a recommended minimum instream flow for the Little Wind system (25 cubic feet/second), both of which support fisheries and riparian conservation.[16] They were

[15] WR22 [22:7]
[16] WR40 [40:6]

also cited as helping to consolidate and disseminate climate science and information to tribal and non-tribal producers, among others.

Still, their ability to deliver water downstream to protect all 15 beneficial uses of the TWC is limited for a number of reasons. For example, although the TWE collaborated with the USFWS, BIA, and water users to establish minimum instream flow requirements in the Little Wind River, one water manager was concerned that in a severe water short year, this "pseudo" instream flow would not be enforced.[17] Also, one informant mentioned that there is not currently a database that clearly identifies and distinguishes "junior" rights holders, though the TWE is working on developing one.[18] Further, the BIA Wind River Irrigation Project infrastructure, including Ray Canal, was built to deliver water according to the Code of Federal Regulations (CFR), which is the code of operations and maintenance on BIA-managed irrigation projects. Under the CFR, all users, regardless of their water rights, share the surpluses and shortages, instead of a prior appropriation system.[19] Both the absence of a database distinguishing "senior" and "junior" rights, and the ways in which the irrigation system was built limits tribal resource managers' ability to efficiently restrict "junior" water rights holders during water short years as per the prior appropriation system determined after Big Horn I. The issues with respect to the way the canal was built to physically deliver water and the way water managers are mandated to administer water rights is reflected in an exemplar from a local water manager,

> "when you go back to try to apply that [prior appropriation system] to the irrigation project, it's kind of like putting a round peg in a square hole because now you're trying to deal with water rights based on a prior appropriation, but not how the system can physically deliver the water."[20]

Administering water to users is challenged because many of the headgates lack measuring devices, and ditch riders are forced to deal with turnouts that are "prehistoric".[21] The BIA has replaced turnouts on some of the headgates, but has not disseminated information that include necessary charts to measure how much water is delivered. Therefore, it is difficult to know for sure how much water is being let down in places. The TWE also has a small number of staff for the size that they manage, further challenging water administration and allocation.

The BIA has authority over reservoir releases, and therefore ultimately determines when water is released from Washakie Reservoir. When water is released too early, as was the case during the 2013 water year (see Examples illustrating the interacting biophysical and social factors that affect water availability), this can create significant water shortages and impacts in the Ray Canal system of the Wind River Irrigation Project, especially for the tribal and non-tribal producers above Ray Lake and west of Fort Washakie that depend on Washakie Reservoir for irrigation water.

---

[17] WR 40 [40:6]
[18] WR41 [41:7]
[19] WR21 [21:4]
[20] WR21
[21] WR25

The water users in Crowheart and Ray Canal have established Cooperative Assistance Programs with the BIA relatively recently in an effort to better manage the Wind River Irrigation Project in their respective systems. The Ray Canal Water User Associations include tribal and non-tribal producers on the Ray Canal System in the Little Wind River, and have taken over some responsibility for the delivery of water, as well as the day-to-day operation and maintenance of canal infrastructure (Figure 5). One informant from the Crowheart Water Users Association described how funds were used to clean upwards of ten miles of canals, and also to rehabilitate structures and headgates.[22] Further, one informant from the Ray Canal Water Users Association reported that the users association took over Ray Canal from the BIA in 2014 and were able to more efficiently administer water to water users than the BIA.[23] They have also developed an invasive plant treatment program, which is funded in part by the User's Association with matching funds from the BIA and county, to treat sensitive areas.[24] Water users and the TWE are working towards the development of a formal enactment of the public law 638 (which stemmed from the 1975 Indian Self-Determination Act) to give the TWE and Water User's Associations more authority over water allocation and delivery across the reservation.[25] [26] However, this is currently on hold (as of March 2017) until a government conflict between the Eastern Shoshone and Northern Arapaho tribes is resolved. These governmental conflicts were cited as a major barrier to supporting tribal programs in general and water management in particular,

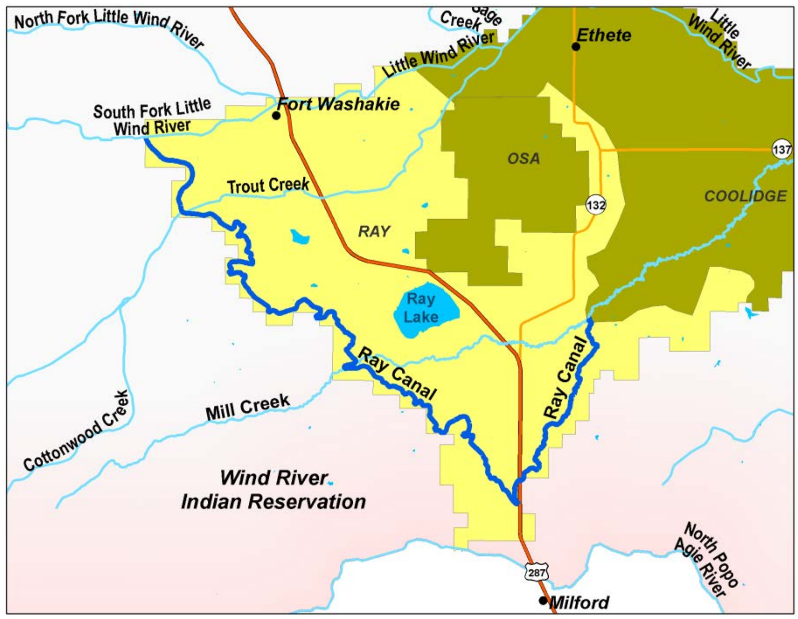


Figure 5: Ray Canal in Little Wind River.

> "there are two separate, sovereign tribes, and depending on the time of year, one might be more supportive of the TWE. And by supportive, it can be both in the problem-solving end of things, or in the financial end of things. We [Water Board] rely – 80 percent of our resources come from the councils – so we rely on them. And if they're in poor financial status, then it affects us."[27]

---

[22] WR34 [34:8]
[23] WR25 [25:2]
[24] WR25 [25:6]
[25] WR23 [23:9]
[26] WR26 [26:6]
[27] WR31 [31:13]

In sum, the legal factors that affect water delivery and availability at WRIR was codified in the Bighorn General Stream Adjudication. These rulings established senior water rights for tribal reserved lands and successors (Walton Rights), and junior, state-based water rights. The patchwork of ownership and resulting patchwork of water rights, at WRIR creates problems in practice when administering water. While subsequent rulings (Bighorn III) found that the State of Wyoming Water Engineer would assume authority of water administration on tribal and non-tribal lands at WRIR, the state generally allows the TWE to administer water in the Little Wind sub-basin according to their TWC. However, the TWE's ability to manage water during water short years is limited due to a number of factors, namely BIA's authority over reservoir releases from Washakie Reservoir downstream. The establishment of Water Users Associations recently has shown to be effective at providing water users with greater autonomy in delivering water in the Wind River Irrigation Project, and TWE is working towards applying for a 638 to take greater control in water management. Below, we describe some the physical irrigation infrastructure factors that affect water availability.

3.1.1.3. Physical irrigation infrastructure factors that affect availability

A dilapidated physical irrigation infrastructure in the Wind River Irrigation Project is a significant barrier to effective water allocation and delivery at WRIR. This includes leaky and neglected canal and reservoir systems, insufficient reservoir storage capacity, and a lack of stream gauges to effectively monitor streamflow. The condition of canals is considered one of the biggest impediments to ensuring water availability at WRIR. Many of the canals in the Wind River Irrigation Project were constructed decades ago, and were never finished and/or have not been sufficiently maintained by the BIA, which is reflected in the following exemplar,

> "you have a dilapidated system of irrigating on the Wind River Reservation, because Bureau of Indian Affairs first started this Ray Canal and other canals, over 100 years ago, and never finished them, and they've never done any maintenance or extremely little maintenance."[28]

> *Section at a glance*
>
> - Inadequacies in the physical infrastructure of the BIA-managed Wind River Irrigation Project are significant barriers to effective water management at WRIR
>   - Dilapidated and neglected canal infrastructure and conveyance systems—deferred maintenance for BIA-managed projects at WRIR is $30-35 million and cost to replace estimated at $93 million
>   - Reservoir capacity is variable across WRIR—BOR-managed systems are reportedly adequate in size, though BIA-managed reservoirs insufficient in size for majority of tribal producers that rely on them. The tribes are working to address this, however, and are currently sponsoring a storage feasibility study for locating new reservoir facilities on the Big Wind and Little Wind Rivers.
>   - Lack of monitoring systems—The majority of stream gauges were decommissioned by the USGS and BIA due to federal spending cuts.

[28] WR23 [23:3]

Additionally, one key informant stated that there would be ample water for everyone if canals were efficient,

> "If this canal [Ray Canal] was…as efficient as Wyoming Canal, we wouldn't have a problem every year. There would be enough water for everything, but as long as this system is screwed up and then no maintenance, they [BIA] don't do any maintenance. It's not going to change, and they're not looking for those kinds of things, changes, they don't look for the funds to do the work."[29]

The most recent estimates of deferred irrigation maintenance costs by the BIA on Wind River Reservation have been estimated to be somewhere between $30-35 million and the cost to remove and replace the existing system is $93 million; the estimate for deferred maintenance for the 16 BIA-operated irrigation projects in the U.S. (for which BIA collects operation and maintenance fees) is half a billion and replacement over $4 billion (U.S. Government Accountability Office, 2015). Despite this, the BIA still collects Operation and Maintenance (O&M) fees on the system yet the money only goes to sustaining BIA administrative costs. Several informants described how the fees continue to rise, which affects producers both in terms of rising costs per acre, but also because deferred maintenance and drought leads to less water availability, which results in reduced crop productivity and therefore reduced incomes for farmers.[30] A water manager for the BIA stated that increasing costs are a function of accommodating federal pay schedules and pay raises for employees, fluctuations in gas prices, and the need to stockpile reserve cash in the event that equipment purchases are needed. Additionally, the informant mentioned that O&M fees paid by the water users are typically the only source of funds for the Wind River Irrigation Project, which further limits investments in rehabilitating the system. The same informant discussed an interesting paradox,

> "as the projects get more and more into disrepair, it makes it harder to manage the project, and so it takes more work, which costs more money…Just to try to keep it where it's at."[31]

In this vein, in the summer of 2016 the BIA proposed yet another rate increase for the users districts in the Wind River Irrigation Project; those user districts where the BIA provides "direct service" (areas with no water users association) will likely see a $1/acre rise in fees (from $22.50 to $23.50 for each irrigable acre), while those areas where water users associations assist with water delivery and maintenance will likely see marginal ($0.25) to no change in fees.[32] The IRRIGATE act (S. 438) was proposed to Congress on February 10, 2015, which would provide $35 million per year of funding for the necessary repair, replacement, and maintenance of Indian irrigation projects in the western United States that are managed by the BIA and have deferred maintenance (Barrasso, 2016). However, the IRRIGATE act has stalled in Congress as of April 27, 2016.

Inadequate funding to maintain BIA infrastructure in the Wind River Irrigation Project results in leaking canals and erosion, which waste a significant amount of water. For instance,

[29] WR23 [23:20]
[30] WR41 [41:11]
[31] WR41 [41:15]
[32] WR41 [41:11]

the Ray Canal was designed to hold approximately 320 CFS, but informants reported that they canal currently maintain a maximum of 280 CFS, and in places much of this leaks out of the sides of canals.[33] Additionally, many of the canals owned and operated by the BIA accumulate debris, which obstructs the delivery of water, and are not properly maintained by the BIA. The TWE secured state and federal funding to update some of the structures, though one informant described these funds as a "drop in the bucket."[34] The TWE has also taken on cleaning debris from some of the canals. However, since the physical infrastructure is owned by the BIA, they have at times refused the TWE access to the structures, which creates tensions between the TWE and BIA, and serves as an example of the BIA not working with the tribes to support efficient water delivery.[35]

Reservoirs operated and maintained by the BOR include Bull Lake, Pilot Butte, and Boysen Reservoir, which hold approximately 152,500, 34,600, and 802,000 acre feet of water, respectively (Table 1). These reservoirs were typically described as sufficient in size for the number of users that rely on them and well-maintained. However, many of the reservoirs at WRIR have insufficient storage capacity for the number of users, and/or are not properly maintained. For instance, Anchor Dam was built by the BOR, and currently operated by the state. Anchor Dam, which is located in the northern section of the reservation, was supposed to hold 17,350 acre-feet of water (Table 1; Figure 1). However, the reservoir was designed improperly and described as leaky; one informant who has monitored the dam since 2003 mentioned that the most the dam has ever held was approximately 7,500 acre-feet, which occurred during the 2015 water year.[36] As a result, this system typically goes under water administration every year (meaning that the "senior" rights holders make formal calls for curtailing "junior" water years annually), and there is reportedly not enough water to satisfy even all "senior" water rights that are now, following the Bighorn I ruling, primarily located upstream in the Arapahoe Ranch area.[37]

Additionally, BIA owned and operated reservoirs at the reservation tend to be insufficient storage for the number of users and/or are not well-maintained/managed. For instance, Dinwoody Lake is a small reservoir (3,900 acre-feet; Table 1) that was constructed in the Crowheart area of the Big Wind River. Informants reported that the reservoir can fill in a couple days when runoff from snowmelt comes down and only provides up to seven days of water running at 220 cubic feet per second per day.[38] This means that the majority of the water goes through the system before it can be put to use.[39] Yet, water availability is typically adequate in this area due to a shorter growing season, and users in this area of the Big Wind drainage are first to receive runoff flows which carries them through the first part of the irrigation season. Also, Dinwoody Glacier "stores" water and offers critical late-season streamflow to augment early-season flows and the limited storage in Dinwoody Lake.

[33] WR25 [25:2]
[34] WR34 [34:15]
[35] WR22 [22:8]
[36] WR39 [39:9]
[37] WR39 [39:9]; WR20 [20:11]
[38] WR33 [33:8]
[39] WR34 [34:3]

Table 1: Estimated storage capacity for reservoirs Wind River Indian Reservation.

Basin	Reservoir	Bureau	Storage capacity (acre feet)	Source
Upper Wind	Bull Lake	BOR	152,000	Midvale Irrigation District 2007; MWH Americas, Inc. et al. 2010
	Pilot Butte	BOR	34,600	Midvale Irrigation District 2007; MWH Americas, Inc. et al. 2010
	Dinwoody Lake	BIA	3,900	MWH Americas, Inc. et al. 2010; Nelson Engineering, 2005
Little Wind	Washakie Reservoir	BIA	7,940	MWH Americas, Inc. et al. 2010
	Ray Lake	BIA	6,980	MWH Americas, Inc. et al. 2010
Lower Wind	Boysen Reservoir	BOR	802,000	https://www.usbr.gov/projects/index.php?id=26
Upper Bighorn	Anchor Dam	BOR	17,354	https://www.usbr.gov/projects/index.php?id=25

Finally, the BIA owned and operated Washakie Reservoir and Ray Lake hold 7,940 and 6,980 acre-feet of water, respectively (Table 1). Washakie Reservoir stores water from snowmelt in late-spring and early summer, which is eventually released in to the Little Wind River where it feeds Ray Canal users, on to the Wind River, and then in to Boysen Reservoir. Ray Lake is filled from the Little Wind River during irrigation off season, and during periods of high water early in the spring. As described by a water manager at WRIR,

> "we ha[ve] some 40,000 acres of irrigable land [in the Little Wind unit of Wind River Irrigation Project] and we have about 14,000 acre feet of storage. We just don't have enough storage."[40]

Washakie Reservoir was described as too small for the number of users and acreage that it supplies, especially since many of the upstream users on the Little Wind River depend entirely on direct flow from the south fork of the Little Wind and Washakie Reservoir for water (Ray Lake is too low in the basin for these users to benefit from that storage). Although Ray Lake is also small, users in the lower end of the Little Wind sub-basin derive water from a number of sources, including the north and south fork of the Little Wind River, Washakie Reservoir, and Ray Lake (Figure 4). As one informant mentioned, irrigation districts downstream (e.g., Coolidge, Left Hand) seem as though they rarely experience water shortages, while upstream users deal with system shortages frequently.[41] Therefore, inadequate reservoir storage capacity is

[40] WR40 [40:1]
[41] WR32

a significant barrier to managing water in many places at WRIR, especially those where the majority of tribal residents reside.

The tribes are working to address this. In 2014 the Eastern Shoshone and Northern Arapaho tribes sponsored two storage feasibility studies (one on the Big Wind and one on the Little Wind Rivers) with funds from the Wyoming State Legislature and Wyoming Water Development Commission (WWDC). Funds were appropriated for a Level II, Phase I reconnaissance for the feasibility of providing new and/or adding on to existing surface water storage facilities in the Big Wind and Little Wind Rivers (http://wwdc.state.wy.us/dam_reservoir/b-l_WindRStorage/b-l_WindRStorage.html). The final report was scheduled to be completed in December 2016, and the TWE is working with the WWDC to move the project forward to the next phase. The WWDC has suggested to the TWE that a reasonable timeline for completion of the study, getting a facility permitted, and finally built is on the order of 15-20 years.[42]

Further, there is a lack of stream gauges to monitor streamflow throughout the reservation. The USGS and the BIA had previously decommissioned many of the stream gauges installed on the reservation; one informant reported that there used to be 48 stream gauges located throughout WRIR, but there are currently only 12-13 gauges that are in operation and online due to federal spending cuts.[43] One of the stream gauges that was offline during the 2013 water year was the gauge above Washakie Reservoir. There is also no gauge for monitoring streamflow coming directly out of Washakie Reservoir. Instead, water managers relied on a "rock method", where managers would estimate water storage based on distance above or below rocks below the dam.[44] As such, managers had relatively little knowledge of the amount of water coming into and out of Washakie Reservoir during this time. As of September 2014, the decommissioned gauge above the Washakie Reservoir was set to be recommissioned by the USGS, and there were talks of installing another gauge in consultation with the TWE.[45]

In sum, inadequacies in the physical infrastructure system at WRIR are a major impact to ensuring water availability. Dilapidated and neglected canal systems waste water and create uncertainties as to when water can and will be delivered to users. Storage capacity is spatially variable, but generally is lacking for the majority of tribal producers and communities. Finally, the lack of gauges to monitor streamflows affects the ability to monitor water availability, which challenges effective water delivery to downstream users.

3.1.1.4. Examples illustrating the interacting biophysical and social factors that affect water availability

2012-2013 Water Year

The extreme drought of 2012 started in July of 2012 and persisted until September of 2013 in many places across WRIR (Figure 6). Informants described the 2012 drought as uncharacteristically hot and dry, with insufficient snowpack and early runoff. In fact, according to a weather station located at Riverton in the Upper Wind sub-basin, the exceptional 2012

[42] WR40 [40:5]
[43] WR21 [personal communication, October 2014 Workshop]
[44] WR25 [25:14]
[45] WR22 [22:8]

drought was the driest (Table 2), and hottest (both tMax and tMin; Table 3), year on record (1919-2012; droughtatlas.unl.edu). Despite this, informants described that there was enough water in the Ray Canal system, but negligence by BIA to clean debris from headgates limited water availability downstream. This is illustrated by an informant who stated,

> "you can call it a manufactured problem. I mean, the water was there in the system, but because of lack of maintenance by the BIA, they did not clean out the headgate…And what had happened is...it built up a lot of sticks, a lot of logs…it caused a head drop going down to the canal with less water. So, there was less water going down to the project under Ray Canal, but you had the amount of water to satisfy it in the river."[46]

This caused many producers to liquidate their herd and purchase supplemental hay to get through the season.

