TECHNICAL MEMORANDUM

SUBJECT: **Green River Basin Plan II**
Green River Basin Climate and Climate Data

DATE: March 29, 2010

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Introduction

To understand and analyze water resources of a particular geography, one must know about its climate, and have access to climate data. Narrative descriptions of Wyoming's climate are available at http://www.wrds.uwyo.edu/sco/climate/wyoclimate.html, and in Wyoming Climate Atlas (Curtis and Grimes, 2004), available at the Water Resources Data System (WRDS) library. Rather than describe the climate of the Green River Basin, this memo describes climate information and data resources for basin locations, and describes several climate- related activities and initiatives. Appendix A is a list of climate-related sources and studies; Appendix B, which includes a folder of electronic files, is a collection of Green River Basin climate summaries, graphs, and maps developed by the WRDS office.

Climate is the cumulative record of weather over time. Observations of the current or short-term elements of weather (e.g., precipitation, solar radiation, wind speed) are essential for management of all types of human activities, from emergency flood warning to planning a recreational outing. Water resources planning typically requires observations that have been compiled over a season, decades, or centuries, that is, climate data. Irrigation water supply forecasting and growing degree day computations for irrigation scheduling are examples of climate data use within a seasonal time frame. Thirty-year normal data[1] and decades-long climate time series underpin demand forecasts, consumptive use estimation, and firm yield analyses. Understanding climate change and drought vulnerability requires insight into the climate of past centuries, which we infer from tree rings and ice core samples.

Planning also requires information about weather across the space domain; with a 30-year record of temperatures at a specific site, we can estimate "normal" conditions and begin to understand the frequency and magnitude of deviations from normal. To develop a basinwide water budget, or design for conditions at a site removed from any long-term records, historical weather observations from multiple locations need to be interpolated across space.

We engage in water resources planning to ensure a water supply that matches or exceeds our demand for water. Climate affects both sides of the planning equation. Water is gathered into rivers and streams as a result of precipitation. Water that "makes it" to the stream is that

[1] "Normal" is a technical term in climatology. It refers to the average value of a parameter over a specific 30-year period. The National Oceanic and Atmospheric Administration (NOAA) and the National Climate Data Center (NCDC) compile and publish temperature and precipitation normal values at the end of each decade, based on the observations of the previous three decades.

which is not evaporated from the surface by solar and wind energy; not intercepted by plants whose capacity and need for water is influenced by solar radiation and relative humidity; and not taken up by the soil moisture reservoir, whose capacity is determined by antecedent precipitation and temperatures. In a snowmelt-driven system, timing and intensity of runoff is related to both accumulated precipitation as snow, and springtime temperatures, radiation, and wind. Hence, the water supply available to support human uses is governed by climate. But demand for irrigation, municipal, and power generation water supply are all also impacted by temperature and precipitation. When conditions are hot and dry, more demand must be met with less water. Loaded with this two-fold punch, climate normals, variability, and shifts need to be considered for effective water resources planning.

In the Green River Basin specifically, climate data are either helpful or essential in these water planning and management activities:

- Estimating evaporative losses from the basin for Consumptive Uses & Losses Reporting to the U.S. Bureau of Reclamation;
- Estimating irrigation water use for the same purpose;
- Determining historical irrigation water requirement (IWR) and crop shortages to quantify base or virgin water supply;
- Determining irrigation water requirement (IWR) and crop shortages to document need for new storage;
- Evaluating effectiveness of cloudseeding operations, and developing protocol for initiating and ceasing seeding;
- Identifying onset of drought

Weather and Climate Data Collection in the Green River Basin

This section describes the hydrometeorologic data collection sites and networks in the Green River Basin. Climate data begins as weather data, meaning measurements of atmospheric conditions as well as the accumulation of precipitation in the snowpack and soil reservoir. Not all weather data meets the standards necessary to become climate data, however. Since “climate” inherently means long-term records of weather observations, a climate station consists of not only a set of instrumentation, but some recordkeeping process. To generate a data set large enough to allow valid statistical analyses, a climate station must be established under a commitment to its longevity. Furthermore, weather data must undergo rigorous quality control before they can be used to understand climate. Instantaneous observations need to be summarized rigorously, a process that invariably involves estimating missing data. Sources for climate information, based on meteorological records, are described in the section following this one.

The material for this section was gathered primarily via the internet. A bewildering array of sources and servers of weather data can be found on the web; one objective of this section is to guide users in pursuing weather and climate information. Quality of data and length of record can render data appropriate or inappropriate for any given application, and should be

explored before incorporating in research or decision making. The professionals at WRDS are available to help users with questions about appropriateness of these publicly available data.

Aviation-based Stations (ASOS and AWOS)

Much of the meteorological data collected across the country is collected in support of aviation. The National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Defense jointly manage the Automated Surface Observing Systems (ASOS) and Automated Weather Systems (AWOS), maintaining 20-minute and more frequent measurements of precipitation, temperature, dewpoint, wind gust, wind speed, and wind direction; barometric pressure; cloud height, visibility, and present weather. ASOS sites meet a higher standard than AWOS sites, in terms of frequency of observation and number of parameters recorded. Stations are usually located at airports, near the touchdown zone of the runway. These weather observations are also used by NWS for weather forecasting, and are available in the form of voice transmissions for subscribers, typically pilots. ASOS or AWOS stations are located at airfields at Big Piney, Rock Springs, Kemmerer, and Pinedale. MesoWest, a server of the University of Utah's Department of Atmospheric Science, displays current and recent data from selected NWS/FAA stations (http://mesowest.utah.edu/index.html).

Transportation Corridor Stations

Wyoming Department of Transportation (WYDOT) and the Union Pacific Railroad (UPRR) maintain weather stations along their corridors, for the purpose of assessing travel conditions. Current air temperature, relative humidity, dewpoint, and wind speed can be accessed via http://map.wyoroad.info, for five Green River Basin sites. Union Pacific Railroad does not maintain a website to disseminate their information. Both organizations provide their data to the Meteorological Assimilation Data System (MADIS), a subscriber-service oriented to the needs of weather forecasting.

WYDEQ

The Wyoming Department of Environmental Quality (WYDEQ) established the Wyoming Visibility Monitoring Network approximately ten years ago. The network was begun in order to more fully understand regional visibility impairment and identify the potential for corrective actions. Monitoring stations collect hourly data pertaining to pollutant levels, visibility, and general meteorology. The last category includes, in addition to temperature and precipitation, relative humidity, solar radiation, wind speed and direction, and barometric pressure readings. The website (http://www.wyvisnet.com/index.html) provides access to validated hourly data for stations at Daniel, Jonah, and Wamsutter.

CoCoRaHS

CoCoRaHS (http://www.cocorahs.org/state.aspx?state=wy) is an acronym for the Community Collaborative Rain, Hail and Snow Network. CoCoRaHS is a non-profit,

community-based network of volunteers of all ages and backgrounds working together to measure and map rain, hail and snow. It began in 1998. Currently, according to the above website, there are 14 active stations in the Green River basin, centered around Pinedale, Kemmerer, Rock Springs, Green River, and Superior. Daily precipitation totals for the current and recent days can be viewed, as well as descriptions of general weather conditions and significant weather events.

