# AN ASSESSMENT OF CLIMATE MONITORING FOR LAND MANAGEMENT APPLICATIONS IN THE GREAT BASIN

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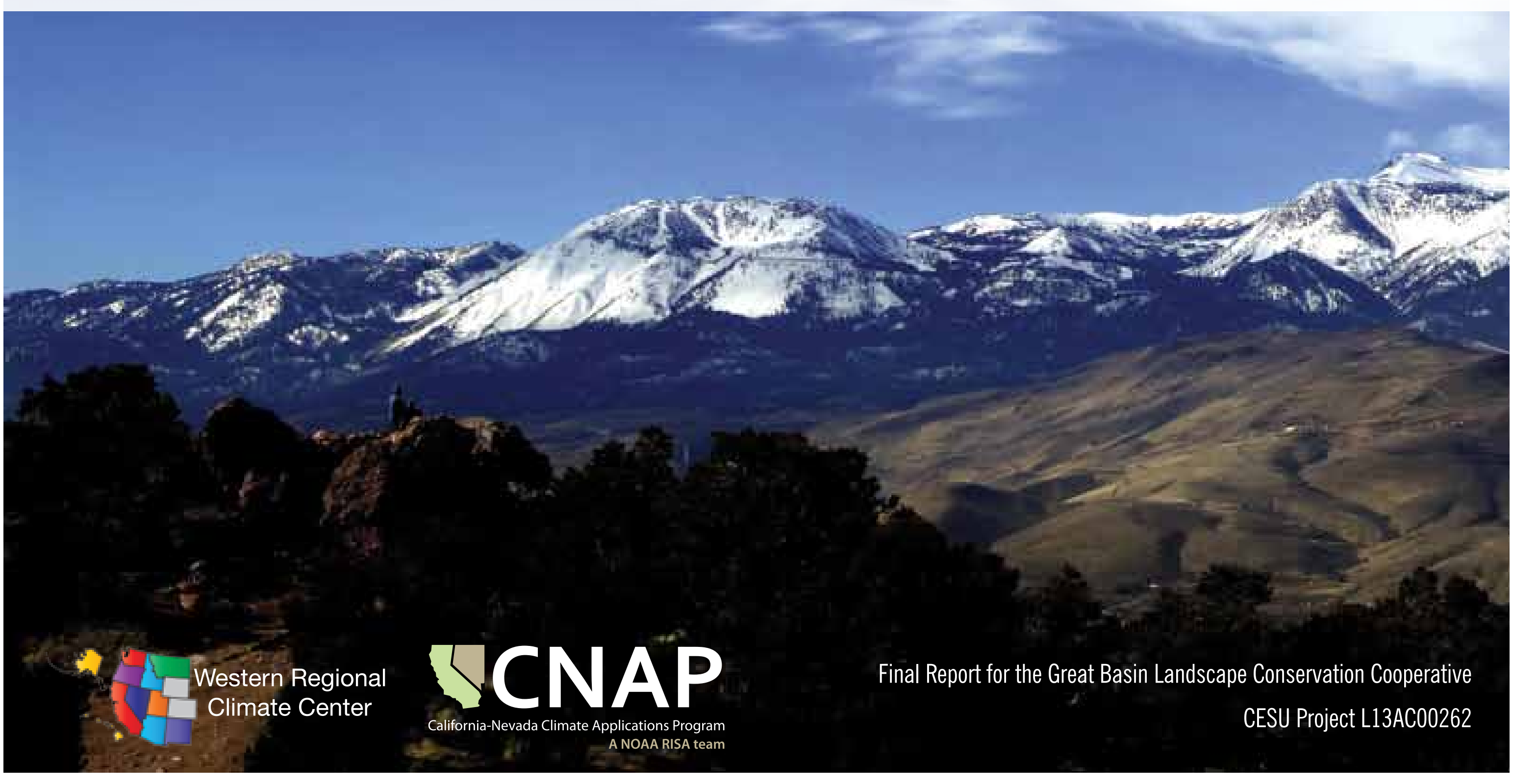

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GREAT BASIN

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# Executive Summary

Recent drought, change agents and the spectrum of greater management needs have highlighted the relative dearth of in situ weather and climate measurement stations in the Great Basin. Thus, interest has grown in supplementing or initiating atmospheric and hydrologic measurements. The purpose of this report is to review the existing station networks in the context of management needs by providing examples of how climate observation gaps can be assessed, and by providing some guidelines for the placement of new or augmented stations.

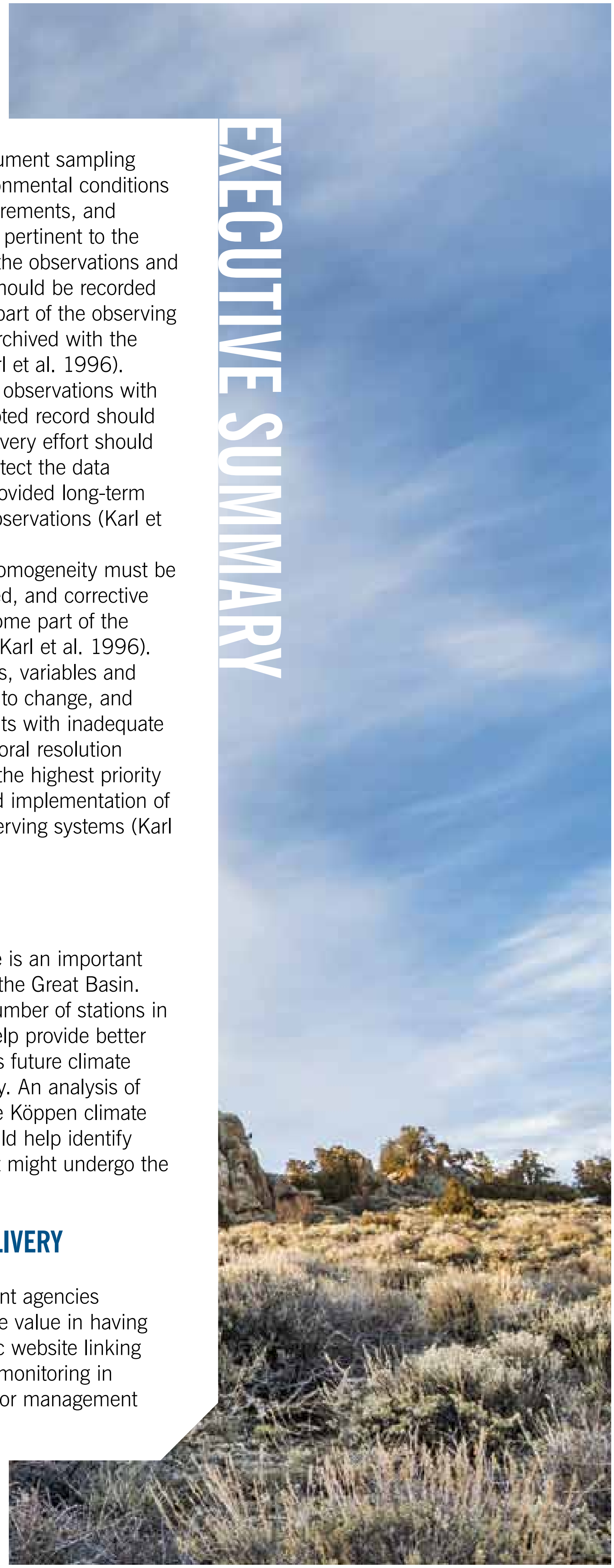
James et al. (2003) describes the value of understanding climate interactions with other measured parameters that are relevant to a management application. It is therefore important to understand climate at the local and landscape spatial scales, and over time. Climate knowledge can effectively inform management strategies and approaches. It answers the question: Are planning assumptions supported by what is known about the climate record?

It is beyond the scope of this report to provide specific location recommendations for new stations. This is because 1) determining the location for a station requires a site visit to assess a number of criteria such as exposure, representativeness, access, and security; and 2) the specific purpose (e.g., management need) of the station must be identified. This report shows how observation gaps can be discovered utilizing basic geospatial data. Three management applications are used: greater sage-grouse habitat, wildfire and grazing allotments. The importance of drought monitoring in the Great Basin is discussed, since drought is a potential impact in nearly all land management applications. Future climate is also briefly discussed.

Based on describing the regional physical characteristics, station siting guidelines, and management applications, a number of recommendations are offered to improve climate monitoring in the Great Basin. The list below is grouped by category, but not given in a particular order:

## STATION COVERAGE AND SITING

1) The number of all weather stations should be increased in the Great Basin. Compared to every place else in the contiguous U.S., the Great Basin has the least number of weather and climate stations. Yet the management needs for climate information are comparable to other regions that have more observations. This will provide valuable information for nearly all management applications, including both historical climatology for analyses, and real-time data for numerical weather prediction.
2) A detailed analysis should be undertaken directly with the land management agencies to assess priority placement of new stations. This needs to be based on both the management application and the specific siting evaluation.




3) The number of stations and specific locations is critically based on understanding the management application need. Other potential uses and benefits should be considered in the process of establishing or expanding a network.

4) All weather station measurements (temperature, humidity, wind, precipitation, solar radiation) are highly valuable for a number of applications. The location of these stations is especially sensitive to the physical surroundings, and siting guidelines should be followed closely to allow for the best representation of an area and/or application.

5) For new Remote Automated Weather Stations (RAWS), the interagency guidelines and standards should be followed, but it also recommended that fire agencies also review the Brown et al. (2011) report for assessing potential station locations.

## DROUGHT AND PRECIPITATION

6) Implementing an improved soil moisture network would be a critical step for providing climate monitoring information especially related to habitat, rangeland and vegetation monitoring and restoration activities. The Great Basin is naturally arid; thus, improved drought monitoring will be beneficial to nearly all land management applications.

7) Increasing precipitation measurements (quantity and quality [i.e., all season precipitation gauges]) across the Great Basin will provide improved information for nearly all land management applications and drought monitoring. This will better capture the highly spatial and temporal aspects of precipitation.

## LONG-TERM CLIMATE MONITORING GUIDELINES

8) Knowledge of instrument, station and/or platform history is essential for data interpretation and use. Changes in instrument sampling time, local environmental conditions for in-situ measurements, and any other factors pertinent to the interpretation of the observations and measurements should be recorded as a mandatory part of the observing routine and be archived with the original data (Karl et al. 1996).

9) In-situ and other observations with a long uninterrupted record should be maintained. Every effort should be applied to protect the data sets that have provided long-term homogeneous observations (Karl et al. 1996).

10) Climate record homogeneity must be routinely assessed, and corrective action must become part of the archived record (Karl et al. 1996).

11) Data poor regions, variables and regions sensitive to change, and key measurements with inadequate spatial and temporal resolution should be given the highest priority in the design and implementation of new climate observing systems (Karl et al. 1996).

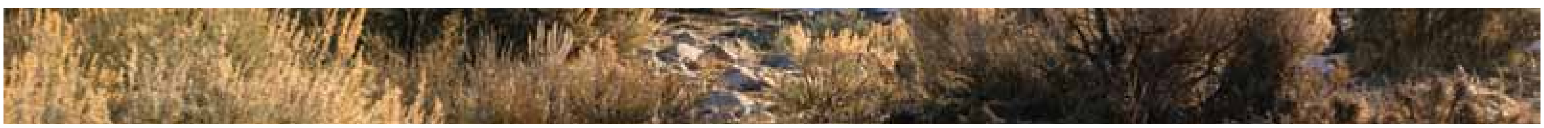
## FUTURE CLIMATE

12) Changing climate is an important change agent in the Great Basin. Increasing the number of stations in the region will help provide better data coverage, as future climate becomes a reality. An analysis of changes in future Köppen climate classification could help identify those places that might undergo the most change.

## INFORMATION DELIVERY

13) Land management agencies should assess the value in having a dedicated basic website linking together climate monitoring in the Great Basin for management applications.

# INTRODUCTION



## MOTIVATION AND BACKGROUND

It has often been noted that effective management of a resource requires monitoring of that resource and the forces that affect its status. Over the historical period of European settlement of the western United States, the Great Basin was often bypassed for the more lush environments and their ocean-bound rivers to its east and west. For many years after European settlement in the West there was minimal motivation for measurement within the Great Basin that resulted in a lower spatial density of environmental observations than in surrounding and more populated areas. However, management needs for environmental information have risen substantially over the past few decades. Habitat, rangeland, and wildfire are examples of key management issues that require environmental data for informed decisions. Four primary change agents have been identified (Comer et al. 2013) that are impacting the Great Basin - wildfire, development, invasive species, and climate change.

Recent drought, change agents and the spectrum of more intensive management have highlighted the relative dearth of in situ weather and climate measurement stations in the Great Basin. Interest has grown in supplementing or initiating atmospheric and hydrologic measurements. The purpose of this report is to document the existing station networks in the context of management needs by providing examples of how observation gaps can be assessed, and by providing some guidelines for the placement of new or augmented stations.

## THE GREAT BASIN

The Great Basin is a distinct geographic region of the western U.S. whose boundary can be defined along various lines including: biologic, ethnographic, floralistic, hydrographic, and physiographic (Grayson, 2011). For the purposes of this report, the Great Basin boundary adopted, as defined by the Great Basin Landscape Conservation Cooperative (GBLCC), encompasses a total area of 217,381 square miles and from a qualitative perspective represents a boundary of the Great Basin whose spatial extent is similar to floristic delineations. Of the 217,381 square miles, nearly 117,878 square miles are under federal stewardship by the Bureau of Land Management (BLM) and 24,860 square miles by the U.S. Forest Service.

The vast majority of the Great Basin is contained within the state of Nevada, but extends into California, Idaho, Oregon, and Utah. It is bounded by the Sierra Nevada Range and southern Cascades to the west, Wasatch Mountains on its eastern edge and by less distinctive boundaries to the north in Oregon and Idaho by the Columbia Plateau and Snake River Plain, respectively, and by the Mojave Desert to the south. From a hydrological perspective, the basin is a closed hydrologic basin; whereby, surface runoff from its mountains has no pathway to the Pacific Ocean, and drains into terminal lakes, such as the Great Salt Lake, Pyramid Lake and Walker Lake.

Another feature that characterizes the Great Basin is its numerous north-south oriented fault block mountain ranges that are divided by broad valleys or basins. The overall basin and range structure is a result of the east-to-west stretching of the earth's crust, and is often referred to horst (upfaulted block) and graben (downfaulted block) topography. Valley bottom elevations are generally positioned between 4,000-5,000 feet along its western and eastern borders while the central portions are slightly higher in elevation ranging from 5,000 to 7,000 feet. Many of these basins feature large dry lakebeds or playas that have the potential to fill during wetter climatic periods, seasonally, or as the result of episodic extreme precipitation events. Depending upon the boundary utilized, it is generally accepted that the highest point in the Great Basin is White Mountain Peak (14,246 feet), which rises dramatically from the Owen Valleys of California. Along its western boundary in the Owens Valley, vertical relief is impressive rising nearly 10,000 vertical feet from the valley floor to over 14,000 feet in the White Mountains that hug the California-Nevada border.

Appendix 1 provides some further descriptive information on the Great Basin.

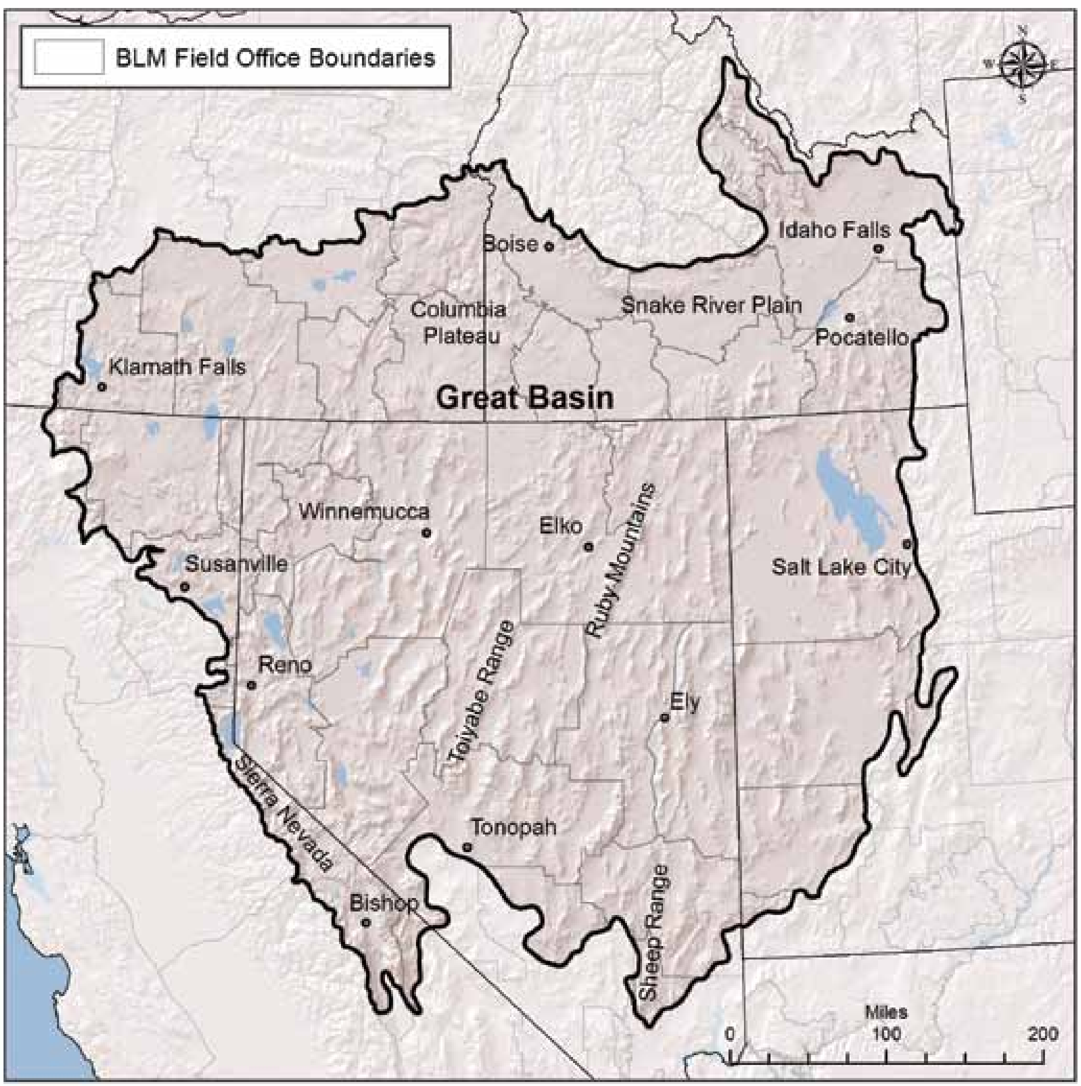



**Figure 1.** Digital elevation map of the Great Basin as defined by the GBLCC delineating the boundary adopted for this report and highlighting major topographic features, and population centers.

## BASIC CLIMATE

The climate of the Great Basin is arid to semi-arid and characterized by large diurnal and seasonal fluctuations in temperature and spatially variable precipitation patterns. The climate of the region is highly regulated by its latitudinal position, complex topography and proximity inland from the Pacific Ocean. Some of the most extreme precipitation gradients in the continental U.S. are found between the windward slopes of the Sierra Nevada Range and the valleys on the east side of the range (WRCC, 2016). Abundant sunshine, limited cloud-cover, and high evaporative rates are characteristic of the climate of the region. The Great Basin's continental interior position influences its temperature cycles marked by large diurnal and seasonal fluctuations with extremes ranging from 110°F to -50°F.

## PRECIPITATION

The complex topography of the Great Basin and its numerous north-south oriented mountain ranges influence precipitation patterns with marked rain shadow effects. Annual precipitation is spatially variable not only between mountain and valleys locations, but within mountain ranges as windward slopes (west-facing) receive more precipitation than leeward slopes (east-facing) as air masses typically approach in a perpendicular manner and are orographically lifted by the terrain; subsequently, ringing out moisture on windward slopes. This relates to an important consideration in station siting because of highly varying climates over short distances given the complex terrain. Figure 2 shows the annual precipitation from 800-meter resolution PRISM[1] calculated from a 30-year (1981–2010) average. The majority of annual precipitation is delivered by mid-latitude storm systems approaching off the Pacific Ocean during the cool season (between October and April), although southern and eastern portions receive rains from the North American Monsoon during July through September. Monsoonal and springtime rains in the northeastern portions of the Great Basin play an important role in the health of rangeland grasses which benefit from abundant sunshine, moist soils, and mild temperatures.

About two-thirds of the Great Basin's precipitation falls on the upper half of its elevation. Individual mountain ranges are always wetter than the surrounding lowlands. Valley floor precipitation increases from about 4-5 inches (100 to 125 mm) in the vicinity of Pyramid Lake and Fallon to about 15 inches (380 mm) near Ely. Annual precipitation is heaviest along the basin's western border in the Sierra Nevada and southern Cascades where annual precipitation can exceed 60 inches (1500 mm). In the east basin the higher elevations of many of the mountain ranges across Nevada receive 15 to 25 inches (380 to 635 mm) of precipitation annually while ranges in northeastern Nevada, such as, the Ruby Mountains and ranges in the headwaters of the Humboldt River basin receive in excess of 40 inches (1000 mm) annually (Figure 2).

Figure 3 demonstrates the spatial variability of the annual precipitation cycle in the Great Basin using four National Weather Service (NWS) Cooperative Observer Network (COOP) stations. Bishop, CA (top left) sits on the southwestern edge of the Great Basin and has a pronounced wet and dry season, which is a common feature of the western Great Basin along the Sierra Nevada. For Bishop, the wet season peaks December through February and is dominated by mid-latitude, frontal storm systems, while the driest months are June through August when it is not uncommon to see months with zero precipitation. The importance of spring precipitation is evident when looking at Preston, ID northeast of Salt Lake (top right), where April and May are the wettest months. Preston also has a dry season in July to August, but there is no real peak in the winter months like what is found in Bishop. The impact of the North American Monsoon is most prevalent in the southeast Great Basin, which can be seen in the Modena, UT (bottom right) annual cycle with a precipitation peak found in July and August. At Great Basin National Park (bottom left) there is no defined annual cycle, and all months average between 0.75 and 1.5 inches of precipitation. Both winter/spring mid-latitude storms and the North American Monsoon leading to a less pronounced annual precipitation cycle compared to other regions affect this east-central region of the Great Basin.