Section at a glance

- The 2012 and 2013 water years are demonstrative of how the combination of physical climate and management issues impact water availability.
- The exceptional drought of 2012 was widespread across the west and persisted in many places into 2013, the impacts of which were devastating.
- Snowpack was below normal for the two water years. Yet, informants reported that during the 2012 and 2013 irrigation seasons there was adequate biophysical availability in the system had it been managed appropriately
- During the 2012 water year, negligence to remove debris from headgates resulted in a system shortage for irrigators on the Little Wind River
- During the 2013 water year, a (now former) project engineer for the BIA mismanaged Washakie Reservoir by releasing the water too early, resulting in system wide-shortages and significant impacts to irrigators on the Ray Canal system.
- Impacts—Producers were forced to liquidate herds, purchase supplemental hay, and/or borrow funds to get through the season.

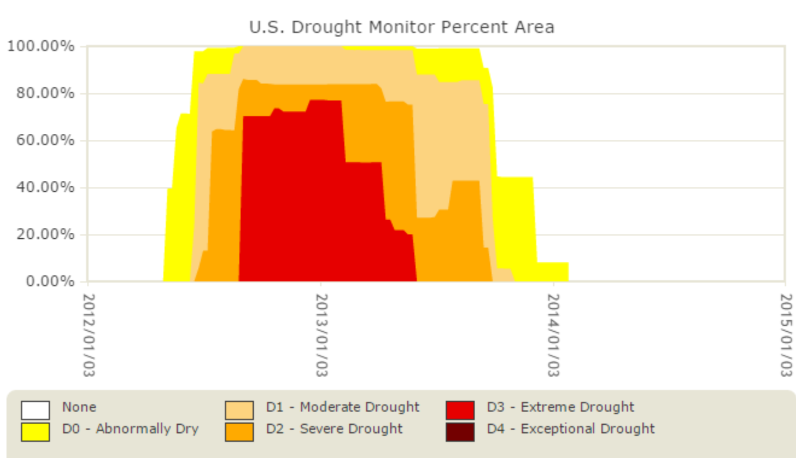


Figure 6: US Drought Monitor illustrating percent area of HUC 6 Bighorn basin under extreme to exceptional drought during 2012-2013. Source: Drought Risk Atlas; http://droughtatlas.unl.edu/.

[46] WR21 [21:2]

Table 2: Top 10 driest and wettest years for period of record (1919-2012) at Riverton Station, Upper Wind River sub-basin. Source: Drought Risk Atlas; http://droughtatlas.unl.edu/.

Precipitation

Driest

Rank	Date	Total (in.)
1	2012	4.00
2	1974	4.12
3	1988	4.57
4	1954	4.85
5	2001	5.09
6	2006	5.17
7	1966	5.73
8	1990	5.76
9	1932	6.05
10	1961	6.06

Wettest

Rank	Date	Total (in.)
1	1923	18.49
2	1941	14.70
3	1993	14.23
4	1998	14.21
5	1921	14.01
6	1995	13.73
7	1971	13.11
8	1997	12.67
9	1947	12.46
10	1944	12.21

Table 3: Top 10 Warmest maximum (Tmax) and minimum (Tmin) temperatures for period of record (1919-2012) at Riverton Station, Upper Wind River sub-basin. Source: Drought Risk Atlas; http://droughtatlas.unl.edu/.

Temperature - Warmest

TMax

Rank	Date	Average (°F)
1	2012	63.83
2	1988	63.63
3	1934	63.13
4	1954	63.06
5	1999	63.04
6	1939	62.64
7	1994	62.57
8	1953	62.42
9	1981	62.29
10	1946	62.15

TMin

Rank	Date	Average (°F)
1	2012	33.31
2	1999	32.50
3	2006	31.29
4	2003	31.25
5	1998	31.25
6	1934	30.85
7	2005	30.82
8	2007	30.50
9	2010	30.36
10	1981	30.25

The drought of 2012 lingered into 2013, and informants described a lack of snowpack and storms in the months of April and May. Although informants described that there was sufficient snowpack and runoff in the system for the 2013 water year, managers reported a system shortage in the Little Wind River. However, the perspectives concerning the factors responsible for driving drought conditions in the sub-basin differ between tribal water managers and producers at WRIR, and those of a manager at the BIA. For instance, a majority of key informants described how a (now former) project engineer for the BIA mismanaged Washakie Reservoir by releasing the water too early, resulting in system wide-shortages and significant impacts to irrigators. Upstream users on the south fork of the Little Wind River (including the Ray Canal Water Users Association producers) rely on water stored in Washakie Reservoir and direct flows from the south fork of the Little Wind during the runoff season. Typically, Washakie Reservoir is filled from early snowmelt in April and May, and the water from Washakie Reservoir is released downstream during the latter part of the irrigation season and/or in the event that direct flows are not satisfying downstream demand. However, reservoir releases in the system are ultimately the authority of the BIA. The BIA project engineer responsible for managing the reservoir made the decision to release water from the reservoir starting June 1, as the lower part of the system was experiencing drought conditions. Releases continued through the month of June, and upstream irrigators on the Ray Canal system did not receive their water from mid-July until the end of the season.[47] Users only had access to stock water until the end of the irrigation season, which typically lasts until the end of September, and sometimes longer (October 11 is the official closure date of irrigation season per the BIA).

This had large-scale impacts on irrigators as described by one informant, "a lot of them lands [sic] never got enough water and even the best of the best farmers they suffered some loss."[48] Precipitation during the month of September broke the system out of drought, but it was too late to recover losses incurred. Many producers had to purchase supplemental hay, and some had to borrow funds to get through. Informants described the disproportionate impacts of drought on producers across WRIR, specifically with regard to how BIA did not take care of many of the Indian irrigators, and how support in the form of grants and drought relief from the USDA were not provided to the poorest producers who needed it the most.[49]

However, one informant, a regional water resources officer for the BIA offered a different perspective. The informant did acknowledge that a new BIA project engineer on the system did contribute in part to the system shortage. Yet, the informant suggested that the installation of new fish screens and a replaced diversion unit in the canal system also contributed to the system shortage. Fish screens and a fish ladder were installed on the Ray Canal system in fall/winter of 2011/2012. [50] The manager mentioned that that BIA had to deal with some "operation/maintenance" issues associated with the fish screens, and that the installation of the screens restricted the flows that could be placed in canals. Additionally, the informant stated that the installation of a new diversion structure for the unit contributed to less water availability for users downstream because the old diversion was leaky, and as a result, kept more water in the stream, whereas the new diversion kept more water in the canal. As such, the informant reported that a lack of water along with management-related issues (new project engineer, fish screens, and new diversion structure) that affected the ways in which the BIA could allocate water contributed to the system shortage observed in the Little Wind River sub-basin.[51]

This case illustrates the ways in which the physical climate and management issues affect water availability. The exceptional drought of 2012 was widespread across the west and persisted in many places into 2013, the impacts of which were devastating. Snowpack was below normal for the two water years. Yet, informants reported that during the 2012 and 2013 irrigation seasons there was adequate biophysical availability in the system had it been managed appropriately. Instead, (mis)management-related issues caused significant water shortages in the Ray Canal system during the 2012-2013 seasons.

2015 Water Year

[47] WR22 [22:8]
[48] WR20 [20:9]
[49] WR23 [23:7]; WR24 [24:13]
[50] WR40 [40:6]
[51] WR41 [41:5]

The 2015 irrigation season in the Little Wind River sub-basin can be characterized as a “micro-drought”, or system drought, which means a drought that is short in duration, highly localized, and due to features that are particular to a system. Below, we first describe the biophysical and social processes under way that contributed to the 2015 “micro-drought” in the Little Wind River sub-basin, and then compare water availability conditions in other sub-basins in WRIR

Informants reported generally below average snowpack through the winter, which deteriorated into the March and April (Figure 7). Additionally, informants reported warmer than normal temperatures during the winter and spring, which changed snow conditions on the ground. For instance, one informant attributed warmer temperatures to changes in the form/density of snowpack observed on a manual snow survey in March, which he predicted would cause accelerated snowmelt,

> “The snow, there was a little bit of a crust on top but the snow under that crust…it had the consistency of mashed potatoes. I've never seen that. There was [sic] no large crystals in it. It had never matured. This stuff was going to come off in a hurry.”[52]

Section at a glance

- 2015 water year was a ‘micro-drought’ that is short in duration, highly localized and due to features that are particular to the Little Wind River system
- The 2015 ‘micro-drought’ is demonstrative of how changes in the timing and seasonality of climate, reservoir storage capacity, and individual management decisions together contribute to water shortages
- The 2015 water year started slow due to warm conditions and below-normal snowpack during the winter and early spring.
- The irrigation season arrived abruptly due to the record-setting May precipitation. This was combined with high temperatures and earlier transitions from snow to rain during the cold season, and high temperatures during the snowmelt season, which led to accelerated snowmelt and an early runoff season.
- Accumulated precipitation for the month of May was ~170-370% of normal across the reservation, which led to an optimistic forecast that the system would be devoid of drought
- However, the size of Washakie Reservoir was insufficient to hold these early-season flows—while irrigators were not calling for the water, the majority of water had to be let downstream before irrigators could put it to use.
- The 2015 water year then closed abruptly for producers who rely on Washakie Reservoir and direct flows from the south fork of the Little Wind for irrigation, and more than a month earlier than is typical
- Impacts—Low reservoir levels caused adverse impacts on local ranching and farming, especially impacts to hay production and concerns about stock water availability through the winter, instream flows for fisheries and riparian ecosystem health, among others

  The lack of sufficient storage capacity to capture these early season flows was cited as the primary barrier to drought management and response. We illustrate this by comparing the impacts of the 2015 water year ‘micro-drought’ on producers in other parts of the reservation.

[52] WR39 [39:12]

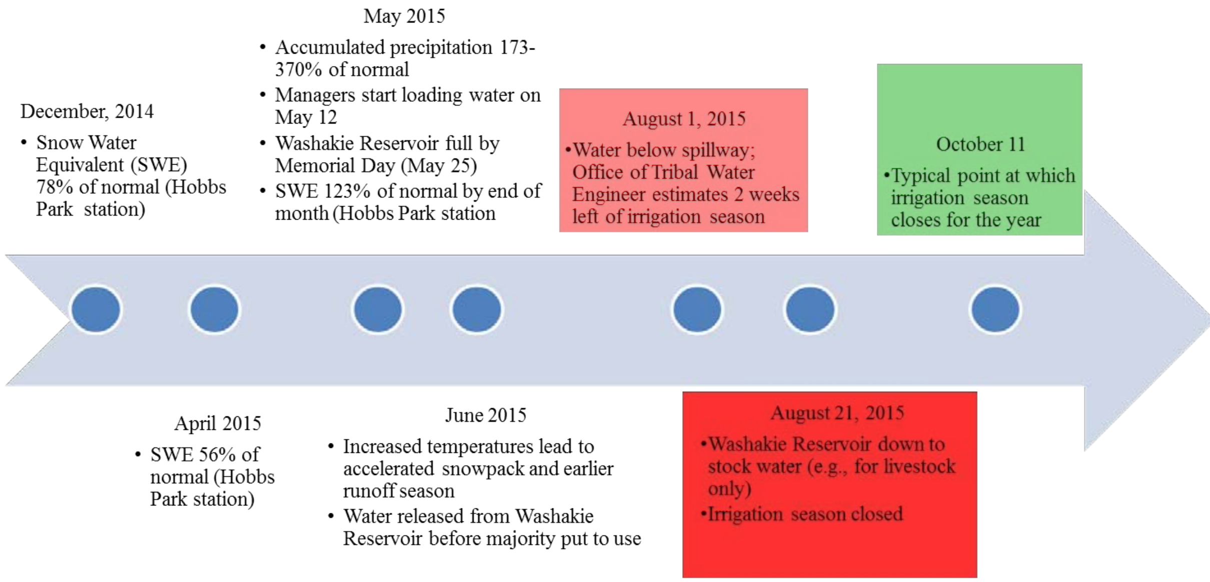


Figure 7: Timeline of biophysical and social factors underway during 2015 water year in Little Wind River basin. SWE and precipitation data accessed from United States Department of Agriculture Natural Resources Conservation Service National Water and Climate Center: https://www.wcc.nrcs.usda.gov/.

These warmer than normal temperatures and observed changes to snow conditions are consistent with changes to the timing of the snow-to-rain transition, which in 2015 occurred 3-7 weeks earlier than average. Together, these changes could contribute to more water coming off the mountain earlier and earlier peak runoff. Yet, conditions on the ground changed abruptly in May. May saw record setting rain throughout the reservation (173-370% of average across WRIR; Figure 7), which was responsible for surface flooding throughout the reservation. This led to an optimistic forecast that the upcoming summer would be devoid of drought despite the conditions experienced earlier in the water year.

Informants observed that May precipitation fell primarily in the form of rain with little snow accumulation and changes to snowpack until the later part of the month. Informants reported that there was very little water (12-25 cubic feet per second) coming into Washakie Reservoir, and the majority of the snowpack was still up in the mountains until later in the month. Yet, as rain transitioned to snow in late May, SWE increased well above the average (Figure 7). Concomitantly, temperatures increased especially at higher elevations, which led to accelerated snowmelt. Water managers started loading water in Washakie Reservoir on May 12, and the reservoir was full by Memorial Day (May 25), which marked the start of the irrigation season in the Wind River Irrigation Project on the Little Wind River (Figure 7).

Despite the record-setting precipitation in May, the below normal snowpack and warmer conditions during winter and early spring, combined with the warmer conditions in late May and throughout June described by key informants contributed to a rapid decline in snowpack and earlier runoff season. Since Washakie Reservoir was full, the water had to be let downstream despite many users not calling for water, and therefore much of the water passed through the system before it could be put to use. In normal years, flows are augmented by precipitation in the summer, though conditions in 2015 were drier than normal (HPRCC, 2016). By August 1st informants reported that the water level was below the Washakie Reservoir spillway, which is when the TWE estimates having about 2 weeks left of water usage (Figure 7). It was during this time that a rapid drying was detected in parts of the reservation (Figure 8). Subsequently, on August 21, water managers explained that the reservoir was down to stock water (i.e. just for animals to drink) and flows coming out of Washakie Reservoir were well below average (e.g., flows were reported at 31 cubic feet/second on August 26, 5 days after the season ended). It was at this point that the irrigation season had to be closed for the Ray Canal Water Users Association irrigators, which can last until the end of September, if not longer, during normal climate conditions (October 11 is the official close of the irrigation system on the BIA-managed Wind River Irrigation Project; Figure 7). [53]

Tribal water managers and producers reported drought impacts in the upper part of the Little Wind River. For instance, low reservoir levels caused adverse impacts on local ranching and farming, especially impacts to hay production and concerns about stock water availability through the winter, instream flows for fisheries and riparian ecosystem health, among others. While some users had fulfilled their irrigation needs, others had just started due to higher expectations of water availability fueled by the wet conditions in May and had not claimed it early on,

> "I think what people thought was because we had such a wet spring that there was all kinds of water up there. But, they just don't seem to understand that Washakie only holds about 8000 acre feet."[54]

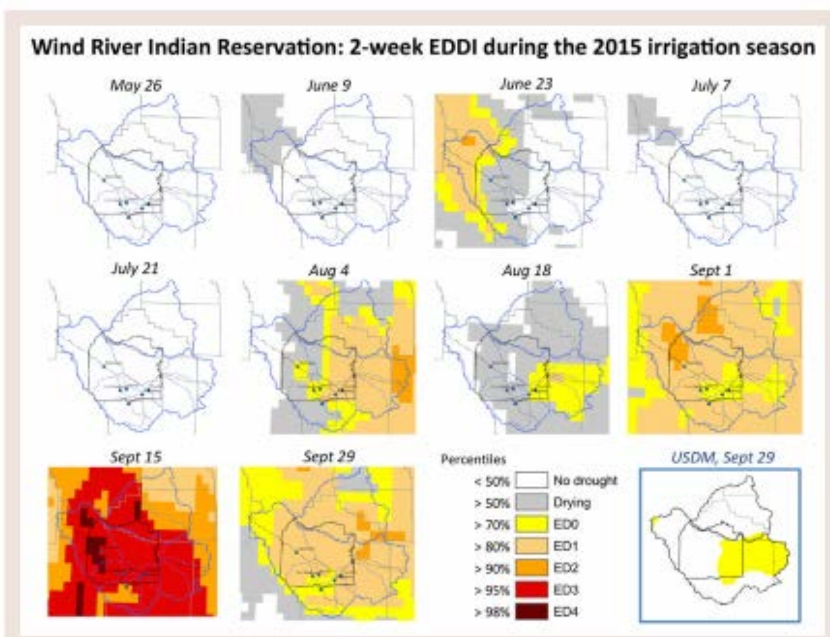


Figure 8: Drought progression during 2015 irrigation season according to the two-week Evaporative Drought Demand Index (EDDI; Hobbins et al., 2016). Accessed at: http://wwa.colorado.edu/publications/reports/EDDI_2-pager.pdf

[53] WR36 [36:3]
[54] WR36 [36.6]

In sum, managers described the 2015 water year as starting slow due to warm and dry conditions in the winter and early spring. The season then arrived abruptly due to the unprecedented May precipitation, which when coupled with high temperatures and changes in the timing of the transition from snow to rain during the cold season and high temperatures during the snowmelt season, led to accelerated snowmelt and an early runoff season. It then closed abruptly and more than a month earlier than is typical as dry, warm conditions continued and snowpack melted at an accelerated rate.

Water availability was very low in the system until the record-setting precipitation in the month of May, which provided an optimistic outlook for the irrigation season. Yet, the size of Washakie Reservoir was insufficient to hold these early-season flows, and while irrigators were not calling for water, the majority of the available water had to be let downstream. Later, when drought intensified there was no water left in the reservoir and all the snowpack had melted, which caused significant impacts to managers in the upper part of the Little Wind River sub-basin. Managers described these changes to the water cycle and timing of water availability as a recent trend very different to conditions during the 80s and 90s, when water was typically available from mid-April through to October. These changes were described by a key informant,

> "Every year, it's getting kind of a worse situation every year…we're just getting our runoff earlier and earlier every year. Simply because the temperatures are warmer. And we're not getting the snowfall that we're supposed to get in the winter time…So basically, we can't use the water management practices of the 80's and the 90's because the water cycle is not that way anymore."[55]

Water is generally stored in snowpack, which accumulates during critical periods in the winter and early spring. Yet, managers are observing changes to the timing and amount of snow during these critical periods. Additionally, warmer temperatures during this "cold" season lead to an earlier transition of snow-to-rain than in the past, the combination of which alters snow condition and form. The warmer temperatures and the earlier transition from snow-to-rain leads to more water coming off the mountain earlier and at an accelerated rate, which leads to an earlier runoff season and less water available to producers when it is needed.

These changes to timing and seasonality of weather/climate patterns, and specifically the recent erratic, extreme events occurring in this region, pose unique stresses to water and resource managers on the reservation, and require adaptation efforts, such as adopting water management practices that streamline water allocation and enhance efficiency under these novel conditions. For instance, informants reported that better irrigation practices (e.g., installing pivots, gated pipe) could help conserve water.[56] However, barriers do exist. Some irrigators are resistant to changing their management practices, while others simply cannot afford to purchase these water-saving technologies. Still, the major barrier that limits water availability during drought in the upper part of the Little Wind River sub-basin is the insufficient storage capacity for late-season use. We illustrate this by comparing water availability during the 2015 irrigation season between users in the Little Wind River sub-basin and other sub-basins at WRIR.