NWS Automated Stations

Precipitation and air temperature are the most commonly collected weather measurements. Some but not all U.S. Geological Survey (USGS) streamgage locations include automated instrumentation for temperature and precipitation. NWS operates five automated weather data collection platforms (Bitter Creek 4 NE, Boulder Lake near Pinedale 13 E, Dixon 1 WSW, Pinedale 1 NE, and Kemmerer 1 WNW) in the Green River basin. These stations collect temperature and precipitation, which are reported at the Hydrometeorological Automated Data System (HADS) website described below.

BLM Remote Automated Stations

The Remote Automatic Weather Stations (RAWS) of the Bureau of Land Management are located in isolated areas and collect hourly data useful for determining wildland fire vulnerability. In addition to air temperature and precipitation, RAWS sensors measure wind speed and direction, wind gusts, solar radiation, relative humidity, fuel (wood) temperature and moisture, and soil moisture and temperature. There are currently five RAWS stations in the Green River basin:

1. Muddy Creek near Bridger 2 NNE
2. Snow Spring Creek near Rocks Springs 17 SE
3. Cow Creek near Baggs 21 NNE
4. Snider Basin near Bridger-Teton National Forest near Big Piney 20 W
5. Half Moon near Pinedale 7 NE

These automatic stations are part of the HADS network described below. They date back to the late 1980's.

NWS COOP Stations

The NWS Cooperative Observer Program (COOP) has been in place since the beginning of the twentieth century. While NWS generally installs and maintains equipment at COOP stations, volunteers or contractors make observations and send them monthly to the National Climate Data Center (NCDC). A cooperative station may be collocated with other types of observing systems such as the ASOS or automated NWS stations described below. Observations consist of daily precipitation, snowfall, and daily maximum and minimum temperatures. While these parameters are among the most basic, this network is the backbone of U.S. climatology. Normal data published each decade by NOAA are based on NWS COOP station data. The Green River Basin is currently home to sixteen NWS COOP stations, as shown in Figure 1. COOP station data are accessible at http://www.ncdc.noaa.gov/oa/ncdc.html.

Long-term NWS COOP stations can and typically have moved from time to time, within certain parameters specified by NWS. Even with limitations on the horizontal and vertical displacement of the site, moves can impact homogeneity of the data record. The U.S. Historical Climatology Network (USHCN) is a subset of the NWS COOP, consisting of stations selected for longevity, percent missing data, number of station moves, and spatial coverage. The NWS COOP station at Pinedale is designated as a USHCN site.

NRCS Snow Stations

The Natural Resources Conservation Service (NRCS) is responsible for measuring snowpack in the mountains of the West and forecasting the water supply. The snow measurement program began in the 1930's with snow courses, designated sites where trained observers measured snow depth and snow water equivalent, generally, once monthly during the winter and spring. Beginning in the 1980's, SNOTEL (for SNOwpack TELemetry) stations, capable of automated and regular collection and transmittal of data, were added to the system. Basic SNOTEL sites have a pressure sensing snow pillow (for reporting Snow Water Equivalent (SWE), storage precipitation gage, and air temperature sensor. Numerous stations are located at higher elevations around the rim of the Green River Basin (see Figure 1). Current and historical data are available at http://www.wcc.nrcs.usda.gov/snow .

NRCS Soil Monitoring Stations

NRCS also administers the Soil Climate Analysis Network (SCAN), a comprehensive, nationwide soil moisture and climate information system designed to provide data to support natural resource assessments and conservation activities. The system focuses on agricultural areas of the U.S., monitoring soil temperature and soil moisture content at several depths, soil water level, air temperature, relative humidity, solar radiation, wind, precipitation, barometric pressure, and more. Wyoming's only SCAN site is at Torrington in the North Platte basin.

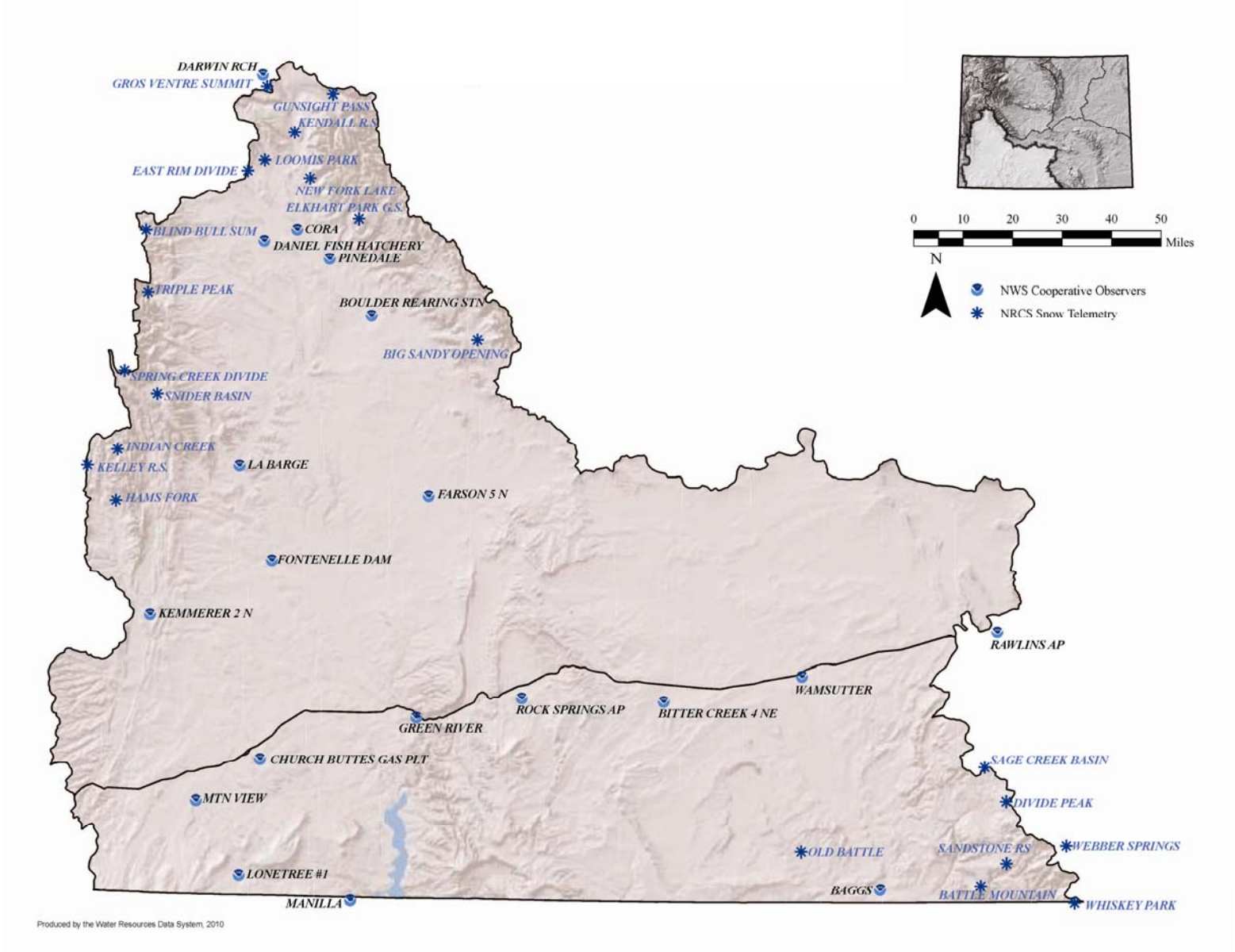

Figure 1 – Current Green River Basin NWS COOP and NRCS Snotel Stations

NOAA Climate Reference Network

The U.S. Climate Reference Network (USCRN) consists of stations deployed for the specific purpose of detecting climate change over the next 50 years. It is managed jointly by three NOAA agencies, the National Climatic Data Center, National Environmental Satellite Data and Information Service, and the Office of Oceanic and Atmospheric Research. The program and network were begun in the last decade, and the network is still being expanded. Sites were selected in pristine areas that are expected to be relatively free of future development. Instrumentation is specified for high accuracy and maintained to high standards. Core parameters measured are air temperature, precipitation, solar radiation, and wind speed; relative humidity, ground temperature, and soil temperature and moisture are included at some stations. Currently there are three USCRN stations in Wyoming, at Moose, Sundance, and Lander. A density study undertaken by the USCRN program to determine the number of stations and locations necessary to capture regional climate change is not yet available. Because USCRN is so new, it does not currently provide long-term climate information, but it will become the premier source of climate observations over time.