To demonstrate the spatial variability of precipitation at a finer scale west-to-east across a single mountain range, Figure 4 (results from McEvoy et al. 2014) shows the cold season (October through March) and warm season (September through April) precipitation totals for the 2012 water year using the Nevada Climate-Ecohydrology Assessment Network (NevCAN; Mensing et al. 2013). NevCAN, located in eastern and southern Nevada, is a new observation network designed to assess climate variability and change and associated impacts on the surrounding ecology and hydrology. The Snake Range transect, located in Great Basin National Park, is presented in Figure XX and is compared to PRISM data. The most prominent feature is the sharp precipitation gradient from the valley floor (SN1 is at 5,880 feet) to the upper elevation of the mountain

[1]PRISM (Parameter-elevation Relationships on Independent Slopes Model) is an interpolation method to produce high spatial resolution climate data of precipitation, temperature, dew point and vapor pressure (Daly et al. 2008).

(SN4 is at 11,005 feet). Based on observations, the cold season and the warm season show very similar precipitation totals, which reinforce the lack of a strong seasonal cycle found here. In general, the PRISM data do a good job replicating the spatial variability of precipitation and changes with elevation. However, there are large biases apparent and networks like NevCAN are critical to understanding these biases and improving the gridded data products.

## TEMPERATURE

The seasonal range of representative temperatures can be illustrated in many ways. Here, for example, Figure 5 shows the 800-meter PRISM 30-year (1981-2010) average monthly daytime maximum temperature for July, and Figure 6 shows the average monthly nighttime minimum temperature for January. These two maps depict the average annual temperature range across the Great Basin. Valley maximum temperatures are typically in the mid-90s in July, and minimum temperatures are typically in the teens in January. The southern portion of the Great Basin is the hottest due to lower elevation and latitude, and temperatures get colder as you move northeast across the basin with higher elevation and latitude. A prominent feature in Great Basin valleys during the summer months is a large diurnal temperature cycle, where the difference between daily minimum and maximum temperatures can exceed 50°F. For example, at the Reno-Tahoe International Airport station, in July the average daily maximum temperature is 91.7°F and the average daily minimum temperature is 51.3°F. In the winter, mountainous areas are typically colder than valleys during mid-latitude storm cycles, but strong temperature inversions are common during periods of high pressure. This feature is amplified when snow cover is present on the ground and the temperature can be colder in the valley at 4,000 feet than it is in the adjacent mountains at 6,000 feet.

To demonstrate the prominent temperature inversions and spatial variability of temperature across a single mountain range, Figure 7 (results from McEvoy et al. 2014) shows the monthly mean minimum temperature during the 2012 water year from the NevCAN Snake Range stations and nearest PRISM data points. Unlike maximum temperature, minimum temperature increases with elevation from the valley floor to the foothill locations (i.e., SN1 to SN2 and SN7 to SN6). Previous studies have also found that in complex terrain, minimum temperature can vary greatly depending on station siting and associated local atmospheric decoupling and cold air drainage (Daly et al. 2009; Holden et al., 2011). The 4km PRSIM data cannot replicate this feature and while the finer scale 800m PRISM does show inversions, the biases are large and inversions are greatly underestimated. This highlights the importance of having mountain transects in remote locations, such as NevCAN, to help improve future generations of gridded climate data like PRISM.

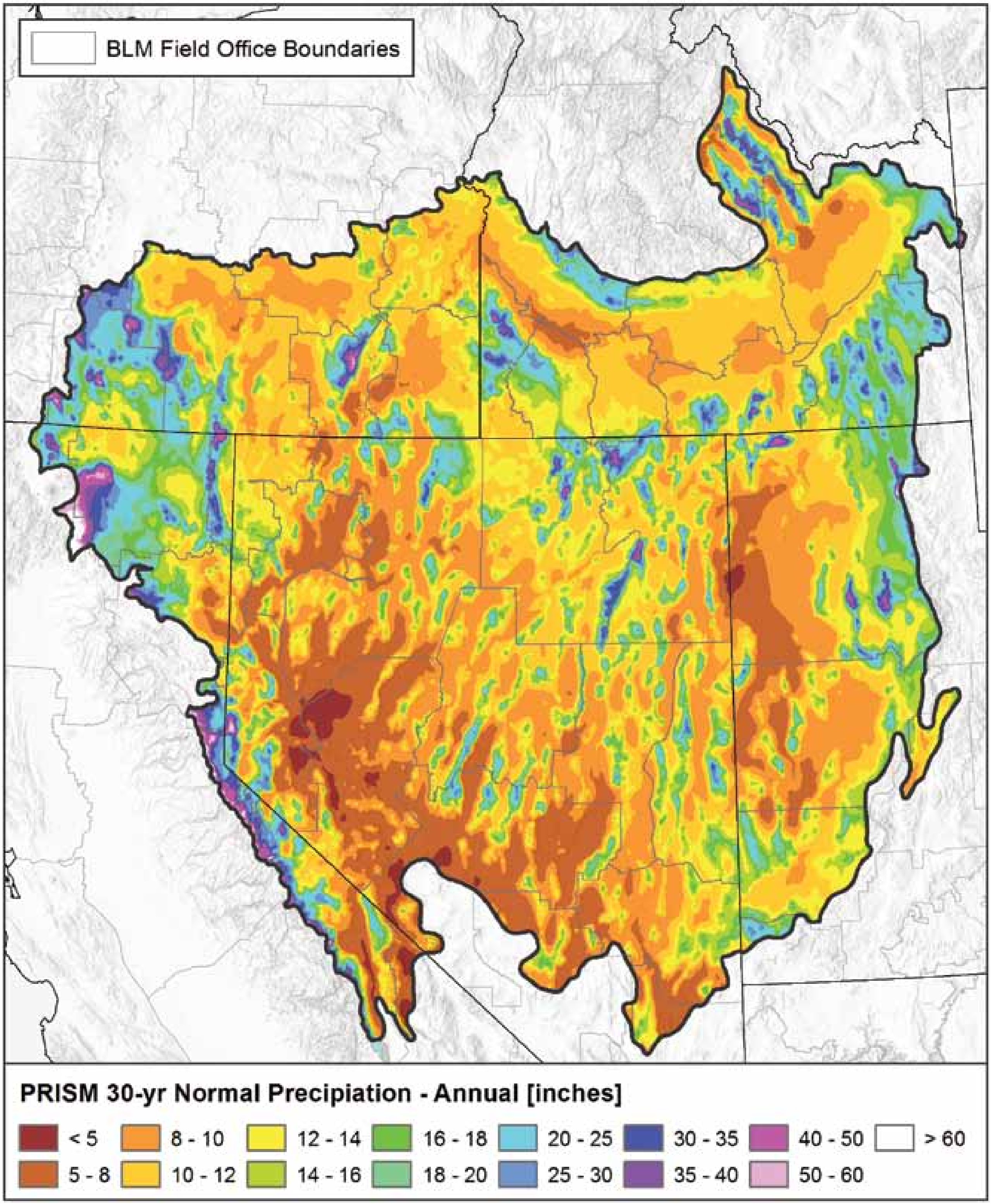



**Figure 2.** Annual precipitation from 800-meter PRISM based on the 1981–2010 30-year average.

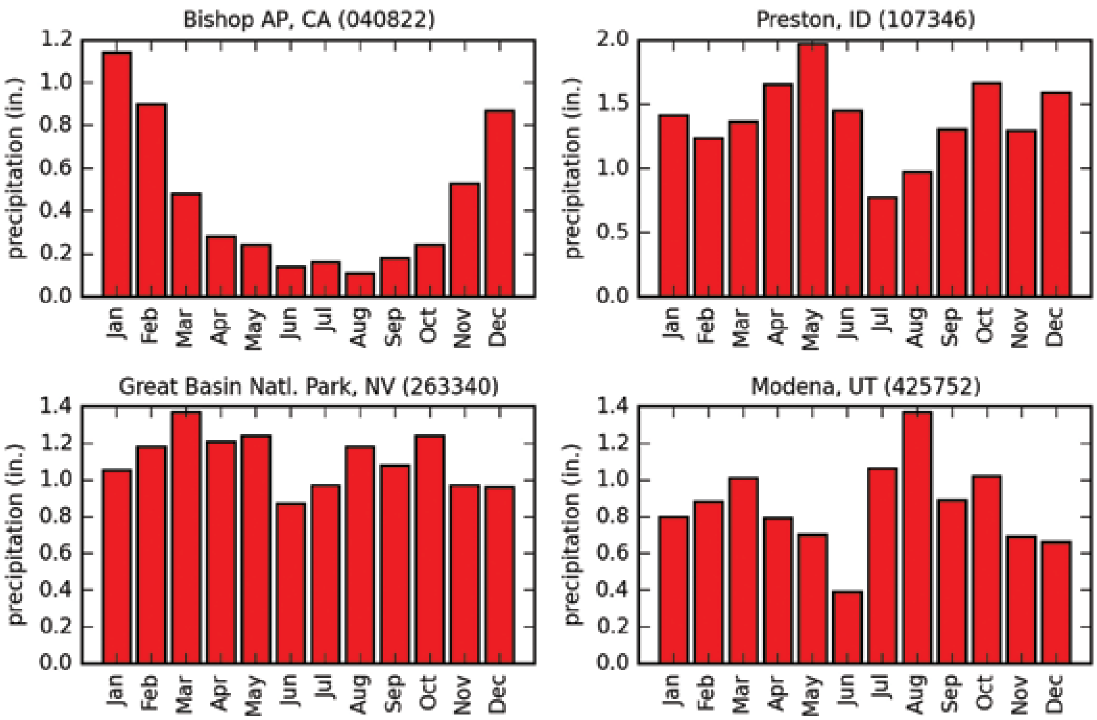



**Figure 3.** Monthly average precipitation from the Bishop AP, CA (period of record: 01/01/1895 to 06/09/2016), Preston, ID (period of record: 10/01/1964 to 06/01/2016), Great Basin National Park, NV (period of record: 07/01/1948 to 03/31/2013), and Modena, UT (period of record: 01/01/1948 to 03/31/2004) COOP stations. Data were obtained from the WRCC (http://www.wrcc.dri.edu/climatedata/climsum/).

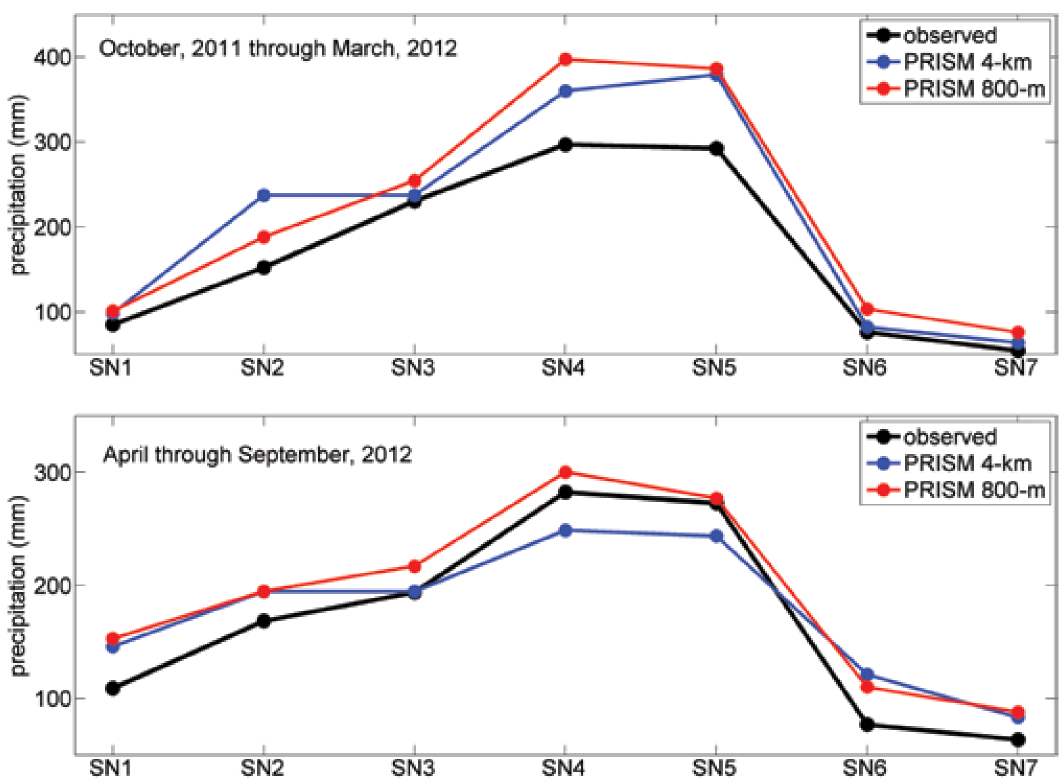



**Figure 4.** NevCAN Snake Range seasonal precipitation totals for water year 2012 and PRISM data nearest to each station. Cold season is shown on the top and warm season on the bottom. X-axis is aligned west to east (left to right) spatially. Stations increase in elevation from SN1 to SN4, and decrease in elevation from SN4 to SN7. Data obtained from the WRCC: http://www.wrcc.dri.edu/GBtransect/. For more details on this study see McEvoy et al. (2014).

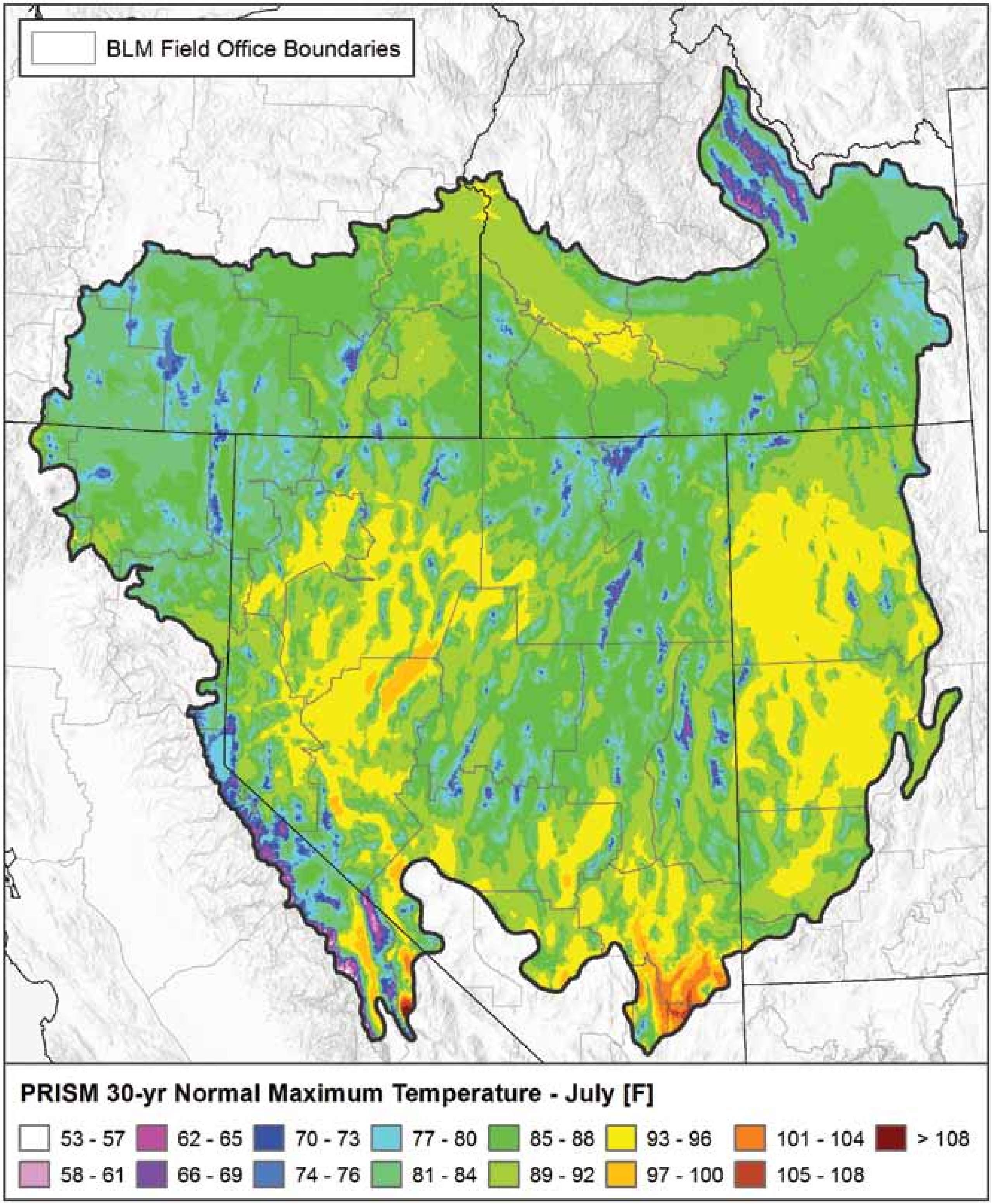



**Figure 5.** Mean maximum temperature during the warmest month (July), 1981–2010.

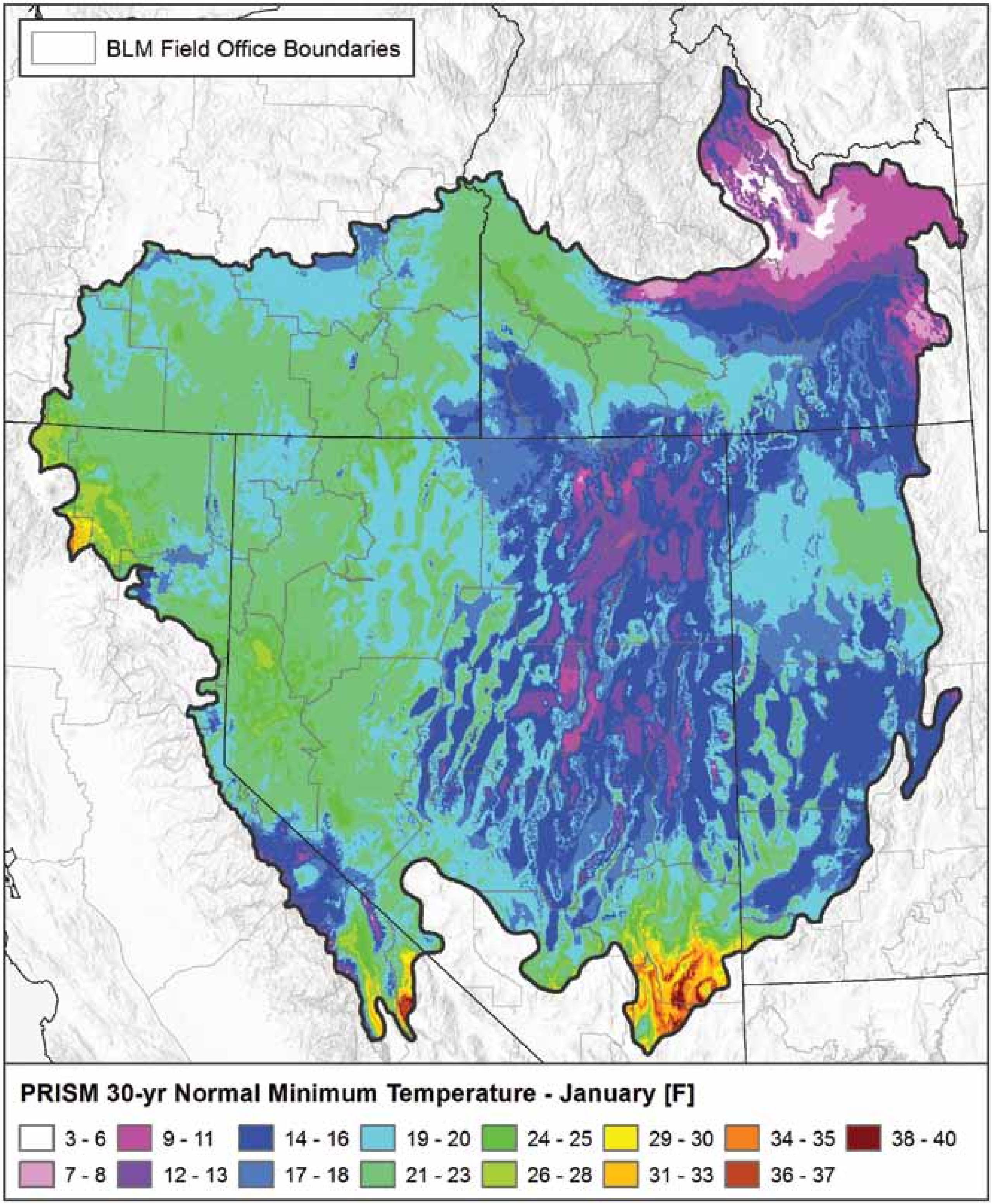



**Figure 6.** Mean minimum temperature of the coldest month (January) 1981–2010.

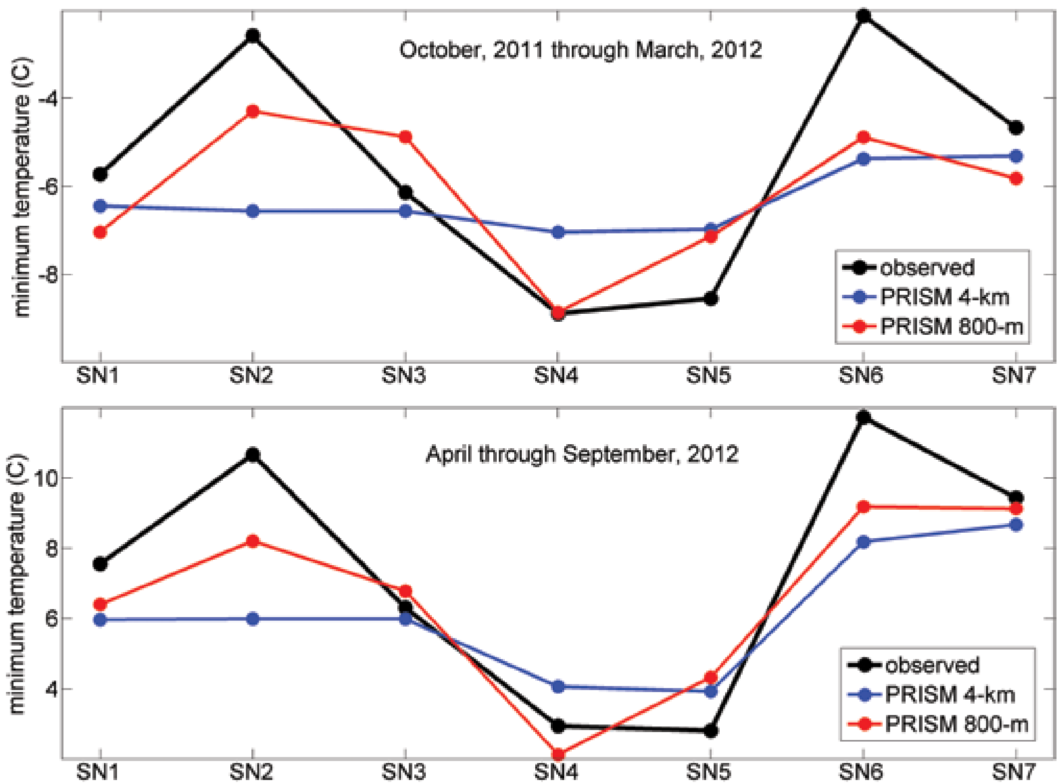



**Figure 7.** NevCAN Snake Range seasonal average minimum temperature for water year 2012 and PRISM data nearest to each station. Cold season is shown on the top and warm season on the bottom. X-axis is aligned west to east (left to right) spatially. Stations increase in elevation from SN1 to SN4, and decrease in elevation from SN4 to SN7. Data obtained from the WRCC: http://www.wrcc.dri.edu/GBtransect/. For more details on this study see McEvoy et al. (2014).

