Program for Climate, Ecosystem and Fire Applications

Great Basin RAWS Network Analysis

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Great Basin RAWS Network Analysis
Forward

This report describes the results of a RAWS network analysis for the Great Basin. The project was done under Task Order 4 of the Assistance Agreement (1422F915A80010) between the Bureau of Land Management Nevada State Office and the Desert Research Institute (DRI) Program for Climate, Ecosystem and Fire Applications (CEFA). The U.S. Forest Service Region 4 provided primary support for the project. The study team included Dr. Timothy Brown and Beth Hall from CEFA, Dr. Kelly Redmond and Greg McCurdy from the Western Regional Climate Center (WRCC). Paul Schlobohm (BLM) and Tenna Biggs (USFS) provided general project guidance and significant comments for this report. For further information regarding this report or the project, please contact:

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Executive summary

This report describes the results of a Great Basin RAWS network analysis study. The goal of the study was to address general station adequacy for purposes of fire danger, climatology, and other current and potential future needs. Our discussion primarily refers to the issues of larger scale fire danger and climatology (long-term applications) information, not site specific characteristics. Based upon the findings, recommendations are offered to meet the three project objectives:

- To develop guidelines for more optimal decisions regarding future acquisition and placement of stations.
- To develop parameters for the optimal placement and operation of weather stations within the Great Basin that have area-wide importance as well as interagency support and value.
- To identify user needs for both climatological (regional assessment) and operational weather (suppression and prescribed burning) information.

The recommendations developed for each objective are primarily based on summarized results from a user survey and a statistical analysis of historical data from Great Basin RAWS sites. The purpose of Objective 1 is to provide RAWS owners with some guidelines for consideration when a new site is being determined either due to a new acquisition or a station move is being contemplated. Parameters determined within Objective 2 are largely from a statistical analysis performed on historical RAWS temperature data within the Great Basin. Recommendations from this objective should provide RAWS managers with some guidance on the optimal placement of stations. Objective 3 is important in order to determine the current (and potential future) needs of RAWS information for both climatological and operational weather purposes. The user survey provides much of the necessary information for identification of these needs.

In brief summary, the authors of this report feel that the current network as configured does a generally good job of addressing many of the issues raised in each of the study objectives. However, some improvements and considerations could and should be made, and these are highlighted in specific recommendations. Perhaps the most important finding in this study is the confirmation by users that RAWS information has very high value for a variety of decision-making and planning aspects. This indicates that decision-making processes themselves should be an integral part of the operation of the network (in terms of both establishing new sites and maintaining existing ones). For example, the question of how decision-making will be improved or degraded by the addition or removal of a station should be considered. Given the importance of information for decision-making, both the current and future network should be thought of as a critical component of fire and resource management, rather than a low priority in the budget process. Therefore, healthy budgets should be secured for the operation of the network. Given the variety of uses, it seems reasonable to suggest that non-fire divisions of agencies that frequently use the data should also contribute funding to the establishment and maintenance of RAWS stations.

An abbreviated list of recommendations for the Great Basin RAWS network is provided below. The expanded version is given in the Recommendations section of this report.

Objective 1 recommendations

General guidelines for a network of Great Basin RAWS stations are provided using a set of suggested international protocol for networks (Karl et al. 1996) as described in this document, and conclusions based upon the results of this study. Some specific recommendations under this objective include:

- No stations currently in the network should be discontinued, unless it is determined by a specific site analysis that the data quality is so poor, that data analyses would be severely comprised by misleading results.

- The international protocol for network design and operation as outlined by Karl et al. (1996) should be incorporated into the Great Basin RAWS network.

- Every effort should be sought to appropriate sufficient budgets to operate existing sites without compromise (including maintenance and data quality control), and to establish new sites.

- If, in the worse case scenario, stations have to be discontinued strictly for budget purposes, those with the shortest records should be removed first, while keeping sites with the longest historical records.

Objective 2 recommendations

Parameters for the optimal placement and operation of RAWS can be developed and identified from both results of the user survey and the statistical analysis of historical station data. The recommended station distances for climatology and fire danger purposes are meant to be maximum spacing recommendations for new acquisitions, and not an indication of restructuring the network. As discussed in detail later in the report, even stations within close proximity of each other all can have unique information and value. Some specific recommendations under this objective include:

- The priority of new installations should go to the sparse coverage and "data poor" regions.

- A maximum distance between stations should be 50 miles for general longer-term applications (e.g., climatology) and larger scale fire danger purposes. At higher elevations, local topographic influences should be an important consideration in establishing a new RAWS site.

- All stations should be equipped with additional non-standard fire danger instrumentation including soil moisture and air quality sensors.

- RAWS sites should be upgraded to year-round all-weather status, with particularly the ability to deal with snow.

Objective 3 recommendations

It is clear based on the user survey that there are numerous uses of RAWS information beyond strictly those for fire danger. Data from most of the RAWS sites are also used for fire behavior and fire use, but many other specific uses were noted such as mine rehabilitation, fire planning, law enforcement investigations, avalanche danger, budget analysis, forest health, range trends, wild horse rehabilitation, and fire rehabilitation. It should be noted that the last recommendation within this Objective is currently being addressed. Web-based access to WIMS is anticipated during Spring 2001, and hourly RAWS via web-based access is planned to be available by the Western Regional Climate Center (WRCC) by Summer 2001 contingent on funding. Some specific recommendations under this objective include:

- The various aspects of decision-making should be taken into consideration with plans to add or remove a station. This includes how decisions will change given the presence or absence of RAWS information, and to what extent management objectives will be affected in either a positive or negative manner as a result of the station change.

- When new station installations are being considered, the various uses should be taken into account when determining the site location (as well as non-fire station funding sources).

- It is recommended that all new station requests indicated in the study survey be accepted.

- A web-based network-wide access system of RAWS data and information should be established.

