TECHNICAL MEMORANDUM

TO: *WWDC*

DATE: *May 22, 2010*

FROM: *MWH*

REFERENCE: *Wind-Bighorn Basin Plan*

SUBJECT: *Task 6C– Climate*

This memorandum summarizes climate studies that are relevant to water resources in the Wind-Bighorn Basin. It summarizes the climate data resources available for the Basin, and discusses recent climate issues and studies, including drought. The document fulfills the reporting requirements for Task 6C of the consultant scope of work for the Wind-Bighorn Basin Plan Update.

Contents

Section 1 – Introduction

Wyoming is generally semiarid, with local desert conditions. The Wind-Bighorn Basin (Basin) has a spatially variable climate. The Wind River and Absaroka Mountain Ranges block the flow of moisture from the west, while the Bighorn Mountains block the flow of moisture from the east. This causes very dry climates in some portions of the Basin and much wetter climates in other portions. Figure 1 shows precipitation within the Bain based on PRISM data. PRISM is a “unique knowledge-based system that uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters” (PRISM Climate Group, 2009). A 1971-2008 PRISM GIS dataset was developed as part of this study by combining the 1971-2000 PRISM data set with individual PRISM datasets for individual years from 2001-2008 and is shown in the map. This document discusses where climate information can be found for the Basin, what the climate has historically looked like and what climate may look like in the future based on climate studies.

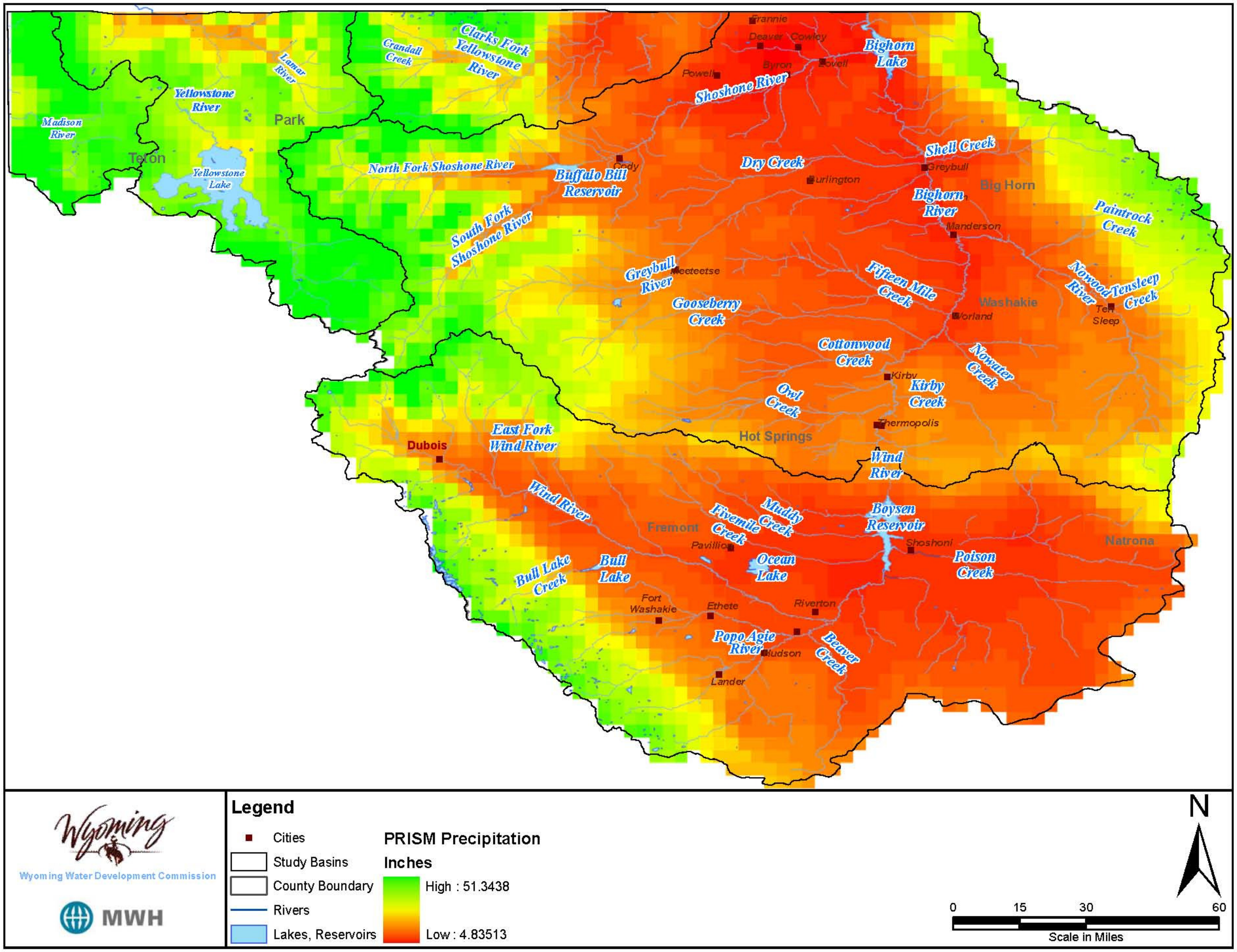

Figure 1. Precipitation in the Wind-Bighorn Basin

Section 2 – Climate Data Resources

The Western Regional Climate Center (WRCC) is the most in-depth on-line resource for raw climate data such as temperature, precipitation and snowfall in the western United States (WRCC 2009). From this website, data for the entire available period of record can be downloaded. Many of the data collection sites within the Wind-Bighorn Basin have extensive periods of record, dating back to the early 1900s, and provide a good overall picture of climate within the Basin. However, additional data sites could strengthen spatial completeness. The Wyoming State Climatologist should be consulted to determine the most appropriate locations for additional sites. The High Plains Regional Climate Center also has useful climate data and has links to the WRCC climate data (HPRCC 2009). For larger quantities of climate information, the National Climate Data Center offers climate data available on a variety of media such as CDs ROMs (NCDC 2009). The community collaborative rain, hail and snow network (CoCoRaHS), a volunteer precipitation reporting network, houses climate data that include precipitation, snow, hail. Figure 2 shows the September 2009 precipitation for the whole state as a percent of the average. Figures such as this can be downloaded from the CoCoRaHS website (CoCoRaHS 2009).