---

[55] WR36 [36:4]
[56] WR36 [36:4]

Although water shortages and impacts to irrigation were experienced by the upstream users in the Little Wind sub-basin, other areas of the reservation did not experience shortages during the 2015 water year, despite similar climate conditions across the reservation. For instance, informants reported that the lower end of the Little Wind River, where producers receive water from Ray Lake (and Washakie Reservoir), as well as direct flow from the south fork and north fork of the Little Wind River, had plenty of stored water in Ray Lake. Additionally, in Crowheart (Upper Wind River), water users rely on water stored in Dinwoody Lake, and runoff from Dinwoody Glacier for late-season streamflow. Although there was very little streamflow during the month of May, informants reported that the rain in May was sufficient to satisfy water users in the early part of the irrigation season and carry the system through until Dinwoody Glacier began to shed water. In fact, as of August 27, 2015, Crowheart had "bank to bank water in the canal."[57] Further, Anchor Dam is a small reservoir (originally constructed to hold ~17,350 acre-feet of water; Table 1) located on the South Fork Owl Creek of the Upper Bighorn sub-basin, which is owned by BOR and managed by the State. Anchor Dam provides water to users in the northeastern part of WRIR that are part of the Owl Creek Irrigation District, as well as users and irrigation districts off-reservation. The 2015 season was described as a phenomenal year in the Upper Bighorn partly due to the rains in May, which carried the system through the early part of the year. The later part of the irrigation season was supplemented by releases from Anchor Dam. Although Anchor Dam was described by informants as leaky and insufficient in size for the number of users that depend on the dam, one informant reported that Anchor Dam held more water in 2015 (~7500 acre-feet) than any other year since he started monitoring the dam in 2003.[58] Additionally, the BOR operates Bull Lake in the Upper Wind River which provides water to several irrigation districts downstream (e.g., Midvale). One informant reported that Midvale Irrigation District started drawing storage out of Bull Lake around mid- to late-July which is expected, and although natural flows were lower than what was typically expected for late August, the system was in good shape for the remainder of the irrigation season.[59] This is partly because Bull Lake holds approximately 152,000 acre-feet of water (Table 1), and is well-maintained when compared to the BIA-managed reservoirs and Anchor Dam. Similarly, Boysen Reservoir is a large BOR-owned and operated reservoir (802,000 acre-feet capacity; Table 1) that is also well-maintained. All the water from direct stream flow and reservoirs in the Little Wind, Upper Wind, and Lower Wind River eventually flows into Boysen Reservoir, which is used to water irrigation districts consisting of non-tribal producers off-reservation despite the tribes' view that this is water they are entitled to use. Therefore, each of these sub-basins experienced similar climate conditions to the Little Wind River during the 2015 irrigation season. However, none of them experienced water shortages as the other basins had sufficient water storage to capture early season flows and provide water for irrigators later in the season.

2016 Water Year

[57] WR36 [36:7]
[58] WR39
[59] WR39

Most of the interviews were completed prior to the 2016 water year (defined as the period of October 1, 2015 – September 30, 2016). However, we conducted a follow up interview with the Tribal Water Engineer at the TWE to better understand the cause of yet another system shortage in the Little Wind River sub-basin that occurred during the 2016 water year. While drought monitor data for the Little Wind River sub-basin is not available, Figure 9 depicts the percent area of the Upper Wind River in drought during throughout the 2016 water year. There was no indication of severe to exceptional drought; however during the winter and early summer season, parts of the basin was considered abnormally dry and a small portion of the basin was in moderate drought during the winter months.

Section at a glance

- The 'micro-drought' during the 2016 water year was in many ways similar to that of the 2015 water year
- Below average snowpack was observed during the early part of the cold season. Yet, wetter conditions arrived in March and April, which is a critical difference between the water years
- Wetter conditions continued into May, when WRIR witnessed above average precipitation
- Wetter spring conditions led to an optimistic forecast for ample water availability throughout the water year.
- Warmer temperatures during the cold season caused more precipitation to fall as rain versus snow earlier than normal. This changed snow conditions on the ground, and when coupled with warm and dry conditions in June led to an abrupt start to the irrigation season as snowpack melted at an accelerated rate and peak runoff occurred earlier than normal.
- Washakie Reservoir could not hold these early season flows, yet downstream irrigators were not yet calling for the water and the majority went down the system before it could be put to use.
- Dry and warm conditions continued throughout the summer and led to a short irrigation season for upstream users in the Little Wind River, which closed more than a month earlier than usual and only a few days after the season closed in 2015.
- Impacts—Producers who rely on Washakie Reservoir and direct flows from the south fork of the Little Wind for irrigation water experienced similar impacts to the 2015 water year (e.g., reduced hay production; concerns about stock water)

The Tribal Water Engineer described the 2016 water year in some ways a "mirror image of last year [2016]."[60] We highlight the important similarities between the 2016 and 2015 water years, and one critical difference, that led to a water shortage in the Little Wind River. Similar to 2015, the informant reported below average snowpack conditions during the winter and early spring; Snow Water Equivalent [SWE] was 50-75% of normal from December to mid-March (NRCS, 2017). On March 16 the TWE issued a drought warning declaration to warn irrigators of potential drought conditions. Shortly after the drought declaration, however, the system started to receive some snow, bringing SWE back up above normal for the month of March and April, which is a critical distinction with the dry conditions during this time for the 2015 water year (NRCS, 2017). Subsequently, TWE reevaluated conditions in early May and removed the drought declaration on May 4 due to the high snowpack. Shortly thereafter, an extreme rain event occurred on May 10. Some parts of the Little Wind received up to six inches of rainfall in a 24/hour period, which caused significant surface flooding. Accumulated precipitation totals for the month of May ranged from 94%-224% of normal across the reservation (NRCS, 2017).

---

[60] WR40 [40:1]

Yet, conditions began to taper off, with well below-average precipitation throughout June-September (HPRCC, 2016). Two to three weeks following the extreme precipitation event (early June) managers observed accelerated snowmelt and early peak runoff, which lasted for a week to ten days. Much of this early runoff passed through the system before it could be put to use as irrigators were not yet calling for the water and were optimistic that wet conditions during March-May would provide ample water throughout the summer.

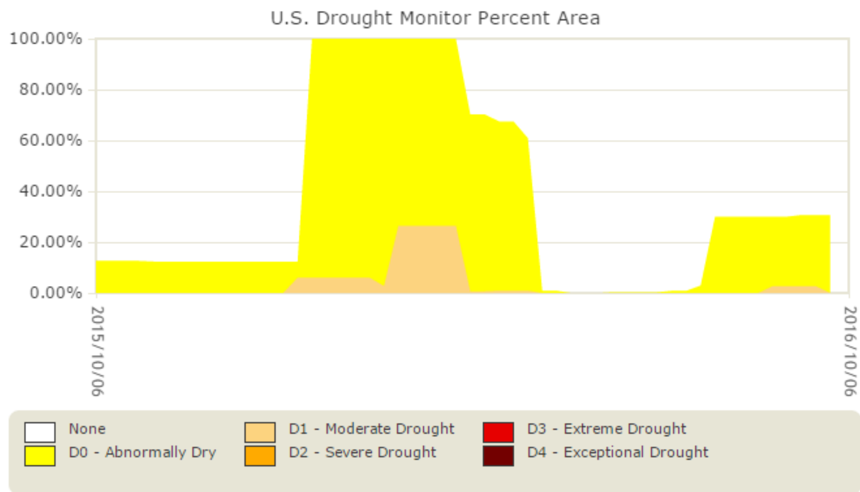


Figure 9: Percent of Upper Wind River Sub-basin (HUC8) in drought conditions through 2016 water year (Oct.1 2015-Sept. 30). Source: Drought Risk Atlas; http://droughtatlas.unl.edu/.

The cause of early runoff was attributed to warm temperatures during the cold season and on in to June, as was the case of the 2015 water year. January-March temperatures ranged from 2-8 ºF above normal for WRIR, while June temperatures were 4-6 ºF above normal (HPRCC, 2016). The combination of warm conditions during the cold season contributes to a change in snow conditions and an earlier transition from snow to rain, which when combined with warmer conditions during the snowmelt season leads to accelerated snowmelt and an early runoff. It is important to note that SNOTEL data does not distinguish between precipitation falling as snow versus rain, which given these results is important to understand and suggests that SNOTEL/SWE are inadequate when used in isolation to estimate water availability and timing of runoff.

Warm, dry conditions continued throughout the summer (HPRCC, 2016), and the informant described that water went below the Washakie Reservoir spillway at about the same time in 2015 (August 1), signaling to water managers that the irrigation season would be closed in around two weeks. On August 24, three days later than the 2015 water year, the irrigation season for producers above Ray Lake on the Ray Canal system was closed. The closure of the system occurred over a month earlier than typical, which can last until the first of October if not later during normal conditions (October 11 is when the irrigation season officially closes as per the BIA). The informant reported that the producers above the Ray Lake system who rely on Washakie Reservoir and direct flows from the south fork of the Little Wind for irrigation water were already experiencing similar impacts to the 2015 water year (e.g., reduced hay production; concerns about stock water, etc.)

In sum, the biophysical conditions that occurred during the 2016 water year to cause a system shortage were in many ways similar to the 2015 water year. 2016 saw below average snowpack during the early part of the cold season. Yet, wetter conditions arrived in March and April, which is a critical distinction to the 2015 water year. Wetter conditions continued into May, when

WRIR witnessed above average precipitation as was the case in 2015. These wetter spring conditions led to an optimistic forecast for ample water availability throughout the water year. Yet, warmer temperatures during the cold season caused more precipitation to fall as rain versus snow earlier than normal. This changed snow conditions on the ground, and when coupled with warm and dry conditions in June led to an abrupt start to the irrigation season as snowpack melted at an accelerated rate and peak runoff occurred earlier than normal. Washakie Reservoir could not hold these early season flows, yet downstream irrigators were not yet calling for the water and the majority went down the system before it could be put to use. Dry and warm conditions throughout the summer led to a short irrigation season for upstream users in the Little Wind River, which closed more than a month earlier than usual and only a few days after the season closed in 2015. In addition, and similarly to the 2015 water year, inadequate storage was cited as the primary barrier to managing water under increasingly erratic seasonality changes and extreme events that cause runoff to occur earlier during the water year,

> "We just don't have enough storage to capture that early run off, because the farmers and ranchers aren't ready to irrigate that early. So by the time they're ready most of the water, the higher run off, has already passed us by and it's in Boysen Reservoir. So it's just a system caused drought for the irrigators."[61]

The informant described that even if BIA were more flexible with the starting/closing dates of the irrigation season to accommodate the early runoff, water users would not call for, and/or use, the water. As mentioned above, the tribes are sponsoring a storage feasibility study. However, the WWDC has suggested to the TWE that a reasonable timeline for constructing the infrastructure is on the order of 15-20 years.[62] Therefore, finding alternative, near term ways to deal with seasonality changes and water availability in the Little Wind River sub-basin is critical.

Other sub-basins saw similar climate conditions, though many did not experience water shortages during the 2016 water year. For instance, the informant mentioned that the Crowheart area (Dinwoody Lake) still had water at the time irrigation was closed in Ray Canal, as did the BOR system,

> "the reclamation districts, they're still irrigating. They still have an adequate supply coming out of Bull Lake. So they should be good until probably the end of September, so they'll have another month on us."[63]

The conditions in the Owl Creeks and those users that depend on Anchor Dam, however, were described as in similar conditions to the Little Wind River sub-basin; early runoff, but no storage to hold that early flow.

The conditions of the 2016 water year, and resulting impacts, to a large extent mirrored that of the 2015 water year. Informants cited that the primary barrier to effective water management in the Little Wind River is storage capacity, which is partly why other parts of the reservation did not experience water shortages. Although the tribes are working with the WWDC to conduct a

---

[61] WR40 [40:1]
[62] WR40 [40:5]
[63] WR40 [40:3]

storage feasibility study, the implementation of new storage facilities could take upwards of 15-20 years.

3.1.2. Spatial variability in drought vulnerabilities within and between watersheds

The factors that contribute to vulnerability to drought at WRIR are spatially heterogeneous, with differences seen in physical climate, physical infrastructure, and social factors within and between watersheds. Here, we provide some examples (some of which were alluded to in the previous section) of these differences within and between the Little Wind, Big Wind (which we include the Upper Wind and the Lower Wind Rivers), and the Upper Bighorn sub-basins (Figure 10).

> *Section at a glance*
>
> - Vulnerability to drought at WRIR is spatially heterogeneous, with differences seen in physical climate, physical infrastructure, and social factors within and between watersheds—Tribal and non-tribal producers in the BIA-managed Wind River Irrigation Project are generally more vulnerable to drought than the primarily non-tribal producers on the BOR-managed system.
> - Little Wind River—storage capacity is generally described as lacking, though users west of Fort Washakie and upstream of Ray Lake are especially vulnerable to drought as users only receive water from Washakie Reservoir and direct flows from South Fork of Little Wind, while users downstream of Ray Lake receive water from a variety of sources
> - Crowheart—Users rely on Dinwoody Lake, direct flows from Big Wind, and glacial melt from Dinwoody Glacier. Dinwoody Lake is small for the number of users, and current and future glacial retreat challenge drought preparedness and response in this area
> - BOR-managed system in Upper and Lower Wind—Storage in Bull Lake, Boysen Reservoir, and Pilot Butte reservoir is adequate for the number of users; canal infrastructure is well-managed and has superior flow capacity of canals when compared to BIA-managed projects; monitoring systems are sophisticated and enable managers to track water availability and allocation in real-time.
> - Anchor Dam—too small and leaky; can only cover 60-70% of land in Owl Creeks and can't support all "senior" users.

The physical climate at WRIR is characterized by microclimate regimes. For example, one informant mentioned that precipitation varies substantially between the Little Wind and Upper Wind sub-basins, and even within the Crowheart area: "You see it will rain in Crowheart but it won't rain down here [Fort Washakie]…[and] it will rain up there in the Dinwoody area and never even come to Crowheart. We can just sit day after day and watch the rain storms up there."[64] These microclimate regimes are also borne out when examining the spatial variability in snow water equivalent (SWE) between four local SNOTEL sites. Table 4 illustrates SWE official percent of normal during January-June 2015, which generally reflect conditions in the Little Wind (Hobbs Park; St. Lawrence), Big Wind (St. Lawrence; Cold Springs), and Upper Bighorn (Owl Creek) sub-basins.

[64] WR20 [20:13]

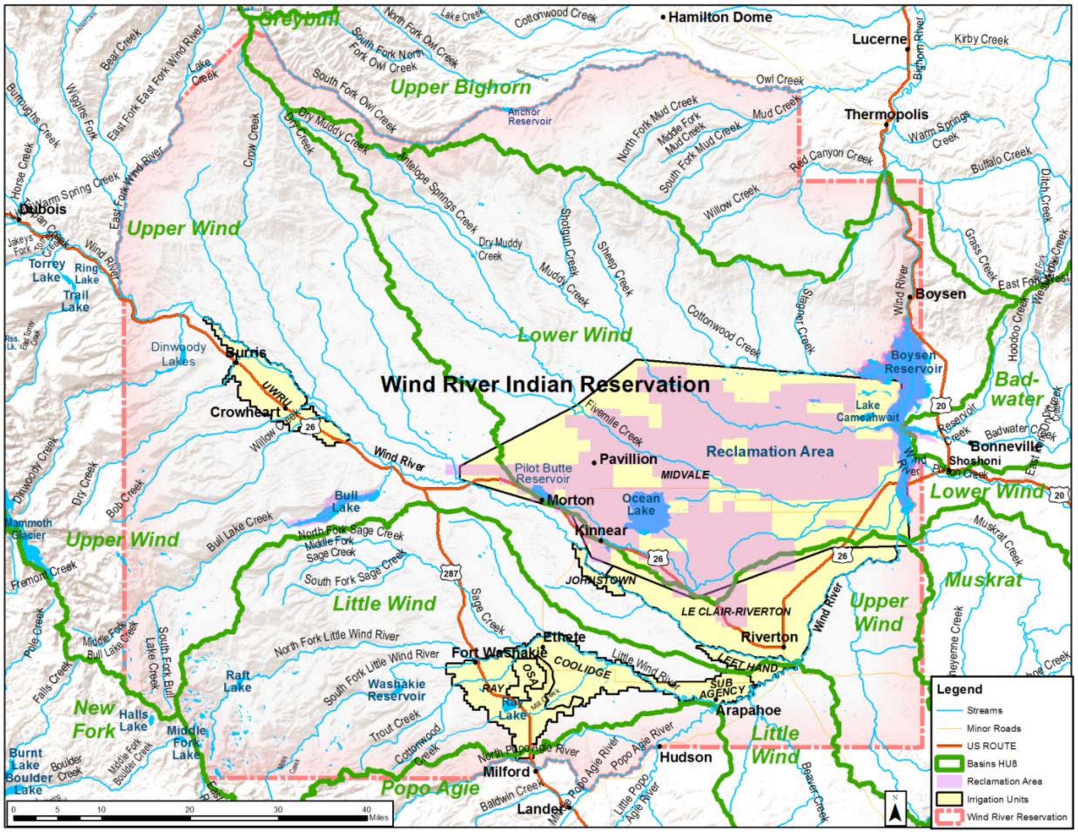


Figure 10: Map of sub-basins in and surrounding Wind River Indian Reservation.

Table 4: Snow water equivalent (SWE) percent of normal at SNOTEL locations in the HUC 6 Upper Bighorn watershed. Values represent official percent of average based on measurements taken the first part of the month. Source: USDA National Resource Conservation Service (NRCS) National Water and Climate Center; http://www.wcc.nrcs.usda.gov/.

Time Period (2015)	Hobbs Park	St Lawrence	Cold Springs	Owl Creek
1-Jan	78%	71%	114%	104%
1-Feb	68%	55%	106%	88%
1-Mar	71%	67%	108%	102%
1-Apr	56%	6%	44%	48%

3.1.2.1. Little Wind River sub-basin

As noted above, informants described the Little Wind River generally as two different systems, one upstream from Ray Lake and west of Fort Washakie (Washakie system), and one downstream that consists of users east of Fort Washakie and below Ray Lake (Ray Lake system).

Although the Tribal Water Engineer described the whole sub-basin as limited in storage capacity for the number of acres that are irrigated in the basin,[65] users in the Washakie system are especially vulnerable to drought conditions because they can only receive stored water from Washakie Reservoir and direct flows from the south fork of the Little Wind River, while users in the Ray Lake system receive water from Ray Lake, Washakie Reservoir, and the north and south fork of the Little Wind River. This means that the Ray Lake system users often do not experience drought, while users in the Washakie system, whose storage capacity was described as insufficient, struggle to maintain water availability throughout the irrigation season most years.