Introduction

As of August 2000, there are approximately 100 Remote Automatic Weather Station (RAWS) sites and approximately 20 manual sites in operation across the Great Basin providing weather observations to wildland fire managers and other users. These sites were originally established based primarily on weather information needs for suppression activities and fire danger, and meet National Fire Danger Rating System (NFDRS) standards (Finklin and Fischer, 1990). The need for weather and climate information across the Great Basin is expanding due to increases in uses such as prescribed burning, resource planning, weather forecasting and historical climate analyses. This leads to a number of fundamental questions, such as 1) is the current network adequate for operational fire danger use? 2) where should new station acquisitions be placed? 3) does the network (both current and future) address longer term applications (climatology) and research needs? and 4) is the network adequate for more broad based fire management issues?

The project intent was not to make recommendations on site specific RAWS locations, but rather, to offer a discussion of topics related to the broader scale issues of network adequacy for purposes of fire danger, climatology, and other potential future needs using as a framework the objectives:

- To develop guidelines for more optimal decisions regarding future acquisition and placement of stations.
- To develop parameters for the optimal placement and operation of weather stations within the Great Basin that have area-wide importance as well as interagency support and value.
- To identify user needs for both climatological (regional assessment) and operational weather (suppression and prescribed burning) information.

As the analyses for this study were undertaken, it was soon recognized that Objectives 2 and 3 in the original Statement of Work needed to be changed somewhat to better reflect the intended scope of the project. Specifically, the original Objectives 2 and 3 were stated as "To establish a set of optimally placed weather stations …" and "To establish a network …", respectively. This implied that as a result of the study, recommendations would be given on where each RAWS site should be located and how the network might need to be reconfigured. Since the original intention was to consider larger scale fire danger and climatology issues, rather than specific site analyses, the Objectives were modified with concurrence of the project managers to those shown above. Specific site analyses may perhaps be in order for certain RAWS sites to improve the quality of the data and usefulness of information, and should be undertaken using appropriate methods if deemed so.

The primary discussion in this report refers to RAWS, though approximately 20 manual stations were noted in the survey. Beyond some basic questions about manual stations discussed below in the Survey section, no formal analysis was performed based on these stations. Also, no reference to portable stations will be given in this report.

Figure 1 shows the region within which the study was focused. The boundaries are defined by the areas of responsibility of the Eastern and Western Great Basin Coordination

Centers. Southern Idaho, Nevada, Utah, and parts of western Wyoming and northwest Arizona are included in the geographic region. This area encompasses over 250,000 square miles, spanning over 6,000 feet of elevational relief, with numerous valleys and mountain ranges. Figure 2 provides a shaded relief map of 1 km resolution elevation across the Great Basin, with locations of current (August 2000) RAWS sites.

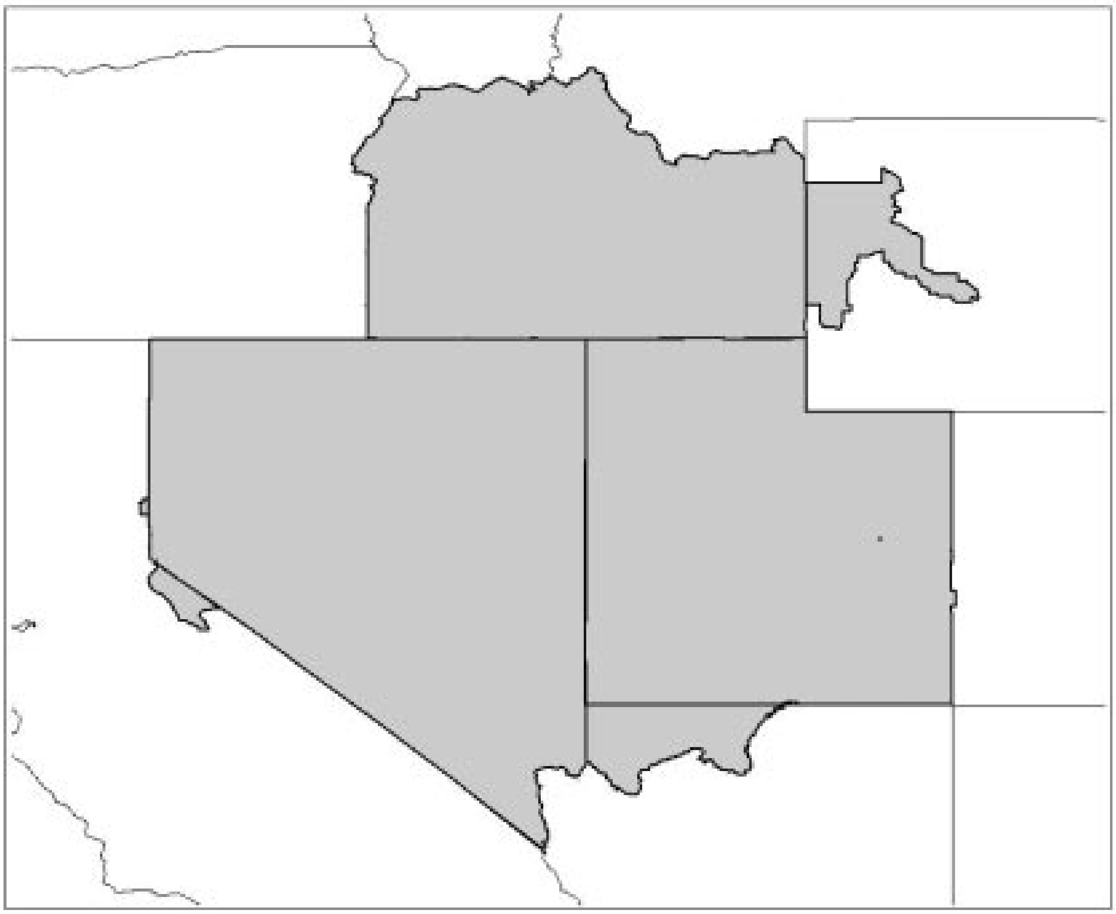

Figure 1. Geographic study area for the RAWS network analysis. This dark shaded region represents the areas of responsibility of the Eastern and Western Great Basin Coordination Centers combined.