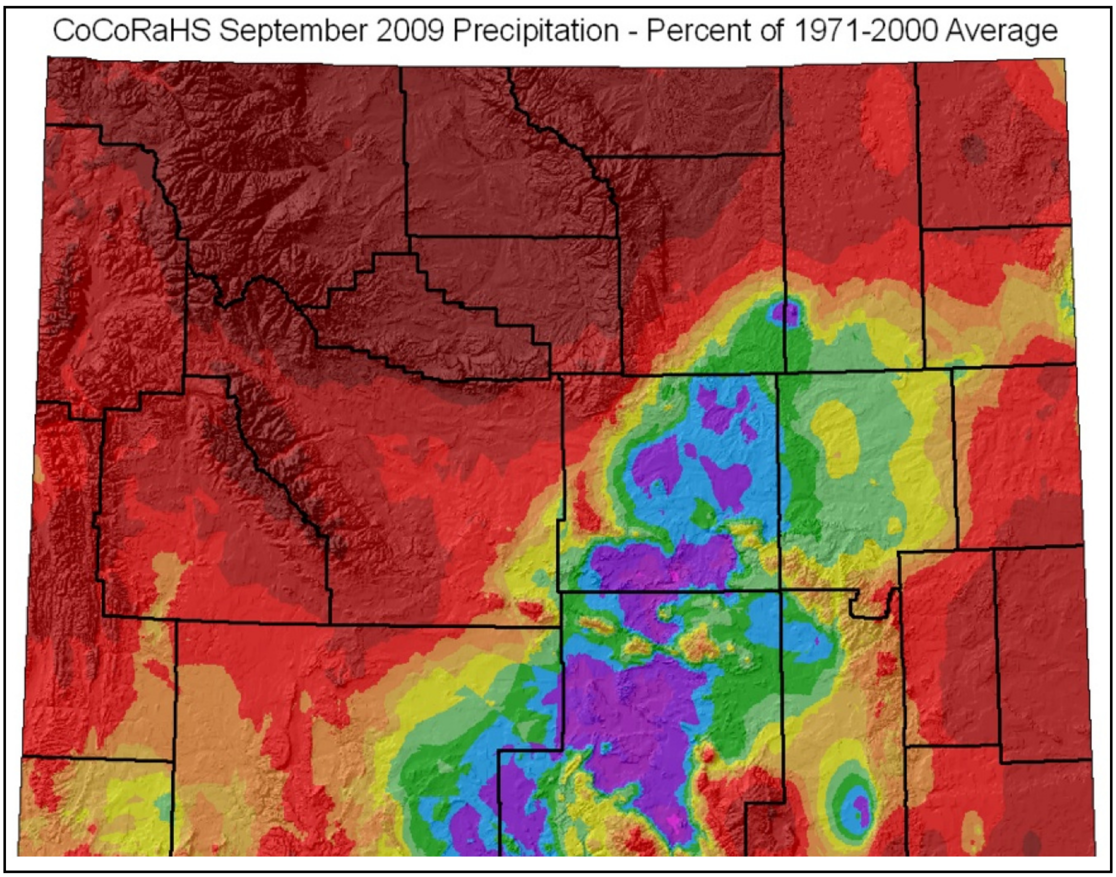

Figure 2. Sample of CocoRaHS Climate Maps - September 2009 Precipitation

The University of Wyoming's Water Resources Data System (WRDS) and the Wyoming State Climate Office provide summaries of climate data, including map-based products such as monthly climate normals (WRDS 2009a). Figure 3 shows the WRDS Climate Data website and the links to temperature and precipitation products available through the site.

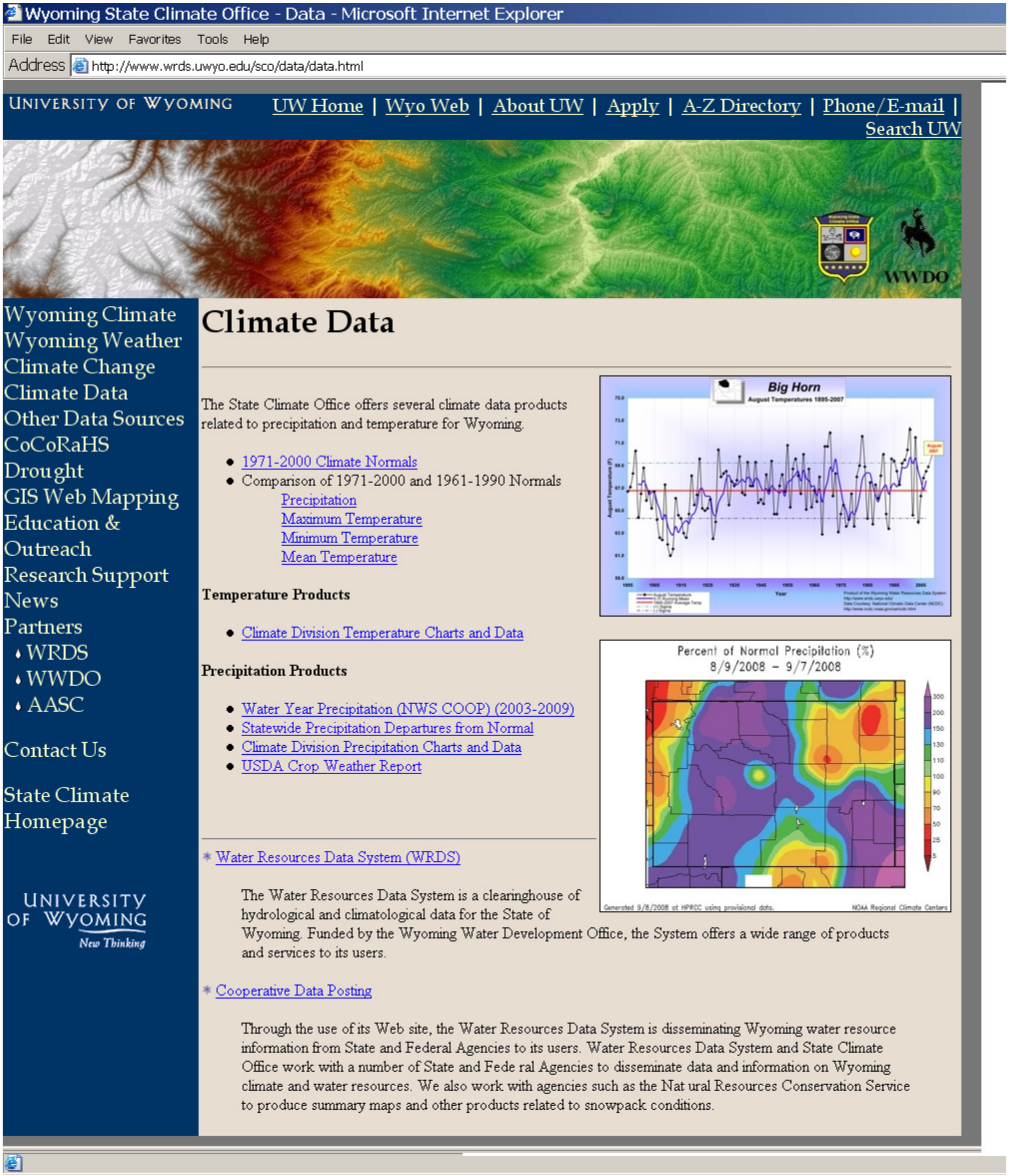

Figure 3. WRDS Climate Data Website

Drought information is primarily assembled by the USGS Water Watch program. The Wyoming drought watch page shows below normal streamflow conditions and links to recent drought related studies (USGS 2009). The U.S. drought monitor (UNL 2009) utilizes the Palmer Drought Index to formulate maps with short term and long term drought indicators. Figure 3 is an example of the drought monitor map for Wyoming on October 13, 2009. The WRDS website also provides many useful links to drought information as well as GIS mapping tools for precipitation, climate and SNOTEL stations (WRDS 2009b). Also, the Natural Resources Conservation Service (NRCS) provides streamflow forecasts for each month of the water year for the western United States, including Wyoming. The forecasts are based principally on measurements of precipitation, snow water equivalent, and antecedent runoff (NRCS 2009).