High Plains Regional Climate Center AWDN

A network of observation stations recording hourly air temperature, humidity, soil temperature, wind speed and direction, solar radiation, and precipitation is maintained by the High Plains Regional Climate Center. Designated the Automated Weather Data Network (AWDN), the system includes four stations in the eastern half of Wyoming, and no stations in the Green River Basin.

USBR AgriMet Stations

AgriMet is the name of the U.S. Bureau of Reclamation's (USBR) network of automatic agricultural weather stations. Initially it was a project of the Pacific Northwest Region, and later expanded to western Montana in the Great Plains Region. All AgriMet stations monitor temperature, solar radiation, relative humidity, wind speed and direction, and precipitation. A subset of stations are equipped for sensing soil temperature and moisture, crop canopy temperature, diffuse solar radiation, pan evaporation, and peak wind. The AgriMet network supports evapotranspiration modeling and irrigation scheduling, as well as integrated pest management, frost protection, and other crop management activities. Wyoming's only AgriMet site is in Afton, in the Snake River basin.

University of Oregon Solar Radiation Network

The University of Oregon Solar Radiation Monitoring Laboratory, supported by the Bonneville Power Administration, National Renewable Energy Laboratory, and various members of the electrical utility industry, operates a solar radiation monitoring network to provide high quality data for scientific research and long-term climate studies. Pacificorp has maintained a station in Green River since 1994. Recent data can be retrieved at http://solardat.uoregon.edu/GreenRiver.html .

NWS HADS

The Hydrometeorological Automated Data System (HADS) is a program of the National Weather Service, primarily to support their flood and flash flood warning systems. Other applications for the information collected include fire weather support services and verification of NEXRAD precipitation estimates. HADS stations transmit data to a centralized facility via the Geostationary Operational Environmental Satellites (GOES), where it is processed for delivery to NWS river forecast centers and other specialized users within NWS. HADS refers to the data transmittal and distribution infrastructure, rather than the weather stations themselves which are maintained by cooperating federal, state, and local agencies. In the Green River Basin, many of the USGS stations mentioned above, the five automated NWS precipitation/temperature stations, and the five RAWS stations are included in HADS. Metadata for HADS stations and provisional current day and recent observations are available at www.nws.noaa.gov\oh\hads.

Climate Data Sources

The data collection systems described above, and their related websites and data sources, typically provide current and recent information, some but not all of which can be downloaded. Depending on the application, users need climate information summarized over time, or mapped across a district or region. Researchers may need to have long-term or period of record time series to conduct modeling. A typical data management challenge might be a combination of summaries and time series, such as converting 15-minute observations to a time series of average monthly values. Fortunately there are resources for obtaining climate data based on some of the networks described above, in various summarized formats.

Wyoming Water Resources Data System (WRDS)

For most users interested in Wyoming climate, the primary source of summarized data is WRDS. WRDS, which houses the Wyoming State Climate Office, is a clearinghouse of hydrological and climatological data for the State. From the website (http://www.wrds.uwyo.edu/) one can download the NCDC's *Climatography of the United States No. 81; Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1971-2000,* based on NWS COOP stations. Tabulations and charts of these and period-of-record information are available on-line, in a variety of formats. Appendix A includes samples of the WRDS products for selected stations in the Green River Basin.

WRDS also provides links to NRCS and NWS sites, and relevant climate related articles from NOAA and the Regional Climate Centers. Researchers with specific needs not matched by the on-line products can request data retrieval by calling WRDS.

Regional Climate Centers

The nation is divided into six regions served by Regional Climate Centers administered by NOAA. The Climate Centers operate in partnership with the National Climate Data Center, National Weather Service, the American Association of State Climatologists and the NOAA Research Institutes. In addition to conducting applied research related to climate issues, and coordinating climate-related activities at state, regional, and national scales, the Regional Climate Centers' mission includes disseminating high quality climate data and data products, and fostering better use of this information in decision-making. Although Wyoming is within the geography mapped to the High Plains Regional Climate Center (HPRCC) by NOAA, data and information for Wyoming are available at both the HPRCC website (http://www.hprcc.unl.edu/) and the Western Regional Climate Center (WRCC) website (http://www.wrcc.dri.edu/). From both sites, one can gather daily and monthly period-of-record summary tables as well as 30-year normal summary tables for the NWS COOP stations. RAWS system historical time series are available through WRCC. HPRCC offers mapping of both current and historical parameters based on NWS COOP, AWDN, and airfield data. Both sites provide links to sources of data not affiliated with NOAA or NWS such as NRCS or the Oregon University Solar Radiation Monitoring Laboratory.

National Climatic Data Center

The National Climatic Data Center (NCDC) serves up an enormous amount of climate data, from a national perspective, at its website. Currently, a .pdf with live links, 'NCDC Climate Product-inventory.pdf' can be downloaded at http://www.ncdc.noaa.gov/oa/climate/climatedata.html by clicking on "Products and Services" and selecting "Free Copy of 2010 Products & Services Guide".

Additional and Future Climate Data Collection

The preceding rundown of climate and weather data collection in the Green River basin reveals a generally adequate network for current and historical precipitation, temperature, and snowpack data. However, the basin lacks a historical network of stations producing high quality relative humidity, solar radiation, wind, and soil temperature and moisture data. These parameters are important to climate-related activities such as crop evapotranspiration (ET) estimation, water supply forecasting, irrigation management, drought monitoring and research, water budget estimation, and climate change research. Specifically, there are currently no USCRN, AgriMet, AWDN, or SCAN stations in the Green River basin.

Crop ET Estimation

An improvement in the state of data for the above listed parameters is imminent. In 2006, the Wyoming State Engineer's Office undertook the Colorado River Compact Administration Program, an initiative to ensure that the State is the leading authority on the allocation and use of water in the Green River Basin. The objective of the program is to protect Wyoming's consumptive use apportionments under the Colorado River Compact and Upper Colorado River Compact. Under the program, five new high quality weather stations are to be deployed throughout the basin in 2010. Exact locations are not yet known but the targeted

locales are centers of agricultural production: the Little Snake valley, Bridger Valley, the Eden Project, and sites close to Pinedale and Big Piney. The stations will collect, in addition to precipitation and temperature data, solar radiation, relative humidity, and wind direction and velocity. Soil moisture probes will eventually be added to the sites. The instrumentation will support estimation of agricultural consumptive use, permitting use of the Hargreaves, Penman-Monteith, and other energy balance models for predicting crop consumptive use. The stations are planned to be long-term. They will become AWDN stations, logging data and automatically transmitting them to HPRCC for quality control, summarization, and dissemination.