3.1.2.2. Big Wind River sub-basin (Upper and Lower Wind Rivers)

There are also differences in the Big Wind, particularly between the BIA-managed Crowheart system, which is part of the Wind River Irrigation Project, and the BOR-managed system. The Crowheart Water Users Association in the Upper Wind unit of the Big Wind system are dependent on snow- and glacier-fed tributaries, which water 10,000 acres of irrigable land and provide water for approximately 75 users.[66] Water users draw water from Dinwoody Lake, direct flow from the Wind River, while Dinwoody Glaciers "stores" water and provides late-season streamflow. Yet, Dinwoody Lake is insufficient in size meaning that the majority of flows are sent downstream before then can be put to use, and managers face risks in losing critical late-season streamflow as Dinwoody Glacier continues to recede. Dinwoody Glacier has lost 34.7% surface area from 1900-2006, and it is suggested that this ice mass wastage of long-term storage accounted for 4-11% of late-season streamflow in Dinwoody Creek from 1966-2006 (DeVisser and Fountain, 2015). Climate projections suggest continued warming in the region, which in turn will increase the amount of glacial retreat, and further reduce late-season streamflows (DeVisser and Fountain, 2015; Rice et al., 2012). This is exemplified by one WRIR water manager,

> "Our storage is in glaciers. That's where our run-off comes from. At the tail end of the season, say from August to the end of September…that's what we rely on to run our system. They say in the next 20 to 50 years there may not be any glaciers up there. Somewhere along these lines storage is going to have to come into the picture or Crowheart is going to be a onetime irrigation system when the high water is here and then we're just going to be done"[67]

The state and storage capacity of physical infrastructure, and monitoring networks, in the BOR-managed system is vastly different from the BIA-managed system in the Little Wind and Crowheart area. The BOR-ceded portion of WRIR in the Lower Wind River (including the Riverton Unit and Midvale Irrigation District and typically referred to as the "Reclamation area"), and two large irrigation districts downstream in the Upper Wind River (Riverton Valley and LeClair Irrigation Districts) consists primarily of non-Indian producers. Bighorn III settled surface water rights for these three districts (under permit 7300), which is the single largest water permit in the state of Wyoming (http://seo.wyo.gov/home/news-and-press-releases). The Riverton Unit, which is managed by the Midvale Irrigation District under contract by the BOR, is located in the Reclamation area (Midvale Irrigation District, 2007). Midvale Irrigation district pulls water off the main stem of the Wind River (through the Wyoming Canal), and from two

[65] WR40 [40:1]
[66] WR34 [34:17]
[67] WR34 [34:3]

storage facilities, including Bull Lake on the Wind River (which holds ~152,000 acre-feet; Table 1), and from Pilot Butte Reservoir (an off-stream reservoir which holds 34,600 acre-feet; Table 1), which eventually flows down to the BOR-managed Boysen Reservoir (storage capacity is 802,000 acre-feet; Table 1), along with all water let downstream from the Big Wind and Little Wind River sub-basins. Although Midvale, Riverton, and LeClair hold the same 1906 priority date, there is a 1917 tripartite agreement between the districts that dictates water allocation to users in their respective irrigation districts. Riverton and LeClair receive priority in use for direct flows over Midvale, and in return Midvale owns all water stored in Bull Lake and therefore augments water availability in that district by drafting storage from Bull lake when what is short.[68]

The infrastructure (e.g., canal systems, reservoir state and capacity) in the Reclamation area (and in the Riverton/LeClair districts) was described as in much better shape when compared to the Crowheart area, and the other sub-basins for a number of reasons.[69] First, the system was described as generally having all the water they need. This is in part due to the fact that Bull Lake alone has over three times the storage capacity of the BIA-managed reservoirs and BOR-managed Anchor Dam in the Upper Bighorn combined, and Boysen Reservoir has over seven times the storage capacity of Bull Lake. Second, there is no comparison between the flow capacity of the BIA-managed canal infrastructure and the Reclamation area. Ray Canal was designed to hold a maximum of 320 cubic feet/second (cfs),[70] while the Wyoming Canal, which leads water from the Wind River Diversion Dam off the Wind River to the Pilot Butte Reservoir and on down to users in the Reclamation area, has a designed capacity of 2,200 cfs (http://midvaleirrigation.net/ProjectFeatures.aspx). Third, the Reclamation area, along with the downstream irrigation districts in the Big Wind River basin has an extensive network of stream-gauges and monitoring system, which is operated by the state and allows them to monitor flows coming into/out of reservoirs in real-time, as well as along most of the canals in the Big Wind system (e.g., Wyoming Canal), thus enabling more efficient water allocation.[71] This network is lacking in the BIA-managed system, where many of the gauges were decommissioned and informants relied on "rock method" to determine capacity and outflow from Washakie Reservoir.[72]

3.1.2.3. Owl Creek, Upper Bighorn sub-basin

Located on the northwest edge of the reservation, Anchor Dam was built by the BOR who then handed the management over to the state Anchor dam was described as too small and leaky to provide for users that rely upon stored water. As one informant described, Anchor Dam can only cover 60-70% of their land and can't even support all the senior 1868 rights in the Upper Bighorn.[73] The ability to allocate water to users is also exacerbated by one unintended consequence of the Bighorn adjudication. Following the adjudication, the location of senior water rights in the sub-basin switched from primarily downstream users off-reservation and east of Thermopolis, to upstream tribal producers in the Arapahoe Ranch area (Figure 10). In order to

[68] WR39 [39:7]
[69] WR23 [23:4]
[70] WR25 [25:2]
[71] WR39 [39:10]
[72] WR36 [36:5]; WR25 [25:14]
[73] WR20 [20:21]

provide water for downstream irrigation districts, pump systems (Lucerne Pumps) were developed to deliver water to upstream "senior" water holders. In exchange, upstream water users do not call for direct flows that can be used to satisfy water rights downstream.[74] This system was described as difficult given these factors, and the Arapahoe system in the Upper Bighorn typically goes under administration (state restricts "junior" rights use), every year.

In sum, there are spatial differences in the biophysical, physical infrastructure, and social factors that contribute to drought vulnerability within and between watersheds at WRIR. In general, these systems suffer from insufficient storage capacity (aside from those larger facilities managed by the BOR in the Big Wind River sub-basin). Further, water delivery is challenged due to several management agencies (e.g., BOR, TWE, and BIA) operating within sub-basins and a patchwork of tribal and non-tribal ownership.

3.1.3. "Futures" water and storage

Several informants discussed "Futures" water rights and storage issues at WRIR, with regards to what these rights entail, the major drawbacks and issues with "Futures" water at WRIR, and locations of where storage for "Futures" water is being, or should be, developed. Futures water rights are the "paper" rights that were awarded to the tribes in the Bighorn Stream Adjudication. The tribes were awarded 499,862 acre-feet of tribal federal reserved water, 290,480 acre-feet were designated "wet" rights they could use today, and the remaining 209,372 acre-feet are the "paper" rights to be used at some point in the future (Robison, 2015). The scope of the tribal reserved rights decided during Bighorn I was based on practically irrigable acres (PIA), or the amount of water that was deemed necessary to support all the practically irrigable acreage on the reservation. Estimates of PIAs were based on assessments of arability, and the engineering and economic feasibility of irrigating land at WRIR, and consideration was made to the number of acres that were put to historical/current use and those that have the potential for future use, the latter referred to here as "Futures" water (Robison, 2015).

Section at a glance

- "Futures" water rights are the "paper" rights awarded to the tribes in the Bighorn General Stream Adjudication—209,372 acre-feet were awarded to be used in the future
- Several drawbacks to "Futures" water rights and uses were described
    - Rights are tied to agriculture purposes—this is contrary to the 15 equal and beneficial uses as described in the Wind River Water Code, and is limited due to fractionated ownership, idle land, limited loan opportunities for ranchers, and increasing prices on BIA allotments. The tribes are currently updating their Agriculture Resource Management Plan (ARMP) to address some of these issues
    - Conflicts with BOR limit storage in existing reservoir facilities
    - Majority of rights are held on the Big Wind and discussions about future infrastructure development do not support the most vulnerable places on the reservation
    - Rights are only applicable to on-stream infrastructure development

[74] WR39 [39:9]

As the decisions from Bighorn I regarding the quantification of water rights at WRIR imply, "Futures" water rights are reserved for irrigation use only, and apply to long-term projects that support new uses, not those that would support existing infrastructure and/or irrigation projects. The majority of water rights for "Futures" water are held on the Big Wind River, though informants reported a limited amount of water rights that are held in the Little Wind River. In the Big Wind River water managers are considering direct flow infrastructure on-stream to support the development of lands that have not yet been put to agricultural production use southeast of Crowheart and to the north of the Big Wind River (Figure 10).[75]

Informants described several drawbacks and concerns with "Futures" water. First, informants reported that the limited scope of "Futures" water rights' ties to irrigation purposes is counter to water management goals of the tribes per the 15 uses in the Tribal Water Code. Tying "Futures" water rights solely to irrigation is problematic also because several informants reported that much of the current "irrigable" land is idle, due to a host of factors. This is partly a result of fractionated ownership (when multiple, sometimes hundreds of, individuals own a single tribal allotment, making land-use decisions almost impossible), limited loan opportunities for new and experienced ranchers, and factors associated with BIA lease agreements (e.g., increasing lease rates).[76][77] For instance, there is a limited amount of programs to support tribal producers, especially with regards to drought compensation funds. One informant who owns trust land at WRIR described how he was forced to sell off livestock during drought in the early 2000's, and found that banks outside the reservation were reluctant to provide loan options on trust land, and there was limited funding options offered internally through the tribes to get producers back in business, and/or for those individuals looking to start a business.[78]

Therefore, putting water to use is constrained because by law it has to serve agricultural purposes first, regardless of whether that land is in production or not, and because finding ranchers and resources to expand to new lands in the future is challenging. The tribes are currently updating their Agriculture Resource Management Plan (ARMP) for the reservation which details many of the issues, goals, objectives, and policies that need to be put in place to address some of the problems associated with ownership, investment opportunities, and land leasing, among others (http://wrir.wygisc.org/content/agricultural-resource-management-plan).

Second, the storing and preservation of "Futures" water for the tribes has created conflicts between tribal water managers and the BOR. For instance, BOR does not provide storage for tribal reserved water on Bull Lake. When the tribes approached the BOR to request some additional water storage in the lake the BOR offered the tribes to trade some of the tribal water that is usually stored in Boysen Reservoir in exchange for additional storage in Bull Lake. However, one informant described how the BOR at times fails to uphold its trust responsibility to protect tribal water rights,

---

[75] WR21 [21:4]
[76] WR22 [22:8]
[77] WR30 [30:16]
[78] WR34 [34:6]

> "So it's kind of a swap of water that would be stored in Boysen, now gets stored up in Bull Lake…But then the next breath that they [BOR] do is they trade irrigators water before it gets there, and they sell it to them. It's the Future water that they're selling."[79]

Third, while the majority of tribal producers reside on the Little Wind River, which is coincidently also one of the most vulnerable systems on the reservation currently, most (though not all) of the "Futures" water rights exist on the Big Wind River. Most discussions about where to place additional storage facilities and put additional lands into production on the Big Wind have been south and east of Crowheart, thus limiting direct benefit to the Water Users Association and tribal producers in that region too. Therefore, places that need infrastructure development the most, i.e., the BIA-managed Wind River Irrigation Project, will be likely left out.

Finally, the provision that "Futures" water rights were only applicable to on-stream infrastructure development was cited as a drawback. Several informants discussed the benefit of building additional storage off-stream, both in the Big Wind and Little Wind sub-basins. For example, one informant suggested adding additional storage in the Red Bluffs area below the Washakie Reservoir. This would provide a second storage source in the Ray Canal system and would provide the means to pipe water from the North Fork of the Little Wind River, where there is no storage, which would ultimately provide a safety net when water is short in the system.[80]

In sum, the ruling of Bighorn I quantified the tribal reserved rights for "Futures" water, however these rulings and the specific uses of "Futures" water has a number of drawbacks. Rights were tied to irrigation purposes only, conflicts with BOR limit storage in existing reservoirs facilities, the majority of rights are held on the Big Wind and discussions about future infrastructure development do not support the most vulnerable places on the reservation, and these rights only apply to new infrastructure, on-stream. The tribes do not currently have the resources to construct all the future projects that would be necessary to convert their "paper" rights to "wet" rights (Kinney, 1993), though as noted above the tribes are sponsoring a storage feasibility study to move in this direction (See Physical irrigation infrastructure factors that affect availability).

3.2. How can interviews inform drought risk assessment and drought planning?

The interviews conducted with water and resource managers at WRIR highlight the biophysical and social context of drought risk. In doing so, these interviews can inform drought risk planning and assessments by the Physical Climate and Ecological Impacts science teams. Below, we highlight a few examples where interviews can inform the other science teams, though it is important to note that this is not an exhaustive list of the ways in which the interviews can provide complementary inputs to the physical climate and ecological assessments.

3.2.1. How do the interviews inform Physical Climate assessments and planning?

---

[79] WR31 [31:11]
[80] WR32 [32:11]

Information gleaned from informants in the interviews helps to inform physical climate assessment by addressing: a) occurrence of, and impacts from, historical drought periods for use as analogs for future impacts b) the indicators and the information sources managers use to monitor drought; c) considerations of the timing and seasonality that is important for managers at WRIR and the decision-contexts during a given water year (e.g., what is used, when it is used, and for what purpose?); and d) additional indicators that are needed to monitor drought risk and plan for drought in the future.

First, informants framed drought risk, impacts, and response in the context of several past droughts periods (Table 5). This included references to drought events from the dust-bowl era of the 1930s up to the most recent "micro-droughts" in the Little Wind River sub-basin during the 2015 and 2016 water years. The more recent droughts of the last fifteen years were those most cited by the informants, followed by droughts in the 1980s (some informants referred generally to the decade, while others discussed drought risk and response with respect to a 1988 drought), and mid-1990s. It is important to note that although the 2015 drought was the fourth highest cited drought period, several of the interviews (n=9) were conducted prior to 2015. Similarly, only two interviews, one of which was a follow up to specifically understand the state and progression of the 2016 water year, were conducted after the 2016 water year system shortage in the Little Wind River. Identifying how past drought periods manifested on the landscape, and to what extent vegetation, wildlife, water users and resource managers were impacted by these droughts provides critical inputs for the physical climate assessment team, specifically with

Section at a glance

- Key informant interviews helped to document historical drought periods for use as analogs for future impacts: Managers framed drought risk, impacts, and response capacities in the context of past drought periods. The physical climate assessment team is comparing these drought periods to historical averages
- They also helped to identify indicators and information sources managers use and considerations of the timing and seasonality that is important for making decisions (what is used?, when it is used?, and for what purpose?): This is important to ensure that physical climate assessment uses relevant data at timescales that match managers' decision context. Also, understanding where users get information is important for developing platforms for output material and identifying potential collaborators for the drought monitoring and planning.
    - Indicators managers used included local observations of snowpack, vegetation, soil condition, temperature, rainfall; SWE; daily temperature; precipitation; PDSI; stream gauges; reservoir storage; drought monitor map
    - Sources of information included local observations; local news and others in community; NRCS; NOAA; BOR; TWE; USGS; NWS; Climate and drought summaries; Farmer's almanac
    - Timing and seasonality factors that are important for making decisions: SWE to estimate runoff magnitude in winter/spring; SWE and daily temperature to estimate timing of runoff during melt season (April-June); spring rainfall to estimate water availability during summer when irrigation demand is high
- Interviews helped to identify needs for monitoring drought risk and for planning for drought in the future. These included: locations of where additional precipitation gauges are needed to capture spatial variability in physical climate across WRIR; the importance of manual snow surveys to ground-truth SNOTEL sites and to get accurate reads on snow form; and locations where additional SNOTEL sites and stream gauges should be located for drought preparedness and planning.

regard to linking instrumental data with informant reports, and to ground-truth models prior to projecting impacts into the future. The physical climate assessment team has started to analyze and compare the instrumental data for these drought periods with respect to historical average trends over the last 35 years.

Table 5: Number of times drought years discussed by key informants in interview transcripts.

Drought Year(s)	Groundedness[1]
2002 drought	17
2012 drought	14
2013 drought	13
2015 [2]	8
1980s	7
2016 [3]	6
1988	5
1990s mid	4
2006	4
2000s	3
2001	3
2003	3
1990s	2
2000s early	2
2007 drought	2
2008	2
1930s Dust Bowl	1
1960s	1
1990s early	1
2010s	1

[1]Groundedness = number of times coded for in-text

[2]Several (n=9) interviews done before 2015 drought

[3]Two interviews occurred after the 2016 drought

Second, informants discussed the drought indicators that they use, including both local knowledge and observations, and climate science and information. Local knowledge and observations of drought included monitoring of snowpack (in visual cues and/or manual snow surveys), vegetation and soil condition, livestock and wildlife condition and mobility, and temperature and rainfall conditions. These local observations were derived from individual interviews, workshops/webinars, and/or in conversations with others in the community such as Elders and members of the WRIR Water Board and the TWE.

The climate science and information used included monitoring of percent of average snow water equivalent (SWE) from four SNOTEL sites located around WRIR (which was the primary source of information cited), daily temperature fluctuations, spring rain, the Palmer Drought Severity Index (PDSI), water availability metrics via stream gauges and reservoir storage, and the NDMC Drought Monitor Map. The primary sources of information cited for the instrumental data included the online climate data from the Natural Resource Conservation Service (NRCS) and the National Oceanic and Atmospheric Administration (NOAA), online reservoir storage and streamflow data from the Bureau of Reclamation (BOR) and United States Geological Survey (USGS), as well as internal documentation from the TWE, and newspapers.

Third, the interviews helped to understand the timing and seasonality that is important for managers at WRIR and the decision-contexts used during a given water year (e.g., what is used, when it is used, and for what purpose?). Each irrigation season, the TWE must develop a water supply forecast, declare drought, normal, or surplus hydrological conditions (as per the Tribal Water Code; see Legal and management factors affecting water availability), and identify the approximate time that these conditions will persist throughout the year.[81] Although the TWE is required to make these declarations at the beginning of the irrigation season, as the season progresses the TWE can also add, amend, and/or remove drought watch/warnings depending on weather conditions and water availability. As the hydrology of the reservation exhibits substantial spatial heterogeneity, the TWE may declare drought conditions in one unit and normal conditions in another. However, the water supply forecasts produced, and declarations made, must derive from hydrological evidence and consider total demands on the system (Wind River Indian Reservation, 1991).

Informants described the seasons at which they used different combinations of indicators to monitor drought conditions and make declarations. For the most part, the first line of action was monitoring snowpack (SNOTEL sites and SWE) during the winter and spring. If snowpack did not rise up over the winter and into the spring (as WRIR typically gets those wet, heavy spring snows in March and April), then water managers know they are headed for a drought.[82] It is at this time that managers pool other climate science information together (e.g., Palmer Drought Severity Index) from a variety of sources (e.g. NRCS, NOAA, USGS) to make a decision whether to declare drought conditions and regulate water to downstream users. Snowpack can give a good indication of the amount of runoff that will be available throughout the year. Additionally, informants described how SWE was used with daily temperature fluctuations during the melt season (April-June), the combination of which provides water managers a good read on not only the amount of runoff, but the timing of runoff.[83] Spring rainfall is monitored during the summer period after runoff to estimate water availability when demand is high.

Further, the interviews provided information on when sources of information might not be used. For instance, when asked under what context an informant relied on the Drought Monitor Map, he replied,

> "If we're in good shape and I don't think things are worsening, I really don't pay a lot of attention to it [US Drought Monitor Map], but if it's continuing and getting worse, then

[81] WR26 [26:6]
[82] WR21 [21:5]
[83] WR22 [22:10]

I'll go back and look at the last few months and see where it's changing and how it's changing."[84]

Therefore, documenting the indicators used, when they are used, and the timing and spatial scales of the decisions for which they are used, for drought are critical points to understand so that the Physical Climate Assessment Team can use similar data sources, and/or different information sources for comparative purposes. Further, understanding where users get information is important for developing platforms for output material and identifying potential collaborators for the drought monitoring and planning parts of the project moving forward.

Fourth, the informants identified locations where additional monitoring should be installed, and offered suggestions of which of the existing sites needed ground-truthing. Figure 11 illustrates the locations of stream gauges, SNOTEL sites, and other weather stations, including the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), at WRIR.