## GREAT BASIN KÖPPEN CLASSIFICATION

The Köppen (pronounced KUR-pen) climate classification system was originally designed by Wladimir Köppen (1846-1940), a German climatologist and botanist. In 1928, he and his student Rudolph Geiger produced the first wall map of world climates. The classification system intent was to relate vegetation distribution with climate, depicted as combinations of annual and monthly temperature and precipitation. Figure 8 shows the Köppen classification across the Great Basin based on Peel et al. (2007) and the monthly 800-m PRISM dataset.

Appendix 2 provides the temperature and precipitation thresholds used to compute the classifications. Fifteen different climate regimes are identified in the Great Basin using this climate classification method. The temperature seasonality of the Great Basin climate is well depicted in this map, along with elevation characteristics of the complex terrain. It is clear from this classification that the Great Basin is either an arid or dry environment. The largest classification area is an arid steppe cold (yellow color). Cold is quantified as having the average warmest summer (July) temperature greater than 50°F and the average coldest winter (January) temperature less than 32°F. The next largest area (dark blue) represents a continental cold (using the same temperature criteria as above), but having dry, warm summers. For a few 800-m grid cells at the highest elevations, there is even a polar classification.

The relevance of this classification for the Great Basin is twofold. First, it visually depicts the spatial (including elevation) climate variations based on combinations of temperature and precipitation, which are two highly import climate elements related to flora and fauna. Second, the classification can provide additional climate context when considering station locations. This is discussed further in the next section.

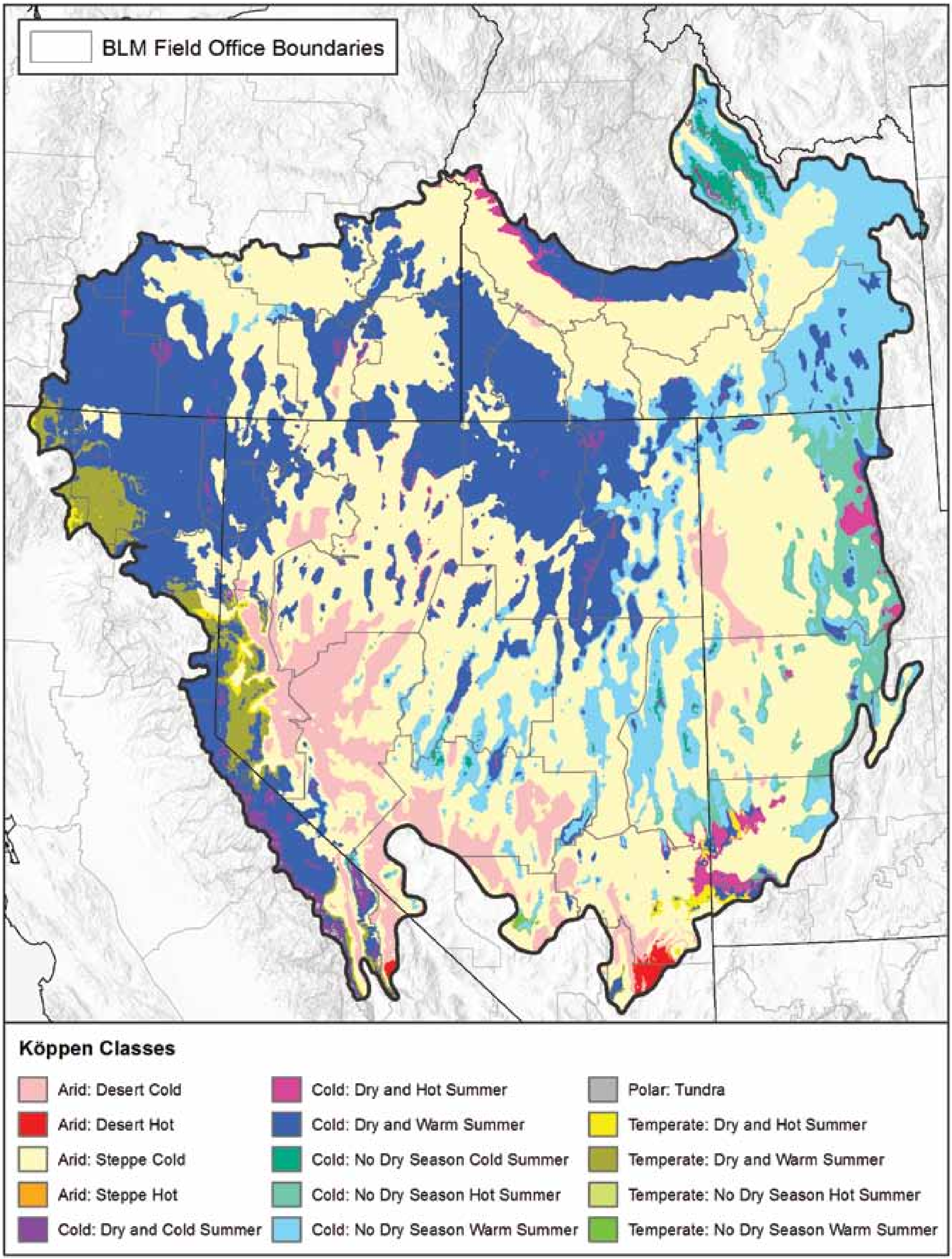



**Figure 8.** Köppen climate classes across the Great Basin.

# Climate Monitoring
## IN THE GREAT BASIN

The most common depictions of Great Basin climate include temperature and precipitation. The COOP network, for example, is a national network dedicated to daily temperature and precipitation measurements. Other networks are designed to measure a variety of atmospheric elements such as wind, humidity, pressure, solar radiation, and snow. The Remote Automated Weather Station (RAWS) network implemented primarily for fire weather is an example of these types of measurements. These more detailed measurement networks also record observations on a sub-daily basis, such as hourly.

Across the Great Basin, the spatial density of climate monitoring stations is generally low with exception of various pockets of higher concentrations of stations in proximity of populated areas (e.g., Reno, Boise), particular mountains ranges (e.g., Ruby Mountain), and in areas of specialized monitoring applications in association with the Department of Defense and Department of Energy (e.g., Nevada Test Site and Idaho National Laboratory). Of the approximately 1100 active stations within the Great Basin, the vast majority (~80%) of stations are situated between 4000-7000 feet in elevation (Figure 9). In terms of active station distribution by land stewardship, 160 stations are currently situated on BLM lands (Figure 10).

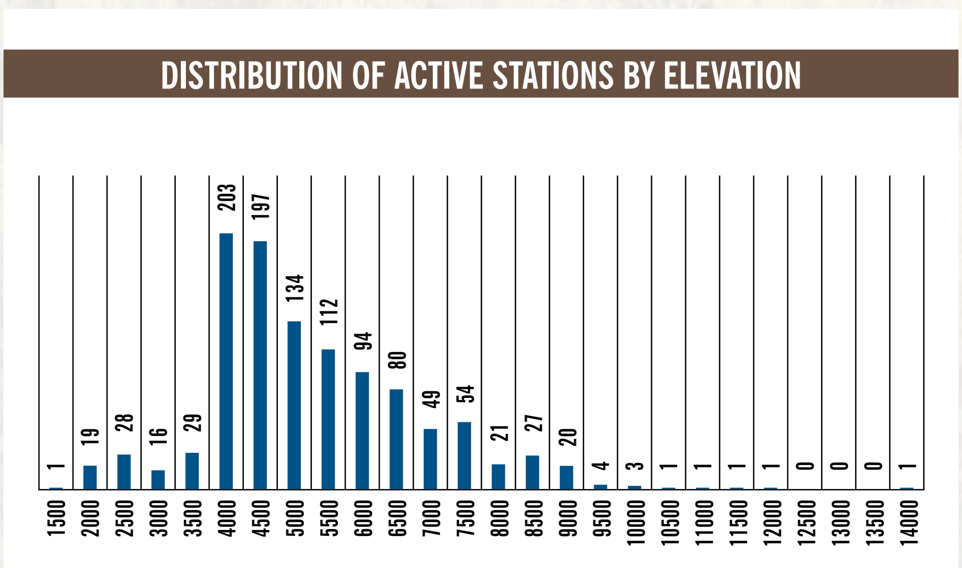



**Figure 9.** Distribution of active weather stations by elevation (feet).

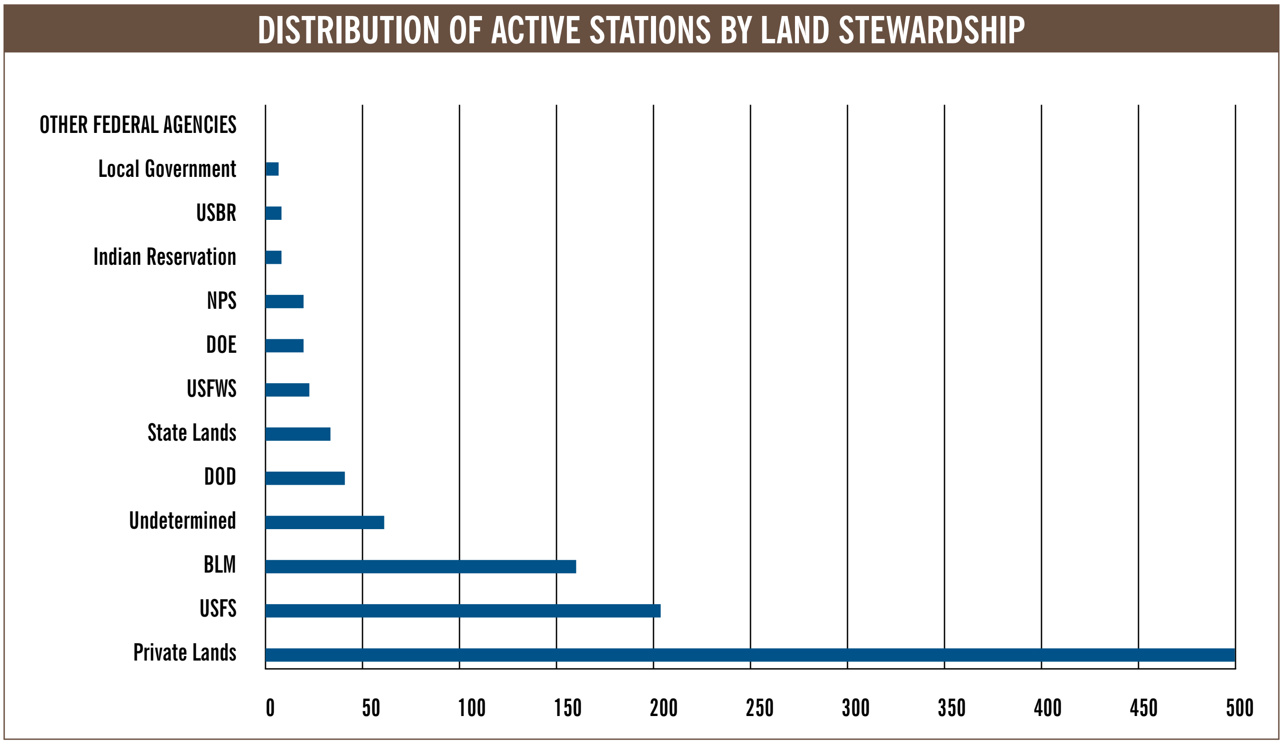



**Figure 10.** Distribution of active weather stations by land stewardship.

Figure 11 shows the locations of the major climate observing networks with active stations in the intermountain West. The relative scarcity (low spatial density) of surface measurements in the Great Basin is seen in nearly every network. The presence of a marker on these maps does not by itself convey information on the quality and consistency of the data, the length of record, current status of the station, nor the completeness or general usefulness of the station record for some application of interest. Some of these factors can be derived from metadata (written description of data) but often we have found that metadata themselves have many problems. The evaluation and rehabilitation of station metadata require significant time in many cases, and a great deal of specialized knowledge about the history and details of each network. In addition, even relatively basic and seemingly simple information, such as station position, is often either incorrect or imprecise. Conversely, changes in station siting known from other sources, or from actual data behavior, are frequently not mentioned in the metadata.

Figure 12 shows stations in major networks and their physical location relation to land stewardship. This does not imply that the land steward is the owner or maintainer of the network. For most networks, ownership and maintenance is done by another entity. However, RAWS is one example where the agencies are the land steward, and own and are responsible for maintaining the station. The networks shown in Figure 12 include large multistate networks such as Agrimet, NWS Coop, RAWS, SNOTEL (Snow Telemetry), as well as spatially less extensive federal and state networks, some operated for specialty reasons (e.g., CEMP). One important consideration is that only a few of these networks (e.g., SNOTEL and Coop) have all-weather precipitation gauges capable of measuring snow. Further network details are provided in Appendix 3.

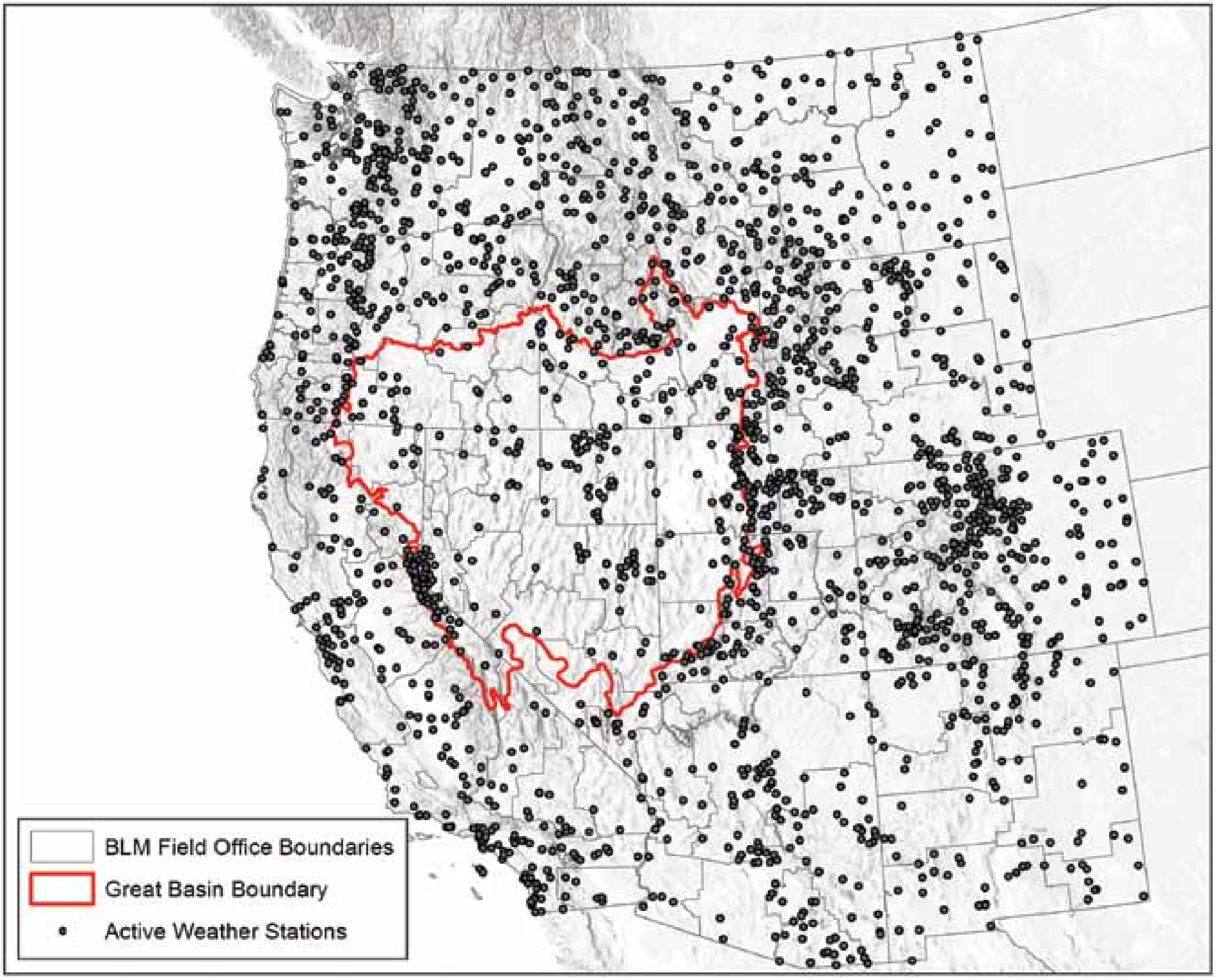



**Figure 11.** Station locations in major networks in the western United States. The relative scarcity of stations in the Intermountain West and Great Basin is evident.

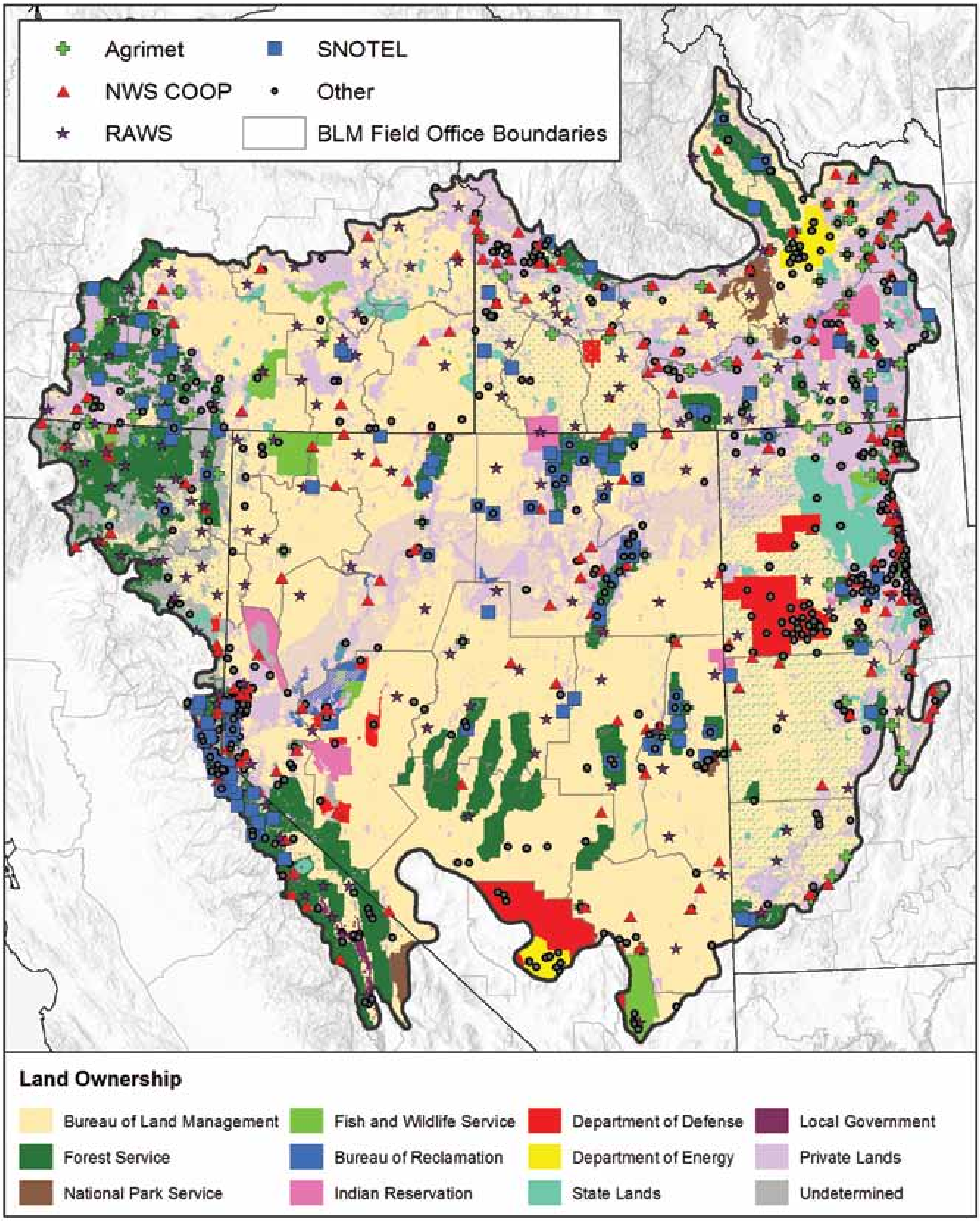



**Figure 12.** Observational networks physical location relation to land stewardship.

Figure 12 includes the distribution of stations in two major federal networks. SNOTEL is capable of accurately measuring the snow water content as well as snow depth. Depth alone can matter by insulating plants and animals below the snow from harsh air temperatures above the snow. Water content of snow on the ground is of great interest for hydrological applications (e.g., streamflow forecasting). The widely used RAWS network has been present since 1983, and the standard configuration found at nearly every station only measures liquid precipitation. Since snow is a substantial contributor to annual precipitation, and melts just before spring green-up, at most stations a sizeable fraction of annual precipitation goes completely unmeasured. Thus, not only is the ability to measure frozen precipitation lost, but also the ability to describe the intensity and duration of specific storm events. While networks such as SNOTEL measure snow, these locations cannot necessarily be used as a "closest station" because of the high degree of spatial variability within short distances.