A component of the Colorado River Compact Administration Program is exploration into use of the METRIC model, remote sensing technology, and LandSAT imagery to make basinwide estimates of crop water use. The University of Wyoming is conducting this research, which could lead to relatively inexpensive means to document annual irrigation consumptive use and compliance with the Colorado River Compacts. Two eddy covariance stations, capable of measuring heat, water, and carbon dioxide flux in a column of air, have been erected at a station near Pinedale to provide as direct measures of ET as can be made. A large aperture scintillometer, measuring heat flux at the scale of a field or plot rather than a point, has also been deployed for this research. This instrumentation will serve the needs of the research, that is, to calibrate the METRIC model, and will not become part of a long-term climate network. Contemporaneous observations from this system and the new AWDN stations could be used to calibrate crop coefficients for climate based ET models, or provide relationships that would allow the ongoing AgriMet stations to be used to "ground truth" future METRIC model results.

Drought Information

Drought is a complex physical and social phenomenon which has proven difficult to define succinctly. Unlike other severe weather events, drought is not a discrete event. Its impact has multiple dimensions: duration and areal extent are of as much importance as deficit in precipitation at a site. Furthermore, drought can be measured or observed from many perspectives including precipitation, streamflow, soil moisture, or reservoir storage, to name a few.

Because of its multi-dimensional nature, there is no probe or instrument to directly measure drought. Instead, a number of drought indices have been put forth by researchers and agencies to characterize and monitor drought. The indices are statistics or values computed from climate parameters, and include simple concepts such as departure of precipitation from the 30-year normal, as well as water budget models that reflect soil Available Water Capacity. A description of drought indices is available at the National Drought Mitigation Center's (NMDC) website, at http://drought.unl.edu/whatis/indices.htm.

Drought Information Available at WRDS

WRDS maintains a Drought page http://www.wrds.uwyo.edu/sco/drought/drought.html, with links to a wide variety of sources for drought information, most of which is regional in scale. These include a link to NDMC, housed at the University of Nebraska-Lincoln, which

maintains an information clearinghouse and drought portal, and maintains the U.S. Drought Monitor website. The U.S. Drought Monitor is a project of the federal climate agencies with support from the State Climatologists' Offices and the Regional Climate Centers. The approach of the U.S. Drought Monitor is explained at the website as follows:

> *Tracking drought blends science and art. No single definition of drought works for all circumstances, so people rely on drought indices to detect and measure droughts. But no single index works under all circumstances, either. That's why we need the Drought Monitor, a synthesis of multiple indices and impacts, that represents a consensus of federal and academic scientists.*
> (http://www.drought.unl.edu/dm/about.html)

The U.S Drought Monitor can display a state map of drought conditions derived, as described, from a broad set of indices and inputs.

The WRDS Drought page also references the USGS Wyoming Drought Watch page (http://wy.water.usgs.gov/projects/drought/) of the Wyoming Water Science Center, and the Wyoming Drought Plan. The former page maps current streamflow relative to historical normals, and offers drought-related research articles and summaries. The latter is a framework plan to minimize impacts of drought on Wyoming's citizens and economy.

The Drought page also includes a lengthy list of links to diverse sources, from generalized drought-related maps (e.g., current Palmer Drought Severity Index produced by NOAA's Climate Prediction Center) to specific data sets (e.g., soil moisture data from the Afton, Wyoming AgriMet station). This serving of drought information by WRDS and the associated State Climatologist's Office is consistent with the role of the State Climatologist described in the Wyoming Drought Plan, which can be viewed and downloaded at the Drought page. The plan calls for the State Climatologist to lead the Climate Monitoring Sub-Group of the Wyoming Drought Task Force; the sub-group's responsibility is to monitor available climatological data, and disseminate information.

National Integrated Drought Information System (NIDIS)

A relatively new development in drought research and vigilance is the National Integrated Drought Information System (NIDIS), called for by the Western Governors Association in 2004, in a report entitled "Creating a Drought Early Warning System for the 21st Century". The report called for more highly integrated observation and data systems, noting that "Weather and climate observations have limited value if they cannot become part of a larger drought risk mosaic." The report acknowledged the U.S. Drought Monitor but suggested that decision makers require information at more relevant spatial and temporal scales to proactively reduce drought risk. By 2007, the NIDIS Implementation Plan was published, outlining the governance structure and milestones needed to meet objectives that included fostering research on risk assessment, forecasting, and management; creating a drought early warning system; and providing an internet drought portal.

In 2008, an NIDIS scoping workshop was held to discuss design and implementation of a drought early warning information system in the Upper Colorado River Basin (above Lake

Powell) (UCRB). Three activities were identified for this geography, which includes the Green River Basin. The first was to perform a monitoring gaps assessment. The assessment report, not yet available, is to include a summary of gaps in observational networks, gaps in analytical products and tools, and gaps in our understanding of drought. In a separate but presumably related workshop sponsored by NIDIS, status of the nation's soil moisture and temperature networks (USCRN, SCAN, and some NWS COOP) was reviewed. Whether the gaps assessment report or the soil moisture and temperature initiative draws attention to the Green River Basin's lack of soil sensors remains to be seen.

The other activities scoped by the UCRB workgroup were to inventory and evaluate existing drought indicators and triggers, and to develop a basin-focused drought monitor as part of the drought portal. A first workshop relevant to the drought indicator activity, to draw up a work plan for reviewing the conceptual basis of the Surface Water Supply Index (SWSI) and improving web-based access to SWSI information, was sponsored jointly with the Colorado Water Conservation Board in August, 2009. Progress toward a basin-focused drought monitor is not reported at the drought portal.

The drought portal (www.drought.gov) is up and running. Currently, it provides, in terms of current drought monitoring and forecasting products, little that is not available at the WRDS Drought page. In other words, it provides links to the NDMC and HPRCC sites, and no new presentation of a basin or local drought index. Notes to the reader declare the website under development. The site does present information about and documentation of NIDIS activities and workshops.

Recommendations

Addition of five AWDN climate stations to the basin under the Colorado River Compact Administration Program is a significant step toward addressing the most obvious need in the basin, which is for high quality instrumentation, and observations of wind, solar radiation, humidity, and soil moisture. These are critical to developing realistic estimates of crop consumptive use, and are integrated with an effort to bring new technologies to that task. In addition to their intended use in consumptive use estimation, these stations can support a variety of applications such as drought monitoring, renewable resources development, irrigation scheduling, and crop protection. The State should remain committed to continuation and maintenance of these stations.

The State should continue to participate in NIDIS through the State Climatologist's Office, and in particular, contribute to the UCRB subgroup's efforts to develop a basin-focused drought monitor. As soil moisture data becomes available via the new AWDN stations, that information could be incorporated into the drought status reporting.

The State should monitor progress and outcome of the NIDIS gaps assessment report, as well as the USCRN program density study, and pursue establishment of a USCRN station in the basin. In high relief areas like the Green River Basin, correlation between reference stations outside the basin and other stations within the basin are not expected to be strong. Establishment of a local high quality station will help with all of the climate-related analysis that we currently do. The primary objective of USCRN, however, is to help us understand

long-term changes in climate, and the network is to have a fifty-to-hundred year life span. The station could eventually be instrumental in downscaling global climate models, which are currently on a scale that does not differentiate between conditions at Lander and conditions at Pinedale, for instance. One criterion for USCRN site selection is proximity and correlation with HCN stations; that requirement suggests a USCRN station near Pinedale.