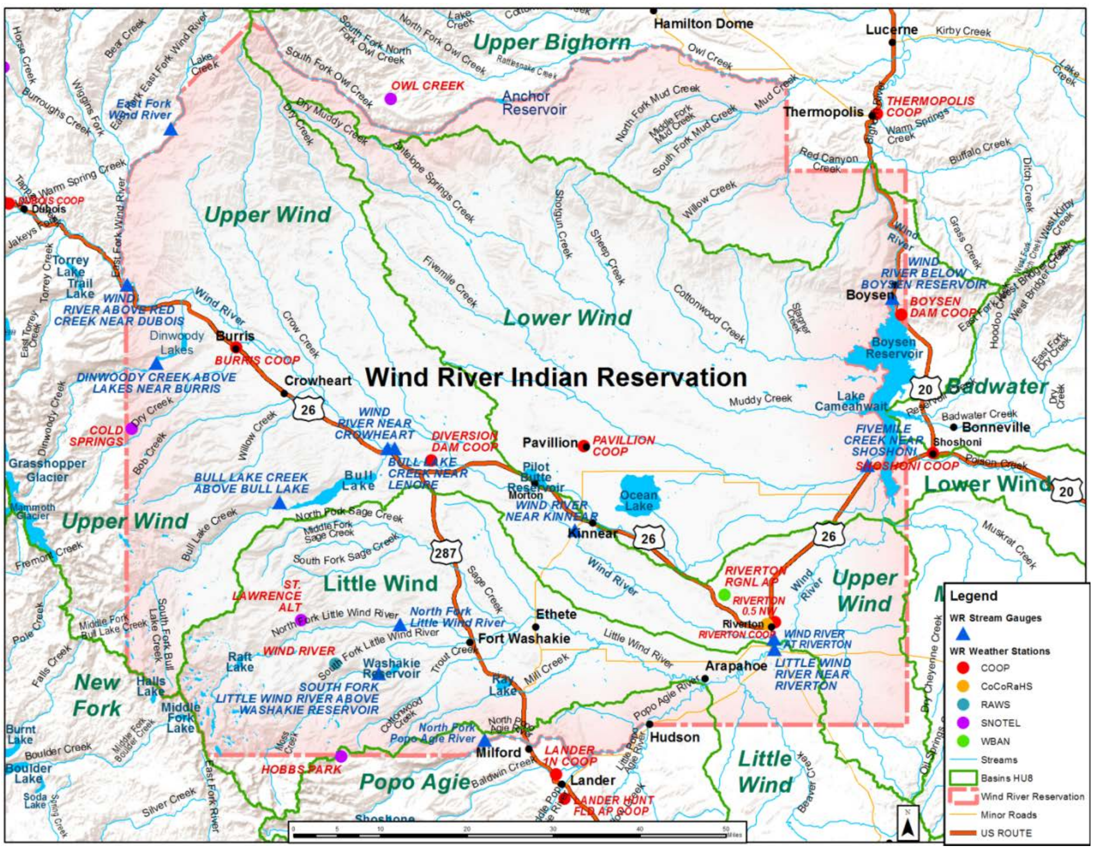


Figure 11: Map of weather stations in and around Wind River Indian Reservation.

One informant mentioned the lack of precipitation gauges on the reservation. The climate on the reservation is spatially heterogeneous both within and between watersheds (see Spatial variability in drought vulnerabilities within and between watersheds). For example, it could rain in Crowheart in the Big Wind River and not rain in the Little Wind River to the south and east, or it may rain in the Dinwoody area above Crowheart and never rain in Crowheart. As such, the

[84] WR39 [39:12]

informant suggested precipitation gauges be placed in a couple locations in the Crowheart area to capture the variability within the watershed (e.g., on the east side of Wind River range at high elevation and at a lower elevation), in the Owl Creek mountains, and several that tie the Big Wind into the Little Wind via Sage Creek down to Ray Canal.[85]

As mentioned, managers rely heavily on SNOTEL sites and SWE to monitor conditions and forecast drought on the reservation. This information is based on monitoring of 4 SNOTEL sites (e.g., Hobbs Park, St. Lawrence Alt, Cold Springs, and Owl Creek) during winter and spring to determine departure from normal conditions. However, their ability to accurately monitor snowpack and assess water availability downstream for any given water year is hampered due to a couple factors. First, one informant described the need to ground-truth the existing sites with snow surveys get a better understanding of snowpack and SWE. SWE does not distinguish between precipitation falling as rain versus snow, which can affect snow conditions and subsequently the timing/rate of snowmelt and runoff. One water manager described the importance of manual surveys to better determine snow density and runoff characteristics,

> "[D]ensity is a big key to what you're going to get. How long it's going to last, how long it's going to sit up there. The only way you're going to really get a good accurate density measure is to go up and measure it."[86]

Second, the same informant described the need for relocating existing SNOTEL sites up in elevation, and adding new SNOTEL in areas that lack sites to more accurately capture the spatial variability in the physical climate system across WRIR. For example, St. Lawrence was considered too low, as was Hobbs Park (even though this station is located at 10,100 feet). The area of Hobbs Park also drains the opposite direction, so is not even an entirely accurate read for the South Fork drainage. Further, the informant suggested an additional SNOTEL site between Hobbs Park and St. Lawrence which would give a better sense of conditions in the Little Wind River and the North Fork of Popo Agie. Finally, the informant was asked to suggest an area that would be indicative of the east and west side of the Wind River Range, to which the informant suggested a SNOTEL site in the Titcomb Basin.[87]

Informants also described additional areas where stream gauges were needed. Many of the gauges operated by USGS have been decommissioned, and some were offline during key water years when issues arose (e.g., the inflow to Washakie Reservoir during the 2012-2013 season). In fact, one informant mentioned that there used to be 48 stream gauges on the reservation, but due to federal funding cutbacks, there are currently only 12-13 gauging stations that are online.[88] There has been work to recommission some of these gauges and install new ones where needed. Several informants described the need to install a gauge for the outflow of the Washakie Reservoir, as managers currently rely on the "rock method" to determine water availability (See Physical irrigation infrastructure factors that affect availability).[89] These three examples illustrate the ways in which interviews can identify which indicators need additional maintenance and the

[85] WR20 [20:13]
[86] WR39 [39:12]
[87] WR39 [39:12]
[88] WR21 [personal communication-October 2014 drought workshop]
[89] WR36 [36:5]

location where new indicators should be installed in order to capture the variability in climate across the WRIR.

In conclusion, these results help define past drought periods to use as analogs for future change and impacts, identify those indicators and sources of information used to monitor drought, document the seasonal decision-contexts for water and drought management, and identify monitoring needs. In turn, these results help to inform drought planning and preparedness.

3.2.2. How do the interviews inform Ecological assessment and planning?

The interviews can inform the Ecological Assessment team by identifying species, habitats, and ecosystems of interest while also identifying the specific relationships, or important variables to consider (Table 6). Drought can limit water availability and cause devastating impacts to both social and ecological systems, though impacts are more often the results of multiple and interacting factors and not solely due to drought. Here, we describe impacts to key management targets that were reported by key informants. First, we highlight impacts to ceremonial activities and ecological targets of cultural importance. We then discuss impacts to vegetation and range productivity, and wildlife. These provide a starting point for interrogating the interviews to determine what species/habitats emerged as important management targets. It is also important to note that informants described impacts in the context of short-term (e.g., sage-grouse survival) and long-term impacts (e.g., shifting plant communities under drier climate). Our findings from the biophysical climate summary and physical climate assessment highlight that managers make decisions, and frame impacts in the context of monthly, seasonal, annual, and decadal timescales. These are not timescales typically addressed in climate models or many of the ecological response models (e.g., habitat occupancy models, state-and-transition models) and therefore would need to be considered via additional inquiry with local experts so that the

Section at a glance

- Key informant interviews help to identify species, habitats, and ecosystems of cultural, spiritual, and management concern, while also identifying the specific relationships, or important variables to consider
- Drought can cause devastating impacts to social-ecological systems, though impacts were primarily the result of multiple and interacting social and ecological factors and not drought alone
- Ecological impacts of cultural importance—shifts in seasonality affects berry harvesting and wildlife (elk, deer, antelope, moose); decline in cottonwood galleries and willow communities are the results of drought, diversions for irrigation, and a lack of flooding in recent years; drought affects abundance of vegetation used for shade in ceremonies (Red Willow and Red Birch); fisheries, such as burbot, sauger, and Flathead chub, impacted by drought, diversions, and reservoir withdrawals
- Impacts to Wildlife—Drought reduces upland forage productivity and impacts grazers, and the combination of drought, shifts in plant communities, human development, and increases in disease transmission impacts sage grouse populations
- Impacts to vegetation—WRIR is experiencing shifts in plant communities from more to less palatable species, and increases in non-native plant species; pest and pathogen disturbance on white bark pine has implications for grizzly bear populations, soil erosion, and changes to timing of runoff.
- Managers at WRIR are responding to these changes in a number of ways, though there are a number of barriers to managing fish and wildlife at WRIR.

evaluation of these species and habitats of interest are done so in manager-relevant scales and contexts.

Table 6: Species or habitats of interest/concern for tribal water and resource managers and example relationships that need to be addressed.

Species or Habitats of Interest	Example Relationships
Ecosystems (sagebrush, forest, periglacial, upland range, riparian, wetlands)	• Effect of mountain pine beetle on snowpack accumulation, and runoff timing and magnitude • Effect of shifting plant communities impact on abundance/distribution of palatable plant species
Vegetation (Cottonwoods, willows, birch, sweetgrass, sage, berry-producing plants [e.g., choke cherries, buffalo berries])	• Effects of drought, diversions, and lack of flooding on cottonwood galleries • Effect of changes in timing/seasonality on berry productivity
Wildlife (Elk, Moose, Deer, Antelope, Grizzly Bear, Sage-grouse)	• Effects of drought, forage production, habitat fragmentation, and disease transmission on sage-grouse • Effect of changes in timing/seasonality on ungulate migration and subsistence hunting • Effect of WBP mortality on Grizzly Bears
Fisheries (Burbot, Sauger, Flathead Chub, Yellowstone cutthroat trout, St. Stevens Clams)	• Effect of reservoir withdrawal on Burbot • Effects of diversions, drought on cool water fisheries

3.2.2.1. Impacts to ecological targets of cultural importance

Drought and changes in the timing/seasonality of weather impacts traditional subsistence strategies, and vegetation and fisheries of cultural and ecological importance. Informants described how changes in the timing and seasonality of berry harvest and migration patterns of wildlife affect traditional cultural practices of the tribes,

> "Native peoples are first affected and most affected by drought conditions and climatic changes that we're dealing with today…[W]e still are hunters and gatherers. We go out and we harvest the berries and we harvest the crops that are out there or the wild onions

and things of that nature…Then we also do the hunting with the ungulates, the deer and the elk and the antelope. And when those historic opportunities have changed to where the migration is different; the berries don't come at the right time,… or they get frozen because they're too late, or the water we need for the longevity of the season melts too quickly in the spring and we have no water the rest of the summer…you know, those things have to be addressed."[90]

Informants also discussed impacts to riparian vegetation and fisheries that are important to the tribes. For instance, informants reported impacts to cottonwoods, and vegetation important for shade and other purposes at ceremonies (e.g., willow, red birch, sage, sweetgrass). Impacts were reportedly due to a combination of drought, lack of flooding, and management practices which has significantly altered the system. For instance, the reductions in cottonwood and willow communities, and changes to fisheries habitat was attributed to the combination of human alteration to the river system which creates wider, shallower, and warmer rivers, and a lack of flooding in recent years. This is illustrated with exemplars from two informants at WRIR,

> "the loss and the decline of the cottonwood is because of there's no more floods anymore. Its' the big major floods that wash gravel in the basin, propagate their kind with seeds, and now that there's drought, there's lower water…[and] [y]ou see a lot of the older stands of trees, but you don't see the re-growth."[91]
>
> "we've changed the system so much, we've removed the willow communities, we've [re]moved the cottonwood communities, we've incised the system and…now the rivers are wider and more shallower than they historically were, and...warmer…you lose a lot of those bed features…You just lose your sediment transport part of the system with the diversions, and so it's… yeah, you've got flowing water, but you don't have ten-foot deep holes anymore in the Wind River so where do those fish have places to harbor? Really none, and so that's the change….we went from a... probably a cold water fisheries quite extensively down the valley to now cold water fisheries are really just above the irrigation unit kind of areas. Below that, we start to run into more cool and warm water fisheries. So we've kind of converted the system in that fashion."[92]

Informants observed a variety of impacts to specific fish species, for instance trout fisheries on Ray Canal, and changes to the abundance and distribution of culturally significant species such as the Flathead Chub, burbot in Bull Lake, and sauger in the Big Wind, Little Wind, and Popo Agie Rivers. For instance, during the 2012 drought informants described a major die-off of trout fisheries in Ray Canal due to low water flow. Sauger (*Sander Canadensis)* in this area are unique in the sense that they occur in the most southern and western end of their distribution, and at the highest elevation. They are also considered genetically pure, meaning that they have not hybridized with walleye. The decline of the sauger populations is thought to be linked to low water flows, diversions, and subsequently poor recruitment following drought periods.[93] The combination of drought and diversions also impacts the abundance and distribution of Flathead Chub in the Big Wind River near Riverton and the Little Wind River,

[90] WR22 [22:18]
[91] WR35 [35:5]
[92] WR27 [27:5]
[93] WR37 [37:7]

> "That fish [Flathead Chub] has essentially disappeared from the system [Big Wind River]. You find a few of them, not very many, but when the instream flows was put in place by the tribes [in the 1990's], those fish were starting to come back, in fairly decent numbers. Now, they're gone, because of what's happening [drought and diversions]…there's only a few places you can pick them up, and I'm not even sure you can find them in the [Big] Wind anymore, but in the Little Wind, there's a few places we know where we can pick up a semblance, but very few."[94]

Burbot *(Lota lota*) is also an important fish to the tribes that has witnessed significant reductions in population numbers. Although there have been several speculations regarding the reduction in burbot, such as over-harvest, competition with lake trout, and entrainment, an informant reported that the most likely reason for the decline is due to habitat loss as a function of reservoir withdrawals from Bull Lake in the fall which increase under drought,

> "Burbot like to live in these interstitial spaces in rocks and it's very important when they're juveniles to have a place to stay like that. They [BOR] pull the water down in the fall, it gets really low that it goes down to the area that is where all the sediment had settled and there's a not a lot of interstitial space in there, so when they pull it down in the fall that's the critical time for fish, like I said, that fall period is when the recruitment's set for the juveniles."[95]

These results illustrate several of the plant communities, fish, and wildlife species that are culturally and spiritually important to the tribes at WRIR, and which should be included in an ecological assessment. Impacts were due to combined and interacting effects of drought, changes to timing/seasonality of weather, and management practices.

3.2.2.2. Impacts to wildlife

Informants reported the impacts of drought, and specifically the impacts of reduced water availability and forage production, to several wildlife species that are important management targets at WRIR, including elk, deer, antelope, and sage grouse. Drought can impact the upland winter range for elk and other grazers, and therefore can impact these populations. For instance, during the 2012 drought, an informant described that antelope numbers declined significantly due to lower plant productivity which resulted in reduced fawn survival rate.[96]

Informants also explained how greater sage-grouse (*Centrocercus urophasianus)* population numbers were influenced by drought. For instance, during the 2002 drought, the number of males per lek fell drastically to around 12 per lek, but when the system returned to a wetter moisture regime, the population rebounded to 60-65 per lek. This trend was linked to the amount of residual grass and forb cover, which can be directly linked to the number of individuals per lek (Figure 12).[97] The same trend was described in relation to the 2006 drought and the 2012 drought; during these drought periods the number of males per lek dropped, but when wetter periods followed, sage-grouse rebounded. However, there are also a series of interacting

---

[94] WR23 [23:14]
[95] WR37 [37:10]
[96] WR27
[97] WR27 [27:14]

variables mentioned that affect sage-grouse under future social and ecological change (Figure 12). For instance, informants mentioned that increased habitat fragmentation due to development in some areas at WRIR, including for instance the area of Fort Washakie down to Lander are causing major impacts to the sage-grouse. This helps not only to identify another factor that may explain the distribution of sage-grouse, but it also points to specific places on the landscape where sage-grouse populations are at increased risk. Further, shifts in plant communities to shorter species on rangelands and reductions in sagebrush production, and the uncertainty with respect to sagebrush die-out[98] has direct implications for sage-obligate species, including the sage-grouse (see Impacts to vegetation; Figure 12). Finally, one informant mentioned an increase in the West Nile Virus in low-land sage-grouse populations, which is most likely driven by warmer temperatures and drought conditions, and has caused significant and compounding impacts.[99]

Therefore, in the case of sage-grouse, the interviews help to: illustrate the ways in which drought affects sage-grouse populations vis-à-vis reduced Annual Net Primary Production (ANPP); identify areas of high and low risk; and demonstrate the interacting social and ecological components that affect sage-grouse at WRIR. In this context, a species distribution model that incorporates a series of these interacting characteristics to better understand suitable and unsuitable habitat, places of conservation concern, etc. would provide a nice starting point to characterize sage-grouse response to drought and climate change, as well as social factors that drive distributional ranges.

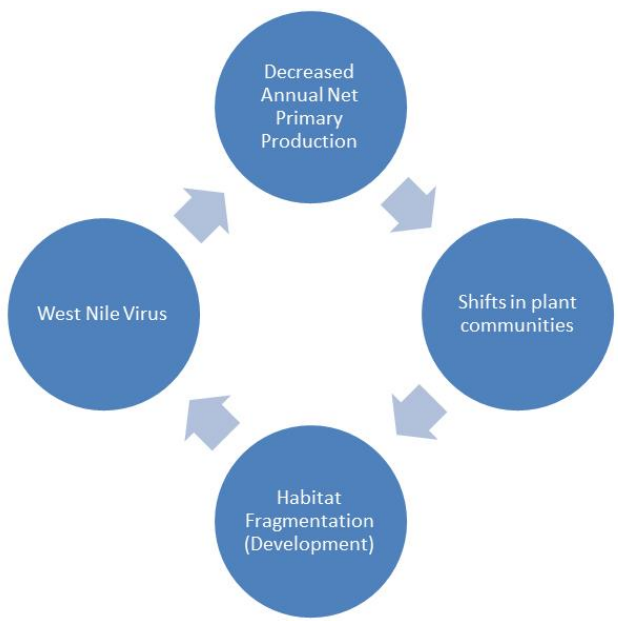


Figure 12: Interacting social and ecological factors that affect sage-grouse populations at WRIR. Drought reduces Annual Net Primary Productivity, while long term aridity trends and persistent drought leads to shifts in plant communities which reduce the suitable habitat for sage-grouse. Sage-grouse populations are further impacted by habitat fragmentation in certain high-risk areas across the reservation, and populations are being decimated by West Nile Virus.

98 WR27 [27:5]
99 WR27 [27:15]

Managers at WRIR are responding to these changes in a number of ways. For instance, the TWE worked with the USFWS, BIA, and water users to establish minimum instream flow requirements in the Little Wind River to support fisheries and riparian habitat restoration. The TWE also constructed fish screens and ladders at diversion structures to enable juvenile fish to pass through the system. Also, the USFWS has worked the TWE to narrow stream channels to restore deeper bed features and reduce water temperature, both of which support native plant communities and fisheries.[100] The USFWS, in consultation with tribes, has also started supplementing sauger. This is done by collecting the males and females before the spawning season, allowing them to spawn in captivity in order to increase survival rate, and then release them back into streams and lakes on the reservation.[101] However, there are a number of barriers to managing fish and wildlife at WRIR. For instance, one informant mentioned that the tools to manipulate habitat and respond to drought for fish and wildlife are limited,

> "We're just limited in our ability to respond because we don't have a lot of tools to respond to it…Like on the wildlife side, it's adjust hunting seasons or hunting areas. Our tools on the fishery, same thing, it's either stocking or reducing take. Those are pretty broad brush tools."[102]

The tools available to manage fish and wildlife are not suitable for responding to long-term drought conditions. In fact, because of the increasing climate variability and change occurring on the reservation, managers emphasized the importance of designing long-term management plans and response capacities that embrace this change and build resiliency into management for fish and wildlife.[103]

3.2.2.3. Impacts to vegetation

Drought reduces forage production, for instance in 2006 grass and forb production was 10-15% of normal range conditions[104], which not only affected livestock but also severely impacted wildlife, including for instance greater sage grouse (*Centrocercus urophasianus*; see Impacts to wildlife). Drought can also increase the frequency and severity of wildfires. In fact, one informant described that for each of the recent drought periods, there was significant forest fires in the Owl Creek Mountains.[105] Rangeland wildfires can lead to rangeland invasive grasses such as cheat grass (*Bromus tectorum*). Informants observed shifts in plant communities from more palatable species (e.g., western wheatgrass; blue bunch) to shorter, less palatable species (e.g., blue gramma; threadleaf sedge), with concomitant increases in non-native species colonization (e.g., cheatgrass).[106] This trend was mentioned on two time scales, either as a function of long-term changes (30 years), as monitored annually in vegetation transects,[107] or in response to

[100] WR27 [27:5]
[101] WR37 [37:2]
[102] WR37 [37:15]
[103] WR27 [27:5]
[104] WR28 [28:4]
[105] WR20 [20:5]
[106] WR28; WR27
[107] WR27 [27:14]

shorter, but persistent drought periods, especially under a grazing regiment in upland range sites.[108]

The long-term changes were reported as observations of long-term monitoring by the BLM and were therefore not specific to WRIR, but more indicative of regional trends in this part of Wyoming, while the short-term changes to upland forage conditions were based on monitoring efforts on the reservation. These changes have impacts on sage-grouse, antelope, elk, and livestock (Figure 13). For instance, these changes have the potential to impact livestock, as one wildlife biologist explained shifts to shorter grass species as being cow-proof,

> "There's not as much forage out there anymore for anything and what forage is there is very… is very difficult to graze because it's so short and a cow…[has] one row of teeth so they use their tongue to kind of wrap around a plant and pull...and so they can't graze as close to the ground."[109]

This particular example highlights the need for evaluating the distribution of native/non-native plants and the temporal trends in shifting communities as a function of different grazing regimes over multiple time scales, and the thresholds at which different species can graze optimally on vegetation. As such, a two-pronged approach using a state and transition model and habitat occupancy models might help to better understand this relationship (Miller et al., 2015).