Precipitation has considerable spatio-temporal variability and thus is only representative of a limited area, requiring a much higher density of stations to provide robust coverage. One way to highlight precipitation across the Great Basin is to calculate seasonal variance at each 800-m grid point. Figure 13 shows the seasonal variance (defined as pseudo sigma[2]) of precipitation across the Great Basin. The four climatological seasons are shown (December-February (winter); March-April (spring); June-August (summer); September-November (autumn)). Note that the color scales change for each season, and darker colors indicate higher variability. Though the winter season has larger variance than spring, both seasons are generally similar. Most of the variance pattern is seen at the higher elevations. Summer is dramatically different showing the highest spatial variability though the variance itself is small compared to the other seasons. The pattern is indicative of the North American Monsoon and convective storms across the Great Basin. Autumn also shows large spatial variability, though the variance is less than winter and spring, but more than summer. These maps highlight the need for robust precipitation monitoring across the Great Basin that also accounts for the varying elevation.

Figure 14 shows the Köppen classification for the Great Basin (same as Figure 8), but now includes active weather/climate stations (black dots). Active station refers to currently measuring a climate element (e.g., temperature, precipitation). The climate classification provides a context for siting stations. In a coarse climatological extent, each station is representing its respective Köppen classification based on the combination of monthly temperature and precipitation. That is, the classification indicates some commonality of temperature and precipitation across the classification area. This initially implies that a minimum number of stations could be representative of these areas. However, as described earlier, the Great Basin is a complex terrain environment with strong elevation gradients (Köppen will capture this to the extent of the spatial data grid size input), and microclimates caused by topographic features such as slope and aspect.
In considering network density for temperature, fewer stations may be required because temperature can be characterized more easily over larger spatial areas than say precipitation, as long as elevation is accounted for. In Figure 14, the Köppen classifications have some larger areas void of stations, but generally appear to be robustly covered. However, there is a catch here. Though PRISM model gridded data were used to create the classifications, station data were needed to inform the model. Not surprisingly then, more station data improves model results, as well as provides for more localized information.

[2]In statistics, variance is a common measure of distribution spread associated with the mean. Since zero is a lower bound for precipitation, the median rather than the mean is often better to denote the centrality of a precipitation distribution (though mean is commonly used). The median equivalent to variance is termed pseudo sigma. The calculation is simply the interquartile range (the 3rd quartile minus the 1st quartile) divided by 1.349.

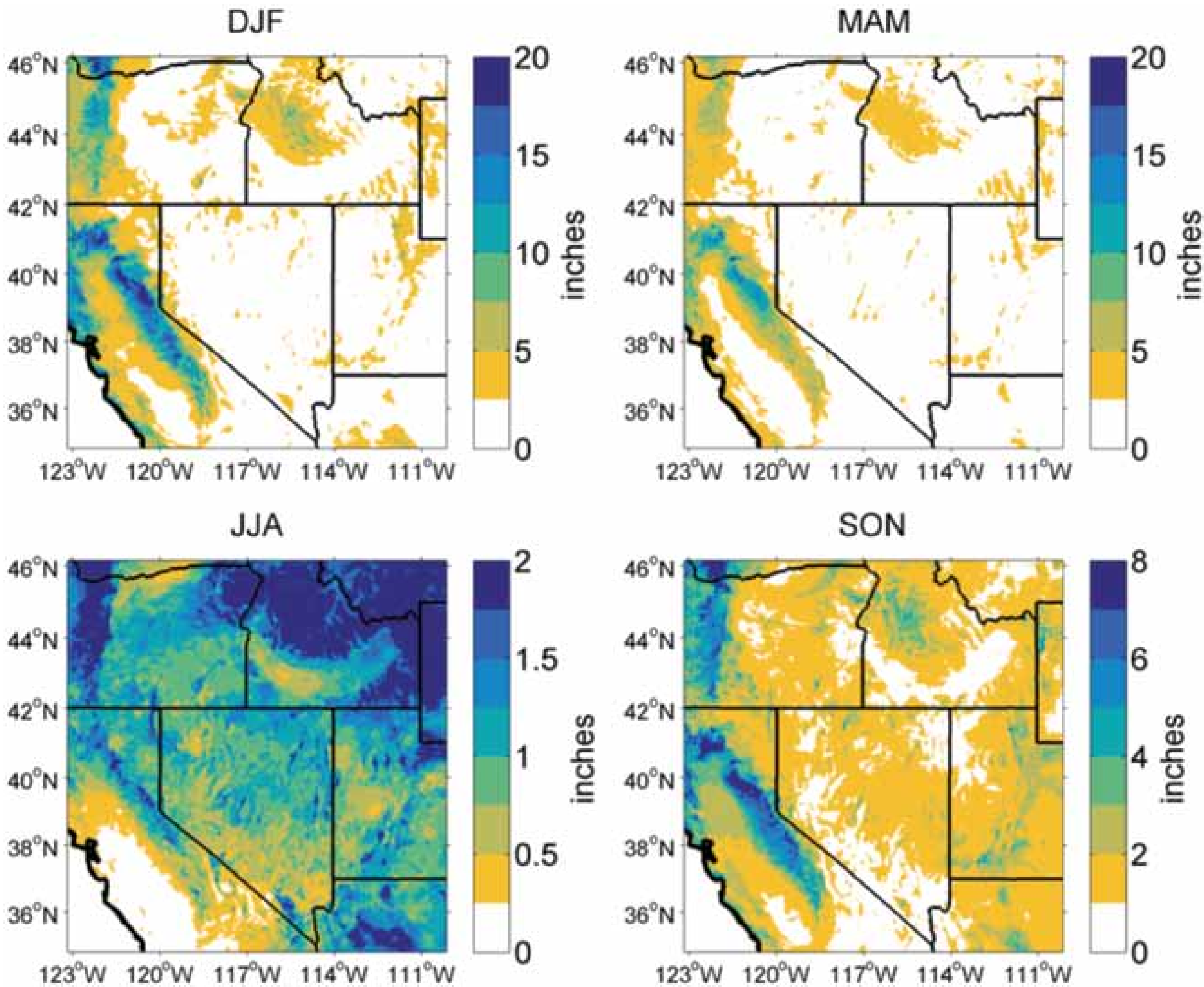



**Figure 13.** Seasonal variance (defined as pseudo sigma) of precipitation across the Great Basin. Note that the color scales change for each season. Darker colors indicate higher variability.

Other elements need special consideration as well. For example, humidity tracks temperature, but is influenced by local precipitation. Wind is very localized in complex terrain, and station siting is especially important to provide for spatial representation. Solar radiation may vary less over large areas, but windward and leeward sides of mountains can have substantially different cloud cover climatologies. Soil moisture is highly variable, corresponding to precipitation and terrain characteristics, but also can vary substantially due to soil types.

A climate network should provide a satisfactory representation of the climate characteristics across the area of interest. There are sophisticated quantitative methods that can be applied in assessing the density of a network. This is discussed further in the next section. Further, the density of a network and the station distribution is highly dependent on the application. Great Basin example applications include the change agents described in the REA (2013) and the land management agency missions and priorities.

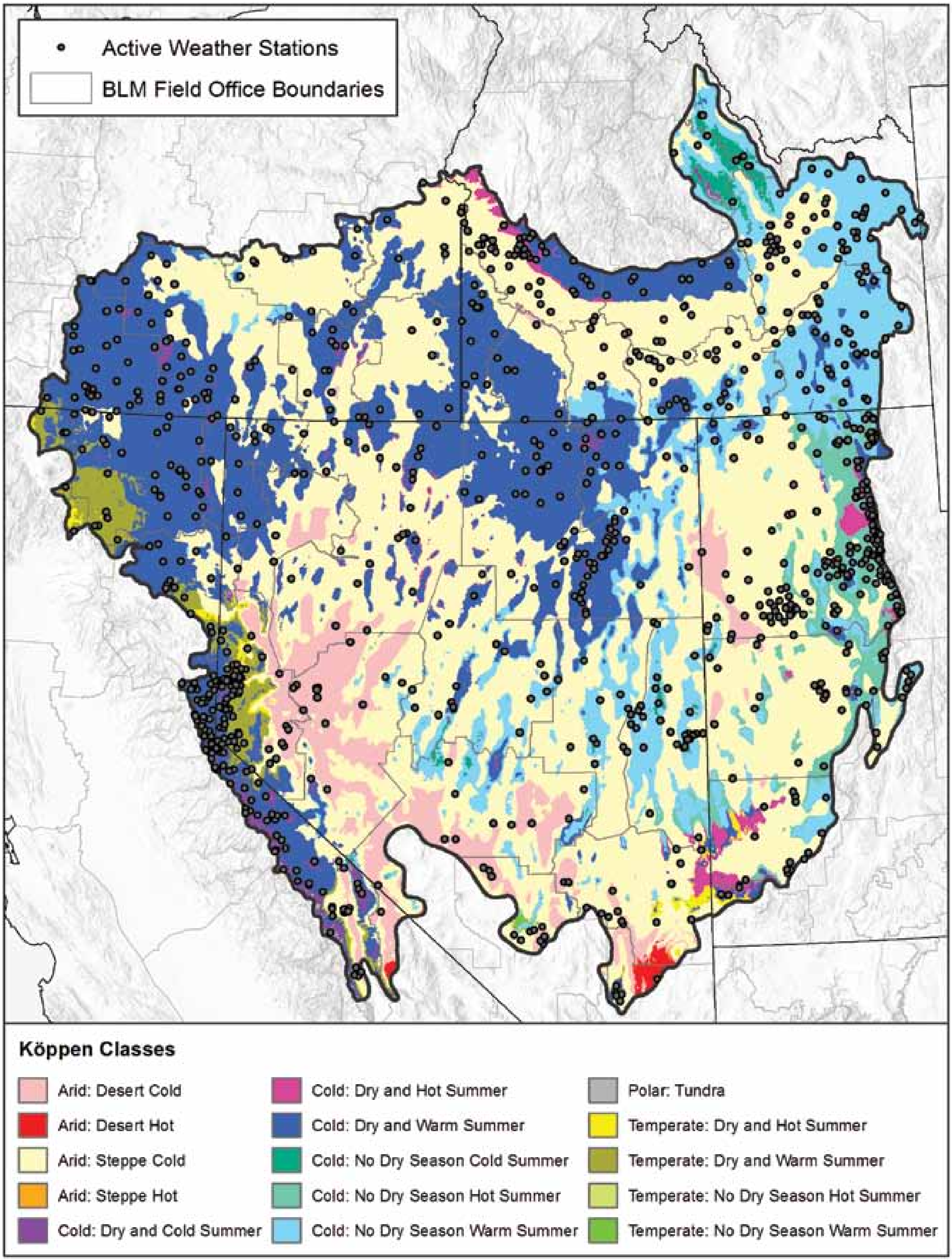
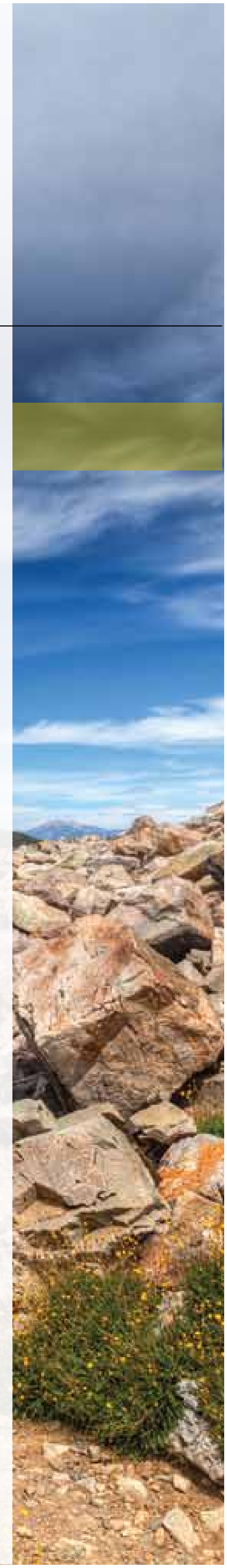



**Figure 14.** Köppen classification for the Great Basin. BLM field office boundaries are shown, along with active weather/ climate stations (black dots).

# Previous Studies

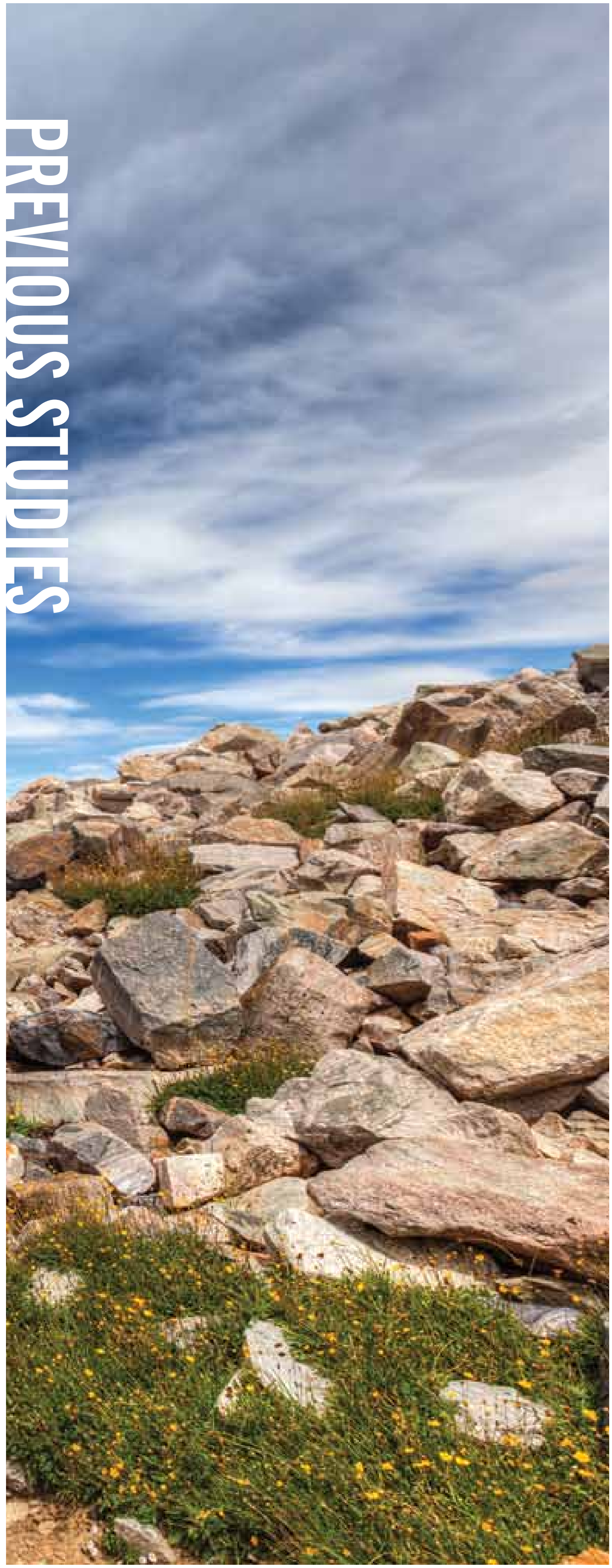
This report builds upon previous studies that have addressed weather station density and data gaps for specific networks and applications in the Great Basin. However, few studies have been undertaken. Two reports have been conducted that focus on the RAWS network and fire weather monitoring. Brown et al. (2001) examined the spatial distribution of RAWS in the Great Basin by correlating meteorological elements of temperature, relative humidity and wind speed, and also applying a geostatistical variogram method to determine optimal station spacing. This study result suggested that RAWS should be no more than 50 miles apart in the Great Basin, but highlighted that elevation should also be factored such that the 50 mile radius applies within each of three elevation bands (<5,000 feet, ≥5,000 feet and ≤7,000 feet, and >7,000 feet). Brown et al. (2011) conducted a more general study on the entire RAWS network covering all of the United States. The primary purpose of this report was to examine RAWS and non-RAWS (Automated Surface Observing System [ASOS)]) observations with regard to their influence on gridded depictions of model initializations. Stone et al. (2007) performed a gap analysis on data regarding water quantity and quality in the Humboldt River Basin (a large watershed in the central Great Basin) and provided recommendations to improve monitoring of several variables including evapotranspiration, precipitation, and streamflow. To help fill the gap in long-term climate monitoring networks in the Great Basin the Nevada Climate-Ecohydrology Assessment Network (NevCAN; Mensing et al. 2013) was deployed beginning in 2010. NevCAN consists of two basin-to-mountaintop transects with one in the Snake Range in northeast Nevada and the other in the Sheep Range of southern Nevada. This is the only monitoring network of its kind in the Great Basin.

A key element that has yet to be studied is the spatial distribution of weather stations measuring variables useful for drought monitoring in the Great Basin. Wood et al. (2015) note that a number of key elements needed for drought monitoring are sparse or declining in recent years, and critical variables of soil moisture and evaporation (e.g., Stone et al., 2007) are not well observed. Garfin et al. (2013) argue that better monitoring of the hydrologic cycle is needed throughout the Southwest (CA, NV, UT, NM, CO, and AZ) to add confidence to our understanding of drought and climate change. Therefore, evaluating the spatial density of stations measuring important variables of soil moisture, evapotranspiration, and reference evapotranspiration (computed from temperature, wind speed, humidity, and solar radiation) in the Great Basin would prove useful for improvements in drought monitoring efforts.



## QUANTITATIVE METHODS FOR ANALYZING METEOROLOGICAL NETWORKS

Numerous quantitative methods have been developed to assist in analyzing meteorological networks. One of the first was Gandin (1970) on the planning of meteorological station networks. Simple methods include spatial correlation of meteorological elements within a given region (e.g., Brown et al. 2001) or applying a maximum radius around stations to identify gaps in the observing network. A more complex method described in Vose and Menne (2004) details a procedure to provide guidance in determining the number of stations required to capture changes in the spatial mean of climate variables over a specific regions. The basis of Vose and Menne (2004) methodology involves degrading the station density of an existing network incrementally and for each incremental decrease quantifying network performance. Mazzarella and Tranfaglia (2000) found fractal characterization to work well when identifying new locations for a rain gauge network. Ashraf et al. (1997) used geostatistics to evaluate partial weather station networks. A complex statistical method network correlational redundancy minimization is described by der Megreditchian (1990). The establishment of station locations for the U.S. Climate Reference Network was based on analysis that used hypothetical networks from representative subsamples of stations in an existing higher-density baseline network, and provided details on how many stations were required to reproduce the variability in an existing station network (Janis et al. 2004). While these methods can be helpful in establishing a network, understanding the application for which the observations will support is a necessary first step, and as discussed in the next section, there are many details to specific siting.



# Station Sitings

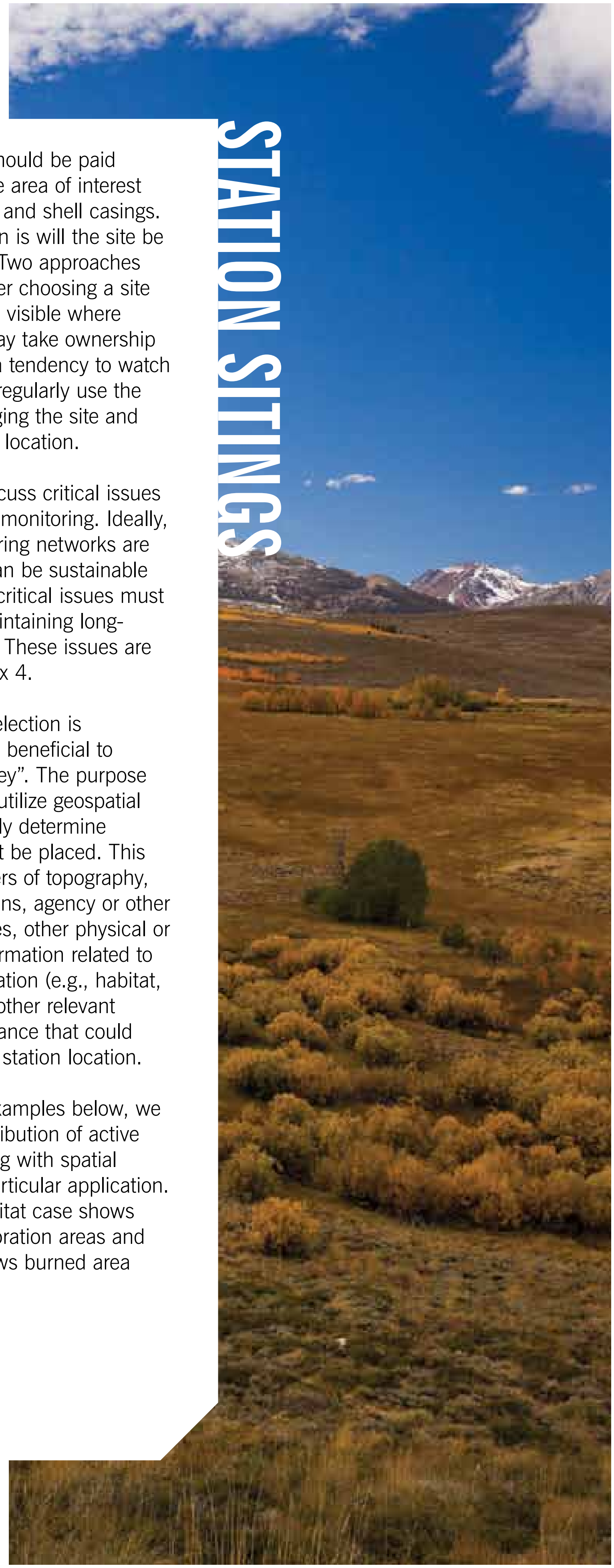
It is beyond the scope of this project to show specifically where stations should be sited. This is because 1) determining the location for a station requires a site visit to assess a number of criteria such as exposure, representativeness, access, and security; and 2) the specific purpose (e.g., management need) of the station must be identified. The networks shown in Figure 12 were established for a variety of reasons. For example, the primary purpose of Department of Transportation stations is to measure the weather in relation to road conditions, Agrimet is geared towards agriculture, and RAWS is primarily for wildfire. This does not mean that the data cannot be used for multiple purposes, but the primary purpose is obviously important for location consideration. In fact, when siting a station, other potential uses of the data should be considered, though sometimes that is not recognized until after a database has been developed. For example, the RAWS network was initially established to provide fire danger and weather information. However, given a long-term climatology for a number of RAWS and an emerging variety of land management decision-making needs, RAWS data are now used for more than just wildfire (Brown et al. 2011).