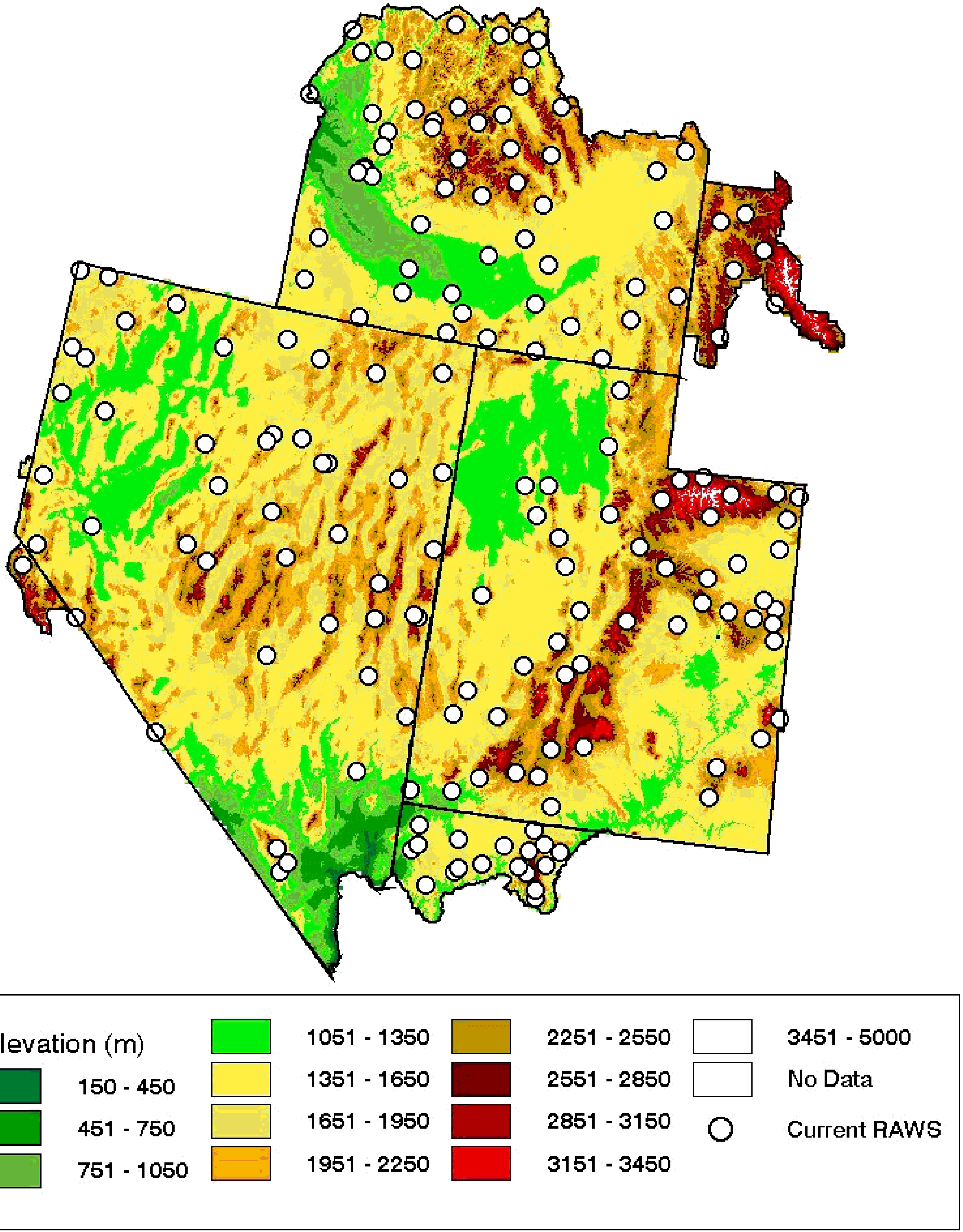

Figure 2. Shaded relief map of 1 km resolution elevation across the Great Basin. RAWS sites (as of August 2000) are shown as circle symbols.

General considerations

The determination of the optimal distribution of stations for any observational network will be affected by the assumptions made about what the data will later be used for. Some of these uses are now known, while other ones, some important, will emerge with time. In essence, what is most required is a de facto *prediction* of what the needs will be a number of years hence.

Ample experience by the authors of this report in dealing with other networks that have longer records but less detailed information than RAWS stations leads to a few overall conclusions. Among these are that many of the future needs in fire and resource management will require reference to historical records of decades or longer. One fundamental limitation is that observations cannot proceed any faster than the flow of time itself. Ten years of data take ten years to obtain. For this reason a premium is always placed on maintaining records that are already long.

It is also worth noting that redundancy, in and of itself, should not necessarily be viewed as “bad”. In the real world, equipment malfunctions, blocked transmissions and garbled data highlight the need for backup data, whether for urgent time-sensitive applications, or to restore key information gaps during subsequent analyses.

The large area and complex terrain of the Great Basin (Figure 2) implies that establishing a weather and climate network that serves multiple purposes is not always easy and straightforward. In comparison, designing a network for a single purpose, such as monitoring fire danger, is relatively easier. However, experience tells us that there are numerous other uses for the same type of information (e.g., prescribed fire, ecosystem health, numerical weather prediction). As the knowledge base of various disciplines expands, many new uses, some requiring more lengthy records, will be conceived. This clearly challenges the design of a comprehensive network, if many of the potential uses of the information have not yet been invented or identified.

The complex terrain of the intermountain West makes site selection of a station a formidable task. Currently, RAWS sites in the Great Basin range from a little under 3000 feet to just over 10,000 feet with an overall elevation change of around 7000 feet. Various terrain factors such as slope, aspect and elevation can affect the climate across the Basin. For example, the range of July monthly mean temperature at Great Basin RAWS sites is 57.2 to 88.4 F.

Elevation influences other climate elements as well. Figure 3 shows annual precipitation patterns across the Great Basin that clearly delineates geographic structure. Precipitation is especially influenced by terrain effects, so valleys and mountain ranges are strikingly revealed when appropriate precipitation scales are chosen. Precipitation, along with other climate elements such as temperature, defines the natural vegetation and fuels patterns across the Basin. In some parts of this region, long-term annual precipitation can vary by a half inch to an inch in just 100-200 yards of horizontal change.