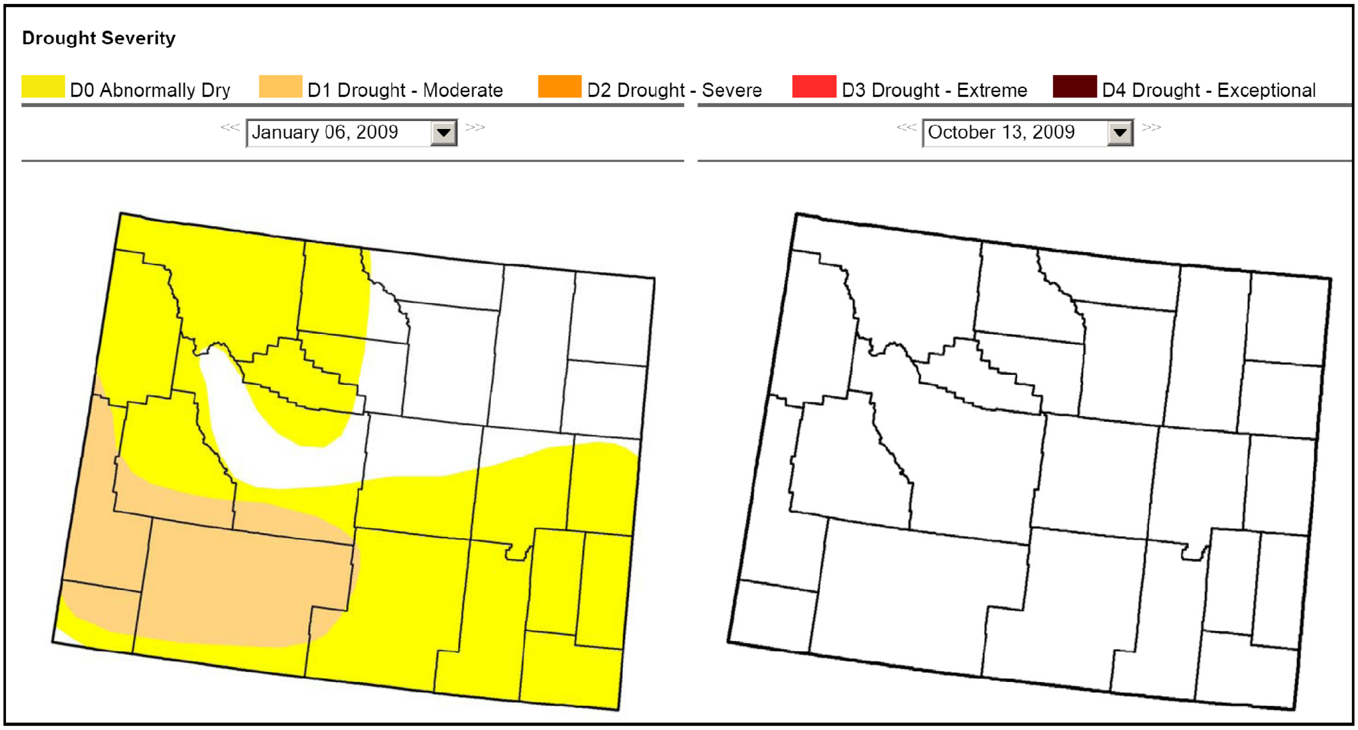

Figure 4. Sample Drought Monitor Map for Wyoming

Historical Climate Data

Historical average monthly and annual temperature data for four stations within the Basin generally representing the lower elevation agricultural and populous areas are shown in Table 1 (WRCC 2009). Monthly data for the full period of record for all stations can be found at the WRCC website (http://www.wrcc.dri.edu/). As shown, the climate within the Basin is relatively cool, with average monthly temperatures less than 80° F for all of the stations. The coolest month is January, with average monthly temperatures in the mid teens for Riverton, Worland and Deaver and about 24° F for Cody.

Table 1. Average Monthly Temperature for Selected Long-Term Gages

	Average Temperature (Degrees Fahrenheit)												
	Jan	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Ann**
Cody (1915—2009)													
Mean	24.3	28.2	35.1	44.1	53.2	61.9	69.8	67.6	57.7	47.6	34.6	26.8	45.9
S.D.	6.9	5.9	4.5	3.8	3.4	3.5	3.1	2.7	3.6	4.0	5.0	5.4	1.9
Max	38.2	40.3	45.4	52.0	64.5	71.0	76.3	73.6	65.7	55.0	46.7	36.1	51.7
Min	5.0	6.8	22.3	33.2	46.0	52.0	60.5	61.6	46.4	33.3	18.4	8.0	40.8
Riverton (1907—2009)													
Mean	14.9	22.4	33.3	44.0	53.9	62.9	70.4	67.8	57.3	44.9	28.6	17.2	43.3
S.D.	7.4	6.6	4.4	3.4	2.9	3.0	2.4	2.2	2.9	3.2	5.3	6.7	1.8
Max	27.3	34.1	43.2	51.4	62.2	72.2	76.1	73.7	63.5	52.0	40.0	31.8	46.9
Min	-7.3	5.1	17.1	34.9	47.3	56.1	64.4	63.3	48.2	32.7	14.9	-2.2	38.8
Worland (1907—2009)													
Mean	15.0	22.8	34.4	45.6	56.0	65.2	72.3	69.6	58.3	46.3	31.2	19.0	44.7
S.D.	7.2	6.8	4.6	3.3	2.9	3.2	2.8	2.6	3.1	3.3	4.8	5.5	1.8
Max	31.6	35.3	44.9	53.3	64.3	75.0	78.7	76.4	65.9	53.2	40.3	29.4	49.2
Min	-5.0	2.8	21.9	37.0	49.5	56.5	64.4	63.1	49.0	34.9	15.8	4.7	40.3
Deaver (1916—2009)													
Mean	16.4	24.0	33.8	44.7	55.0	63.6	71.5	68.8	57.8	45.7	30.7	20.1	44.4
S.D.	7.0	6.4	4.3	3.5	3.2	3.6	2.7	2.5	3.1	3.4	4.7	5.1	1.7
Max	31.4	35.0	44.7	52.5	63.8	73.1	77.7	74.5	65.5	52.9	39.2	28.3	48.0
Min	-2.3	3.3	23.6	37.3	49.0	49.5	61.9	64.1	47.4	33.6	15.1	6.5	40.1

Ten-year average temperature was calculated for each station from 1932 to 2008. If a single month had more than two days of missing data, the entire year was omitted from the calculation and is indicated on the graph by a marker. Data for Deaver had enough months with missing data that it was omitted from this analysis. As shown in Figure 5, there has been a slight increase in temperatures since record keeping began. Except for Cody, all of the stations averaged around 43°F in the beginning of the study periods and average around 46° at the end. Cody ten-year averages rise a similar magnitude of three degrees, from about 44.5° to 48°. Except for Worland, average temperatures during the last 10 to 15 years generally exceed the 10-year average during any other time during the period-of-record. Very recent 10-year averages are beginning to show a slight decrease in average temperature. It cannot be determined based upon this elementary analysis of temperature whether the warmer temperatures are within the long-term historical variation in temperature or indicative of general warming within the area. No trend lines were added to these graphs because the relatively short periods-of-record may arbitrarily bias the trend. In addition, some variation in temperature could be caused by changes in the types of recording instruments used at the sites, movement of the sites, or changes in conditions surrounding the sites, such as urban development or other changes in land use.

Ten-year precipitation averages were calculated for each station from 1932 to 2008 (Figure 6). If a single month had more than two days of missing data, the entire year was omitted from the analysis and is indicated on the graph by a marker. Data for Deaver had enough months with missing data that it was omitted from the graph. Although no detailed trend analyses were performed Figure 6, there do not appear to be any significant long-term trends in annual precipitation over the study period. The effect of the climate on streamflow is discussed in Technical Memorandum 4A-Surface Water Hydrology along with a discussion of the impact of the recent and historical multi-year drought events on the Basin.