Once the need is identified, the site selection process is governed by a combination of both scientific and practical considerations including:

- **Spatial representativeness**
- **Total number and density of sites necessary to address relevant scientific questions**
- **Long-term site stability**
- **Avoidance of artificial heating sources or potential encroachment of human built structure**
- **Ease of year-round access for deployment and routine maintenance**
- **Site security.**

The spatial representativeness of the site is a primary consideration in the site selection process. The concept of spatial representativeness is a guiding factor that addresses whether the site is intended to represent the climate on a broader regional scale or some other finer scale that may be of interest towards a particular application, e.g., representing a particular habitat or microclimate. Additionally, the total number of sites (and density) may influence the site selection process because one site may have to address a variety of scientific and management-related questions. In such case, it may be necessary to identify a location that is climatically representative of a broader region, such as a large basin or a particular elevation extent.

# STATION SITINGS



Other factors in the site selection process focus on the physical characteristics of the site and how those may enhance or hinder the measurement process. Some considerations may include: type of vegetative cover; density of vegetation; height of trees or shrubs; canopy gap size; distance from water bodies (streams, rivers, lakes, reservoirs); and slope aspect/angle. Some physical environments may be favorable for differing types of measurements; for example precipitation, where having some canopy cover surrounding the site can help reduce turbulence, which is favorable in trying to capture precipitation particularly in windy areas. However, the same area may not be as advantageous for measuring solar radiation, which may be obstructed at certain times of the day and year by the canopy.

Some practical considerations include long-term site stability, avoidance of artificial heating sources, ease of access, and site security. Practical considerations should weigh equally in the site selection process; however, they are often overlooked. One of the primary goals in long-term climate monitoring is to limit data gaps that are bound to arise over time due to sensors malfunctioning or vandalism. When emergency maintenance is necessary, it is important that access to the site is relatively easy so the site can be repaired as quickly as possible. Sites in very remote areas, particularly in mountainous terrain, can be seasonally snowed in and inaccessible for long periods; thus, increasing the possibility that the site may not be repaired in a timely manner. Logistical considerations need to be well thought out and leaning towards a conservative approach for long-term success. Site security is another issue of importance in the site selection process. Particular attention should be paid towards "clues" in the area of interest such as broken glass and shell casings. An important question is will the site be visible to the public? Two approaches can be taken: 1) either choosing a site location that is highly visible where people in the area may take ownership of the site and have a tendency to watch over it because they regularly use the data, or 2) camouflaging the site and placing it in a remote location.

Karl et al. (1996) discuss critical issues for long-term climate monitoring. Ideally, when climate monitoring networks are implemented, they can be sustainable efforts. A number of critical issues must be considered for maintaining long-term climate records. These issues are described in Appendix 4.

Before specific site selection is determined, it can be beneficial to perform a "desk survey". The purpose of this first step is to utilize geospatial information to coarsely determine where a station might be placed. This includes relevant layers of topography, nearby station locations, agency or other geographic boundaries, other physical or cultural features, information related to the purpose of the station (e.g., habitat, fire, rangeland), and other relevant factors known in advance that could influence the general station location.

For the application examples below, we show the spatial distribution of active weather stations along with spatial boundaries for the particular application. For example, the habitat case shows potential habitat restoration areas and the wildfire case shows burned area perimeters.

# Application Examples

In the following sections, we provide examples of first step station siting for three management applications and additionally for drought monitoring needs. Numerous spatial layers were collected into a dataset that include greater sage-grouse habitat boundaries, wildfire perimeters and grazing allotment. The sources for these data are provided in Appendix 5.

## HABITAT EXAMPLE

Greater sage-grouse populations have declined in the West over the past 40 years (e.g., Knick et al. 2003, Aldridge et al. 2008) and a large effort has been put into conserving the sage-grouse through restoration of habitat. Figure 15 shows regions throughout the Great Basin that have been selected by the BLM as potential restoration zones (Comer et al. 2013). Much of the potential restoration area is void of active weather stations. Climate change is likely to impact sage-grouse conservation both directly and indirectly through changes in distribution of sagebrush (the ecosystem sage-grouse need for survival), more intense and longer lasting droughts, and changes in wildfire frequency (Schrag et al. 2011; REA 2013). Therefore, it would be beneficial to sage-grouse conservation to improve the distribution of weather stations throughout the potential restoration zones.

Existing research provides an example of the climate monitoring need. Blomberg et al. (2012) highlight that annual rainfall and summer maximum temperature have a strong relationship with great sage-grouse recruitment and adult survival, respectively. The annual variation in precipitation variables (e.g., rainfall or snow depth) explained as much as 75% of the annual variance in population size. Additionally, winter snow depth is correlated to male survival. These results highlight the importance of temperature and precipitation monitoring for greater sage-grouse habitat.

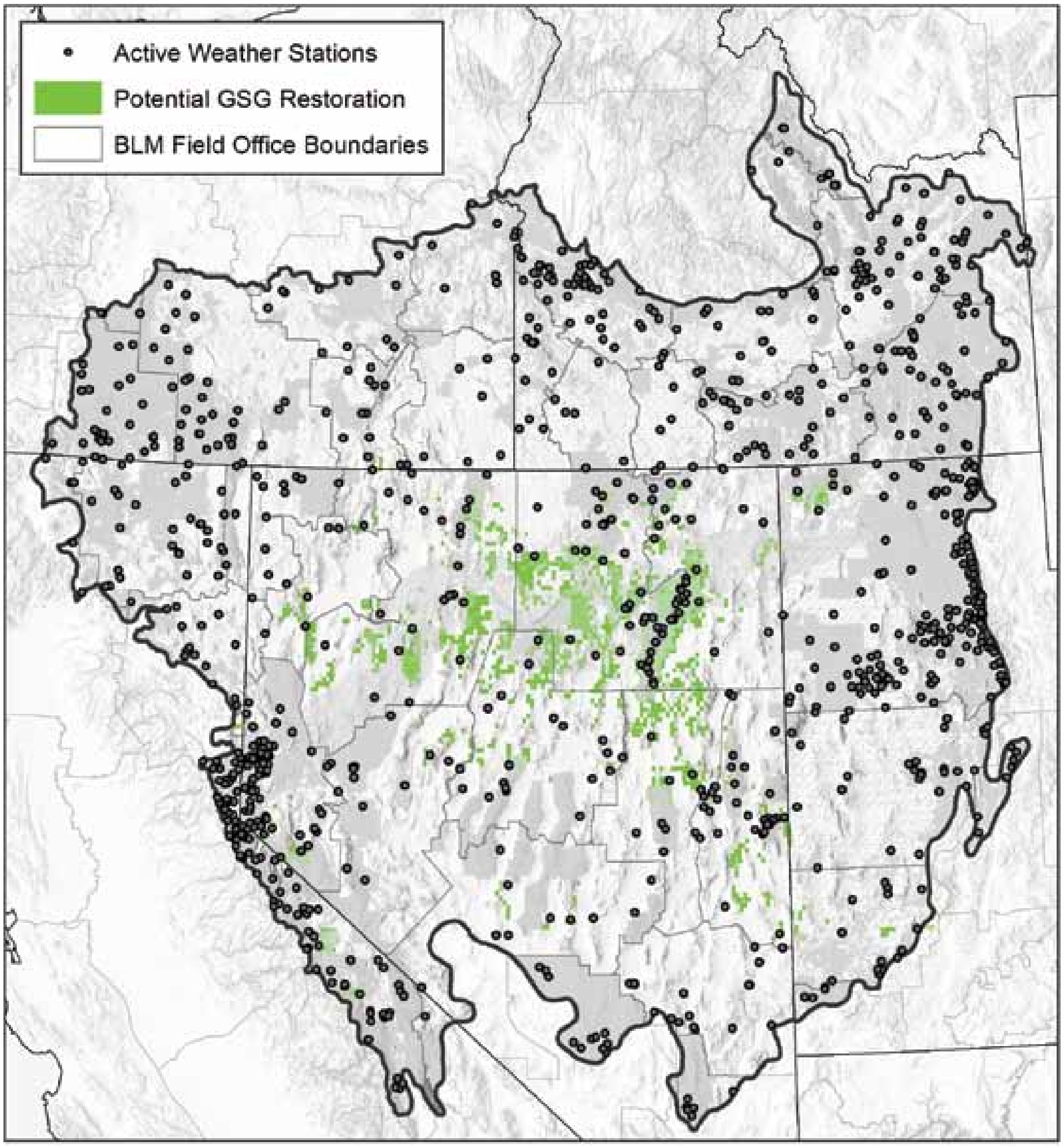



**Figure 15.** Potential greater sage-grouse restoration area shaded in green (data from Comer et al. 2013), solid symbols showing active station locations in the Great Basin.

Figure 16 highlights a potential zone for station siting to the northwest of Austin, NV. This region is also a designated BLM grazing allotment that has been identified as a potential greater sage-grouse restoration zone. A benefit of this zone is that the BLM manages rangeland in this region that is also populated by wildlife such as wild horse and burros. Thus, monitoring here would serve the primary purpose of greater sage-grouse habitat monitoring, but also other wildlife monitoring.

The nearest station to the siting zone is the Austin RAWS and is approximately 15 miles away. This station measures temperature, liquid precipitation, wind, humidity, pressure and solar radiation, but does not include solid precipitation (i.e., snow). While several other stations do exist in the surrounding area within 50 miles, these may not be sufficient for precipitation monitoring since that element is critical for the greater sage-grouse. Hence, it could be desirable to place at a minimum precipitation monitoring in the larger potential restoration areas on the map to the north and northeast of the indicated potential siting zone.

Greater sage-grouse are nearly completely reliant on sagebrush for parts of their life cycle. Though sagebrush has a deep root system, it is obviously dependent upon precipitation and soil moisture for its health. This link highlights a value of increased monitoring in the habitat areas. While more long-term precipitation monitoring would be of value in assessing drought and vegetation conditions, soil moisture measurements in relation to grouse habitat would be highly beneficial for habitat monitoring and restoration. Across the Great Basin there is a significant lack of stations that measure soil moisture. The NICE Net (Nevada Integrated Climate and Evapotranspiration Network), SCAN (Soil Climate Analysis Network), and SNOTEL networks provide soil moisture measurements, but NICE Net is located in an irrigated region and SNOTEL and SCAN at high elevations; thus not indicative of mid- to low-elevation conditions.

Another element related to greater sage-grouse is the lack of frozen precipitation measurements. RAWS and SCAN both use tipping buckets to measure precipitation which can be inaccurate at measuring liquid content of frozen precipitation (i.e., snow that has to naturally melt). The SNOTEL is the only station in the region that can accurately measure snow, but it is not representative of the greater rangeland region. Snow measurements are also crucial to understanding the local water budget and also for drought monitoring purposes.

Both soil moisture and snow are important measures for assessing drought conditions (see the following page), and thus serve immediate multiple application purposes.

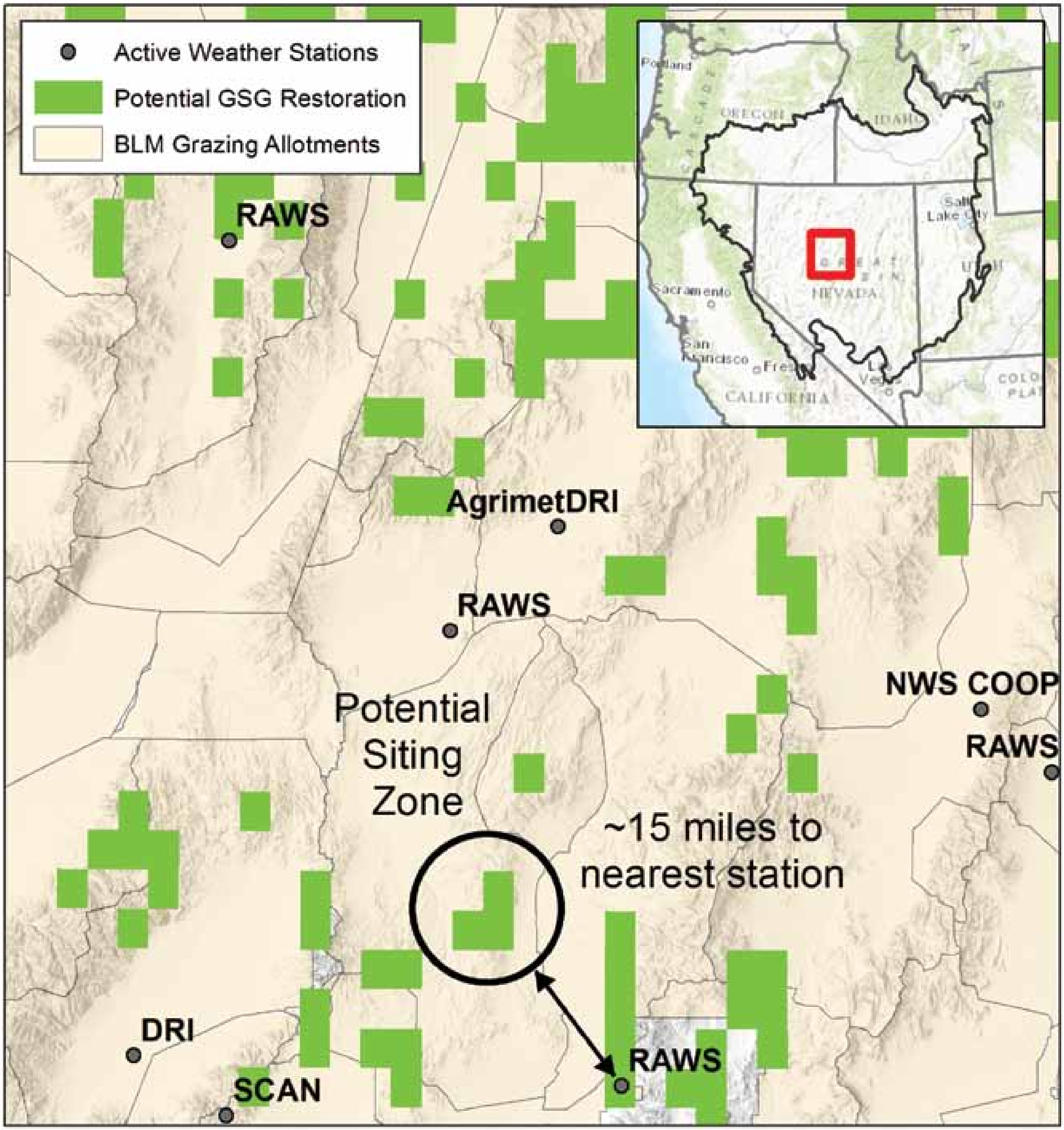



**Figure 16.** Siting example for a station located in potential greater sage-grouse restoration zone station. Red box in lower left panel shows the zoomed in area of the top panel.

## WILDFIRE EXAMPLE

Wildfire is a natural feature of the Great Basin during the summer months that is often caused by lightning strikes. Weather data are crucial for determining fire danger and monitoring fire behavior conditions. The RAWS network was established in the early 1980s for fire weather. According to the Fire Environmental Committee October 2007 RAWS/ROMAN Study Report (available from the authors of this monitoring report), "The purpose of the RAWS network is to support point and gridded applications of fire weather for fire program analysis, fire danger rating, fire behavior prediction, fire weather forecasting, and smoke management." Other networks in the Great Basin such as ASOS were not specifically designed to support fire applications, but their observations can be used for wildland fire assessments. Figure 11 and Figure 12 above show RAWS in relation to other networks. Figure 17 show all the burned areas (orange boundaries) that have occurred during 2000-2014 and the active weather stations (solid red symbols) in the Great Basin that measure fire weather elements (temperature, humidity, wind and precipitation). These stations include other networks besides RAWS, but unlike RAWS may not measure solar radiation, which is now a necessary component of the fire danger rating system. Note that much of the burned area does not include a weather station within the perimeter.

Many of the burn perimeters do not have a station directly in the area (not that they should be in a location susceptible to direct fire). For analysis and monitoring purposes, the nearest RAWS are often used, though in complex terrain, the nearest RAWS may not always be the most representative. The wildland fire management agencies likely have the best sense if their fire weather needs are being sufficiently met. However, an example is provided below based on a coarse desk survey.

The RAWS network is a special case for monitoring because interagency wildland fire weather station standards and guidelines are well established (NWCG, 2014). For station siting, the general guidelines are:

"The standard fire weather station should be located in a large, open area away from obstructions and sources of dust and surface moisture. The station should be on level ground where there is a low vegetative cover. Furthermore, it should be situated to receive full sun for the greatest possible number of hours per day during the fire season (generally 7a.m. to 7p.m.). If located on a slope, a south or west exposure is required to meet fire danger rating standards."

Additional siting standards and guidelines are given in Appendix 6.

Figure 18 shows a potential siting zone for a new fire weather station. Much of this zone has previously burned sometime during the 2000 through 2015 period. The nearest fire weather stations are about 50 miles away. Brown et al. (2001) recommended that the maximum distance between stations should be 50 miles for climatology applications and fire danger purposes. However, this spatial distance was very elevation dependent; three zones were examined (<5000 feet, 5000-7000 feet, and > 7000 feet) in the study. Further, this was the maximum recommended spatial scaling largely based on temperature and humidity. As noted throughout this report, precipitation is much more variable. Figure 18 does indicate a sizable gap given fire occurrence and the nearest RAWS. Hence, a potential siting zone is indicated. Now that a general area of interest has been identified, site visits would be necessary to determine a specific station location. It is likely that experienced field personnel would have a good sense of where a RAWS should be located to represent either a basic fire danger rating area or a more specific fire prone area.

Brown et al. (2011) discuss a more detailed analysis utilizing an objective tool to assist with station siting. This tool developed by John Horel and a graduate student at the University of Idaho (Myrick and Horel 2008) can be used to quantify the impact of adding or removing stations from a network (referred to as data denial). The procedure utilized RAWS and ASOS data, two major networks that have observations suitable for fire weather purposes. The concept is that the commonality between observations and forecasts is a grid of some given size, in this case 5km. Brown et al. (2011) expanded this concept specifically for RAWS and created the RAWS uniqueness index (RUI), which in addition to the data denial index included maintenance, period of record and terrain complexity.

Fire danger is defined as a geographic area of relatively homogenous climate, fuels and topography, tens of thousands of acres in size, within which the fire danger can be assumed to be uniform. This suggests that weather stations can potentially be generally sparse and still provide relevant fire danger information. However, fire behavior, which is the manner in which a fire reacts to the influences of fuel, weather, and topography, depends on localized conditions. Many wildfire assessments utilize the nearest RAWS for understanding characteristics of an incident or for smoke management. Thus, ideally more stations would be available to address these needs, as well as providing increased coverage of highly spatially variable elements such as precipitation.

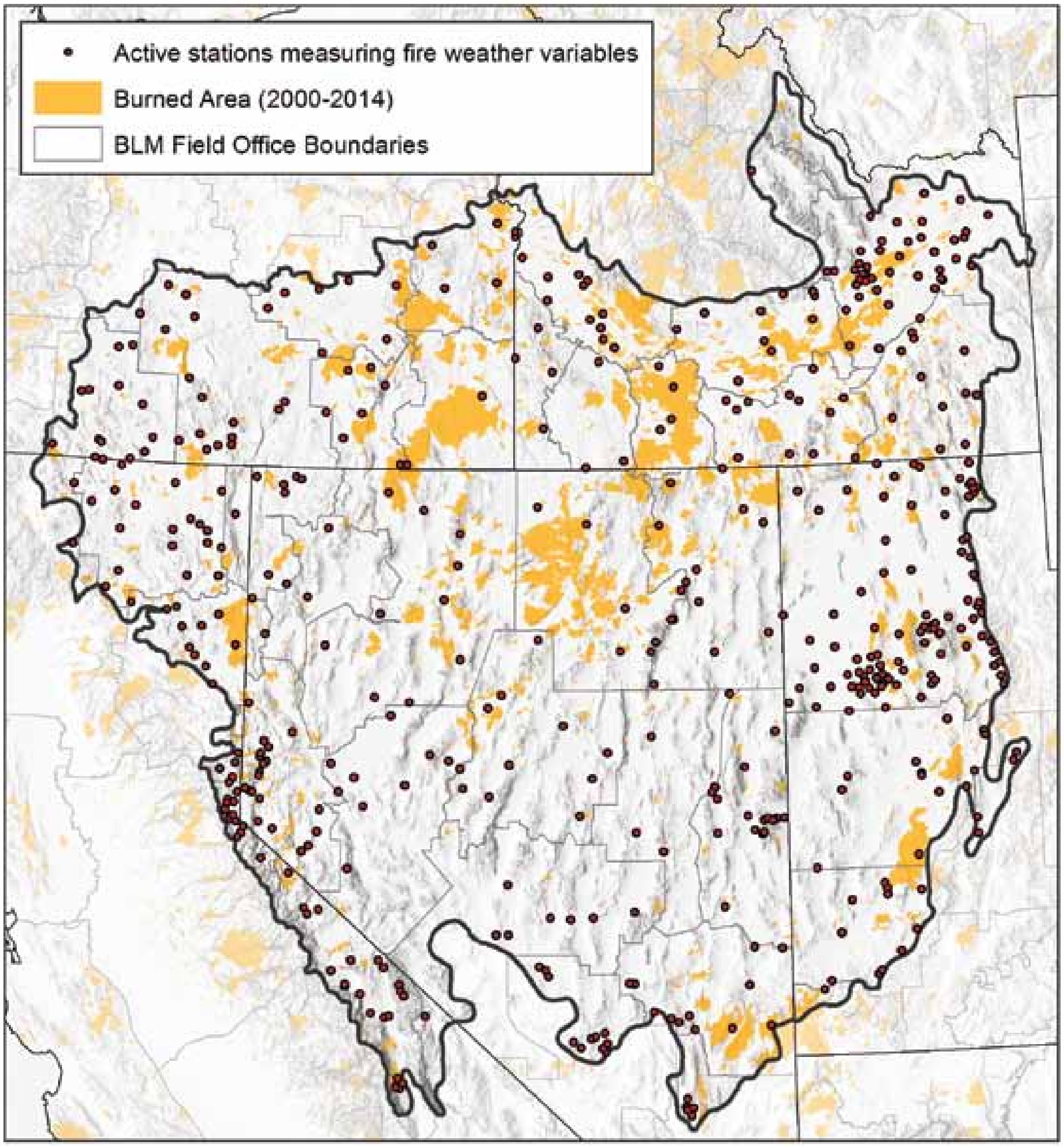



**Figure 17.** Locations of active stations (solid red circles) that measure fire weather variables (temperature, humidity, wind speed, and precipitation). Burned areas where fires have occurred (2000-2014) are shaded in orange (see Appendix 5 for data source).