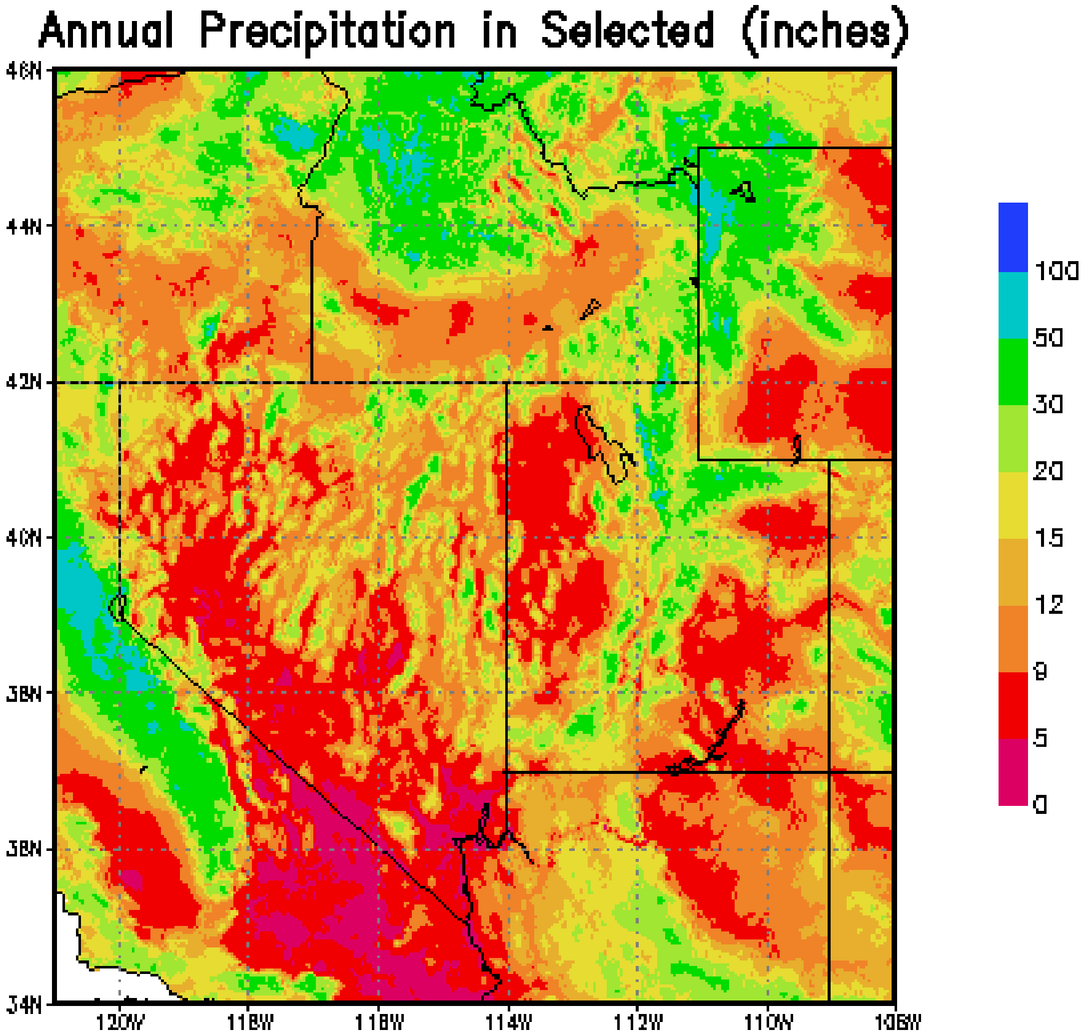

Figure 3. Annual precipitation (inches) based on Oregon State Climate Office PRISM data. Map provided by the Western Regional Climate Center. Period represented is 1961-1990.

The spatial scale of climate anomalies can be large, including nearly all of the Great Basin at one given time. For example, most of the Basin could be above average in temperature or below average in precipitation. In such circumstances, however, there are often localized areas where the anomaly is not as strong due to terrain effects. The impact of an anomaly pattern could be more significant at lower elevations than higher ones, or vice versa. For example, it is possible for lower elevations to be drier than average while upper elevations are wetter than average. Thus, it is the extent, or spatial scale, of climate patterns that needs to be examined in order to determine regional impacts, and used to help identify an appropriate spacing of monitoring stations.

Climate can be thought of as the complete set of statistical descriptions of weather over time. As an example of one such statistic, monthly mean temperature may be calculated by averaging the daily or hourly mean temperatures for that month. In the context of this study, the most typical uses for climate records are to relate sequences or averages of weather—that is, climatology—to sequences or averages of other factors important to resource management decisions, that are themselves affected by climate. Some of the uses for climate data require long records to average over enough conditions, or conversely, to show the range of conditions that must be considered. Other uses require relatively complete records. For this reason, the longer a station has been in existence, the greater the value of its historical record, and the greater the priority it should have for continuation. The important aspect of climate is that it provides a history of weather.

The climate of a site or area is very much an indicator of fire danger for those same locations. In a simplistic sense, hot and dry conditions in an area yields increased fire danger. Generally, climate anomalies (departures from average or normal) of a particular sign and value tend not to occur only at a single point, but extend over large distances. For example, much of the Great Basin can experience above average maximum temperature during a summer fire season. Given the close relation between climate and fire danger, this implies that the same area is also experiencing similar and uniform fire danger index (e.g., energy release component) values. Thus, in a broad sense, recommendations based upon our statistical analysis of climate data (in our case temperature), is also applicable to fire danger. On the other hand, fire behavior and fire use are likely to be more site specific, as other factors such as local wind and topography, for example, play an important role. All of this implies that there are many different spatial scales of fire danger (as well as temporal scales). Mostly in this report, we are concentrating on the larger scale issues.

Rather than focusing strictly on separation distance, a better question is to ask how representative the station data need to be to answer a particular question. That is, most locations of interest are not at a station. In complex terrain, this representativeness can change greatly in short distances. For example, mountain slopes and valley bottoms, almost side by side, can have very different climate behavior. Furthermore, some elements (such as temperature) have different spatial representativeness than do others (humidity, wind, precipitation, etc). Even closely spaced stations in mountain environments (a few miles apart and within sight of each other, but at different elevations) can show poor annual correlations of temperature or precipitation quantities.