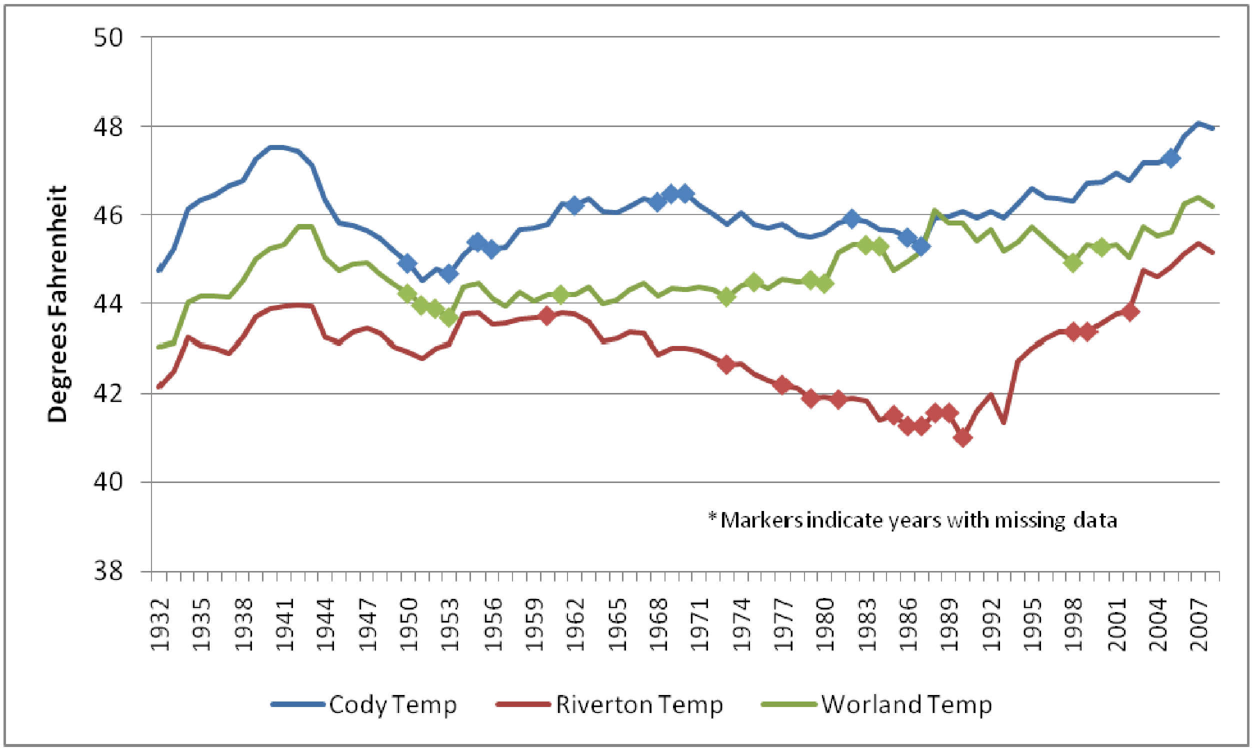

Figure 5. 10-year Average Temperature for Selected Gages

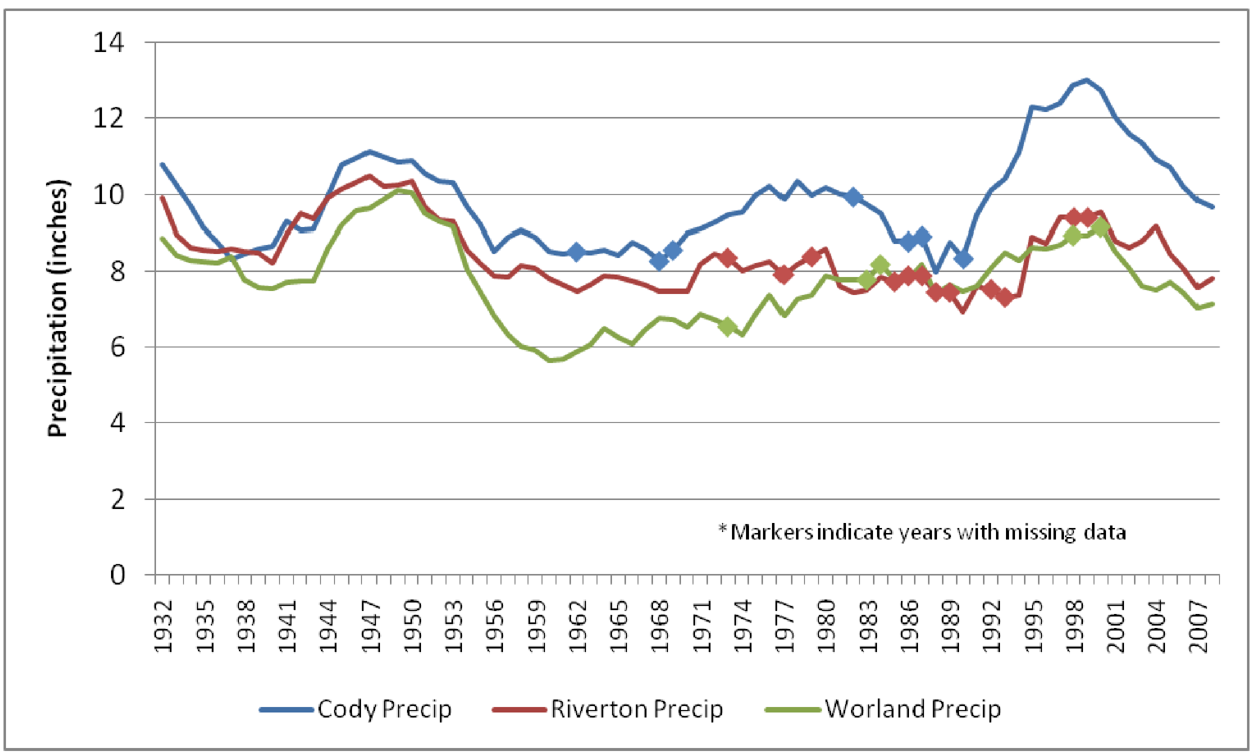

Figure 6. 10-year Average Annual Precipitation for Selected Gages

Average monthly and annual snowfall for each station is shown in Table 2. Cody and Riverton average much more snow than Worland or Deaver. The spring months have the most snowfall in the Cody and Riverton areas, while the winter months have the most snowfall in Worland and Deaver.