Acknowledgements

This memorandum was created with the support of the staff of WRDS. Barb Muller helped with the literature search reported in Appendix A. Dr. Steve Gray, with assistance from Tony Bergantino and Chris Nicholson, provided the maps and figures for the memo. The maps and charts presented in Appendix B were also prepared by WRDS.

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"Wyoming SCAN Sites." Natural Resources Conservation Service. Accessed February 4, 2010 from http://www.wcc.nrcs.usda.gov/scan/Wyoming/wyoming.html.

"Wyoming Travel Information Map". Wyoming Department of Transportation. Accessed January 2010 from http://map.wyoroad.info/hi.html.

Appendix A
Green River Basin Climate Reports and Studies

This appendix lists studies related to climate in the Upper Green River Basin, primarily in Wyoming. A rapidly growing body of studies on paleoclimate and paleohydrology of the Colorado River Basin serves an important role in developing our understanding of natural climate variability and detection of climate change. However, a truly comprehensive review of this literature was beyond the scope and resources of the Green River Basin Plan; furthermore, much of the research tends to be regional in focus, evaluating the entire basin or the basin above Lees Ferry. The list below reflects Wyoming authorship, including many reports that are available on-line at the WRDS library website (http://library.wrds.uwyo.edu/). These are followed by the report identification number (WWRC YY-xx).

Barnett, Faires Anthony. 2007. Upper Green River Basin Streamflow Reconstructions and Drought Variability, M.S. Thesis, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming.

Barnett, F.A., T. Watson, S. Gray and G. Tootle. 2008. Upper Green River Basin Streamflow Reconstructions and Drought Analysis, in Press.

Bellamy, J., G. Tootle, G. Kerr and L. Pochop. 2008. Frequency and Duration of Drought in the Green River Basin, WY, USA. *Proceedings of the ASCE World Water & Environmental Resources Congress 2008, May 11-17, 2008,* Honolulu, HI.

Curtis, J. 2004. Wyoming Climate Atlas. Cheyenne, WY: Wyoming Water Development Commission. (WWRC 86-09)

Follum, Michael Lee. 2009. Upper Green River Basin Precipitation Reconstructions and Drought Analysis, M.S. Thesis, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming.

Gray, S. T. 2003. Long-term Climate Variability and its Implications for Ecosystems and Natural Resources Management in the Central Rocky Mountains. Ph.D. Dissertation, Botany, A&S College, University of Wyoming, Laramie, Wyoming.

Gray, S.T., S.T. Jackson and J. L. Betancourt. 2002. Tree-ring based reconstruction of precipitation variability in northeastern Utah. *Proceedings of the 2003 Pacific Region Climate Workshop (PACLIM)*, Pacific Grove, California.

Hidalgo, H., T. Piechota and J. Dracup, “Alternative principal components regression”, Pochop, L. and R. Burman. 1987. Development of Evapotranspiration Crop Coefficients, Climatological Data, and Evapotranspiration Models for the Upper Green River. Report to the Wyoming Water Development Commission and the Wyoming Water Research Center. (WWRC 87-06)

Pochop, L., K. Warnaka, J. Borrelli and V. Hasfurther. 1985. Design Information for Evaporation Ponds in Wyoming. Report to the Wyoming Water Research Center. (WWRC 85-21)

Pochop, L., R. Marston, G. Kerr and M. Varuska. 1989. Long-Term Trends in Glacier and Snowmelt Runoff, Wind River Range, Wyoming. Report to Wyoming Water Research Center. (WWRC 89-05)

Schumaker, J., B. Bajusz, L. Pochop and J. Borrelli. 1984. Predicting Temperature and Precipitation at Ungaged Sites in the Upper Green River Basin. In Conference Volume: Third Conference on Mountain Meteorology, Oct. 16-19, 1984, Portland, Oregon. pp. 152-154. (WWRC 84-25)

Tootle, G., S. Gray, T. Hunter, T. Watson, A. Barnett, J. Bellamy. 2008. Predicting Dorught in the Green River Basin, Final Report. USGS-WWDC Water Research Program.

Appendix B

Green River Basin Climate Charts and Maps

(includes electronic attachment GRB_Climate.zip)

Green River Basin Climate Charts and Maps

Prepared by: Water Resources Data System

Introduction

Recognizing the importance of sustainable water use and resource stewardship, the Wyoming Water Development Office (WWDO) is producing a series of River Basin Plans that address water use profiles, surface and ground water availability, water demand projections, and future water use opportunities in each of the state's seven river basins. In the past these river basin plans have been criticized for not included detailed examinations of regional climate and for an apparent failure to link water resources to climate variability. However, these shortcomings were largely a product of available climate data being greatly limited in many river basins, as well as problems with stakeholder access to these data. As a result, the Water Resources Data System (WRDS) was charged with developing a comprehensive summary of climatic conditions across Wyoming's river basins. This technical memorandum addresses the data, techniques and resulting products used to describe climate patterns within the Green River Basin. The products are included as an electronic attachment, a file with several folders organizing the summaries described below.

Climate Data

Charts of Station-Level Monthly Precipitation

Data from the National Climatic Data Center's *Climatography of the United States No. 81; Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1971-2000 (CLIM81)* were graphed to show the yearly distribution of monthly precipitation for select stations in the Green River Basin. Graphs for National Weather Service Cooperative Observer stations of Farson, Kemmerer, Rock Springs, Big Piney, and Cora were included as a way to give the reader a representative look at the distribution of precipitation within the basin. Figure B1 is a sample. Image files and the Excel spreadsheets containing these data and the original charts are included in folder 'Station Precipitation Averages 1971-2000' in the electronic attachment. Additional charts for all stations having 1971-2000 Normals for Precipitation may be found at:
http://www.wrds.uwyo.edu/sco/data/normals/1971-2000/coop_precip.html