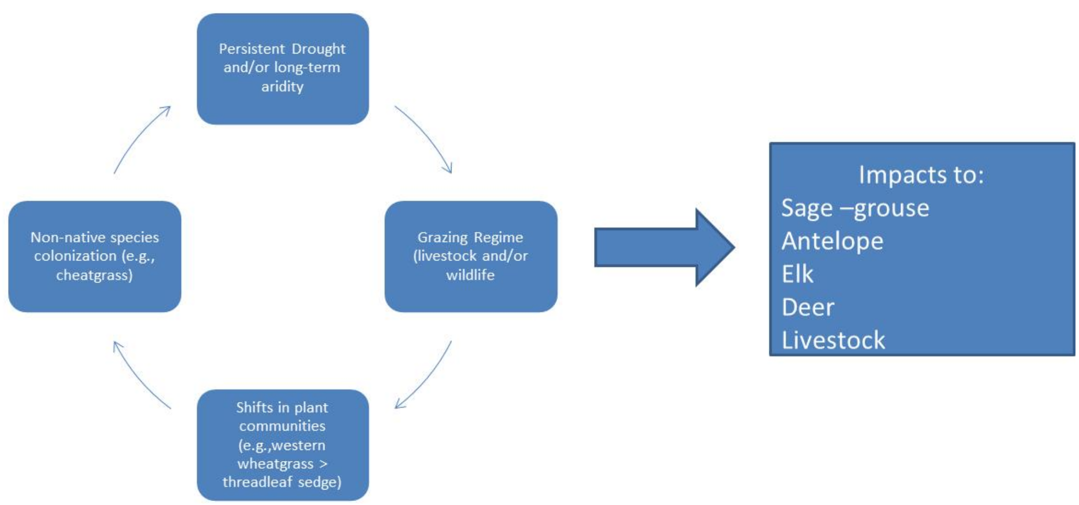


Figure 13: Impacts of drought on plant community structure and impacts to wildlife and livestock. Persistent drought, combined with grazing, has resulted in shifting plant communities and non-native species invasions which directly impacts many of the wildlife species and livestock that depend on these plant communities.

Another interesting point that emerged from the interviews was the concern about sagebrush die-out, something that has occurred across Wyoming, in response to a persistently drier climate. For instance, sagebrush was able to withstand the extended dry period associated with the 2002 drought. However, one informant observed that this rebound is not occurring currently, which can have significant impacts for sage-obligate species.[110] Finally, the impact of pest and pathogen disturbance (which is driven in part by drought and warmer winter temperatures) on white-bark

[108] WR28 [28:2]
[109] WR27 [27:14]
[110] WR27 [27:5]

pine mortality was discussed by a few informants, with respect to the impacts of pine mortality on grizzly bears, and on soil erosion and the changes to the timing and amount of runoff.[111] These results highlight short-term and long-term impacts of drought to vegetation and the associated concern about impacts to wildlife that depend on them.

3.3. What are the additional research questions that emerged from the interviews?

The collection and analysis of semi-structured, in-depth interviews with key informants and experts in land and resource management at WRIR spurred the development of additional research questions. We highlight a few examples that emerged from the interview analysis below. Additional questions and research objectives can, and should, be driven by the Tribes and the other research teams. Depending on the additional questions/objectives, we can determine whether we need to delve deeper into the current database and/or collect additional information from more focused key informant interviews and other sources.

1. How does fractionated land ownership and idle land affect water use and allocation, and agricultural production/development?

   When discussing water rights, allocation, and "Futures" water use, many informants touched on issues associated with the General Allotment Act of 1887 (aka Dawes Act) and fractionated ownership when allocating water, in addition to the processes that give rise to, and issues regarding water use associated with, idle land. However, this was described as a complicated topic, and one which would require some additional, more focused interview questions and/or document analysis.

2. What are the best ways to share and communicate drought and climate-related information?

   The interviews helped to determine what indicators of drought were used and the sources of that information, both local knowledge and observations, and climate science. However, another question/objective that would support drought planning would be to understand how information is shared and communicated, and in what ways, platforms, etc., tribal resource managers and producers use climate information. This is in part being addressed through iterative meetings and discussions with the physical climate and social science teams, and tribal resource managers to co-produce climate and drought summaries, using indicators and scales relevant to managers. However, identifying best practices for communicating this information to a broader base of tribal and non-tribal producers will help drought awareness, preparedness, and planning.

3. In what ways are the climate and drought summaries helping to prepare for, and/or, respond to drought? And how might they be improved?

   Asking more specific questions about developing and communicating drought and climate-science information could directly lead to "ground-truthing" the climate and

[111] WR25 [25:5]

drought summaries currently being produced for the producers and water managers on the reservation. Specifically, we could identify what is working, what isn't, and how to make these summaries better, and perhaps help cater these summaries to different management sectors (e.g., fisheries, wildlife, ranching, food crops, etc.).

4. How have the Water Users Associations in Crowheart and the upper reaches of the Little Wind River (Ray Canal) helped tribes/producers better respond to drought conditions?

   These Water Users Associations have started relatively recently (the Ray Canal Water Users Association assumed some allocative authority over water in the Little Wind in 2014), and several informants suggested that these associations have helped. We would like to know specifically in what ways, and what is the path moving forward to assume greater control in these regions, and across the reservation (e.g., filing a 638).

5. What are the effects of drought and climate variability on traditional or cultural practices (e.g., wild food harvest and sharing across WRIR)?

   Initial interviews spoke to the ways that changes in timing and seasonality has impacted the procurement of meat and berries, and the availability of water and vegetation for ceremonies. We could expand on this using a suite of social and ecological methods. This would require additional interviews to deepen our focus on who is impacted, what is impacted, and work towards projecting future impacts.

6. How might "Futures" water be limited by drought, climate change, and other legal, political, and/or infrastructural drivers?

   "Futures" water was discussed by a few informants in the context of what it entailed, where the rights were held, and some of the drawbacks of the water rights. However, "Futures" water was not discussed necessarily in the context of drought and climate change, and was only briefly discussed regarding the legal context of where those rights exist and how they were stipulated. Additional interviews and document analysis could identify how the "Futures" water is managed (e.g., how are rights divided between sub-basins, where it is stored, etc.), in what ways the storage feasibility study relates to "Futures" water storage and rights for the tribes, among others.

4. Conclusions

This report described initial analyses of interviews with water and resource managers at WRIR, as part of the WRIR Drought Preparedness Project. The purpose was to: 1) document local observations of drought risk, responses, and barriers to drought planning and preparedness; and 2) demonstrate the ways in which local knowledge of drought risk and response options can inform drought planning for the project. This integrated vulnerability assessment was framed by a social-ecological systems approach and interviews were analyzed according to a modified grounded theory approach.

We first outlined three major storylines that emerged from the analysis. These included: 1) demonstration of the unique biophysical, physical infrastructure, and legal and management-related factors combine to contribute to water shortages at WRIR; 2) the ways in which differences within and between watersheds across WRIR creates differential drought exposure and vulnerabilities; and the drawbacks associated with "Futures" water rights and use. The second section of this report provided a discussion of how key informant interviews can inform physical climate and ecological impacts assessments for drought risk and planning. The third and final section provided some examples of additional research questions/objectives as the WRIR Drought Preparedness Project moves forward.

The ultimate goal of this report is to help inform drought preparedness planning and adaptation efforts under current and future climate change and variability. In doing so, we hope that the Eastern Shoshone and Northern Arapaho tribes use the information in this report to manage the land and water resources at WRIR as they see fit.

Acknowledgements

We would like to thank all the water resource managers and producers at Wind River Reservation for taking the time to share their knowledge and experiences of drought on their landscape. Thanks also to Robert Flynn at the North Central Climate Science Center (NCCSC) for help in creating several of the maps used in this report, and to Lindsey Middleton at the NCCSC for designing the cover page and title page. This research was supported by the tribes at Wind River Reservation, Wind River Office of the Tribal Water Engineer, the Wind River Water Resources Control Board, and the NCCSC. Funding for this work was provided by the United States Geologic Survey (USGS) NCCSC. The contents presented in this report are solely the responsibility of the authors. The contents do not necessarily represent the views of the NCCSC, the National Climate Change and Wildlife Science Center, or the USGS. The U.S. government is authorized to reproduce and distribute reprints of this report for governmental purposes.

References

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change 16, 268–281. doi:10.1016/j.gloenvcha.2006.02.006

Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity, in: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 717–743.

Adger, W.N., Barnett, J., Brown, K., Marshall, N., O'Brien, K., 2013. Cultural dimensions of climate change impacts and adaptation. Nat. Clim. Change 3, 112–117. doi:10.1038/NCLIMATE1666

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., Lund, J., 2015. Water and climate: Recognize anthropogenic drought. Nature 524, 409–411. doi:10.1038/524409a

Amadio, C.J., Hubert, W.A., Johnson, K., Oberlie, D., Dufek, D., 2005. Factors affecting the occurrence of saugers in small, high-elevation rivers near the western edge of the species' natural distribution. Trans. Am. Fish. Soc. 134, 160–171. doi:10.1577/FT03-225.1

Barnes, J., 2017. The future of the Nile: climate change, land use, infrastructure management, and treaty negotiations in a transboundary river basin. Wiley Interdiscip. Rev. Clim. Change 8. doi:10.1002/wcc.449

Barrasso, J., 2016. Irrigation Rehabilitation and Renovation for Indian Tribal Governments and Their Economies (IRRIGATE) Act, S. 438, Report No. 114–245.

Bergersen, E.P., Cook, M.F., Baldes, R.J., 1993. Winter movements of burbot (Lota lota) during an extreme drawdown in Bull Lake, Wyoming, USA. Ecol. Freshw. Fish 2, 141–145.

Berkes, F., Colding, J., Folke, C. (Eds.), 2003. Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK and New York, USA.

Berkes, F., Folke, C. (Eds.), 1998. Linking social and ecological systems: Management practices and social mechanism for building resilience. Cambridge University Press, Cambridge, UK.

Bernard, H.R., 2006. Research Methods in Anthropology: Qualitative and Quantitative Methods, 4th ed. AltaMira Press, New York, NY.

Bierbaum, R., Smith, J.B., Lee, A., Blair, M., Carter, L., Chapin, F.S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E., Verduzco, L., 2013. A comprehensive review of climate adaptation in the United States: more than before, but less than needed. Mitig. Adapt. Strateg. Glob. Change 18, 361–406. doi:10.1007/s11027-012-9423-1

Bryant, A, Charmaz, K, 2007. The SAGE Handbook of Grounded Theory. Sage Publications, Thousand Oaks, CA.

Chambers, R., Conway, G., 1992. Sustainable rural livelihoods: practical concepts for the 21st century (No. IDS Discussion Paper). Institute of Development Studies (UK).

Chapin III, F.S., Kofinas, G.P., Folke, C. (Eds.), 2009. Principles of ecosystem stewardship: resilience-based natural resource management in a changing world. Springer Science & Business Media, New York, NY.

Charmaz, K., 2011. A constructivist grounded theory analysis of losing and regaining a valued self, in: Wertz, F. J., K. Charmaz, L. M. Mcmullen, R. Josselson, R. Anderson & E. Mcspadden (Eds.) Five Ways of Doing Qualitative Analysis: Phenomenological Psychology, Grounded Theory, Discourse Analysis, Narrative Research, and Intuitive Inquiry. Guilford Press, New York, NY, pp. 165–204.

Chief, K., Meadow, A., Whyte, K., 2016. Engaging Southwestern Tribes in Sustainable Water Resources Topics and Management. Water 8, 350. doi:10.3390/w8080350

Christian-Smith, J., Levy, M.C., Gleick, P.H., 2015. Maladaptation to drought: a case report from California, USA. Sustain. Sci. 10, 491–501. doi:10.1007/s11625-014-0269-1

Corbin, J., Strauss, A., 2008. Basics of qualitative research: Techniques and procedures for developing grounded theory. Sage Publications, Inc., London, UK.
DeVisser, M.H., Fountain, A.G., 2015. A century of glacier change in the Wind River Range, WY. Geomorphology 232, 103–116. doi:10.1016/j.geomorph.2014.10.017
Ford, J.D., Keskitalo, E.C.H., Smith, T., Pearce, T., Berrang-Ford, L., Duerden, F., Smit, B., 2010. Case study and analogue methodologies in climate change vulnerability research. Wiley Interdiscip. Rev. Clim. Change 1, 374–392. doi:10.1002/wcc.48
Füssel, H.-M., Klein, R.J.T., 2006. Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Clim. Change 75, 301–329. doi:10.1007/s10584-006-0329-3
Glantz, M.H., 1994. Drought follows the plow: cultivating marginal areas. Cambridge University Press, New York, NY.
Glaser, B, Strauss, A, 1967. The Discovery of Grounded Theory: Strategies for Qualitative Research. Aldine, Chicago.
Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: The process of individual adaptation to climate change. Glob. Environ. Change 15, 199–213. doi:10.1016/j.gloenvcha.2005.01.002
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256. doi:10.1073/pnas.1222475110
Hayes, M.J., Wilhelmi, O.V., Knutson, C.L., 2004. Reducing drought risk: bridging theory and practice. Nat. Hazards Rev. 5, 106–113. doi:http://dx.doi.org/10.1061/(ASCE)1527-6988(2004)5:2(106)#sthash.djB79Oii.dpuf
Hill, M., Engle, N.L., 2013. Adaptive Capacity: Tensions across Scales: Water Governance and Adaptive Capacity. Environ. Policy Gov. 23, 177–192. doi:10.1002/eet.1610
Hobbins, M., Wood, A., McEvoy, D., Huntington, J., Morton, C., Verdin, J., Anderson, M., Hain, C., 2016. The Evaporative Demand Drought Index: Part I-Linking Drought Evolution to Variations in Evaporative Demand. J. Hydrometeorol. 17, 1745–1761. doi:10.1175/JHM-D-15-0121.1
HPRCC, 2016. ACIS Climate Maps. High Plains Reg. Clim. Cent. Available online at: http://www.hprcc.unl.edu/maps.php?map=ACISClimateMaps.
Hwang, S., 2007. Utilizing Qualitative Data Analysis Software: A Review of Atlas.ti. Soc. Sci. Comput. Rev. 26, 519–527. doi:10.1177/0894439307312485
Kallis, G., 2008. Droughts. Annu. Rev. Environ. Resour. 33, 85–118. doi:10.1146/annurev.environ.33.081307.123117
Kinney, T., 1993. Chasing The Wind : Wyoming Supreme Court Decision in Big Horn III Denies Beneficial Use for Instream Flow Protection , But Empowers State to Administer Federal Indian Reserved Water Right Awarded to The Wind River Tribes. Nat. Resour. J. 33, 841–871.
Krueger, K.L., Hubert, W.A., 1997. Assessment of lentic burbot populations in the Big Horn/Wind River drainage, Wyoming. J. Freshw. Ecol. 12, 453–463. doi:10.1080/02705060.1997.9663556
Krueger, K.L., Hubert, W.A., White, M.M., 1997. An assessment of population structure and genetic purity of sauger in two high-elevation reservoirs in Wyoming. J. Freshw. Ecol. 12, 499–509. doi:10.1080/02705060.1997.9663564
McNeeley, S.M., 2014. A “toad’s eye” view of drought: regional socio-natural vulnerability and responses in 2002 in Northwest Colorado. Reg. Environ. Change 14, 1451–1461. doi:10.1007/s10113-014-0585-0
McNeeley, S.M., 2012. Examining barriers and opportunities for sustainable adaptation to climate change in Interior Alaska. Clim. Change 111, 835–857. doi:10.1007/s10584-011-0158-x
McNeeley, S.M., Even, T.L., Gioia, J.B.M., Knapp, C.N., Beeton, T.A., 2017. Expanding vulnerability assessment for public lands: The social complement to ecological approaches. Clim. Risk Manag. doi:10.1016/j.crm.2017.01.005

McNeeley, S.M., Lazrus, H., 2014. The cultural theory of risk for climate change adaptation. Weather Clim. Soc. 6, 506–519. doi:10.1175/WCAS-D-13-00027.1

Midvale Irrigation District, 2007. Midvale Irrigation District: Handbook of Water User Rules, Policies and Procedures, and District By-Laws. Midvale Irrigation District, Pavillion, Wyoming.

Miller, B.W., Frid, L., Chang, T., Piekielek, N., Hansen, A., Morisette, J., 2015. Combining state-and-transition simulations and species distribution models to anticipate the effects of climate change. AIMS Environ. Sci. 2, 400–426. doi:10.3934/environsci.2015.2.400

Moser, S.C., Ekstrom, J.A., 2010. A framework to diagnose barriers to climate change adaptation. Proc. Natl. Acad. Sci. 107, 22026–22031. doi:10.1073/pnas.1007887107

MWH Americas, Inc., Short Elliott Hendrickson, Inc., Harvey Economics, 2010. Wind-Bighorn Basin Plan Update. Wyoming Water Development Commission, Cheyenne, Wyoming.

NRCS, 2017. National Water and Climate Center's Interactive Map. United States Department of Agriculture Natural Resources Conservation Service, Accessed online: https://www.wcc.nrcs.usda.gov/snow/snow_map.html.

O'Brien, K., Eriksen, S., Nygaard, L.P., Schjolden, A., 2007. Why different interpretations of vulnerability matter in climate change discourses. Clim. Policy 7, 73–88.

Orlove, B., Caton, S.C., 2010. Water Sustainability: Anthropological Approaches and Prospects. Annu. Rev. Anthropol. 39, 401–415. doi:10.1146/annurev.anthro.012809.105045

Pahl-Wostl, C., 2007. Transitions towards adaptive management of water facing climate and global change. Water Resour. Manag. 21, 49–62. doi:10.1007/s11269-006-9040-4

Patton, M.Q., 2002. Qualitative research and evaluation methods. Sage Publications, Thousand Oaks, CA.