Study methodology and analysis

The network discussion in this study is largely based upon two types of input. The first consisted of comments solicited via a user survey sent to RAWS users and managers in the region. This largely established the locations of fire danger needs, as well as establishing a number of other uses of weather and climate information. The second type of input consisted of a statistical analysis of historical RAWS data to assess how rapidly various measures of climate experienced decreased correlation with each other as their separation distance increased. A part of the motivation for this is to help determine approximate RAWS locations and the spacing desirable to develop a Great Basin region climate baseline. This is not only for a variety of fire and resource management aspects, but also factors such as fire weather forecasting, data for ingestion into weather, climate and hydrologic models and regional monitoring of climate extremes.

Survey

Survey questions were constructed by the authors of this report with substantial and significant input from Tenna Biggs (USFS) and Paul Schlobohm (BLM). The questions primarily were concerned with information about existing stations, use of information, problems that should be addressed, and general network related needs. After selecting the set of desired questions, a survey form was developed and placed on the CEFA web site. A number of individuals, primarily within USFS and BLM, were contacted to participate in the survey. Survey responses were processed by simply tabulating results for fixed questions (e.g., indicate fire danger, fire behavior and fire use), and condensing and summarizing results for those general questions allowing for more varied response. The survey results are discussed in the main Survey section below.

Statistical analysis

Statistical methods are commonly used for the analysis of meteorological networks (e.g., Gandin 1970). Fujioka (1986) examined an objective statistical method explicitly for designing a fire weather network. In the present study, geostatistics was used to establish the maximum station spacing based solely on a single climate variable, which should also be a representation of a scale of fire danger (refer to discussion in previous section). Examining spatial autocorrelation structure has been applied to other environmental and ecological data (e.g., Cressie and Ver Hoef 1993). The July monthly mean temperature at each RAWS site was computed and used as the primary data source for the analysis. Temperature was chosen because it is a variable that in a relative sense is fairly uniform in structure across large scales, as compared to precipitation or wind that can be highly variable even across short distances. Figure 4 shows the spatial distribution of the 116 stations used in the analysis. These stations were selected based on having a sufficient amount of data for analysis. For each site, a minimum of 8 years of data (not necessarily consecutive) was required to compute the long-term monthly mean. July was used as a representative summer wildfire month. Because of the general uniformity of temperature, each of the summer months yields similar spatial correlation results. The summer and winter seasons will differ somewhat in spatial correlation due to the occurrence of stronger temperature inversions during the cool season. Also, daytime versus nighttime correlation values may differ substantially. Typically, nighttime values exhibit lower correlations due to localized effects such as mountain-valley wind patterns and cold air drainage and pooling into valleys. The monthly mean temperature used in this analysis represents the average of daily maximum and minimum values.

Spatial correlations can be calculated and analyzed over many different climate time scales, such as daily, weekly, monthly, seasonal, annual, decadal or century. Short time scales (i.e., daily) often yield lower correlation values because local weather has a bigger influence than climate. But at longer time scales (e.g., weekly, monthly) local weather is smoothed out in the averaging process. We chose monthly as a desirable time scale in this study. This represents a "middle" in between daily and seasonal fire danger. With monthly values, intraseasonal variability can be identified and weather is smoothed out to produce a regional climate signal. From a statistical perspective, this is a time scale that usually produces spatial continuity.

The first part of the statistical analysis incorporated a form of the empirical variogram (a plot of variance of paired sample measurements as a function of distance) – the correlogram given by,

$$\rho(h) = 1 - \frac{\gamma(h)}{C(0)},$$

where $\gamma(h)$ is the variogram for pairs of points separated by Euclidean distances h, $C(0)$ is the finite variance of the random spatial field, $\rho(h)$ (rho) is the spatial correlation. These definitions assume the isotropic case where h is a scalar (magnitude only); in other words, all directions are equal. The variogram $\gamma(h)$ is defined by,