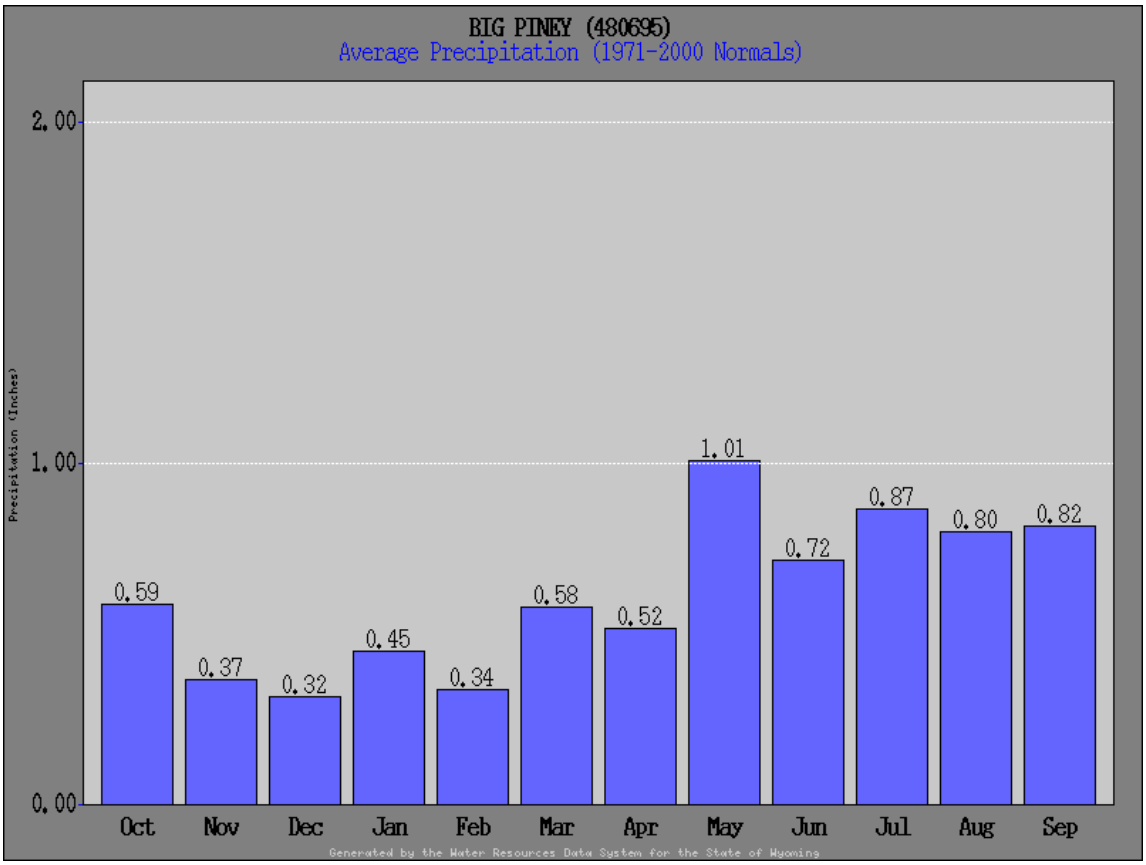


Figure B1 Distribution of Monthly Precipitation Based on 1971-2000 Normals (Big Piney)

Charts of Station-Level Temperature Variability

Temperature data from the National Weather Service's Cooperative Observer Network stations were obtained from the Western Regional Climate Center (http://www.wrcc.dri.edu), and then summarized using standard techniques. These summaries show the distribution of maximum and minimum temperatures on a daily basis throughout the year. Mean values and the distribution of extremes (a.k.a. "records") were calculated using data from the station's entire period of record. One annual graph and twelve monthly graphs, as illustrated in Figure B2 are provided for five stations in the Green River basin--Farson, Kemmerer, Rock Springs, Big Piney, and Cora. Image files and the supporting Excel spreadsheet can be found in the folder 'Station Temperature Records'.

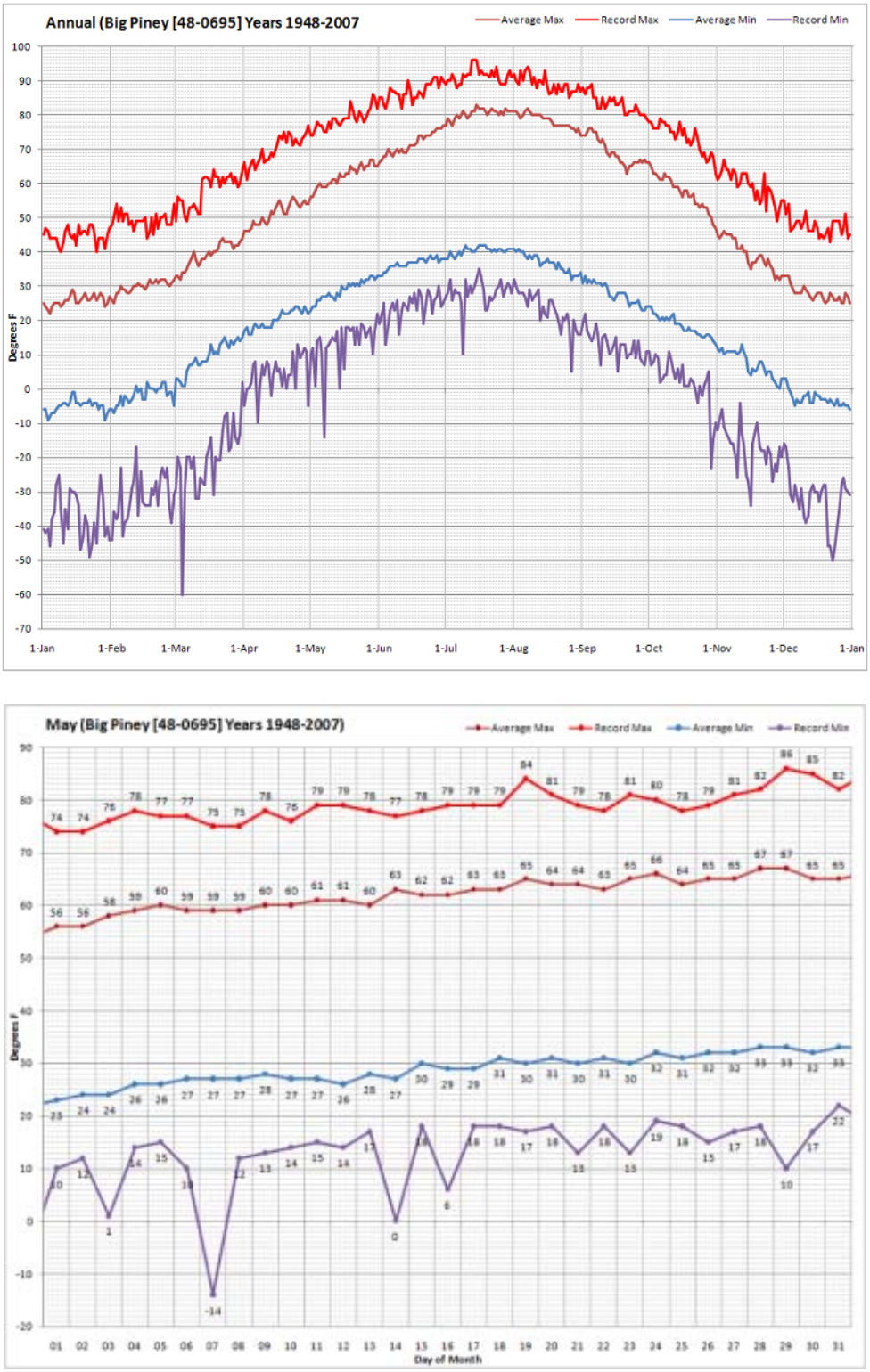


Figure B2 Mean and Extreme Daily Temperatures, by Year and by Month, for Station Period of Record (Big Piney)

Growing Season Statistics

Figure B3 is an example of the growing season summaries in the folder 'Station Growing Season Stats.' Data related to the onset, character and duration of the growing season were obtained from both the High Plains Regional Climate Center (http://www.hprcc.unl.edu/) and Western Regional Climate Center (http://www.wrcc.dri.edu/). These data are presented for two key stations in the Green River Basin—Pinedale and Rock Springs. Stations were chosen for analysis based on the length, completeness and reliability of the records they provided. Days above or below critical temperature thresholds and growing degree days (based on a 50° F growing threshold) are included in these tables. First and last frost dates are also presented. Averages for the 1971-2000 period are given for numbers of days above/below critical thresholds, while all other averages values are based on the entire period record. Values for individual years through 2008 follow the average values.