Renn, O., 2011. The social amplification/attenuation of risk framework: application to climate change. Wiley Interdiscip. Rev. Clim. Change 2, 154–169. doi:10.1002/wcc.99

Rice, J., Tredennick, A., Joyce, L.A., 2012. Climate change on the Shoshone National Forest, Wyoming: a synthesis of past climate, climate projections, and ecosystem implications. General Technical Report RMRS-GTR-264. U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Robison, J.A., 2015. Wyoming's Big Horn General Stream Adjudication, 1977-2014. Wyo. Law Rev. 15, 243–312.

Scoones, I., 1998. Sustainable rural livelihoods: a framework for analysis (No. IDS Working Paper 72). University of Sussex, Brighton.

Smit, B., Pilifosova, O., 2003. Adaptation to climate change in the context of sustainable development and equity, in: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 877–912.

Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Glob. Environ. Change 16, 282–292. doi:10.1016/j.gloenvcha.2006.03.008

Strübing, J., 2007. Research as pragmatic problem-solving: The pragmatist roots of empirically-grounded theorizing, in: Bryant, A., Charmaz, K. (Eds.), The Sage Handbook of Grounded Theory. Sage Publications, London, UK, pp. 580–602.

Underwood, Z.E., Mandeville, E.G., Walters, A.W., 2016. Population connectivity and genetic structure of burbot (Lota lota) populations in the Wind River Basin, Wyoming. Hydrobiologia 765, 329–342. doi:10.1007/s10750-015-2422-y

U.S. Government Accountability Office, 2015. Indian Irrigation Projects: Deferred Maintenance and Financial Sustainability Issues Remain Unresolved. Washington, D.C.

Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A.I.J.M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A.J., Tallaksen, L.M., Uijlenhoet, R., Hannah, D.M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., Van Lanen, H.A.J., 2016. Drought in the Anthropocene. Nat. Geosci. 9, 89–91. doi:10.1038/ngeo2646

Van Loon, A.F., Lanen, H.A.J., 2013. Making the distinction between water scarcity and drought using an observation-modeling framework. Water Resour. Res. 49, 1483–1502. doi:10.1002/wrcr.20147
Wagener, T., Sivapalan, M., Troch, P.A., McGlynn, B.L., Harman, C.J., Gupta, H.V., Kumar, P., Rao, P.S.C., Basu, N.B., Wilson, J.S., 2010. The future of hydrology: An evolving science for a changing world. Water Resour. Res. 46. doi:10.1029/2009WR008906
Wandel, J., Diaz, H., Warren, J., Hadarits, M., Hurlbert, M., Pittman, J., 2016. Drought and vulnerability: a conceptual approach, in: Diaz, H., Hurlbert, M., Warren, J. (Eds.), Vulnerability and Adaptation to Drought: The Canadian Prairies and South America, Energy, Ecology, and the Environment Series. University of Calgary Press, Calgary, Alberta, pp. 15–36.
Westley, F., Carpenter, S.R., Brock, W.A., Holling, C.S., Gunderson, L.H., 2002. Why systems of people and nature are not just social and ecological systems, in: Gunderson, L.H., Holling, C.S. (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, D.C., pp. 103–119.
Wilhite, D.A., Buchanan-Smith, M., 2005. Drought as hazard: understanding the natural and social context, in: Wilhite, D.A. (Ed.), Drought and Water Crises: Science, Technology, and Management Issues. CRC Press Taylor & Francis Group, Boca Raton, FL, pp. 3–29.
Wilhite, D.A., Glantz, M.H., 1985. Understanding: the drought phenomenon: the role of definitions. Water Int. 10, 111–120.
Wind River Indian Reservation, 1991. Wind River Water Code.

Appendix 1: University and government agency partners on WRIR drought preparedness project

Organization
Bureau of Indian Affairs (BIA)
Eastern Shoshone Tribe
U.S. Fish and Wildlife Service (USFWS)
High Plains Regional Climate Center, University of Nebraska-Lincoln (HPRCC, UNL)
Montana State University (MSU)
North Central Climate Science Center (NC CSC)
National Drought Mitigation Center (NDMC), UNL
National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Research in Environmental Sciences (CIRES)
NOAA National Integrated Drought Information System (NIDIS)
NOAA Regional Integrated Sciences and Assessments (RISA) Wester Water Assessment
NOAA Earth Systems Research Laboratory (ESRL) Physical Sciences Division (PSD)
Office of the Tribal Water Engineer, Eastern Shoshone and Northern Arapaho Tribes
Ray Canal
University of Colorado-Boulder
University of Wyoming
University of Wyoming Experimental Program to Stimulate Competitive Research (EPSCoR)
University of Wyoming Extension
U.S. Department of Agriculture (USDA) Northern Plains Regional Climate Hub
USDA Natural Resources Conservation Service (NRCS)
U.S. Geological Survey (USGS) Wyoming Water Science Center
USGS Earth Resources Observation and Science (EROS) Center
Wind River Indian Reservation

Appendix 2: Drought Risk and Adaptation in the Interior (DRAI) interview questions

1) How do you define or think about drought in the context of your landscape?

2) Do you view drought as a significant risk to your management activities?

3) [if yes to #2] At what time of year is drought most problematic (how/why) [this is getting at seasonality/timing issues)?

4) What year (or years) was the worst drought in this area? What happened?

5) What management decisions do you have to make that are affected by drought?

6) a. What, if any, indicators do you use to know if/when/how drought is going to cause negative impacts on your landscape?
b. What do you consider to be the best source or sources of information on drought?

7) Are there fish, wildlife, and/or plant species you haven't mentioned impacted by drought in your landscape?

8) a. Are there human livelihoods or other activities impacted by drought in your landscape?

b. Does this cause any conflicts?

c. Do you collaborate with other stakeholders or jurisdictions on drought-related issues? If so, with whom and how?

9) Do you have the capacity to either respond to or prepare for drought?

10) Are there barriers that inhibit your ability to respond to or prepare for drought?

11) Anything else we haven't discussed?

Appendix 3: Context for overarching research questions for DRAI project

In the sections that follow, we provide primarily raw data output that was used to frame our analysis and the results we presented above. We first illustrate the number of times each code was mentioned by key informants in the transcripts we analyzed (code groundedness; Table A3.1). We also provide the raw output related to number of times each code was described in relation to the major interview/research question codes (code co-occurrence): drought risks that impact management actions on the ground (Table A3.2); the indicators that managers use to prepare for and respond to drought (Table A3.3); management decisions impacted by drought (Table A3.4); and the adaptive capacities and barriers to respond to drought (Tables A3.5 and A3.6, respectively). Finally, we developed complex network analyses of the management decision context (Figure A3.1), and the adaptive capacity and barriers to drought management at WRIR (Figure A3.2). The network analyses reflect an iterative and interpretive analysis of the transcripts to link concepts and codes (referred to as axial coding and comparative analysis).

Table A3.1: Code groundedness. Number of times each code (variable) was referred to in interview transcripts.

Code (n=234)	Groundedness[1]
Irrigation	124
Ranching and grazing	111
BIA	102
Streams, rivers, and streamflows	95
Reservoirs and storage	90
Decision-Type-Water Allocation or Delivery	84
Fish and fisheries	80
Infrastructure, physical	70
Summer	69
Management decision	67
Water rights and allocation	65
Snow	63
LWR	60
State government or agencies	60
Wildlife	58
TWE	56
Spring	54
Barriers	52
Water shortage	49
Livelihoods	48
Timing/seasonality	48
Conflict	46
Vegetation	45
Precipitation	43

BWR or UWR	42
Crowheart	42
Wind River Water Resources Control Board	41
Policy	40
Tribal government/programs	40
Adaptive capacity	39
Water availability	37
Climate science and information	36
Agriculture food crops	35
Collaboration/cooperation	35
Decision-Spatial-Sub-Basin	32
Pasture and Haying LU	30
Runoff	30
BOR	29
Fish and Wildlife Service	29
Funding or financial	28
Water use	27
Winter	27
Decision-Type-Reservoir Release	26
ISF	26
Management plan	26
Traditional or Cultural Use or Activities	26
Fall	25
Management responses	25
Spatial scale or variability	25
Indicators or triggers, drought or climate	24
Temperature	23
Tribal Water Code	23
Decision-Type-Grazing Management	22
Monitoring and assessment	22
Drought or climate risk	21
Rangeland LU	21
Drought definition	20
Land tenure	20
Grass	19
Trees	19
Decision-Spatial-Allotment	18
Deer	18
NRCS Natural Resources Conservation Service	18
Riparian ecosystems	18

2002 drought	17
Elk	17
Forage ES	17
Glaciers	17
Climate change	16
Decision-Type-Fish and Wildlife Management	16
Decision-Type-Stocking/Utilization Rates	16
Municipal or domestic water use	16
Persistent drought	16
Ray Canal Water Users Association	16
Recreation and tourism	16
USGS	15
2012 drought	14
2013 drought	14
Antelope	14
Fire	14
Soil and soil erosion	14
Decision-Spatial-Regional and/or Inter-Agency	13
Local knowledge and observation	13
Climate variability	12
Contacts	12
Water quality	12
Wetland LC	12
2015	11
drought declaration	11
Floods and flooding	11
Groundwater	11
Springs, hydrology	11
USDA	11
Birds	10
Energy	10
Health & Disease	10
Private lands and landowners	10
Productivity Vegetation ES	10
Sage Grouse	10
Storms	10
Decision-Type-Crop Management	9
Invasive species	9
CFR	8

Habitat ES	8
Human health or death	8
Personnel	8
University	8
1980s	7
Decision-Spatial-Field Office or Reservation	7
Decision-Temporal-Seasonal	7
Decision-Type-Supplemental Feed	7
Forest LC	7
NOAA	7
2016	6
bears	6
Decision-Temporal-Decision Calendar	6
Grassland LC	6
Lakes	6
NGOs	6
1988	5
Beetles	5
BLM	5
Decision-Type-Wetland Management	5
Desert	5
Horse	5
Owl Creeks	5
Shrubland LC	5
Shrubs	5
T&E species	5
Tribal Fish and Game	5
Water utilities	5
1990s mid	4
2006	4
Agricultural or ranching water use	4
County government	4
Cultivated Crops LU	4
Cultural Use of Vegetation ES	4
Decision-Temporal-Annual	4
Decision-Type-Vegetation Management	4
Extreme events	4
Growing season	4
Moose	4
Public perception	4
Trust	4

Uplands	4
US Forest Service	4
Wind River Enviromental Quality (WREQ)	4
2000s	3
2001	3
2003	3
2011 Flood	3
ARMA ARMP	3
Bighorn Sheep	3
Bison	3
bureaucracy	3
Climate projections	3
Creeping or slow onset	3
Decision-Temporal-LongTerm	3
Decision-Type-Fish Passages/Screens	3
Educational Capacity	3
Multi-jurisdictional cooperation	3
Ponds	3
Riparian Vegetation LC	3
Water temperature	3
Waterfowl	3
wolves	3
1990s	2
2000s early	2
2007 drought	2
2008	2
2012 flood	2
2016 Flood	2
Casinos	2
Clams	2
Climate change adaptation	2
Conservation	2
crop insurance	2
CSC	2
Decision-Type-Native Species Management	2
Decision-Type-Restrict Water Use	2
Economic development	2
Equity	2
Insects and Spiders	2
lynx meow	2
Mice	2

NEPA	2
Resilience	2
Uncertainty	2
Ungulates	2
US Drought Monitor Map	2
USDA Drought disaster declaration	2
1930s Dust Bowl	1
1960s	1
1990s early	1
1995 flood	1
2010 Flood	1
2010s	1
Amphibians and Reptiles (herps)	1
Army Corps of Engineers	1
Beaver	1
Conservation Reserve Program	1
Consultants	1
Coyote	1
Decision-Temporal-Daily	1
Decision-Temporal-Inter-annual	1
Decision-Type-Fire Management	1
Decision-Type-Flood Management	1
Decision-Type-Open/Close headgates	1
Decision-Type-Reintroduction	1
Development	1
DOE	1
Dust	1
EPA	1
Farmers Almanac	1
financial capital	1
Fox	1
human capital	1
Indian Health Services	1
Industrial water use	1
Leadership	1
Mammals	1
Mining and Minerals	1
Mountain Lion	1
NPS	1
Pinyon-Juniper LC	1
Racoons	1

Regime shift	1
Regulating Vegetation ES	1
Resource Conservation Districts	1
Sediment	1
Transfer of knowledge, tools, information	1
Water bottling plant	1
Wind	1
Wolverines	1
Total	**3628**

[1]Groundedness refers to the number of times each variable/code was mentioned in the transcripts.

Table A3.2: Drought or climate risk co-occurrence. Number of times code/variable co-occurred in same segment of text as the code *drought or climate risks*. This resulted primarily from the question, “Do you view drought as a significant risk to your management activities?”. [ ] = groundedness (number of times *drought or climate risk* was referred to in interview transcripts).

Drought or Climate Risk [21]	
Code (n=112)	Number of co-occurrences
Ranching and grazing	11
Streams, rivers, and streamflows	7
Irrigation	6
BIA	5
Decision-Type-Water Allocation or Delivery	5
Infrastructure, physical	5
Reservoirs and storage	5
Summer	5
Water availability	5
LWR	4
Vegetation	4
Wildlife	4
Climate variability	3
Livelihoods	3
Management decision	3
Monitoring and assessment	3
NRCS Natural Resources Conservation Service	3
Rangeland LU	3
Snow	3
Spatial scale or variability	3
Spring	3

Temperature	3
Timing/seasonality	3
Trees	3
Decision-Spatial-Sub-Basin	2
Fall	2
Fish and fisheries	2
Glaciers	2
Grass	2
Grassland LC	2
Invasive species	2
Management plan	2
Management responses	2
Municipal or domestic water use	2
Persistent drought	2
Policy	2
Precipitation	2
Riparian ecosystems	2
Runoff	2
Tribal government/programs	2
Uplands	2
Water rights and allocation	2
1930s Dust Bowl	1
1980s	1
1988	1
1990s mid	1
2000s	1
2000s early	1
2002 drought	1
2012 drought	1
Adaptive capacity	1
Agriculture food crops	1
Antelope	1
Barriers	1
Beaver	1
Bighorn Sheep	1
Birds	1
BWR or UWR	1
Climate change	1
Conflict	1
Conservation	1
County government	1

Creeping or slow onset	1
Crowheart	1
Cultivated Crops LU	1
Cultural Use of Vegetation ES	1
Decision-Spatial-Allotment	1
Decision-Temporal-Annual	1
Decision-Temporal-Decision Calendar	1
Decision-Type-Crop Management	1
Decision-Type-Grazing Management	1
Decision-Type-Stocking/Utilization Rates	1
Decision-Type-Supplemental Feed	1
Decision-Type-Vegetation Management	1
Deer	1
Desert	1
drought declaration	1
Elk	1
Fire	1
Fish and Wildlife Service	1
Forage ES	1
Forest LC	1
Groundwater	1
Growing season	1
Health & Disease	1
Indian Health Services	1
Land tenure	1
Multi-jurisdictional cooperation	1
Pasture and Haying LU	1
Ponds	1
Private lands and landowners	1
Productivity Vegetation ES	1
Ray Canal Water Users Association	1
Recreation and tourism	1
Riparian Vegetation LC	1
Sage Grouse	1
Shrubland LC	1
Shrubs	1
Soil and soil erosion	1
Springs, hydrology	1
State government or agencies	1
Storms	1
Traditional or Cultural Use or Activities	1

Tribal Fish and Game	1
Tribal Water Code	1
TWE	1
USGS	1
Water quality	1
Water shortage	1
Water use	1
Wetland LC	1
Winter	1
Total	**208**

Table A3.3: Indicators or triggers, drought or climate co-occurrence. Number of times that codes co-occurred with the code *indicators or triggers, drought or climate*. This code was primarily used when informants answered the questions: a) “What, if any, indicators do you use to know if/when/how drought is going to cause negative impacts on your landscape?” and b) What do you consider to be the best source or sources of information on drought?” Informants described a variety of indicators or triggers that they used to understand drought and other climate conditions. These included SNOTEL (to monitor snowpack), water availability metrics (e.g., stream gauges for streamflow and reservoir storage), spring precipitation, vegetation conditions, and other signals from wildlife (e.g., ungulate mobility). The informants descriptions of these indicators helped to better understand what types of indicators were used (e.g., local/experiential knowledge, climate science and information), the sources of information (e.g., NRCS), places where monitoring and metrics lacked and requests for additional indicators, and the decision context for what indicators are used, when they are used and for what purpose (see How do the interviews inform Physical Climate assessments and planning? for a more detailed discussion). [ ] = groundedness (number of times *indicators or triggers, drought or climate* was referred to in interview transcripts).

Indicators or triggers, drought or climate [24]	
Code (n=101)	Number of co-occurrences
Snow	18
Climate science and information	12
Local knowledge and observation	10
Streams, rivers, and streamflows	10
Spring	9
NRCS Natural Resources Conservation Service	7
Reservoirs and storage	7
Timing/seasonality	7
Vegetation	7
Precipitation	6
Ranching and grazing	6

Crowheart	5
Monitoring and assessment	5
Temperature	5
Wildlife	5
NOAA	4
Runoff	4
Soil and soil erosion	4
State government or agencies	4
Summer	4
Trees	4
TWE	4
Water shortage	4
Winter	4
Agriculture food crops	3
BIA	3
Fire	3
Fish and fisheries	3
Forage ES	3
Grass	3
Irrigation	3
Management decision	3
Spatial scale or variability	3
Storms	3
USGS	3
Water availability	3
Wind River Water Resources Control Board	3
Antelope	2
Barriers	2
BOR	2
BWR or UWR	2
Decision-Type-Crop Management	2
Decision-Type-Grazing Management	2
Decision-Type-Water Allocation or Delivery	2
Deer	2
drought declaration	2
Elk	2
Extreme events	2
Fall	2
Floods and flooding	2
Glaciers	2
LWR	2

Management plan	2
Rangeland LU	2
Tribal government/programs	2
University	2
US Drought Monitor Map	2
Water rights and allocation	2
Water use	2
1990s early	1
2002 drought	1
2006	1
2012 drought	1
2015	1
2016	1
2016 Flood	1
Agricultural or ranching water use	1
bears	1
Climate projections	1
Climate variability	1
Conservation Reserve Program	1
Contacts	1
County government	1
Decision-Spatial-Sub-Basin	1
Decision-Temporal-Annual	1
Decision-Temporal-Decision Calendar	1
Decision-Type-Reservoir Release	1
Decision-Type-Stocking/Utilization Rates	1
Drought definition	1
Dust	1
Farmers Almanac	1
Fish and Wildlife Service	1
Forest LC	1
Horse	1
Human health or death	1
Industrial water use	1
Insects and Spiders	1
ISF	1
Management responses	1
Mice	1
Moose	1
Municipal or domestic water use	1
Pasture and Haying LU	1

Riparian ecosystems	1
Sediment	1
Shrubland LC	1
Traditional or Cultural Use or Activities	1
US Forest Service	1
USDA	1
USDA Drought disaster declaration	1
Water temperature	1
Total	**280**

Figure A3.1: Management decision typology network analysis

Informants at WRIR described a variety of management decisions that were affected by drought. Through the analysis of interviews we have started to organize these management decisions and responses into a typology representing four categories. First, the typology captures what kind of decisions were made, which included decisions about water (e.g., *reservoir releases*, *wetland management*), ranching and grazing (e.g., *stocking/utilization rates*), agriculture (e.g., *crop management*), fish, wildlife, and vegetation (e.g., *native species management; stocking/utilization rates*), and fire management. Second, the temporal scale at which decisions were made included decisions made on a daily basis, during a particular season, annually, inter-annually, and long-term decisions. Also, the code *decision calendar* was used to capture descriptions from informants regarding specific periods and/or dates throughout a season when decisions are made (therefore, it co-occurred substantially with the *decision-Temporal-seasonal* code). Third, informants described decisions that were made on a variety of spatial scales, from those decisions made by individual water users, for example, on private plots or allotments, to decisions that impact users within a sub-basin on the reservation (e.g., Little Wind River), to decisions that are impacted by drought at the reservation level, and finally decisions that span the greater Wind River and/or Bighorn Region, or involve multiple agencies (e.g., USFWS, State, County). Fourth, we highlighted relevant policy contexts that impact the decisions that are made at WRIR and must be considered under drought.