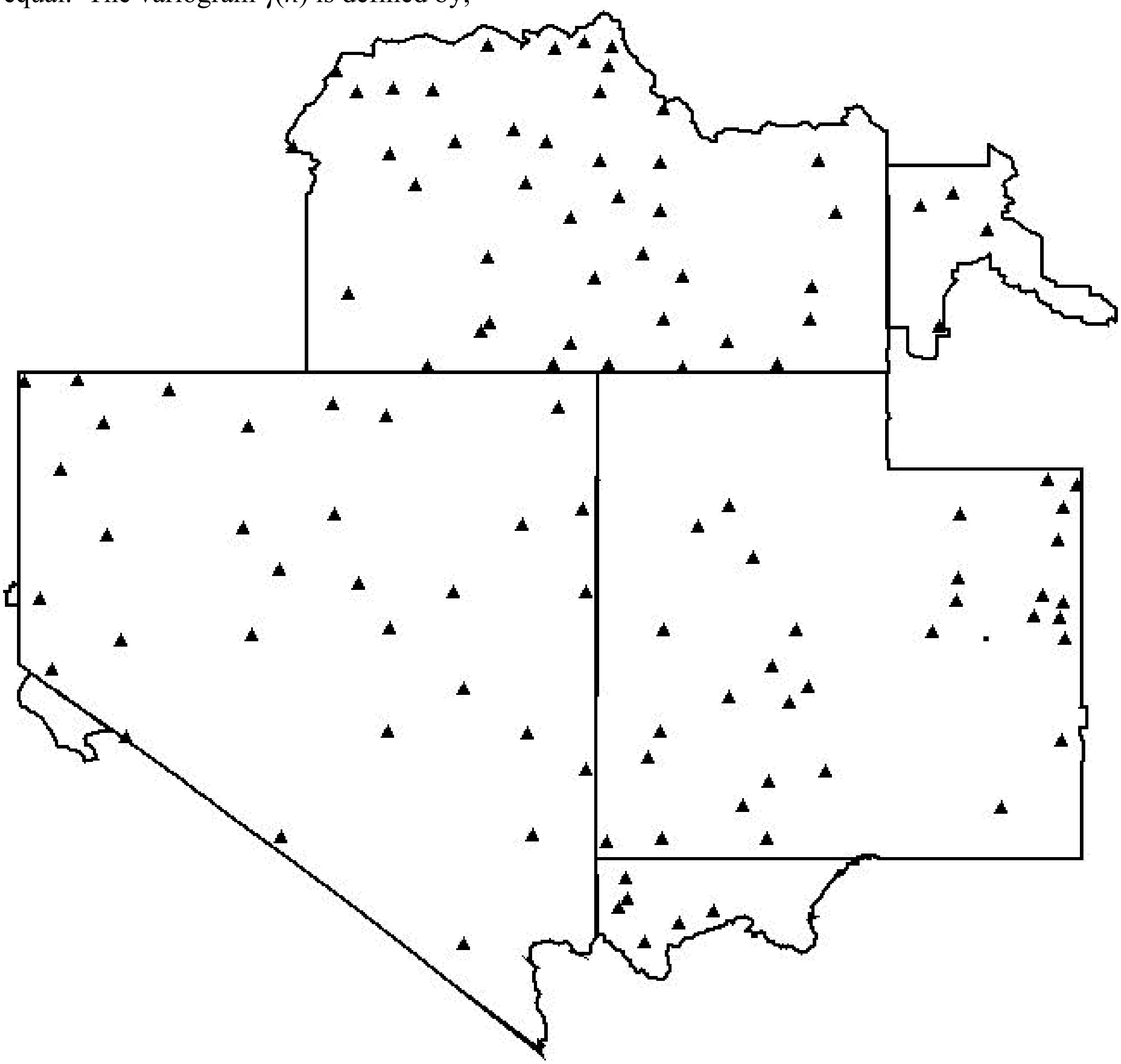

Figure 4. Location of Great Basin RAWS stations used in the spatial correlation statistical analysis.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{N(h)} (z_i - z_j)^2 ,$$

where $N(h)$ is the set of all pairwise Euclidean distances i-j=h, and z_i and z_j are data values at spatial locations i and j, respectively. Further details of the methodology can be found in Isaaks and Srivastava (1989) and Kaluzny et al. (1998).

How does this work for our purposes? Each point in Figure 4 has a longitude and latitude position in degrees. In the formulation above, two point locations are given by i and j, respectively. The variable h is the straight line distance in degrees between any two points i and j. All of the points combined represent $N(h)$, and $N(h)$ is the total number of possible distinct pairs of points. The variable z represents the actual data value, in this case monthly mean July temperature. $C(0)$ is the variance of the z values for all points. Isotropic noted above refers to the spatial continuity of the field. In a non-isotropic (or anisotropy) field, one would expect better correlation in one spatial direction versus another. This was not the case for the data used in this study, as uniform correlation was found in all directions.

During the computational process of $\gamma(h)$ a lag increment is chosen that stipulates distances at which the variogram is calculated. For example, suppose a square spatial field of points with 5 degrees (latitude, longitude) per side is analyzed using a lag increment of 0.3 degrees. Starting in the lower-left corner of the spatial area, an arc will be extended from the first point out to 0.3 degrees in all forward directions. All points inside this region are paired (with the lower-left corner point), and a correlation found for all of the associated temperature values. This process closely resembles plotting paired values on a scatterplot, and calculating the association using the Pearson product-moment correlation coefficient. As the process continues another arc area will be formed from 0.3 to 0.6 degrees and pairs formed with the first point. This procedure is done for all points and across the entire region such that all point pairs for all lag distances are accounted for. One alteration in our computations is that we incorporated a more robust procedure for the variogram as defined by Cressie and Hawkins (1980). The advantage of this method is that the effect of outliers is reduced. This is important since outliers, especially in small samples, can substantially change the results and lead to misinterpretation. The choice of the lag distance for the variogram is largely an exploratory process. In fact, the entire process of computing a variogram fits well into the class of statistics known as exploratory data analysis. This implies some subjectivity on the researcher's part, but with the goal of achieving optimal results.

The variogram is an analysis of spatial autocorrelation. That is, the extent that points in space are correlated. For example, consider a monthly time series of temperature values at points A, B, C and D along a straight line, each separated by a distance of say 50 miles. If a simple correlation analysis was performed on points A and B, B and C, and C and D, one might find the three correlation values to be similar. However, if correlation values were computed for points A and B, A and C and A and D, it is likely that the correlation values will be less for the points A and D compared to A and B. In other words, the correlation decreases with distance. This is intuitive with daily weather; one would expect the farther away one traveled from a starting point, the less similar the weather would be. At some point away, the weather may become similar again, but may not necessarily be related to the original location.

Usually the purpose of establishing an empirical variogram is to determine a mathematical model function that fits the data based results, then proceed with some point estimation process and establishing a uniform gridded field of values. The next step in the analysis process is to fit a mathematical model to the values determined from the empirical variogram exploration. This theoretical model mathematically describes the variogram values which will be used in the last part of the analysis to generate point estimates of a uniform field based upon the original values. To do this, a method termed ordinary kriging is employed.

Kriging produces point estimates of a regular grid from irregular spaced points, such as those we are working with. The method is linear based, using the variogram model to calculate statistical bias and error variance of each point based upon weights of nearby samples. This employs a standard objective technique of minimizing the error variance (see e.g., Isaaks and Srivastava 1989 or Cressie 1991 for detailed descriptions of variogram modeling and kriging). We are not particularly interested in the point estimates themselves, but rather the error at each point. This can be used to establish a "radii of influence" around each RAWS, which can be interpreted as the maximum distance of station spacing.

The error at each point is given by

$$error = (Y_p - Y_o),$$

where *p* and *o* represents predicted and observed, respectively. The estimation variance is then found by

$$s^2 = \sum_{i=1}^{n} (Y_{ip} - Y_{io})^2 .$$

The square root of the estimation variance yields,

$$s = \sqrt{s^2},$$

the standard error of the estimate. Thus, the better the point estimate, the smaller the standard error becomes. The original observed value estimated for will have the smallest standard error, with the error increasing in value with distance from the original value until the next observed value is approached. One can subjectively choose a distance away from each point that diminishes confidence in the estimate. For our purposes we have chosen one standard error as this distance, that is, one degree F.