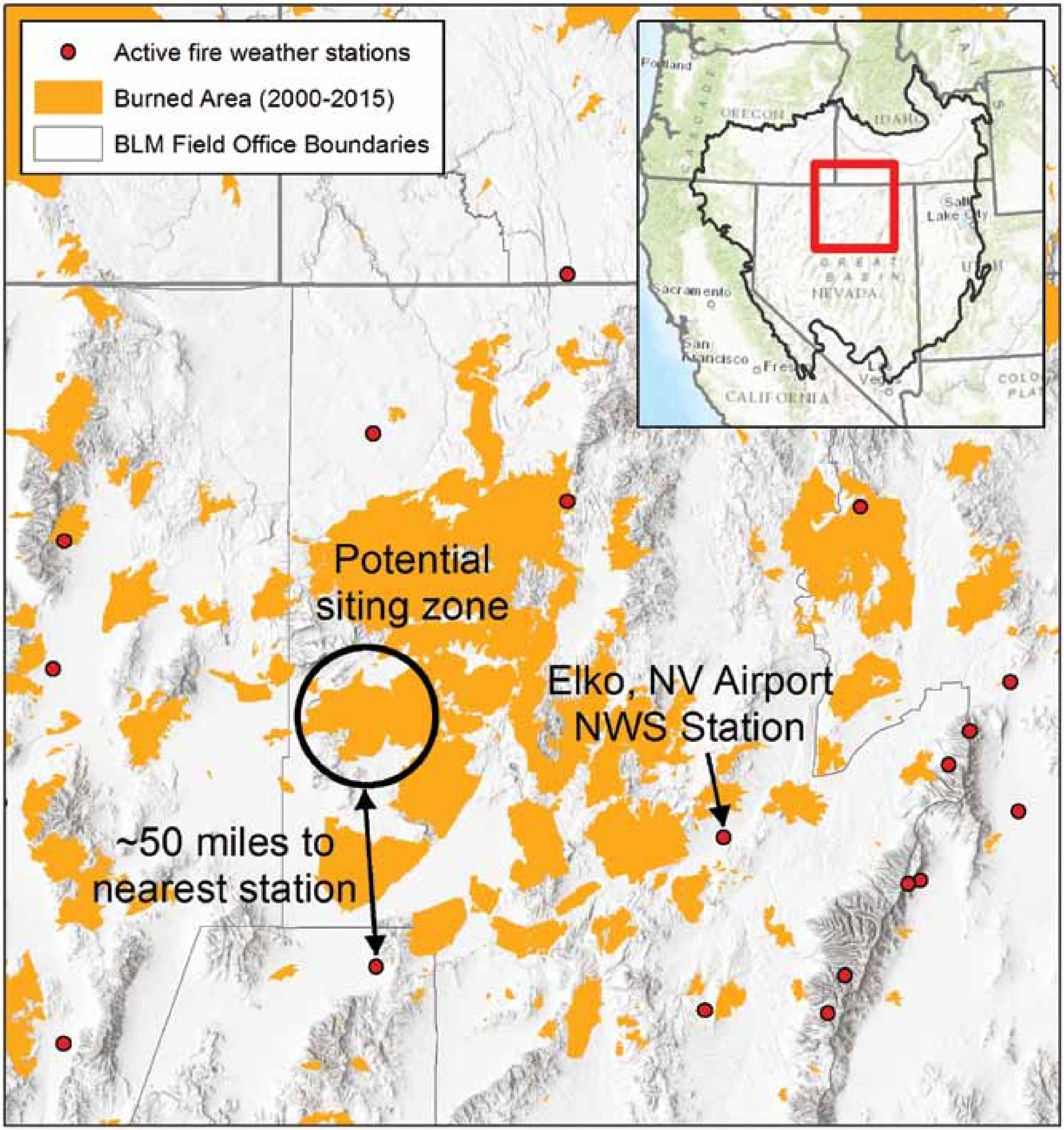



**Figure 18.** Siting example for a new fire weather station. Red box in lower left panel shows the zoomed in area of the main panel.

## RANGELAND EXAMPLE

Ranching makes up the largest sector of agriculture in Nevada (http://diversifynevada.com/key-industries/agriculture), yet there is a major lack of observations in the rangelands of Nevada for drought monitoring and ecological health purposes (Figure 19). The ecology of rangelands is largely determined by the spatial and temporal distribution of precipitation and its effects on soil water availability (Campbell et al. 1997; Knapp et al. 2001; Morgan 2005). Though temperature is an important component of rangeland productivity, soil moisture can be the predominant limiting resource for productivity, and the timing of precipitation plays an important role in regulating net primary production (NPP) (Izaurralde et al. 2011). Development of a rangeland monitoring network that includes, at the very least, measurements of temperature, precipitation (frozen and liquid), humidity, solar radiation, wind speed, and soil moisture would benefit not only the ranching community, but would also be a valuable contribution to the Drought Monitor (see next section).

While all of the Great Basin is data sparse, soil moisture measurements are even less prevalent since it is not a standard variable for most observing networks (Figure 20). The two types of networks that contribute most of the soil moisture observations to the Great Basin are SNOTEL (not all SNOTEL, only enhanced stations) and agricultural networks (e.g., AgriMET and NICE Net). SNOTEL are located in high elevation mountain sites and agricultural networks in irrigated farming locations leaving a major gap in the native rangelands of the Great Basin. Establishment of a long-term network with soil moisture in the Great Basin would also be beneficial to the larger scale problem of a general lack of soil moisture measurements over CONUS, and could potentially become incorporated into the North American Soil Moisture Database (NASMD; http://soilmoisture.tamu.edu/). A number of satellite missions are equipped with instrumentation to estimate soil moisture (Table 1), and a unified data networks such as the NASMD are a crucial component for validation in data sparse regions.

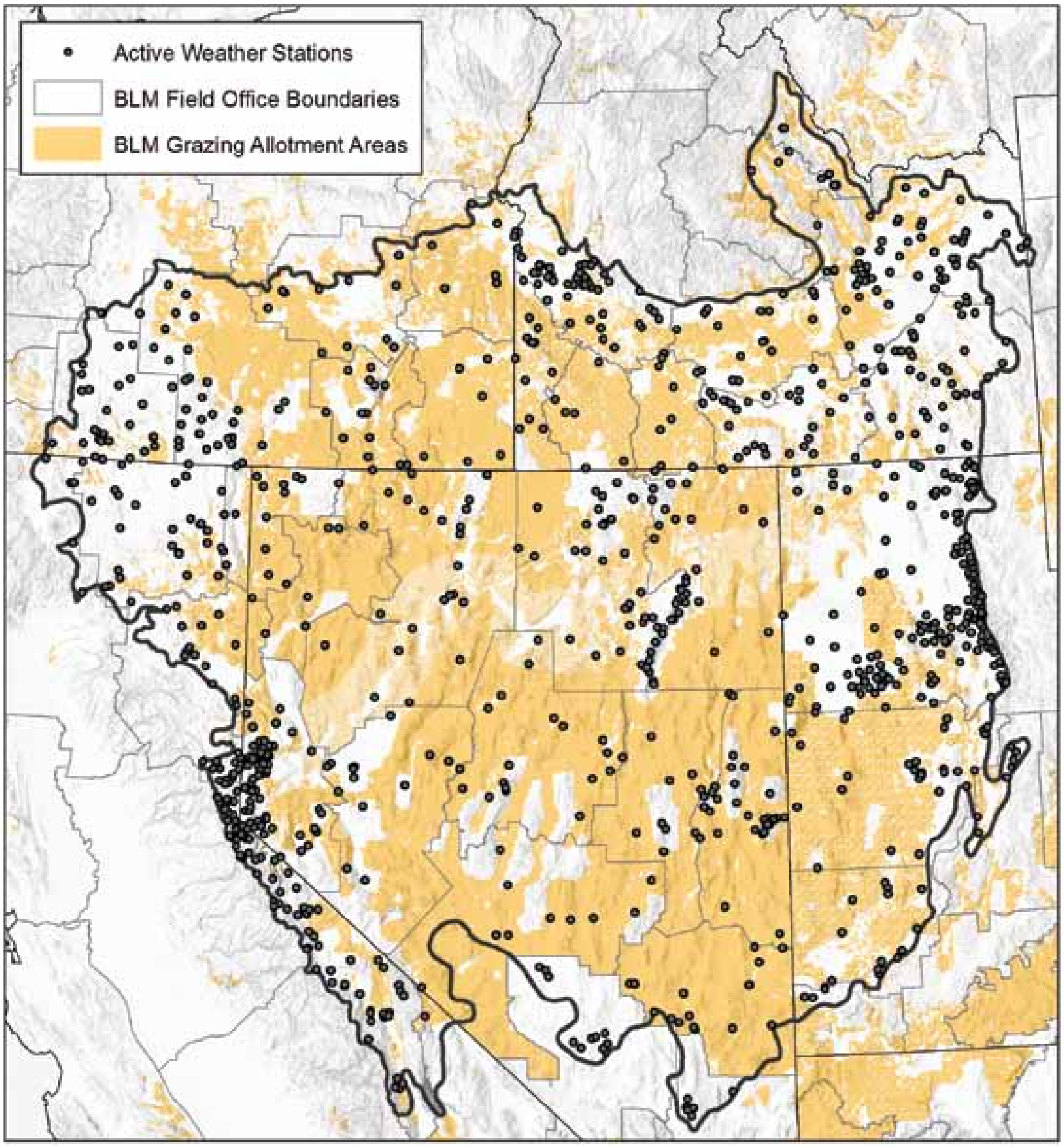



**Figure 19.** Location of active weather stations and BLM grazing allotment areas (see Appendix 5 for data source).

Table 1. Synopsis of recent and future satellite soil moisture missions. (From Ford et al. 2014)

| Mission | Period of record | Temporal Resolution | Spatial Resolution | Type | EMR-Band | Mission Website |
|---|---|---|---|---|---|---|
| SSM/I | 1987-2008 | Daily | 25 | Passive | C | http://podaac.jpl.nasa.gov |
| TRMM TM | 1998-2002 | Daily | 50-56 | Passive | C | http://trmm.gsfc.nasa.gov/ |
| Aqua AMSR-E | 2002-2011 | Daily | 56 | Passive | C | http://aqua.nasa.gov/ |
| ERS 1-2 SCAT | 1991-2010 | 35 days | 25-50 | Active | C | http://www.ipf.tuwien.ac.at |
| SMOS | 2009-present | 3 days | 50 | Passive | L | http://ilrs.gsfc.nasa.gov/missions/ |
| SMAP | 2015-present | 2-3 days | 10-40 | Both | L | http://smap.jpl.nasa.gov/ |
| MetOp ASCAT | 2007-2014 | 29 days | 50 | Active | C | http://www.ipf.tuwien.ac.at/ |

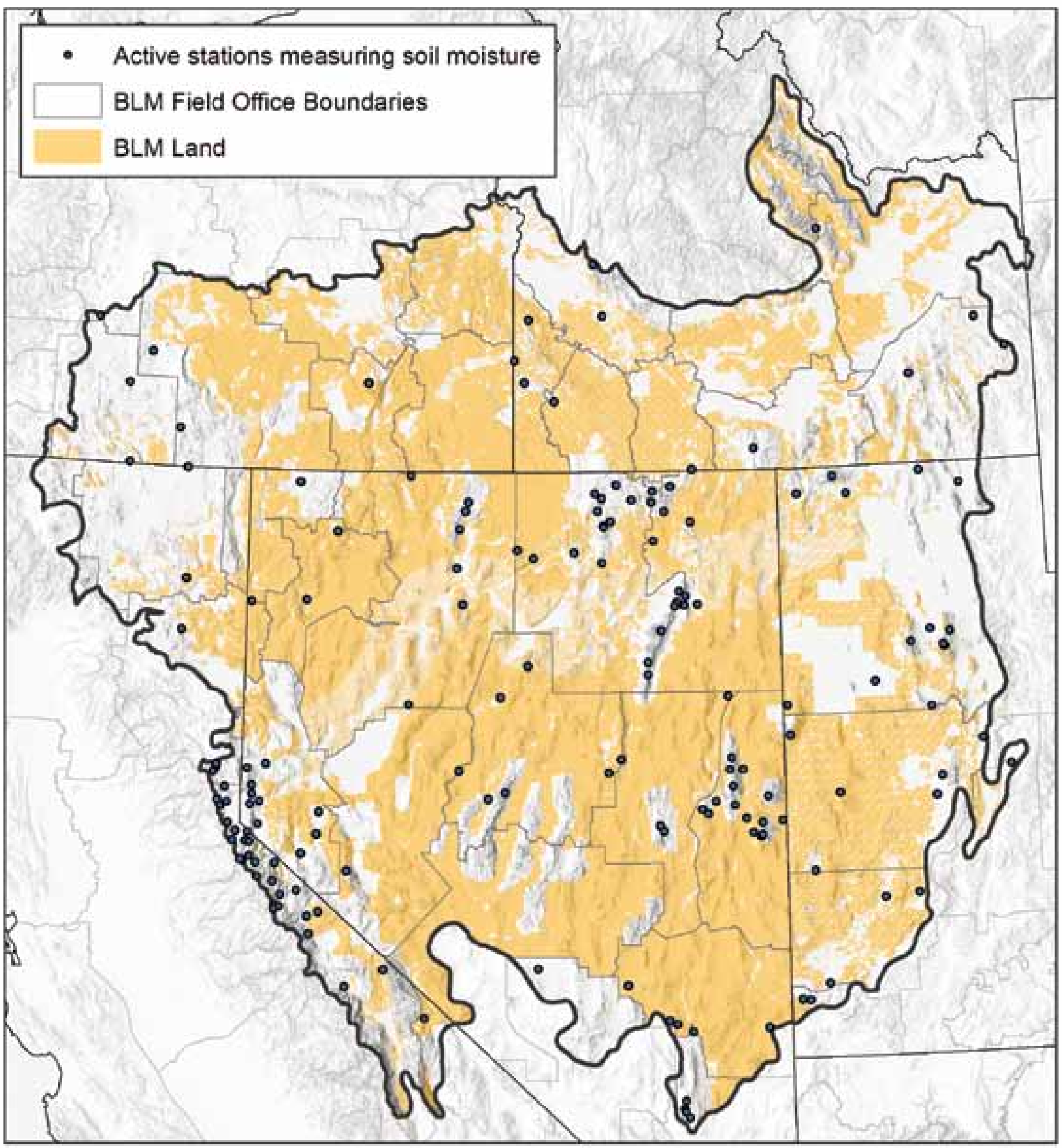



Figure 20. Location of active stations (green solid symbols) in the Great Basin that measure soil moisture (data source WRCC).

Figure 21 provides a hypothetical example of a siting location specifically implemented for rangeland drought monitoring. The potential siting zone is located in the Oregon BLM's Vale District; the most heavily used district for grazing in Oregon. The selected region is void of stations that measure soil moisture with nearest station approximately 85 miles away. All stations shown in Figure 21 are SNOTEL, which means they represent only high elevation locations, and thus there is a significant lack of mid- and low-elevation (grazing elevation) stations measuring soil moisture in this region.

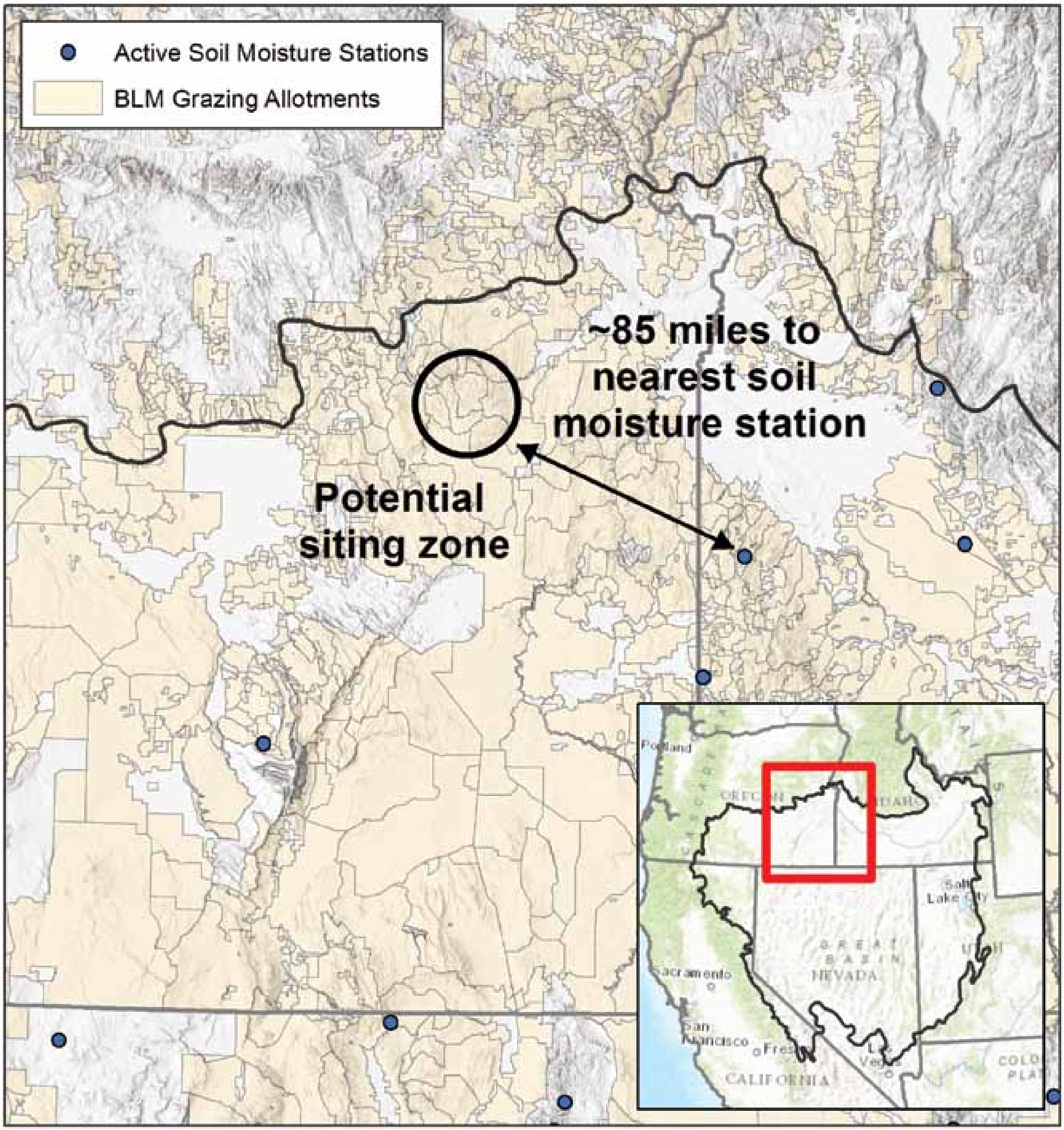



**Figure 21.** Siting example for a rangeland drought monitoring station. Red box in lower left panel shows the zoomed in area of the top panel.

## DROUGHT MONITORING

A common thread through all of the previous application examples is drought. Drought is a common feature of the climate of the Great Basin. By definition, drought is a precipitation deficiency that occurs over extended periods ranging from seasons to a decade or more and differs from aridity—a permanent climatic feature of a region where low annual precipitation amounts are normal. Operational definitions of drought are often utilized not only describe drought, but as a means to define its onset, severity, and end of drought periods. The National Drought Mitigation Center, at the University of Nebraska, Lincoln, identifies four types of drought: agricultural, hydrological, meteorological, and socioeconomic—each having a slightly different set of indices or indicators that constrain it.

According to the U.S. Drought Monitor, the Great Basin hydrologic basin (defined by the 2-digit hydrologic unit code) has experienced three distinct drought periods between 2000 and 2016 (Figure 22). The most recent drought started during the winter of 2011-12 and has persisted through early 2016; although shorter-term improvements during 2015 have led to improved conditions in various parts of the Great Basin. However, the longer-term impacts in relation to reservoir storage (Figure 23), groundwater supplies (Figure 24), and agricultural sectors have yet to recover in many areas.