ROCK SPRINGS FAA AP (487845)	Spring Season Last Date<=28F	#Days missing	Fall Season Earliest Date<=28F	#Days missing	Spring Season Last Date<=32F	#Days missing	Fall Season Earliest Date<=32F	#Days missing	Accum GDD 50F	#Days missing	# Days >= 80 F	#Days missing	# Days >= 90 F	#Days missing	# Days <=0 F	#Days missing	# Days <=32 F	#Days missing
POR-2008/1971-2000 Norm	5/11	---	9/30	---	5/29	---	9/21	---	1788	---	60	---	0	---	0	---	193	---
Calendar Year																		
2008	5/10	0	10/10	0	6/11	0	10/10	0	1806	0	72	0	7	0	17	0	202	0
2007	5/23	0	10/18	0	6/8	0	9/24	0	2324	0	84	0	25	0	16	0	179	0
2006	5/10	0	10/10	0	5/29	0	9/16	0	2087	0	76	0	13	0	10	0	197	0
2005	5/2	0	9/13	0	6/8	0	9/13	0	1736	0	68	0	13	0	5	0	189	0
2004	4/30	0	10/31	0	5/30	0	9/21	0	1733	0	53	0	4	0	12	0	181	0
2003	5/20	0	9/18	0	6/7	0	9/17	0	2315	0	76	0	29	0	5	0	188	0
2002	5/23	0	10/2	0	6/10	0	9/22	0	2062	0	79	0	25	0	10	0	206	0
2001	6/13	0	10/5	0	6/13	0	10/4	0	2280	1	86	1	15	1	6	0	193	0
2000	5/13	0	9/22	0	6/1	0	9/20	0	2055	0	73	0	14	0	3	0	195	0
1999	5/17	0	9/27	0	5/17	0	9/26	0	1688	31	44	31	0	31	3	31	166	31
1998	4/20	0	10/18	0	6/17	0	10/5	0	1735	0	52	0	3	0	8	0	185	0
1997	5/3	0	10/11	0	5/19	0	10/8	0	1731	0	48	0	3	0	14	0	190	0
1996	4/29	0	9/25	0	5/21	0	9/19	0	1874	1	69	1	2	1	16	1	189	1
1995	5/14	2	9/20	0	6/9	0	9/20	0	1500	2	47	0	2	0	9	2	198	2
1994	4/30	0	9/22	0	5/2	0	9/21	0	2057	3	75	2	7	2	5	3	178	3
1993	5/9	0	9/14	0	5/10	0	9/13	0	1278	0	20	0	0	0	22	0	193	0
1992	4/25	0	10/7	0	6/15	0	9/18	0	1756	0	43	0	0	0	14	0	172	0
1991	5/5	0	10/4	0	5/15	0	9/15	0	1820	0	57	0	2	0	20	0	197	0
1990	5/16	0	10/7	0	6/1	0	10/6	0	2005	0	74	0	16	0	11	0	187	0
1989	4/30	0	9/11	0	5/31	0	9/11	0	1865	0	58	0	10	0	22	0	182	0
1988	5/3	0	11/1	0	6/1	0	9/19	0	2247	0	86	0	17	0	9	0	180	0
1987	4/21	0	10/9	0	5/4	0	9/28	0	1858	0	55	0	1	0	14	0	180	0
1986	5/23	0	missing	---	5/23	0	missing	---	1193	31	33	31	1	31	7	31	196	31
1985	5/13	0	9/22	0	5/31	0	9/13	0	1994	0	63	0	7	0	24	0	195	0
1984	5/7	0	9/25	0	6/9	0	9/22	0	1765	0	57	0	2	0	13	0	209	0
1983	missing	---	missing	---	missing	---	missing	---	184	288	2	288	0	288	10	288	58	288
1982	missing	---	missing	---	missing	---	missing	---	15	305	0	305	0	305	12	305	56	305
:																		
:																		
1949	4/15	0	10/8	0	5/7	0	9/13	0	1790	0	57	0	4	0	30	0	188	0
1948	5/10	0	10/5	0	5/12	0	10/5	0	2037	0	75	0	5	0	20	0	200	0

Figure B3 Growing Season Statistics Summary (Rock Springs)

Climate Division Temperature and Precipitation

Monthly climate-division temperature and precipitation data were obtained from the NOAA-National Climatic Data Center (http://www.ncdc.noaa.gov/), and these are provided in the folders 'Climate Division Precipitation' and 'Climate Division Temperature'. Climate divisions are a basic unit of climate monitoring used by NOAA and NCDC; the Green River Basin and Bear River Basin constitute Climate Division 6 in Wyoming. Each monthly temperature or precipitation value is the product of an averaging procedure that includes station-level data from all available stations within a division. Climate divisions provide some of the longest (1895-present) and most complete precipitation and temperature datasets available because the impact of missing station-level data is minimized via the averaging procedure. Inclusion of a small number of Bear River basin stations in the averages actually improves the quality of the regional representation. This is because the Bear River stations (e.g., Evanston) help to effectively infill portions of the record where reports from other stations with the Green are limited (e.g., pre-1920). Climate division graphs may be especially useful for depicting regional conditions since the

last Green River Basin plan was completed. Figure B4 is a sample of the precipitation charts. Water Year and Calendar Year charts are provided for precipitation only.

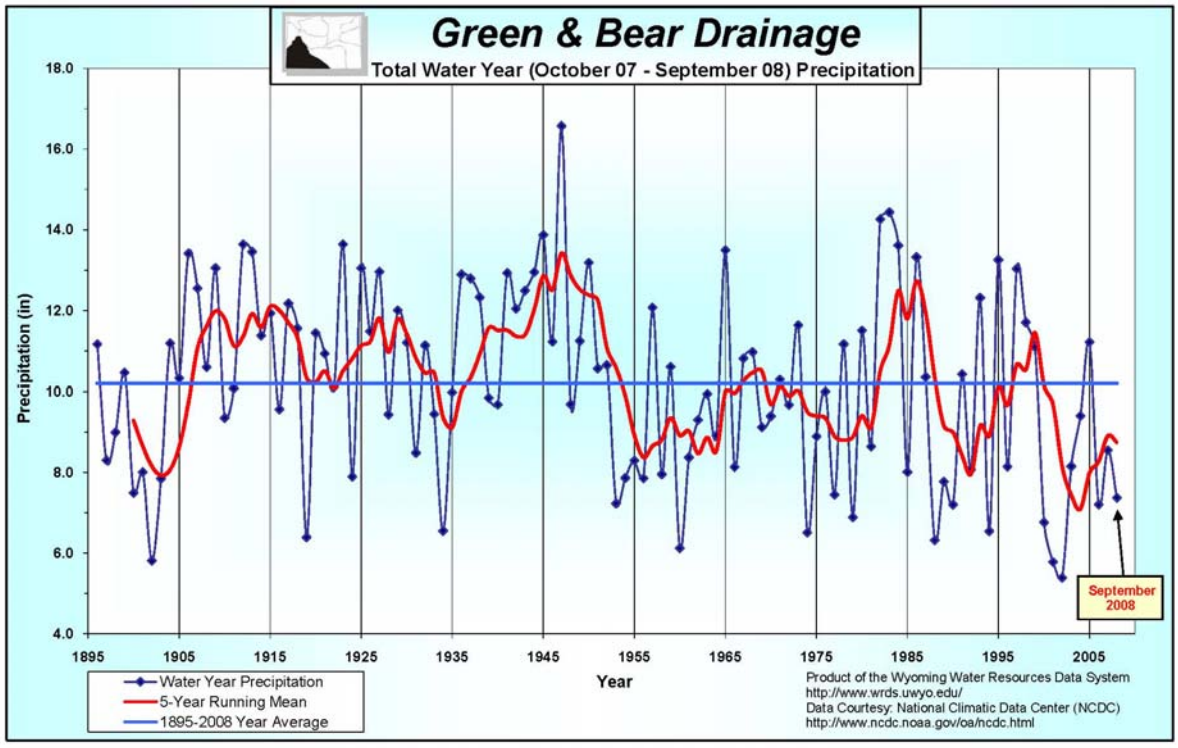
Maps of Precipitation and Temperature Normals