Table 2. Average Snowfall

	Average Snowfall (inches)												
	July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Ann**
Cody (1915—2009)													
Mean	0	0	0.4	3.74	5.7	5.96	6.24	5.07	6.7	5.22	0.64	0.03	40.19
S.D.	0	0	1.45	4.55	4.57	5.24	5.83	5.04	4.73	5.58	1.85	0.24	14.9
Max	0	0	8	19	19	23.5	26.3	23	19	28	10	2	73.4
Min	0	0	0	0	0	0	0	0	0	0	0	0	13.9
Riverton (1907—2009)													
Mean	0	0	0.58	3.33	4.8	4.51	3.69	4.3	5.56	5.61	1.01	0.18	33.21
S.D.	0	0	1.79	5.3	4.85	4.48	3.79	4.5	4.56	6.74	2.32	1.12	12.58
Max	0	0	13	23.5	22	19	16.5	22.5	21.7	31.7	11	9.5	60.5
Min	0	0	0	0	0	0	0	0	0	0	0	0	1
Worland (1907—2009)													
Mean	0	0	0.09	0.77	2.07	2.91	3.47	2.37	2.6	1.17	0.1	0.01	16.85
S.D.	0	0	0.4	2.17	3.26	3.15	3.64	3.48	2.99	2.17	0.66	0.12	11.57
Max	0	0	2.5	14.1	14.4	15	13.5	19	15.9	12.5	5.5	1.1	53.4
Min	0	0	0	0	0	0	0	0	0	0	0	0	0
Deaver (1916—2009)													
Mean	0	0	0.3	0.49	1.35	2.21	3.14	1.44	1.63	1.42	0.12	0.01	12.16
S.D.	0	0	1.45	1.29	2.34	2.87	3.6	2.45	2.03	3.85	0.54	0.05	9.21
Max	0	0	11	9	10.1	14	15	12	8	24	4	0.4	34.6
Min	0	0	0	0	0	0	0	0	0	0	0	0	0

Section 3 – Weather Modification Program

The Wyoming Water Development Commission (WWDC) and the State of Wyoming are currently conducting a pilot weather modification program. The program entails winter cloud seeding in the Medicine Bow/Sierra Madre Mountains and the Wind River Range to increase snowpack and subsequent runoff. The Shoshone National Forest and the Bridger-Teton National Forest are two specific target areas for the pilot project in the Wind River Range (WWDC 2007). A request for an extension of the program will go before the Legislative Select Water Committee and the WWDC for the 2010 session. It is believed that an additional three years are needed to be able to detect a 10% increase (95% confidence-interval) in snowpack due to seeding (WWDO 2009b). A 10% increase in snowpack in the target areas will yield 130,000 to 260,000 acre-feet per year of additional runoff each spring (WWDC 2007).

Silver iodide based seeding agents are introduced into storm clouds by aircraft or ground generators. There are 10 ground generators on the Wind River Range. During the 2008-2009 season, there were 13 seeding events in the Wind River Range target area with 648 total generator hours seeded (WWDO 2009a). At the time of the WWDO publication, data from the seeding efforts was still being analyzed. However, initial results from the Sierra Madre Range target area seeding operations were positive. It is thought that these projects could increase snowpack by 10-20% per year. Because this is within the range of natural storm variability and inter-seasonal variability, there should be no noteworthy adverse environmental impacts (WWDC 2007).

Section 4 – Drought Management

A model was developed as part of the previous Basin Plan to determine available surface water within the Basin and to locate areas where shortages may occur. Wyoming water law is based on prior appropriation (see Technical Memorandum 3H- Water Law and Water Administration); therefore, individual water rights will dictate who receives water in drought situations. Technical Memorandum

4C-Available Surface Water Determination describes updates to the surface water model and indicates reaches where shortages would occur in drought years. The model is a useful tool for each entity to evaluate reliability of general water supply sources during drought conditions. However, care should be taken in using the model to anticipate drought conditions for individual nodes within the model, because the model does not consider water rights when allocating water during water short situations. Individual drought management plans should be developed by the individual entities to mitigate shortages based on general water supply during drought conditions, tolerance of demands within the system to water shortages, availability of other water sources, such as storage or leases, and budget available to mitigate water shortages.

Section 5 – Climate Studies

Several major climate studies have occurred within the Basin. There have been two studies involving tree-ring reconstructions of precipitation and streamflow. There has also been great interest in the glaciers in the Basin for the paleoclimatic data found in ice cores. The University of Wyoming is conducting a formal glacier study in the Wind River Range. Research efforts include the effect of oceanic-atmospheric variability on snowfall, streamflow reconstructions and associated climate variability, the contribution of glacial meltwater to streamflow, glacial area and volume change and field mapping and evaluations of the Dinwoody Glacier. Additionally, studies are being conducted in the Western U.S. to investigate potential changes in hydrology as a result of the bark beetle infestation. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) reports give a broad look at how the climate and hydrology within the Basin has changed over history and may be changing into the future. The IPCC is “the leading world-wide scientific body for the assessment of climate change, established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences” (IPCC 2009). It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change.

Climate Change Studies

The Environmental Protection Agency (EPA) has produced several reports based on findings from the IPCC on global climate variability. Regional predictions of future climate have been made throughout the continental United States. The models used and the knowledge of the physical processes that govern climate give a high degree of certainty in the predictions of a warmer western United States. The most recent IPCC report utilized 21 models that indicate that Wyoming will receive more winter precipitation (5-10%) and slightly less (0-5%) precipitation in the summer (IPCC 2007).

The Bureau of Reclamation has also recently released a document that summarizes recent literature that pertains to climate change and water resources (Reclamation 2009). Studies reviewed by this document estimate a general decline in spring snowpack and an earlier snowmelt runoff. They also report increases in crop water consumptive use within the Great Plains (GP) region. Some studies suggest that the growing season length has increased by about 1 week during the 20th century and will be more than 2 weeks longer by the end of the 21st century (Gutowski et al., 2008).

Glacier Studies

Glaciers in the Wind-Bighorn Basin have been recently studied as a source of paleoclimatic data. In particular, several ice-cores have been extracted from the Upper Fremont Glacier in the Wind River Mountain Range. The chemical and physical components of the layers of ice in the glacial cores provide scientists with information about the historical climatic environment. Approximately 250 years of record are preserved at the Fremont Glacier ice core site. A record of air temperature changes is also preserved in glacial ice. An analysis of relative ratios of oxygen-18 (^{18}O) to oxygen-16 (^{16}O) revealed what is known as the Little Ice Age which occurred from approximately 1740 to 1845 A.D.

(USGS 2000). The transition out of the Little Ice Age probably took fewer than 10 years, which indicates an abrupt end to the Little Ice Age in the alpine regions of the Wind River Range (Schuster et al., 2000).

The earliest references to the Wind River glaciers date back to 1851 with formal studies as early as 1878. Most of the studies indicate that the glaciers have been steadily retreating since the 1850's. The total annual runoff from glaciers in the Wind River Range is estimated to be approximately 56,756 ac-ft for the annual melting period of July through October. Assuming equitable distribution of flows based upon aerial location, 77% of glacial runoff would enter Wind River drainages or 43,783 ac-ft on an annual basis. This flow represents approximately 8% of the total flow in the Wind River during the same period. (Pochop, Marston, et al., 1989). The assumption made by Marston, et al., 1989 and Naftz, et al., 2002 regarding the life span of the glaciers was that if the current warm / dry climate trends continue without ceasing, the Wind River glaciers could disappear completely. Thus, flow to the Wind River would be reduced by approximately 8% (Marston, et al. 1989; Naftz, et al. 2002).

The University of Wyoming glacier study used remote sensing data and aerial photography to quantify glacier area changes for 42 glacial complexes in Wyoming's Wind River Range. The average surface area change from 1985 to 2005 was a 37% decrease. Glaciers located in the central portion of the glaciated area for the Wind River Range had smaller reductions in surface area than the glaciers on the north and south sides of the range. The differences may be attributed to the larger glaciers in this area, which tended to show smaller reductions in area than did the smaller glaciers. Larger glaciers did show significant volume loss (UW 2007). Many of the Basin's rivers originate from glaciers and their flow characteristics make them valuable for mid- to late summer water supply needs of irrigators in the Basin. Total loss of the Wind River Range glaciers would impact water supply within the Basin.