Here is how this works specifically for our situation. We compute an estimated value of temperature at regular grid points of 0.1 degree spatial resolution. The standard error is computed for each estimate, and plotted on a map. Standard errors are examined for each one-tenth degree grid point around the original observed point until a value of the original error plus one occurs. For example, if the original error was 0.8, then the search would stop at around 1.8. Multiplying the number of grid cells within one standard error in a north and south direction by 69.06 statute miles per one degree latitude yields a radius distance around the station in miles. An example output is given in the results section below.

Survey results

As part of the project, a web-based survey was prepared consisting of questions regarding RAWS and manual stations, and related questions of general usage. Prior to distribution the questions were critiqued by WRCC staff experienced at responding to data requests, as well as by agency personnel. A request for potential participants to complete the survey was made through state (BLM) and region (USFS) offices. Primary contacts were managers of RAWS sites and regular users of RAWS information. A total of 33 responses were received. Though we recognize that not all regular users had an opportunity to participate in the survey, we believe that the responses received reflect the various uses and general concerns regarding the Great Basin network. A summary of results from the survey is presented in this section.

Fixed RAWS

Survey question 1. List all fire weather sites you work with on a regular basis.

Of the 181 current (August 2000) active sites, 124 were identified as being used regularly by those individuals or groups responding to the survey. Some users or offices did not respond, and some undoubtedly and unintentionally were not contacted, so that absence of mention of particular stations cannot necessarily be ascribed to lack of interest. Despite that not all stations were accounted for, a reasonable assessment of usage can be summarized by the sample provided. Figure 5 provides locations of RAWS sites (open circle symbol), and those station locations listed in question 1 of the survey responses (open circle symbol with center dot). Thus, some locations may appear as a single symbol when the two site types overlap. Dots that appear by themselves are for non-RAWS stations indicated by the respondent.

Along with the identification of station locations, four categories of usage were identified: NFDRS, fire behavior, fire use and other. For purposes of the survey, NFDRS usage refers primarily to daily fire danger operations, though other purposes such as running FireFamily Plus might be included. Fire behavior usage refers primarily to behavior during a specific fire event or estimates of fire behavior for planning purposes. Fire use refers primarily to fire management practices such as prescribed burning. The remaining category (other) refers to any purpose that does not generally fit within the previous three groups. Survey respondents frequently indicated that specific stations are used by more than one individual and for more than one purpose. Also, the results of the survey indicate that most sites are used for multiple purposes (e.g., NFDRS and fire behavior).

Not surprisingly, RAWS sites are extensively used in the first three categories. The percentage use of RAWS sites by primary category are: NFDRS – 84%, fire behavior – 91% and fire use – 86%. Other uses identified were high elevation soil moisture and temperature, mine rehabilitation, NFMAS analysis, precipitation measurement, law enforcement investigations, avalanche danger, budget analysis, forest health, range trends, wild horse rehabilitation, and fire rehabilitation. This clearly shows that RAWS sites have multiple uses. However, the primary funding for all of these sites comes from the fire operations of USFS and BLM.

Survey question 2. Where would you put a weather station(s) if you could and why?

Of the 33 responses to this question, only 4 indicated no need or desire to presently add any new RAWS stations to their area of interest. Figure 6 provides a Great Basin map indicating locations where users have identified a need for a RAWS site for purposes of NFDRS, fire behavior, fire use or other needs. Current stations are shown as solid circle symbols and additional new desired stations by solid triangle symbols. There were no statements in the survey suggesting that any current station should be moved. Some of the desired sites are replacements for previous removals, and others are a conversion from manual to RAWS. The conversion from manual to RAWS is advantageous as a permanent site provides continuity (standardization) in the observations, more frequent observations, and improved reliability in the archival and retrieval of site data.