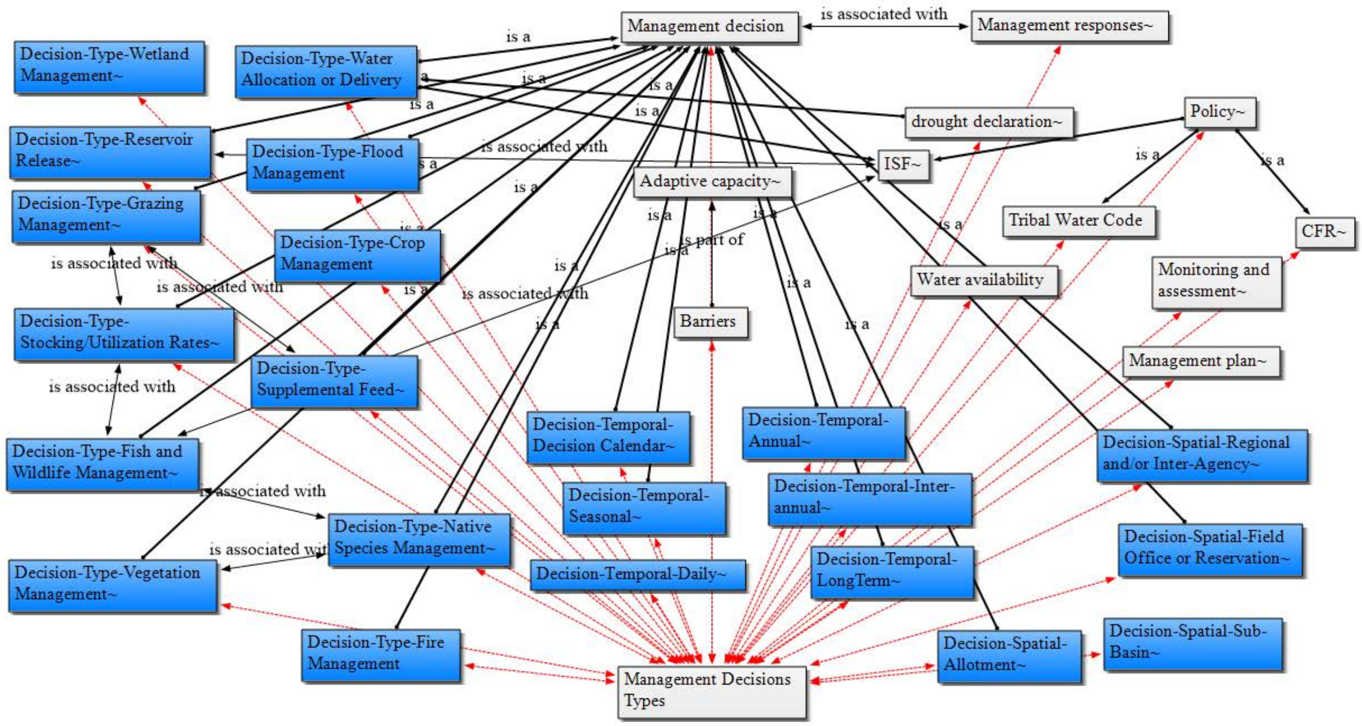


Table A3.4: Management decisions co-occurrence. Number of times a code/variable co-occurred in same segment of text as the code *management decision*. [ ] = groundedness (number of times *management decision* was referred to in interview transcripts).

Management Decision [67]	
Code Name (n=160)	Number of co-occurrences
Decision-Type-Water Allocation or Delivery	48
Irrigation	41
BIA	38
Infrastructure, physical	31
Reservoirs and storage	29
LWR	28
Streams, rivers, and streamflows	28
Ranching and grazing	27
Water rights and allocation	26
Summer	22
Decision-Spatial-Sub-Basin	20
Fish and fisheries	20
Decision-Type-Reservoir Release	19
Spring	18

Conflict	17
State government or agencies	17
TWE	17
Crowheart	16
Snow	16
BWR or UWR	15
Precipitation	15
Decision-Type-Fish and Wildlife Management	14
Decision-Type-Grazing Management	14
Decision-Spatial-Allotment	12
Fish and Wildlife Service	12
Water availability	12
Water shortage	12
Barriers	11
BOR	11
Collaboration/cooperation	11
ISF	11
Timing/seasonality	11
Vegetation	11
Water use	11
Wind River Water Resources Control Board	11
Adaptive capacity	10
Pasture and Haying LU	10
Wildlife	10
Winter	10
Decision-Spatial-Regional and/or Inter-Agency	9
Decision-Type-Stocking/Utilization Rates	9
Livelihoods	9
Management plan	9
Management responses	9
Tribal government/programs	9
Agriculture food crops	8
Climate science and information	8
Policy	8
Ray Canal Water Users Association	8
Riparian ecosystems	8
Runoff	8
2015	7
drought declaration	7
Fall	7

Glaciers	7
Land tenure	7
Soil and soil erosion	7
Spatial scale or variability	7
Temperature	7
Decision-Spatial-Field Office or Reservation	6
Springs, hydrology	6
Wetland LC	6
Climate change	5
Decision-Temporal-Seasonal	5
Decision-Type-Crop Management	5
Floods and flooding	5
Groundwater	5
Habitat ES	5
Persistent drought	5
Rangeland LU	5
Trees	5
Tribal Water Code	5
2002 drought	4
2013 drought	4
CFR	4
Contacts	4
Decision-Type-Supplemental Feed	4
Drought definition	4
Monitoring and assessment	4
Traditional or Cultural Use or Activities	4
1988	3
2012 drought	3
2016	3
Agricultural or ranching water use	3
Antelope	3
Birds	3
Climate variability	3
Decision-Temporal-Annual	3
Decision-Type-Fish Passages/Screens	3
Decision-Type-Vegetation Management	3
Decision-Type-Wetland Management	3
Deer	3
Drought or climate risk	3
Elk	3
Fire	3

Funding or financial	3
Grass	3
Grassland LC	3
Indicators or triggers, drought or climate	3
Local knowledge and observation	3
NRCS Natural Resources Conservation Service	3
Private lands and landowners	3
Public perception	3
Recreation and tourism	3
Storms	3
USGS	3
Waterfowl	3
1980s	2
2001	2
2016 Flood	2
Beetles	2
Decision-Temporal-Decision Calendar	2
Decision-Type-Native Species Management	2
Extreme events	2
Growing season	2
Invasive species	2
Lakes	2
Municipal or domestic water use	2
NGOs	2
Productivity Vegetation ES	2
Shrubland LC	2
University	2
Uplands	2
US Forest Service	2
Water temperature	2
Water utilities	2
1990s mid	1
2000s early	1
2003	1
2011 Flood	1
2012 flood	1
Bison	1
BLM	1
Climate change adaptation	1
Conservation	1

Creeping or slow onset	1
Cultivated Crops LU	1
Decision-Temporal-Daily	1
Decision-Temporal-Inter-annual	1
Decision-Temporal-LongTerm	1
Decision-Type-Reintroduction	1
Decision-Type-Restrict Water Use	1
Desert	1
Energy	1
Forest LC	1
Health & Disease	1
Human health or death	1
Mice	1
NPS	1
Owl Creeks	1
Ponds	1
Regime shift	1
Regulating Vegetation ES	1
Resilience	1
Riparian Vegetation LC	1
Sediment	1
Uncertainty	1
Ungulates	1
USDA	1
Wind	1
Total	**1123**

Figure A3.2: Adaptive capacity and barriers to drought management at Wind River Reservation: Network analysis

Figure A3.2 is a simplified network analysis that illustrates the adaptive capacities and barriers to preparing for, and responding to, drought that were identified by the key informants interviewed. Codes are organized under capital asset categories (e.g., financial capital, natural capital, human capital, physical capital, and social capital) according to the sustainable livelihoods framework (Chambers and Conway, 1992; Scoones, 1998). Note that these asset categories are not codes themselves, as managers did not describe adaptive capacities and barriers in the context of these categories. Instead, these categories provide a useful heuristic to understand the multiple social and ecological factors that affect drought preparedness and response. The codes that are linked to these categories (via red arrows) summarize managers' responses. The codes in red are those that had the highest co-occurrence with the codes *adaptive capacity* and *barriers*.

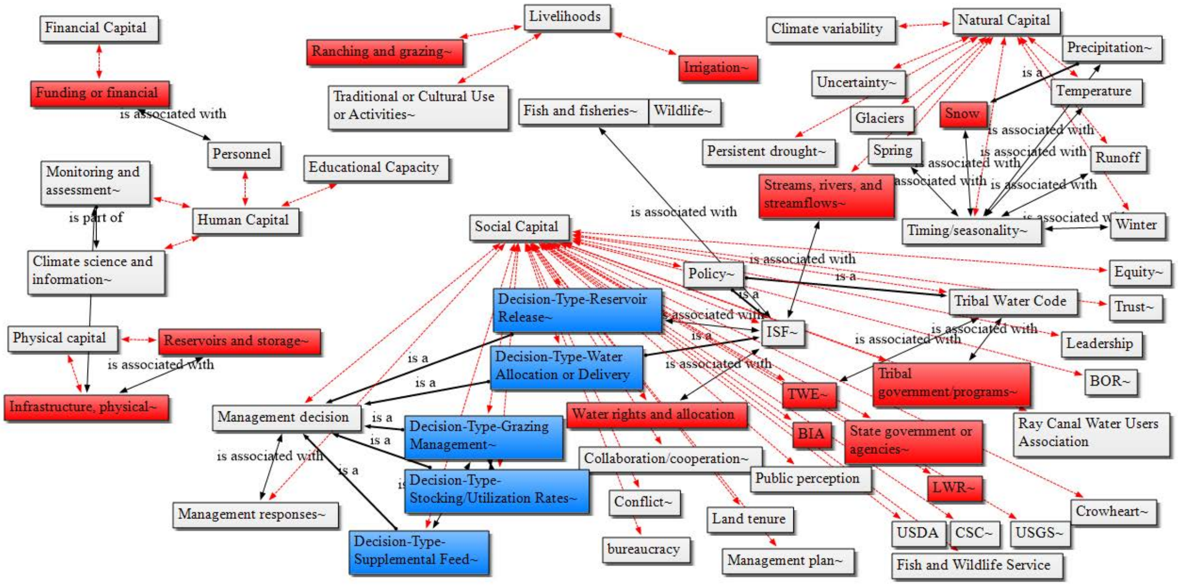


Table A3.5: Adaptive capacity co-occurrence**.** Number of times a code/variable co-occurred in same segment of text as the code *adaptive capacity*. [ ] = groundedness (number of times *adaptive capacity* was referred to in interview transcripts).

Adaptive Capacity [39]	
Code (n=115)	Number of co-occurrences
Barriers	17
BIA	17
Funding or financial	16
Irrigation	14
Infrastructure, physical	13
TWE	13
Streams, rivers, and streamflows	12
Policy	11
Management decision	10
Ranching and grazing	10
Reservoirs and storage	10
State government or agencies	10
Water rights and allocation	10
LWR	9
Decision-Type-Water Allocation or Delivery	8
Livelihoods	8
Conflict	7
Decision-Type-Reservoir Release	7

Snow	7
Collaboration/cooperation	6
Fish and fisheries	6
Management responses	6
Personnel	6
Summer	6
Wind River Water Resources Control Board	6
BWR or UWR	5
Decision-Spatial-Regional and/or Inter-Agency	5
Decision-Type-Grazing Management	5
Decision-Type-Stocking/Utilization Rates	5
Land tenure	5
Management plan	5
Spring	5
Timing/seasonality	5
Water availability	5
Wildlife	5
Climate science and information	4
Crowheart	4
Decision-Type-Fish and Wildlife Management	4
Decision-Type-Supplemental Feed	4
ISF	4
Precipitation	4
Runoff	4
Tribal government/programs	4
Tribal Water Code	4
Water use	4
2012 drought	3
2013 drought	3
BOR	3
Educational Capacity	3
Fish and Wildlife Service	3
NRCS Natural Resources Conservation Service	3
Trust	3
University	3
USDA	3
USGS	3
Vegetation	3

Water shortage	3
Antelope	2
Decision-Temporal-Decision Calendar	2
Decision-Temporal-LongTerm	2
Deer	2
Equity	2
Fall	2
Glaciers	2
Groundwater	2
NOAA	2
Persistent drought	2
Public perception	2
Ray Canal Water Users Association	2
Recreation and tourism	2
Soil and soil erosion	2
Storms	2
Uncertainty	2
Wind River Enviromental Quality (WREQ)	2
Winter	2
2002 drought	1
2015	1
bears	1
BLM	1
CFR	1
Climate change	1
Climate change adaptation	1
Climate variability	1
Conservation	1
Consultants	1
Contacts	1
Creeping or slow onset	1
CSC	1
Decision-Spatial-Allotment	1
Decision-Spatial-Sub-Basin	1
Decision-Type-Crop Management	1
DOE	1
drought declaration	1
Drought or climate risk	1
Elk	1
Energy	1
Floods and flooding	1

Grass	1
Growing season	1
Habitat ES	1
Health & Disease	1
Lakes	1
Multi-jurisdictional cooperation	1
Pasture and Haying LU	1
Private lands and landowners	1
Rangeland LU	1
Riparian ecosystems	1
Riparian Vegetation LC	1
Sage Grouse	1
Spatial scale or variability	1
Springs, hydrology	1
Temperature	1
Traditional or Cultural Use or Activities	1
Water quality	1
wolves	1
Total	**447**

Table A3.6: Barriers co-occurrence**.** Number of times a code/variable co-occurred in same segment of text as the code *barriers*. [ ] = groundedness (number of times *barriers* was referred to in interview transcripts).

Barriers [52]	
Code (n=145)	Number of Co-occurrences
Irrigation	24
BIA	22
Funding or financial	22
Reservoirs and storage	21
Infrastructure, physical	19
Adaptive capacity	17
Streams, rivers, and streamflows	16
TWE	16
Ranching and grazing	15
Decision-Type-Water Allocation or Delivery	14
LWR	13
Policy	13
State government or agencies	13

Water rights and allocation	13
Tribal government/programs	12
Decision-Type-Reservoir Release	11
Management decision	11
Management plan	11
Snow	11
Conflict	10
Water availability	10
Runoff	9
Timing/seasonality	9
Climate science and information	8
Land tenure	8
Spring	8
Water use	8
Decision-Spatial-Regional and/or Inter-Agency	7
Fish and fisheries	7
Livelihoods	7
Management responses	7
Precipitation	7
Summer	7
Vegetation	7
Crowheart	6
Ray Canal Water Users Association	6
Wildlife	6
2013 drought	5
Decision-Spatial-Sub-Basin	5
ISF	5
Municipal or domestic water use	5
Pasture and Haying LU	5
Personnel	5
Temperature	5
Tribal Water Code	5
Water shortage	5
Wind River Water Resources Control Board	5
Agriculture food crops	4
BWR or UWR	4
Fall	4
Traditional or Cultural Use or Activities	4
2002 drought	3
BOR	3

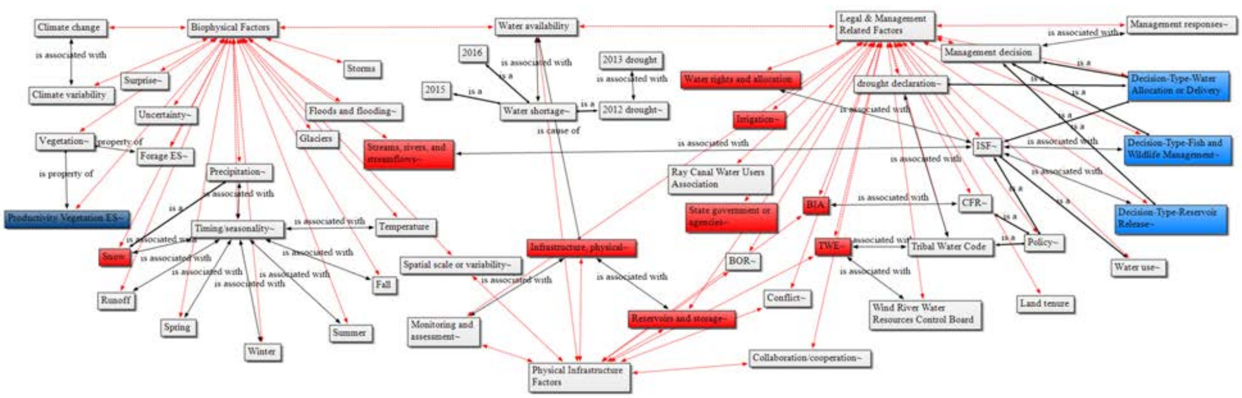
bureaucracy	3
Contacts	3
drought declaration	3
Fish and Wildlife Service	3
Floods and flooding	3
Grass	3
Monitoring and assessment	3
NRCS Natural Resources Conservation Service	3
Persistent drought	3
Private lands and landowners	3
Public perception	3
Trees	3
USDA	3
USGS	3
Wind River Enviromental Quality (WREQ)	3
2012 drought	2
2015	2
2016	2
ARMA ARMP	2
Beetles	2
Climate variability	2
Collaboration/cooperation	2
crop insurance	2
Cultural Use of Vegetation ES	2
Decision-Spatial-Allotment	2
Decision-Type-Fish and Wildlife Management	2
Fire	2
Glaciers	2
Indicators or triggers, drought or climate	2
NEPA	2
Riparian ecosystems	2
Soil and soil erosion	2
Spatial scale or variability	2
Springs, hydrology	2
Trust	2
Winter	2
1990s mid	1
2000s early	1
2003	1

2006	1
2016 Flood	1
Antelope	1
Army Corps of Engineers	1
bears	1
Birds	1
Bison	1
CFR	1
Climate change	1
Climate change adaptation	1
County government	1
Creeping or slow onset	1
Decision-Temporal-Decision Calendar	1
Decision-Temporal-LongTerm	1
Decision-Type-Crop Management	1
Decision-Type-Grazing Management	1
Decision-Type-Reintroduction	1
Decision-Type-Restrict Water Use	1
Decision-Type-Stocking/Utilization Rates	1
Decision-Type-Supplemental Feed	1
Decision-Type-Wetland Management	1
Desert	1
Drought definition	1
Drought or climate risk	1
Elk	1
Extreme events	1
financial capital	1
Forest LC	1
Groundwater	1
Growing season	1
Habitat ES	1
Health & Disease	1
human capital	1
Human health or death	1
Lakes	1
Leadership	1
lynx meow	1
Multi-jurisdictional cooperation	1
NGOs	1
NPS	1
Owl Creeks	1

Ponds	1
Productivity Vegetation ES	1
Rangeland LU	1
Recreation and tourism	1
Regulating Vegetation ES	1
Storms	1
T&E species	1
Uncertainty	1
Ungulates	1
US Forest Service	1
Wolverines	1
wolves	1
Total	**646**

Appendix 4: Complex network analysis of interacting and unique biophysical, physical infrastructure, and social drivers that result in system shortages at Wind River Reservation

This figure illustrates the relationships between biophysical and social factors that impact water availability, and which can lead to water shortages (example water years are provided in Examples illustrating the interacting biophysical and social factors that affect water availability), at WRIR. This is the result of iterative and inductive analysis of transcripts to link concepts and codes. The boxes biophysical factors, legal and management related factors, and physical infrastructure factors are concepts we created to organize codes and concepts described by key informants in the interviews.



Above: Wind River Canyon. Photo by J. Stephen Conn