In early September 2003 a glacial outburst flood known as a jökulhlaup, burst from an ice-dammed lake at the head of Grasshopper Glacier in the Wind River Range (Figure 7). It was estimated that 2,600 acre feet of water drained from the lake, flowing underneath the glacier through Dinwoody Lakes and into the Wind River valley. The outburst flood was recorded at the "Dinwoody Creek above Lakes" USGS stream gage (06221400; drainage area 88.2 mi^2) approximately 20 miles downstream from the ice-dammed lake. The 1,289 cfs flow was 59% greater than the average annual peak snowmelt flow. Repercussions of the jökulhlaup include minor structural damage to the Downs Fork Bridge, siltation of irrigation ditches in the upper Wind River Indian Reservation and diminished glacial reservoirs on which irrigators rely on for late-season irrigation (Oswold and Wohl, 2007).

Figure 7. Ice-dammed lake that drained from head of Grasshopper Glacier (Oswold and Wohl 2007)

Jökulhlaups are associated with volcanic, seismic, and meteorologic triggers (Cenderelli and Wohl 2001, 2003; Walder and Costa 1996). No direct association with regional, meteorologic or seismic events and the Grasshopper Glacier jökulhlaup could be made. However, the jökulhlaup did occur during unseasonably warm weather in the fifth year of a severe regional drought. Work by Naftz et al. (2002) on the Upper Fremont Glacier, 6.5 miles from Grasshopper Glacier, indicates a warming trend at high elevations in the Wind River Range during the past 50 years. It is thought that the warming in this area produced increased meltwater in the ice-dammed lake which led to the jökulhlaup. It is likely that continued warming and melting of glaciers in the Wind River Range will result in future and perhaps more frequent outburst flood events (Oswold and Wohl, 2007).

Tree-Ring Studies

Tree rings enable scientists to extend historical records of precipitation and streamflow by hundreds of years. Recent droughts have increased interest in understanding precipitation and streamflow variability over long periods of time. Studies worldwide have shown that instrumental records are often insufficient for capturing the true variability as they rarely exceed 100 years in length (Gray et. al 2004).

Gray et al. 2004 reconstructed precipitation records from 1260-1988 based on tree-rings of climate sensitive evergreen trees in the Bighorn Basin. The full reconstructions show that the worst drought years in recorded history (1934 and 1956) within the Basin were likely equaled or exceeded on numerous occasions in the preceding seven centuries. The twentieth-century contains just 2 of the 37 most severe drought years in the reconstructed time series. Severe droughts lasting about 20 years occurred in several previous centuries, suggesting that prolonged dry events were common in the Bighorn Basin before 1750 AD. Conditions after 1750 were generally much wetter than the long-term average. Table 3, from Gray et al. 2004, shows that the driest 20-year period in the twentieth century (1917-1936) ranks as the 149th driest 20-year period in the reconstruction.

Table 3. Driest Precipitation Periods

TABLE 4. Driest 10-, 15-, and 20-yr periods in the 1260–1998 A.D. proxy record, based on inferred MAP over the respective intervals. The driest periods in the twentieth century are shown for comparison.

Driest 10-yr period	Rank	MAP (cm)	Driest 15-yr period	Rank	MAP (cm)	Driest 20-yr period	Rank	MAP (cm)
1738–47	1	22.4	1580–94	1	23.3	1262–81	1	23.6
1272–81	2	22.6	1267–81	2	23.4	1579–98	2	23.7
1735–44	3	22.6	1268–82	3	23.4	1263–82	3	23.8
1271–80	4	22.8	1734–48	4	23.4	1261–80	4	23.9
1273–82	5	22.9	1579–93	5	23.5	1580–99	5	23.9
—	—	—	—	—	—	—	—	—
1951–60	28	23.7	1948–62	68	24.5	1917–36	149	25.0

From Gray et al. 2004. MAP=Mean annual precipitation

Streamflow records can also be extended using tree-ring data. Watson et al. extended three streamflow gages in the Wind River Basin on smaller tributary streams. These were Bull Lake Creek above Bull Lake; the Little Popo Agie River near Lander, Wyoming; and Wind River near Dubois, Wyoming. Figure 8 presents the reconstructions and the historical USGS gage data for ten-year averages (Gray 2009). These streams are not often reconstructed as the historical gaged data used for calibration is often short compared to that of larger rivers. (Watson et al. 2009).

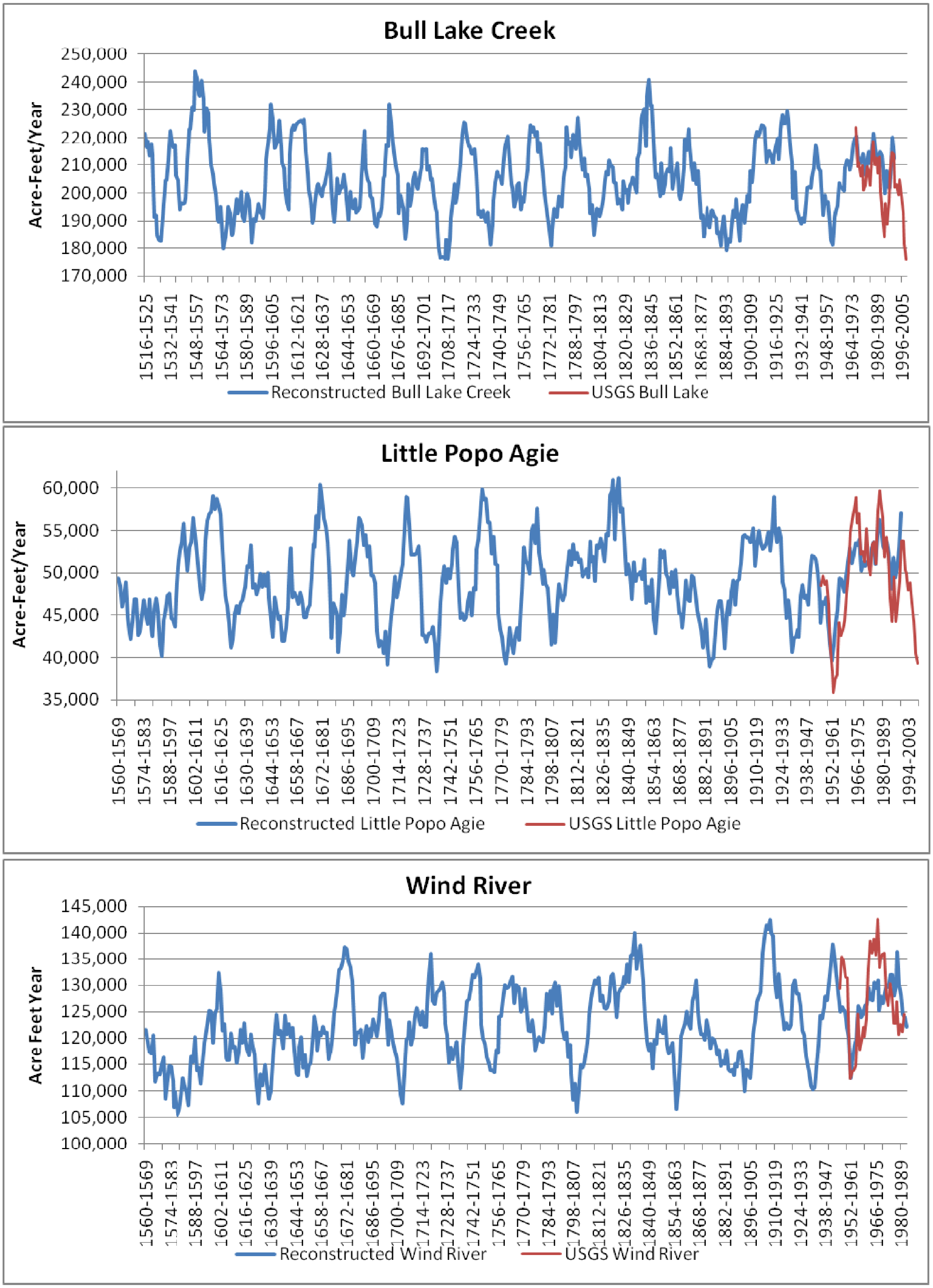

Figure 8. Streamflow Reconstructions (data from Gray 2009)