By documenting both precipitation and temperature normals through a series of maps, it is possible to examine climate trends across the entire basin. To create these maps, PRISM (Parameter-elevation Regressions on Independent Slopes Model)-based estimates of climate are used to supplement individual station records and to provide a platform for examining the spatio-temporal relationships between water and other natural resources.

PRISM data sets contain spatially gridded average monthly and annual precipitation for the climatological period 1971-2000. Distribution of the point measurements to a spatial grid was accomplished using a series of algorithms developed by Dr. Christopher Daly at Oregon State University. The PRISM model uses point data, digital elevation models (DEM) and 30 year climatological averages (e.g. 1971- 2000 average) to generate gridded estimates of monthly and annual precipitation and temperature. The final data output for the PRISM model consist of 800 meter gridded data layers. These data sets are made available on the PRISM website in ArcInfo ASCII format for all base climate parameters.

In previous basin studies, discussion of climate was based upon data from individual stations from within the basin. Given the inconsistency in reporting and paucity of stations in some key areas around Wyoming (see State Climate Office website http://www.wrds.uwyo.edu/sco/data/wtryr/wtryr.html for an accounting of NWS Station reports), it is often beneficial to use data that are averaged or interpolated across the entirety of the basin and state, leaving fewer gaps not only on the landscape but also across time. PRISM Data supply a uniform coverage (with 800 meter to 4 kilometer resolution) of precipitation and temperature for the entire period of record, making it a better-quality climate data resource.

With these data, WRDS has created a series of maps that display Average Annual Precipitation (1971-2000), Monthly Average Precipitation (1971-2000), and Annual Temperatures (Average, Maximum, and Minimum)(1971-2000) for the entire Green River Basin. They are included in the electronic attachment in a single file, GRB_Climate_Maps.pdf.



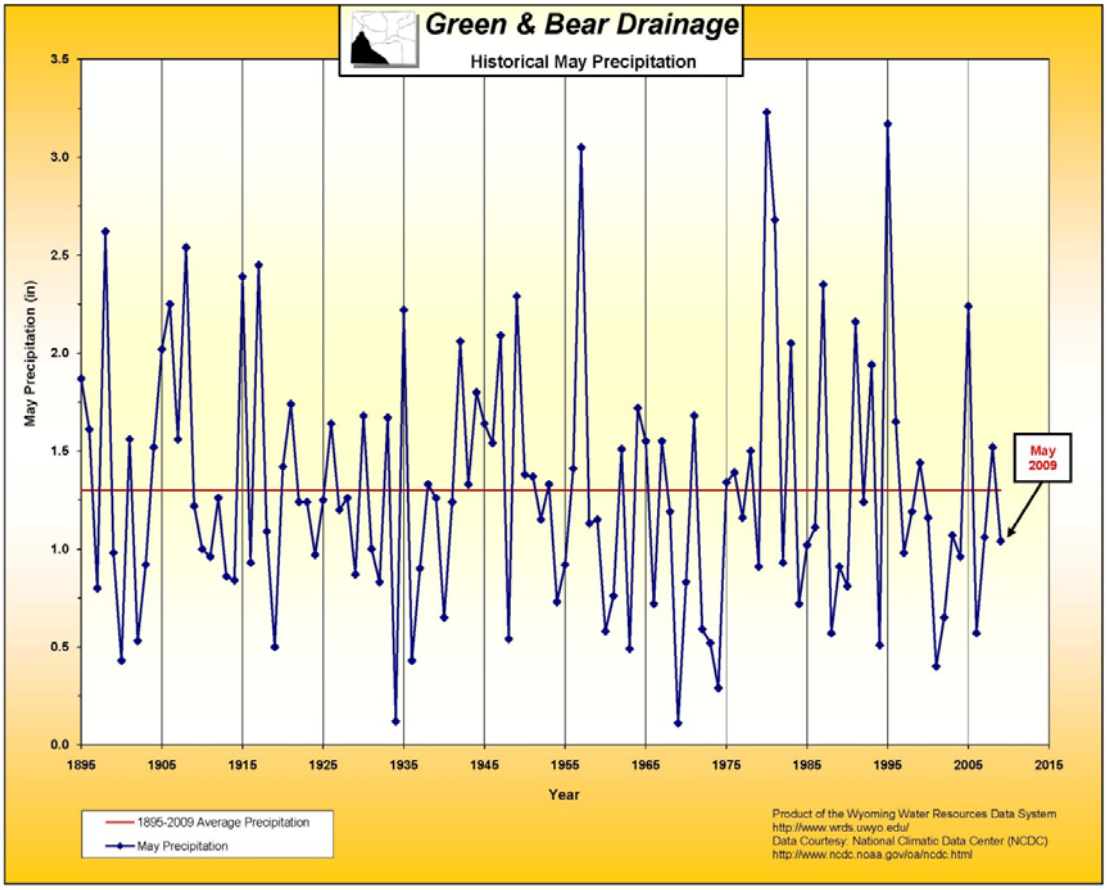


Figure B4 Climate Division Precipitation Summaries (Temperature also Available)

Map 1: Average Annual Precipitation (1971-2000)

This map displays the Average Annual Precipitation for the entire Green River Basin and outlying areas. On average, the basin receives between 10 to 15 inches of precipitation annually with less than 13% of the basin receiving more than 20 inches. (Table 1) The southwestern slopes of the Wind River Range, the eastern slopes of the Wyoming Range, and the western slopes of the Sierra Madres receive the most precipitation in the basin. Lower elevations receiving the most precipitation are located in the upper portion of the basin in the vicinity of Pinedale.

Table 1: Percent of Precipitation in inches

Precipitation (inches)	**%**
<10	14.00
10-15	63.41
15-20	9.66
20-25	5.62
25-30	3.52
30-35	2.63
35-40	0.61
40-45	0.44
>45	0.13

Maps 2 and 3: Average Monthly Precipitation (1971-2000)

These maps illustrate the average monthly precipitation beginning with October, the start of the water year. On average, the basin receives the most precipitation in April and May, and the least in December and February. The higher elevations receive the majority of their precipitation in winter months (October – March) while the lower elevations in the middle of the basin are at their driest.

Map 4: Green River Basin Temperatures

This series of maps illustrate the average annual temperature, the maximum annual temperature and minimum annual temperature. Temperatures tend to grade from cooler to warmer from the northwest to the southeast. The warmest average annual temperatures tend to occur in the Flaming Gorge region with the coldest average annual temperatures occurring in the upper portions of the basin, between the Wyoming and Wind River Ranges.