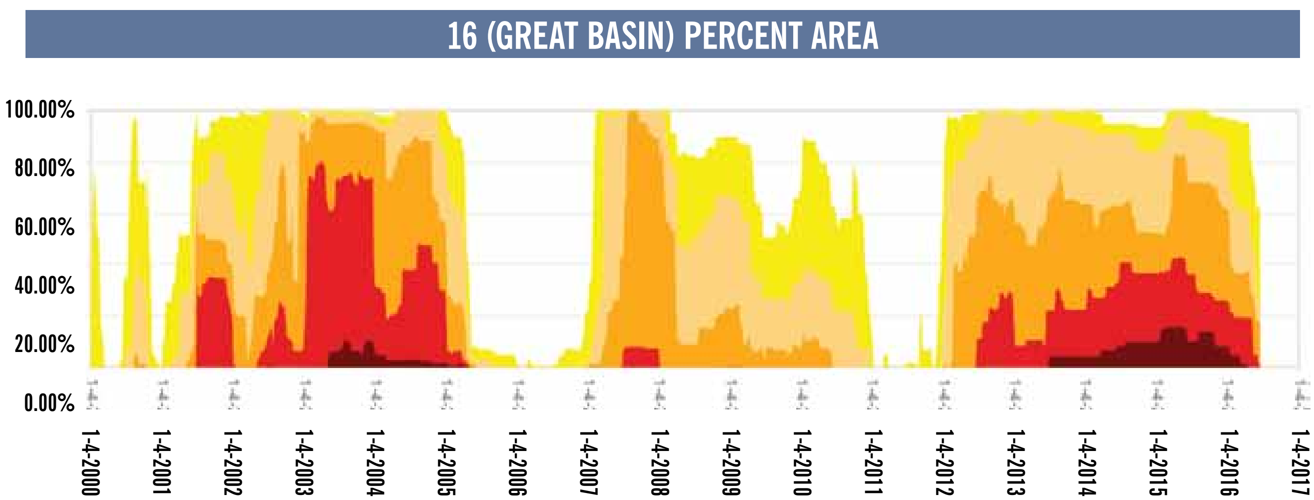



**Figure 22.** Time-series graphical representation of drought severity classifications for the Great Basin hydrologic basin for the period of 2000 to early 2016. (Data source: U.S. Drought Monitor, 2016).

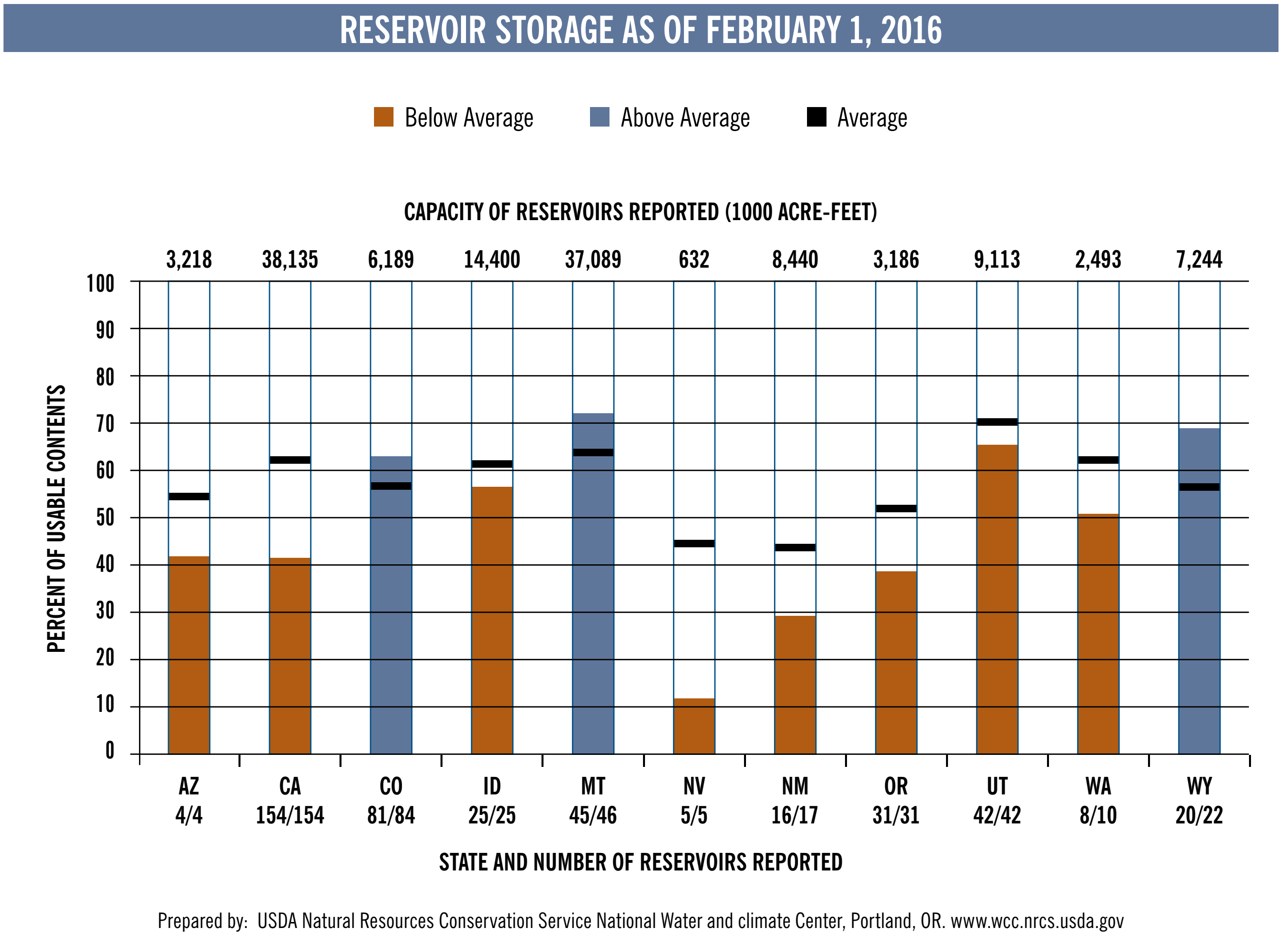



**Figure 23.** Reservoir storage conditions across the western U.S. as of February 1, 2016 (Data source: NRCS).

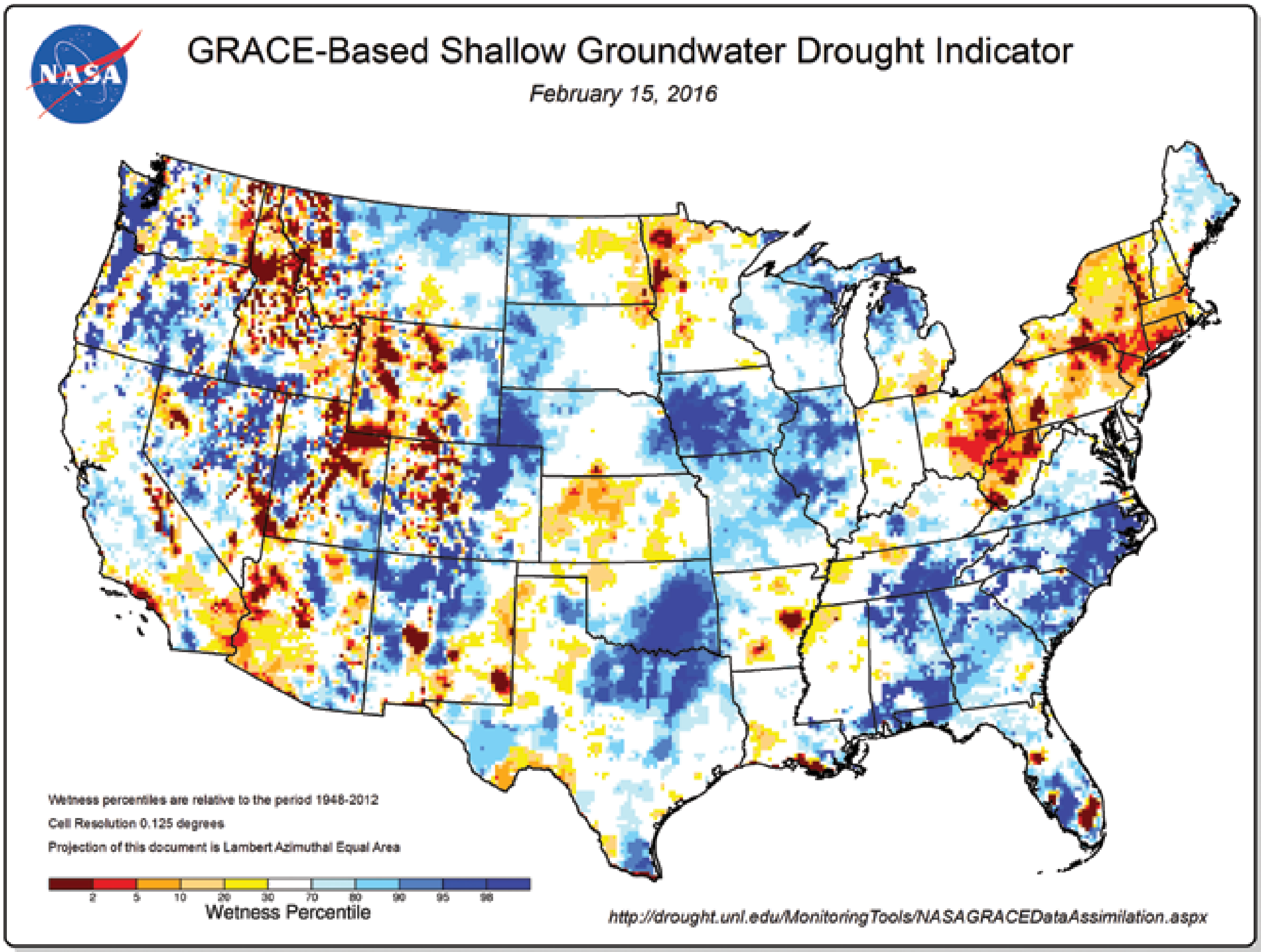



**Figure 24.** NASA GRACE-Based shallow groundwater drought indicator depicting areas of drought across the Great Basin—primarily in northwestern and southeastern portions.

Looking at longer-term trends in drought across the region using the National Drought Mitigation Center's Drought Risk Atlas (http://droughtatlas.unl.edu) provides insightful, contextual information regarding the frequency and duration of drought in the Great Basin. For instance, data from the NWS Cooperative Observer Program station (NWS COOP station ID #262573) at the Elko Regional Airport yields 12 distinct drought periods occurring since 1912 with average drought duration of 18 months and the longest duration lasting 94 months (1986-1994). Further west, the NWS COOP station at the Winnemucca Municipal Airport (NWS COOP ID #269171) shows 5 distinct drought periods since 1949 with an average duration of 56 months with the longest lasting 103 months (1986-1995).

Drought coordination activities across the region has been improving in recent years as drought has significantly impacted most of the western states during the past ten to fifteen years. Water resource-related issues have been at the forefront; however, impacts to agriculture, recreation (ski industry, fishing), and to the natural environment (drought-induced tree mortality, fishery issues) have brought about the need to enhance coordination activities. Efforts led by the National Drought Mitigation Center (http://drought.unl.edu/Home.aspx), National Integrated Drought Information System (http://www.drought.gov/drought/), U.S. Drought Monitor (http://droughtmonitor.unl.edu/), and the Western Governors' Association (http://www.westgov.org/initiatives/drought-forum) have been pivotal in improving coordination activities between federal, state, local, and private sector entities to address the complex array of issues associated with drought.

Assessment and monitoring of drought for operational purposes (as employed by the U.S. Drought Monitor) is a data-driven process that relies heavily on access to high-quality environmental data products (climatic, hydrologic, soil moisture, etc.) as well as input from an extensive network of contributors across the nation that acts as "boots on ground" providing verification of data products as well as key information on observed local impacts. Currently, the U.S. Drought Monitor has about 450 contributors nationwide from various federal, state, and local government entities. In the Great Basin, coordination activities have improved, however, assessment of drought impacts remains an area of opportunity especially as it relates to obtaining timely feedback from the entities such as the BLM and from ranchers regarding rangeland conditions during the spring and summer months.

Addition of new monitoring stations equipped with all-season precipitation gauges, soil moisture sensors, and cameras would aid in the assessment process. Despite improvements in data products and coordination, the general nature of assessing and monitoring drought remains complex and challenging because drought impacts various natural systems and socioeconomic sectors in differing manners and time-scales. Recovery from drought may occur over the course of a season, i.e., ski industry, or it may linger on for many years or decades in the case of hydrologic impacts in relation to reservoir storage and groundwater systems.

In the Great Basin, assessment of drought presents its own unique set of challenges because of its large areal extent, complex topography, spatially variable climate, and low density of weather-climate observational sites. The scarcity of quality precipitation measurements (liquid and frozen precipitation) in its numerous mountain ranges and valleys make depiction of conditions across this extensive region difficult. In addition to the overall low spatial density of observing sites is the issue of the actual quantity of stations possessing long-term records from which to derive climatologies that are essential in order to provide necessary context to current conditions. Aside from surface observational data, the U.S. Drought Monitor relies on various modeled products (informed by observational data), such as the North American Land Data Assimilation System (NLDAS) that is utilized to depict soil moisture conditions (http://www.emc.ncep.noaa.gov/mmb/nldas/drought/). However, ground-truthing of NLDAS and other remote sensing products is hampered by the lack of in-situ soil moisture measurements. Additionally, several remote sensing-based products are regularly used to depict the vegetative health, soil moisture, and shallow groundwater conditions including: NASA GRACE Data Assimilation (groundwater, root zone soil moisture, surface soil moisture http://drought.unl.edu/monitoringtools/nasagracedataassimilation.aspx); and VEGDRI (vegetation stress - http://drought.unl.edu/MonitoringTools/VegDRI.aspx).

## CLIMATE CHANGE

Climate change has been identified as an important change agent in the Great Basin (REA, 2013). The REA report utilized climate projection output to depict possible future change later in the century. There are many different models and scenarios to depict future climate. Common elements typically shown from the models are temperature and precipitation. Higher certainty is associated with future temperature projections as the models are considered to have reasonable predictive skill for this element. Future precipitation is less certain as this is a more difficult element to predict. What is highly uncertain, however, is the amount of future greenhouse gas (GHG) emissions because this is directly related to political and social factors. The uncertainty in future GHG emissions creates a wider range of possible future climate scenarios. However, regardless of the global climate model used, in all cases the temperature continues to increase across the Great Basin. A relevant question then is how best to utilize climate change projections in relation to monitoring.

One method would be to use climate model output of temperature and precipitation to compute the Köppen classification, and compare the spatial maps of the future classification to a baseline period such as the past 30 years. This would show spatial shifts in climate if it occurs, and then climate monitoring stations could be assessed in relation to any shifts. Basically, this is producing a future climate map of Figure 14, and assessing station locations in the context of the new map and in association with potential changes in the management application. Global climate model output is quite coarse in grid size, and statistical methods would be required to downscale the information to a higher spatial resolution such as provided by PRISM. Changes in the Köppen classification can be identified by this type of analysis as shown in other studies (e.g., Diaz and Eischeid 2007; Rubel and Kottek 2010).

# Recommendations

Based on describing the regional physical characteristics, station siting guidelines, and management applications, a number of recommendations are offered to improve climate monitoring in the Great Basin. The list below is not given in any particular order:

## STATION COVERAGE AND SITING

1) Compared to every place else in the contiguous U.S., the Great Basin has the least number of weather and climate stations. Yet the management needs for climate information are comparable to other regions that have more observations. The number of all weather stations should be increased in the Great Basin. This will provide valuable information for nearly all management applications, including both historical climatology for analyses, and real-time data for numerical weather prediction.
2) A detailed analysis should be undertaken directly with the land management agencies to assess priority placement of new stations. This needs to be based on both the management application and the specific siting evaluation.
3) The number of stations and specific locations is critically based on understanding the management application need. Other potential uses and benefits should be considered in the process of establishing or expanding a network.
4) All weather station measurements (temperature, humidity, wind, precipitation, solar radiation) are highly valuable for a number of applications. The location of these stations is especially sensitive to the physical surroundings, and siting guidelines should be followed closely to allow for the best representation of an area and/or application.
5) For new RAWS, the interagency guidelines and standards should be followed, but it also recommended that fire agencies also review the Brown et al. (2011) report for assessing potential station locations.

# RECOMMENDATIONS

## DROUGHT AND PRECIPITATION

6) The Great Basin is naturally arid; thus, improved drought monitoring will be beneficial to nearly all land management applications. Implementing an improved soil moisture network would be a critical step for providing climate monitoring information especially related to habitat, rangeland and vegetation monitoring and restoration activities.

7) Precipitation is both highly spatially and temporally variable. Increasing precipitation measurements (quantity and quality [i.e., all season precipitation gauges]) across the Great Basin will provide improved information for nearly all land management applications and drought monitoring.

## LONG-TERM CLIMATE MONITORING GUIDELINES

8) Knowledge of instrument, station and/or platform history is essential for data interpretation and use. Changes in instrument sampling time, local environmental conditions for in-situ measurements, and any other factors pertinent to the interpretation of the observations and measurements should be recorded as a mandatory part of the observing routine and be archived with the original data (Karl et al. 1996).

9) In-situ and other observations with a long uninterrupted record should be maintained. Every effort should be applied to protect the data sets that have provided long-term homogeneous observations (Karl et al. 1996).

10) Climate record homogeneity must be routinely assessed, and corrective action must become part of the archived record (Karl et al. 1996).

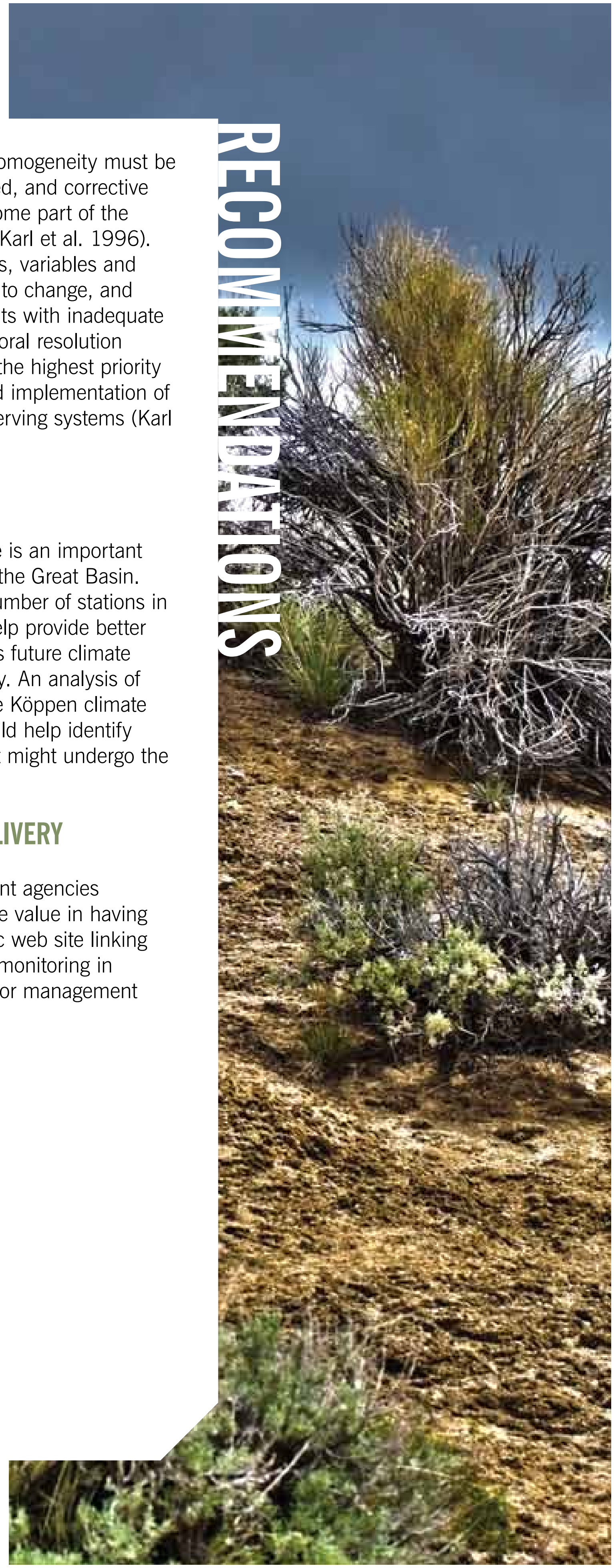
11) Data poor regions, variables and regions sensitive to change, and key measurements with inadequate spatial and temporal resolution should be given the highest priority in the design and implementation of new climate observing systems (Karl et al. 1996).

## FUTURE CLIMATE

12) Changing climate is an important change agent in the Great Basin. Increasing the number of stations in the region will help provide better data coverage, as future climate becomes a reality. An analysis of changes in future Köppen climate classification could help identify those places that might undergo the most change.

## INFORMATION DELIVERY

13) Land management agencies should assess the value in having a dedicated basic web site linking together climate monitoring in the Great Basin for management applications.