As seen in the streamflow reconstructions, there are several droughts that occurred prior to the gaged record and flows seem to oscillate regularly between wet and dry periods. The reconstructed time periods were from 1516-2000 for Bull Lake, from 1560-1999 for the Little Popo Agie, and from 1560-1992 for the Wind River (Watson et al. 2009). Inter-annual variability is much more defined in the reconstructed records due to its longer time period and changes between years from wet to dry are more readily identified. The longer, reconstructed records may help to better assess the potential for sustained drought (Tarboton 1995; Young 1995) and to test the ability of water systems to meet future demand (Harding et al., 1995; Jain et al., 2002; Woodhouse and Lukas, 2006). Actual gage data was available through 2008 except for the Wind River which was available through 1991.

The more recent gage data has some 10-year average periods that are lower than the reconstructed data. Short calibration periods can influence streamflow reconstructions. As a result, an added measure of caution should be used when working with such records. To demonstrate this, Watson et al. recalibrated the reconstructions of the Little Popo Agie based on portions of the gaged record, to represent even shorter periods of record. Noticeable differences in flow between the calibrations show up in means of 10 years or more (Watson et al. 2009). Often, small tributary streams like the ones used in this study tend to have short periods of gaged records.

The ranking of driest years correspond best with those from the precipitation reconstructions (Gray et al. 2004) at the Little Popo Agie gage. Particularly, the driest 15-year period corresponds exactly with the precipitation data. However, all gage reconstructions show several extreme, multi-year droughts in the reconstructed time periods (Watson et al. 2009). When historical gaged data is compared to the reconstructions, the driest 10-year period at the Popo Agie gage occurs during the 1950s in the gaged dataset (Table 4).

Table 4. Driest Streamflow Periods for the Little Popo Agie

Driest 10-yr period	Rank	AF/Yr	Driest 15-yr period	Rank	AF/Yr	Driest 20-yr period	Rank	AF/Yr
Reconstructed from Tree Ring Data (Gray 2009)								
1735-1744	1	38,415	1703-1717	1	39,827	1886-1905	1	42,426
1885-1894	2	38,979	1704-1718	2	40,271	1770-1789	2	42,681
1708-1717	3	39,143	1772-1786	3	40,529	1883-1902	3	42,805
1773-1782	4	39,359	1579-1593	4	41,460	1885-1904	4	42,833
1952-1961	5	39,609	1730-1744	5	41,511	1884-1903	5	43,170
Historical USGS Gaged Data								
1953-1962		35,807	1948-1962		42,531	1988-2007		43,400
Spreadsheet Model Study Period—USGS Data (1973-2008)								
1999-2008		39,352	1989-2003		45,089	1988-2007		43,400

The tree ring data tells us that the region has seen extreme and prolonged drought in the past. While the historical gage record does reflect some very dry periods, they are not unprecedented. While we do not know what the future holds for climate, drier conditions and longer droughts have been seen before and may be seen again.

Bark Beetle Studies

Mountain pine beetle (*D. ponderosae)* is native to the forests of western North America. Mountain pine beetles develop in pines, particularly ponderosa, lodgepole, scotch and limber pines. A related insect, the Douglas-fir beetle (*D. pseudotsugae*), damages Douglas-fir. The spruce beetle (*D. rufipennis*) is a pest of Engelmann and Colorado blue spruce and the western balsam bark beetle (D. confuses) typically attacks sub-alpine fir and occasionally attacks Engelmann spruce, grand fir and lodgepole pine (Leatherman et al. 2007). All four are responsible for tree die-off in the forests of the Wind-Bighorn Basin (Figure 9).

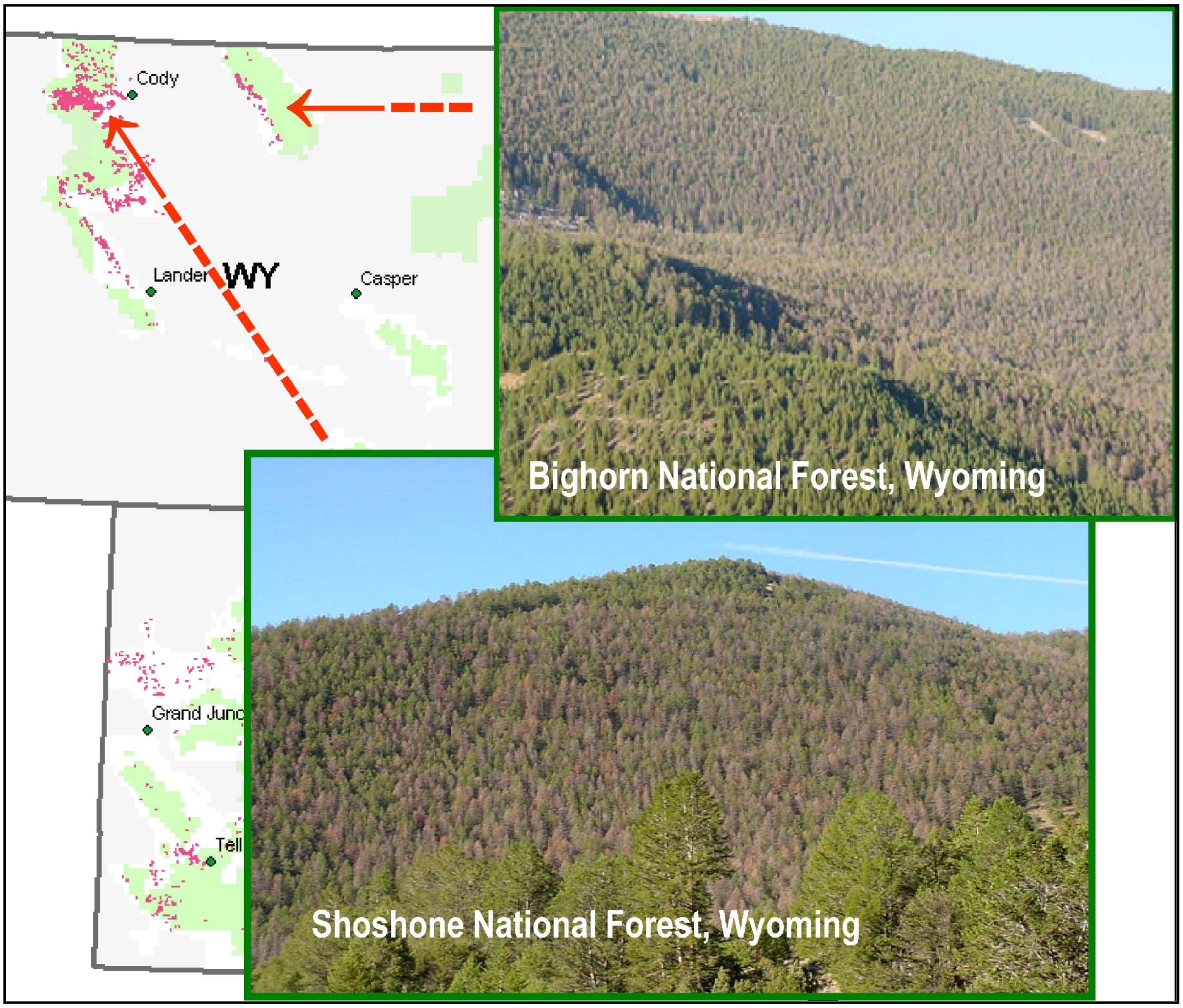

Figure 9. Current Bark Beetle Activity in the Wind-Bighorn Basin (Cain 2008)

The Shoshone National Forest has been particularly hard-hit by bark beetle (Figure 10). By 2007 an estimated 449,900 (35% of forested acres) had been decimated by bark beetle (USFS 2009a). Aerial photography shows that the bulk of the devastation occurred between 2000 and 2005, but that tree loss continues to occur.

It is thought that the combination of older denser stands of evergreen trees at approximately the same age and the warmer drier weather conditions associated with the 1998-2003 drought made conditions optimal for the bark beetle infestation currently seen in Wyoming (Cain 2008). Drought makes the trees more susceptible to attack and a warmer climate prevents the beetles from freezing in the winter months. An article in the journal Nature suggests that tree die-off reduces forest carbon uptake and increases future emissions from the subsequent decay of the trees. This impact on the carbon cycle will convert the forest from a small net carbon sink to a large net carbon source, both during and immediately after the outbreak, and may have repercussions on climate variability (Kurz et al. 2008). Future trends toward a warmer climate could affect frequency and severity of bark beetle outbreaks.

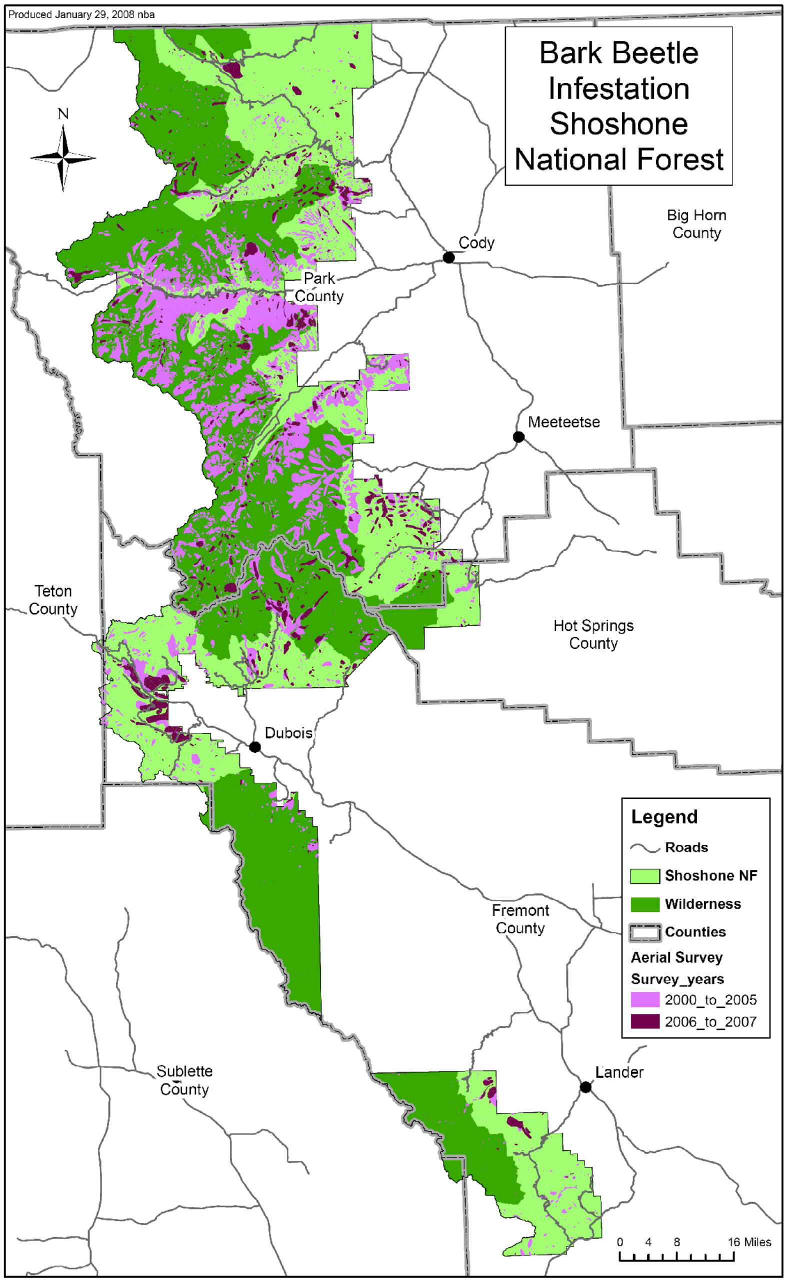

Figure 10. Shoshone National Forest Bark Beetle Infestation (USFS 2009)

How the beetle infestation will affect streamflow in Wyoming is yet to be determined. A study in Colorado in 1974 showed an increase in streamflow after a beetle kill epidemic (Bethlahmy 1974). Initial assumptions have been that beetle-kill effects on streamflow will be similar to forest harvesting. In forests without significant understory, annual water yield increases, flow increases in late summer and fall and peak flows may occur earlier in the year. Timber harvesting removes the forest canopy and increases water yield due to the reduction in winter interception and summer evapotranspiration (Stednick 1996). However, a recent study in Northern Colorado shows streamflow changes are much more variable and depend on the age and composition of the forests affected. Forests with even-aged tree stands, with little to no understory vegetation demonstrated increased water yields after a beetle-kill epidemic. Watersheds with uneven-aged trees tended to have much more understory vegetation which intercepted and utilized the soil moisture bypassed by their now-dead competition. Accelerated growth was seen in the understory and actually reduced the Basin's water yield (Stednick and Jensen 2007).

The beetle-kill is extensive in the Basin's forests. Warmer temperatures and extended drought may have exacerbated the onset of the epidemic. Fire is a concern for affected areas. It is expected that there will be impacts to runoff due to the tree death and potential subsequent fire damage. In a region that relies heavily on snow melt runoff, water managers must stay informed about how bark beetle damage is affecting their watersheds.

Section 5 – Summary

Climate variability and potential climate change are important factors in water management. Warmer temperatures and less snowfall could affect spring snowmelt and glacial melt water contributions to streams. Shifts in the timing of peak flows may be seen if spring temperatures increase. Agricultural irrigation demands may change with a longer growing season or with a change in preferred crops.

While it is yet unknown what the future climate of the Wind-Bighorn Basin will entail, studies have shown dramatic variability in both precipitation and streamflow over the past several centuries. Water managers need to consider this and the predictions made by the global climate scientists when developing new projects. A "wait and see" approach to managing water under climate change, while the cheapest in the short-term, could have enormous long-term impacts on water users and water system reliability. Yet, designing and building new infrastructure based on climate predictions runs the risk of making expensive and inaccurate design decisions (Gleick 1998). The American Water Works Association (AWWA) recommends a "no regrets" scenario-based style of analysis for water managers. This includes evaluating projects and operations under a broader range of climate and risk scenarios than managers usually consider. Water managers should evaluate structural and non-structural system vulnerability under a range of potential climate scenarios (AWWA 2007).

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