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# APPENDIX 1. GREAT BASIN DESCRIPTIVE INFORMATION

**Table A1.1.** Topographic characteristics of the Great Basin outline in the main report body Figure 1 as percent area.

| Min Elevation (meters) | Max Elevation (meters) | Min Elevation (feet) | Max Elevation (feet) | Percent |
|---|---|---|---|---|
| 200 | 400 | 656 | 1312 | 0.01% |
| 400 | 600 | 1312 | 1969 | 0.34% |
| 600 | 800 | 1969 | 2625 | 1.74% |
| 800 | 1000 | 2625 | 3281 | 2.17% |
| 1000 | 1200 | 3281 | 3937 | 6.01% |
| 1200 | 1400 | 3937 | 4593 | 21.08% |
| 1400 | 1600 | 4593 | 5249 | 20.16% |
| 1600 | 1800 | 5249 | 5906 | 18.37% |
| 1800 | 2000 | 5906 | 6562 | 14.14% |
| 2000 | 2200 | 6562 | 7218 | 7.61% |
| 2200 | 2400 | 7218 | 7874 | 3.89% |
| 2400 | 2600 | 7874 | 8530 | 2.06% |
| 2600 | 2800 | 8530 | 9186 | 1.10% |
| 2800 | 3000 | 9186 | 9843 | 0.58% |
| 3000 | 3200 | 9843 | 10499 | 0.33% |
| 3200 | 3400 | 10499 | 11155 | 0.19% |
| 3400 | 3600 | 11155 | 11811 | 0.10% |
| 3600 | 3800 | 11811 | 12467 | 0.05% |
| 3800 | 4000 | 12467 | 13123 | 0.03% |
| 4000 | 4200 | 13123 | 13780 | 0.01% |
| 4200 | 4400 | 13780 | 14436 | 0.00% |
| 4400 | 4600 | 14436 | 15092 | 0.00% |

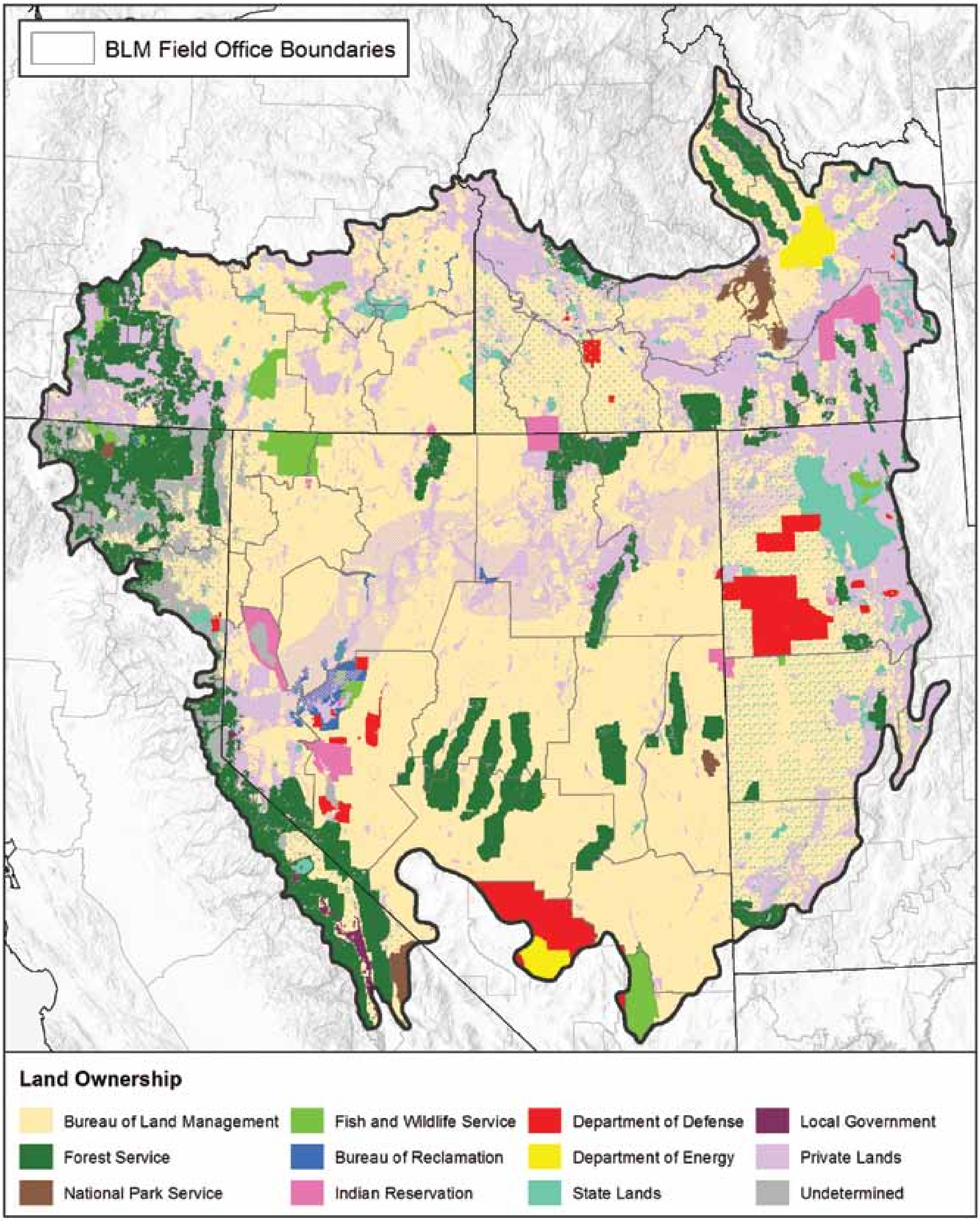


**Figure A1.1.** Land stewardship in the Great Basin.

**Table A1.2.** Breakdown of land ownership in the Great Basin.

| Owner | Square Miles | Percent |
|---|---|---|
| Bureau of Land Management | 117,878 | 55.7 |
| Bureau of Reclamation | 927 | 0.4 |
| Department of Defense | 5581 | 2.6 |
| Department of Energy | 1504 | 0.7 |
| Fish and Wildlife Service | 3189 | 1.5 |
| Forest Service | 24,860 | 11.7 |
| National Park Service | 1319 | 0.6 |
| Other Federal Agencies | 27 | 0.0 |
| Indian Reservation | 2715 | 1.3 |
| Non California Private Lands | 44,656 | 21.1 |
| California private Lands | 5606 | 2.6 |
| State Lands | 8037 | 3.8 |
| Local Government | 380 | 0.2 |
| Undetermined | 701 | 0.3 |

**Table A1.3.** Number of square miles and percentage of the total area (for all categories above 0.50%) for the region. Highlighted in grey are the categories with the six largest areas.

| Vegetation Type | Area (mi ^ 2) | Percent |
|---|---|---|
| Alpine Dwarf-Shrubland, Fell-field and Meadow | 590 | 0.50% |
| Aspen Forest, Woodland, and Parkland | 823 | 0.70% |
| Aspen-Mixed Conifer Forest and Woodland | 49 | 0.04% |
| Barren | 4507 | 3.84% |
| Big Sagebrush Shrubland and Steppe | 38818 | 33.03% |
| Blackbrush Shrubland | 239 | 0.20% |
| Chaparral | 77 | 0.07% |
| Creosotebush Desert Scrub | 153 | 0.13% |
| Deciduous Shrubland | 113 | 0.10% |
| Desert Scrub | 3364 | 2.86% |
| Developed-Roads | 249 | 0.21% |
| Developed-Upland Herbaceous | 99 | 0.08% |
| Developed-Upland Shrubland | 140 | 0.12% |
| Douglas-fir Forest and Woodland | 87 | 0.07% |
| Douglas-fir-Grand Fir-White Fir Forest and Woodland | 181 | 0.15% |
| Douglas-fir-Ponderosa Pine-Lodgepole Pine Forest and Woodland | 74 | 0.06% |
| Grassland | 1195 | 1.02% |
| Grassland and Steppe | 1920 | 1.63% |
| Greasewood Shrubland | 7761 | 6.60% |
| Introduced Annual and Biennial Forbland | 1690 | 1.44% |
| Introduced Annual Grassland | 11377 | 9.68% |
| Introduced Perennial Grassland and Forbland | 766 | 0.65% |
| Juniper Woodland and Savanna | 828 | 0.71% |
| Low Sagebrush Shrubland and Steppe | 14966 | 12.74% |
| Mountain Mahogany Woodland and Shrubland | 717 | 0.61% |
| Open Water | 195 | 0.17% |
| Pinyon-Juniper Woodland | 11447 | 9.74% |
| Ponderosa Pine Forest, Woodland and Savanna | 333 | 0.28% |
| Salt Desert Scrub | 12206 | 10.39% |
| Sparse Vegetation | 1964 | 1.67% |
| Western Riparian Woodland and Shrubland | 581 | 0.49% |

# APPENDIX 2. KÖPPEN CLASS DESCRIPTIONS

Peel et al. (2007) developed an updated world map of the Köppen-Geiger climate classification. This same methodology was used to create the data for Figure 8 and 14. The table below provides details for the classification.

**Table A4.1.** Description of Köppen climate symbols and defining criteria.

| 1st | 2nd | 3rd | Description | Criteria* |
|---|---|---|---|---|
| A | | | Tropical | $T_{cold}$≥18 |
| | f | | - Rainforest | $P_{dry}$≥60 |
| | m | | - Monsoon | Not (Af) & $P_{dry}$≥100–MAP/25 |
| | w | | - Savannah | Not (Af) & $P_{dry}$ |
| B | | | Arid | MAP<10×$P_{threshold}$ |
| | W | | - Desert | MAP<5× $P_{threshold}$ |
| | S | | - Steppe | MAP≥5× $P_{threshold}$ |
| | | h | - Hot | MAT≥18 |
| | | k | - Cold | MAT<18 |
| C | | | Temperate | $T_{hot}$>10 & 0< $T_{cold}$ <18 |
| | s | | - Dry Summer | $P_{sdry}$< 40 & $P_{sdry}$<$P_{wwet}$/3 |
| | w | | - Dry Winter | $P_{wdry}$< $P_{swet}$/10 |
| | f | | - Without dry season | Not (Cs) or (Cw) |
| | | a | - Hot Summer | $T_{hot}$ ≥22 |
| | | b | - Warm Summer | Not (a) & $T_{mon}$10≥4 |
| | | c | - Cold Summer | Not (a or b) & 1≤$T_{mon}$10<4 |
| D | | | Cold | $T_{hot}$ >10 & $T_{cold}$ ≤0 |
| | s | | - Dry Summer | $P_{sdry}$< 40 & $P_{sdry}$<$P_{wwet}$/3 |
| | w | | - Dry Winter | $P_{wdry}$< $P_{swet}$/10 |
| | f | | - Without dry season | Not (Ds) or (Dw) |
| | | a | - Hot Summer | $T_{hot}$ ≥22 |
| | | b | - Warm Summer | Not (a) & $T_{mon}$10≥4 |
| | | c | - Cold Summer | Not (a, b or d) |
| | | d | - Very Cold Winter | Not (a or b) & $T_{cold}$ <–38 |
| E | | | Polar | $T_{hot}$<10 |
| | T | | - Tundra | $T_{hot}$ > 0 |
| | F | | - Frost | $T_{hot}$ ≤0 |

*MAP = mean annual precipitation, MAT = mean annual temperature, $T_{hot}$ = temperature of the hottest month, $T_{cold}$ = temperature of the coldest month, $T_{mon}$10 = number of months where the temperature is above 10, $P_{dry}$ = precipitation of the driest month, $P_{sdry}$ = precipitation of the driest month in summer, $P_{wdry}$ = precipitation of the driest month in winter, $P_{swet}$ = precipitation of the wettest month in summer, $P_{wwet}$ = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

# APPENDIX 3. NETWORK DESCRIPTIONS

**Table A3.1.** Description of station networks in the Great Basin.

| Network Name | Purpose of Network | Primary Management Agencies | Website | Variables Measured | Sampling Frequency | Reporting Frequency |
|---|---|---|---|---|---|---|
| Community Environmental Monitoring Program (CEMP) | Monitor airborne levels of man-made radioactivity from activities at the Nevada Test Site. | WRCC and DRI | http://www.cemp.dri.edu/ | T, PPT, RH, TDEW, U, UD, P, and SRAD | Hourly | Hourly |
| NWS Cooperative Observer Program (COOP) | Provide observational, meteorological data required to define U.S. climate and help measure long-term climate changes. Provide observational, meteorological data in near real-time to support forecasting and warning mechanisms and other public services programs of the NWS. | NOAA (NWS) | http://www.noaa.gov/ | TMIN, TMAX, PPT, SD, and SF | Daily | Daily or monthly (station dependent) |
| NOAA Climate Reference Network (CRN) | Provide long-term homogeneous measurements of temperature and precipitation that can be coupled with long-term historic observations to monitor present and future climate change. | NOAA | http://www.ncdc.noaa.gov/ | T, PPT, U, and SRAD | Precipitation can be sampled either 5 or 15 minutes. Temperature sampled every 5 minutes. All other elements sampled every 15 minutes. | Hourly or every three hours |
| U.S. Department of Energy Nevada Test Site (DOENTS) Network | Provide weather data in support of activities at the Nevada Test Site. | NOAA/Air Resources Laboratory/Special Operations and Research Division | http://www.sord.nv.doe.gov | T, PPT, U, UD, RH, and P | Unknown | Every 15 minutes |
| Desert Research Institute | Sample weather and climate in various desert and mountain locations in support of ongoing research activities at WRCC and Desert Research Institute. | WRCC and DRI | http://www.wrcc.dri.edu/weather/index.html | T, PPT, U, UD, RH, P, TDEW, SRAD, and SM (some stations) | Every three seconds | Every 10 minutes |
| USDA/NRCS Snowcourse Network (NRCS-SC) | Collect snowpack and related climate data to assist in forecasting water supply in the western U.S. | NRCS | http://wc/sc/egov/usda.gov/nwcc/rgrpt?report=snowcourse | SD and SWE | Monthly or seasonally | Monthly or seasonally |
| Remote Automated Weather Stations (RAWS) | Provide near real-time (hourly or near hourly) measurements of meteorological variables for use in fire weather forecasts and climatology. Data from RAWS also are used for natural resource management, flood forecasting, natural hazard management, and air-quality monitoring. | WRCC and National Interagency Fire Center | http://www.raws.dri.edu/index/html | T, PPT, U, UD, RH, P, TDEW, SRAD, and SM (some stations) | 1 or 10 minutes (element dependent) | Generally hourly. Some stations report every 15 or 30 minutes. |
| USDA/NRCS Snowfall Telemetry (SNOTEL) Network | Collect snowpack and related climate data to assist in forecasting water supply in the western U.S. | NRCS | http://www.wcc.nrcs.usda.gov/snow/ | All stations: T, PPT, SD, SWE Some stations: U, UD, RH, SRAD, and SM | 1-minute temperature; 1-hour precipitation, snow water content, and snow depth. Less than one minute for relative humidity, wind speed and direction, solar radiation, and soil moisture and temperature (all at enhanced site configurations only). | Reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours. |

Variables: T = air temperature, PPT = precipitation, U = wind speed, UD = wind direction, RH = relative humidity, P = barometric pressure, TDEW = dew point temperature, SRAD = solar radiation, SM = soil moisture, SD = snow depth, SF = snowfall, and SWE = snow water equivalent.

# APPENDIX 4. CRITERIA FOR LONG-TERM MONITORING

The following are extracted directly from From Karl et al. (1996):

1. The effects on the climate record of changes in instruments, observing practices, observation locations, sampling rates, etc. must be known prior to implementing such changes. This can be ascertained through a period of overlapping measurements between old and new observing systems or sometimes by comparison of the old and new observing systems with a reference standard. Site stability for in-situ measurements, both in terms of physical location and changes in the nearby environment, should also be a key criterion in site selection. Thus, many synoptic network stations, primarily used in weather forecasting but which provide valuable climate data, and all dedicated climatological stations intended to be operational for extended periods, must be subject to such a policy.

2. The processing algorithms and changes in these algorithms must be well documented. Documentation of these changes should be carried along with the data throughout the data archiving process.

3. Knowledge of instrument, station and/or platform history is essential for data interpretation and use. Changes in instrument sampling time, local environmental conditions for in-situ measurements, and any other factors pertinent to the interpretation of the observations and measurements should be recorded as a mandatory part of the observing routine and be archived with the original data.

4. In-situ and other observations with a long uninterrupted record should be maintained. Every effort should be applied to protect the data sets that have provided long-term homogeneous observations. "Long-term" for space-based measurements is measured in decades, but for more conventional measurements "long-term" may be a century or more. Each element of the observations system should develop a list of prioritized sites or observations based on their contribution to long-term climate monitoring.

5. Calibration, validation and maintenance facilities are a critical requirement for long-term climatic data sets. Climate record homogeneity must be routinely assessed, and corrective action must become part of the archived record.

6. Where feasible, some level of "low-technology" backup to "high-technology" observing systems should be developed to safeguard against unexpected operational failures.

7. Data poor regions, variables and regions sensitive to change, and key measurements with inadequate spatial and temporal resolution should be given the highest priority in the design and implementation of new climate observing systems.

8. Network designers and instrument engineers must be provided long-term climate requirements at the outset of network design. This is particularly important because most observing systems have been designed for purposes other than long-term climate monitoring. Instruments must have adequate accuracy with biases small enough to document climate variations and changes.

9. Much of the development of new observation capabilities and much of the evidence supporting the value of these observations stem from research-oriented needs or programs. A lack of stable, long-term commitment to these observations, and lack of a clear transition plan from research to operations, are two frequent limitations in the development of adequate long-term monitoring capabilities. The difficulties of securing a long-term commitment must be overcome if the climate observing system is to be improved in a timely manner with minimum interruptions.

10. Data management systems that facilitate access, use, and interpretation are essential. Freedom of access, low cost, mechanisms, which facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.) and quality control should guide data management. International cooperation is critical for successful management of data used to monitor long-term climate change and variability.

# APPENDIX 5. DATA SOURCES

Several data sources were used to prepare the maps in this report. Station data information were retrieved from Western Regional Climate Center metadata and from the Regional Climate Center program Applied Climate Information System (ACIS). The soil moisture station map in Figure 20 was derived from SNOTEL and SCAN metadata. Spatial data layers used for the management applications are available as follows:

**Burned area for 2000–2014:**

http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/historic _ fire _ data/

**Metadata:**

http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/historic _ fire _ data/us _ historic _ fire _ perims _ dd83 _ METADATA.htm

**Grazing allotments URL:**

http://www.geocommunicator.gov/GeoComm/services.htm#Download

**GDB file:**

http://www.geocommunicator.gov/shapefilesall/GA/BLM _ Grazing _ allotments.zip

**Metadata:**

http://www.geocommunicator.gov/GeoComm/metadata/rangeland/Grazing _ Allotment _ Metadata.htm

**Greater Sage Grouse - Opportunities for habitat restoration/enhancement**

http://www.landscape.blm.gov/geoportal/rest/document?id={1A80979F-86E3-4102-A626-3C93BDA2E345}

# APPENDIX 6. STATION SITING GUIDELINES

The following is directly from the Interagency Wildland Fire Weather Station Standards and Guidelines (National Wildfire Coordinating Group, 2014):

## SITE SELECTION GUIDELINES

The standard fire weather station should be located in a large, open area away from obstructions and sources of dust and surface moisture. The station should be on level ground where there is a low vegetative cover. Furthermore, it should be situated to receive full sun for the greatest possible number of hours per day during the fire season (generally 7a.m. to 7p.m.). If located on a slope, a south or west exposure is required to meet fire danger rating standards. (John E. Deeming, 1972). Consider security (from animals and human vandalism) when selecting a site. To prevent any damage from wildlife, livestock etc., installation of a fence is highly recommended.

The following rules govern the location of a National Fire Danger Rating System (NFDRS) fire weather station:

- Locate the station in a place that is representative of the conditions existing in the general area of concern. Consider vegetative cover type, topographic features, elevation, climate, local weather patterns, etc.

- Select a site that will provide for long-term operation and a relatively unchanged exposure. Consider site development plans, e.g., roads, buildings, parking areas; ultimate sheltering by growth of vegetation; and site accessibility during the intended operational period.

- Arrange the station so as to give data that is representative of the area in which the station is situated. Consider exposure requirements for each instrument in relation to such things as prevailing winds, movement of the sun, topography, vegetative cover, nearby reflective surfaces, and wind obstructions.

In accordance with the above rules, the following situations should be avoided when selecting a station site:

- **Sources of dust** such as roads and parking areas. If unavoidable, locate station at least 100 feet on the windward side of the source.

- **Sources of surface moisture** such as irrigated lawns, pastures, gardens, lakes, swamps, and rivers. If unavoidable, locate station several hundred feet to the windward side of the source.

- **Large reflective surfaces** such as white painted buildings. The same holds for natural reflective surfaces such as lakes, ponds, canals, and large rock surfaces. If unavoidable, locate station on north side, but far enough away so as not to be artificially shaded or influenced (at least a distance equal to the height of the reflective surface or 50 feet, whichever is greater).

- **Extensively paved or black-topped areas**. If unavoidable, locate station at least 50 feet to the windward side.

- **Large buildings, trees, and dense vegetation**. Locate station at least a distance equal to the height of the obstruction. Ideally, when dealing with tall, dense vegetation the station should be located a distance that is equal to seven times the height of the obstructing vegetation.

- **Distinct changes in topography** such as gullies, peaks, ridges, steep slopes, and narrow valleys.

The following is from the Climate Reference Network (CRN) Site Information Handbook (NOAA/NESDIS, 2002):

A significant consideration when examining specific instrument sites is whether the area surrounding the candidate instrument site has a high degree of probability of continuing in its present condition, without major changes for very long periods of time (50 to 100 years). The need for unchanging physical surroundings, particularly encroachment by man-made structures, is a key factor in determining the probable long-term stability of a potential site.

## GENERAL GEOGRAPHIC LOCATION FACTORS

The factors below are considered when exploring and examining the suitability of the general geographic location, as well as the specific instrument site:

- Regionally and Spatially Representative. Stations will be distributed to ensure that all major nodes of regional climate variability are captured while taking into account largescale regional topographic factors. The Network Spatial Density Study will provide guidance.

- General location sensitive to measuring long term climate variability and trends. The site location is representative of the climate of the region, and is not heavily influenced by unique local topographic and mesoscale/microscale features/factors.

- Reasonably high probability of Long Term Site Stability and surrounding area. Minimize risk of man made encroachments over time and/or the chance the site will close due to the sale of the land or other factors. Stations located on government (federal, state, local) land or at colleges (granted/deeded land with land use restrictions) often provide a higher stability factor. This criterion also includes the need for USCRN deployment and maintenance personnel to have reasonably convenient access to the site. A review of recent (last ten years) and possible future population growth patterns in the area is a part of the overall evaluation process.

- Avoid high-risk sites: Extreme/above average frequency of tornado incidents; Enclosed locations that may “trap” air and create unusually high incidents of fog, cold air advection, etc.; Vicinity of orographically induced winds, such as Santa Ana and Chinook; Complex meteorological zones, such as adjacent to an ocean or other large bodies of water; and Persistent periods of extreme snow depths (e.g., several meters/tens of feet). Digital topographic maps and a climatological profile of the area will be examined as part of the overall site evaluation and selection process. When available, aerial photographs are very useful.

- Proximity. Site is within a few tens of kilometers to an existing or former observing site with a relatively long period of record (decades) of daily maximum and minimum temperature and precipitation is highly desirable. The historical data (metadata) record and observational data from these sites should be of sufficient quality and detail to permit reasonable processing of the data to account for changes with a high degree of confidence (i.e., documented vegetation and terrain changes, changes in the location of the station and/or instruments, type of instruments described, the observation time, the observing practices, etc.).

- Vicinity. Site is located in the vicinity of other similar observing systems, which are operated and maintained by personnel with a knowledge, understanding, and appreciation for the purpose of climate observing systems.
- Avoid endangered species habitats and sensitive historical locations of a sensitive nature.

- AC power source available nearby. However, in some cases solar panels may be an alternative to achieve the use of an otherwise desired location.

- Relatively easy year round access by vehicle for installation and periodic maintenance.