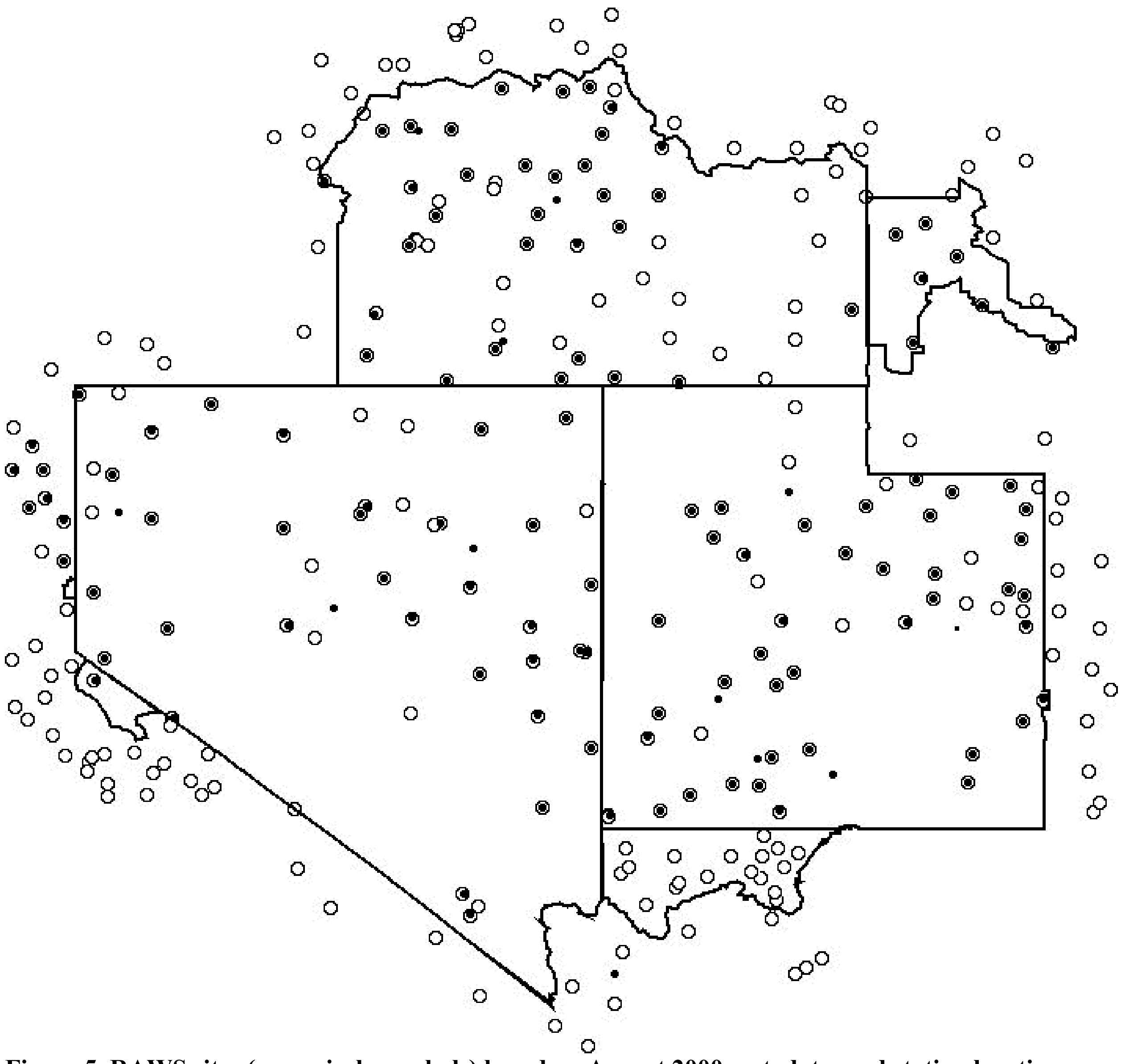

Figure 5. RAWS sites (open circle symbols) based on August 2000 metadata, and station locations listed in the participant survey (open circle symbol with inner dot). Locations not shown as survey indicate that either there was no response to the survey, or the proper individual was not contacted for information. RAWS sites within 50 miles of the Great Basin survey region are also shown. Individual dots show latitude/longitude positions given in the survey but not corresponding to RAWS metadata.

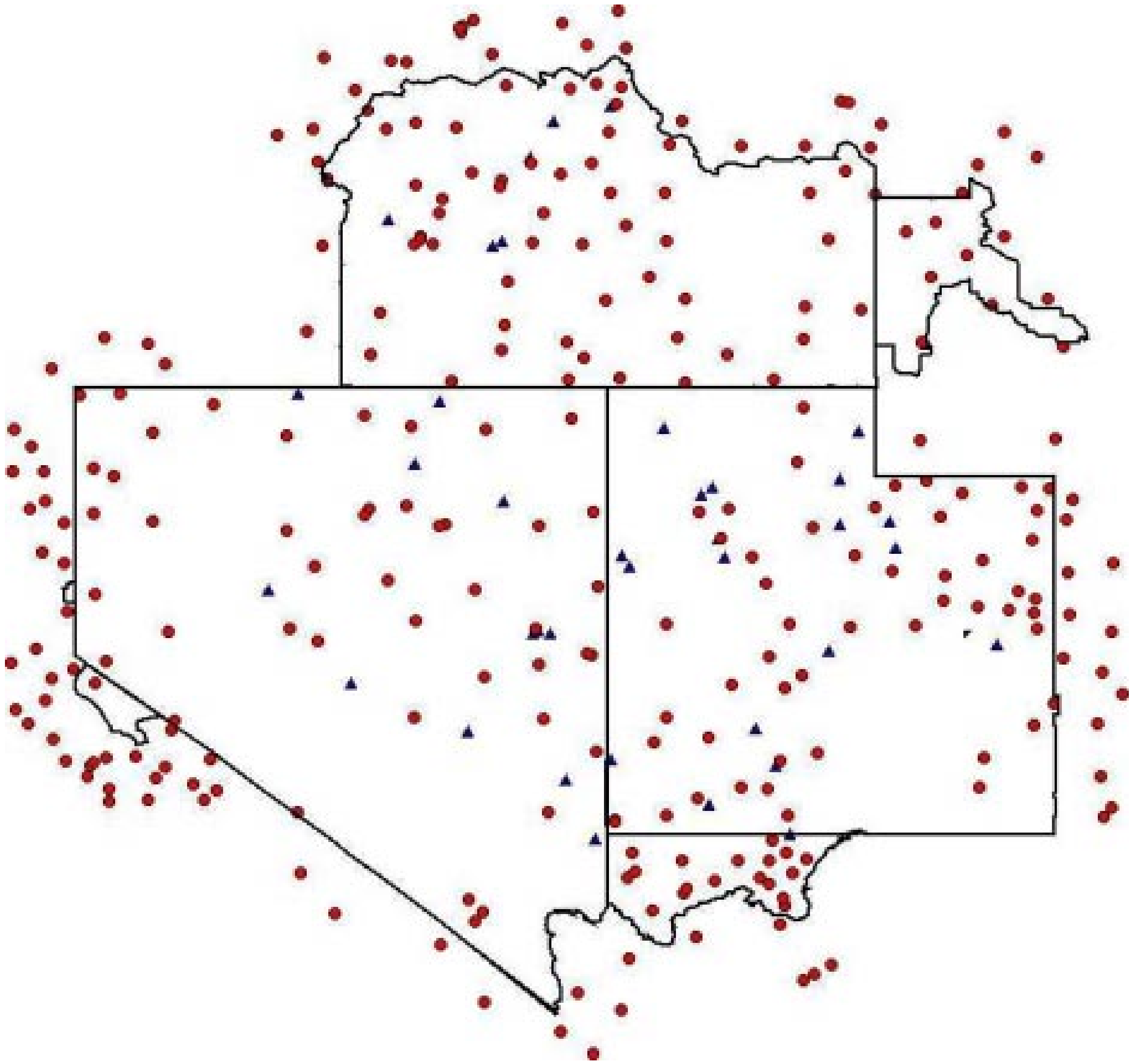

Figure 6. Solid circle symbols indicate RAWS sites (as of August 2000) and solid triangle symbols indicate locations where a new RAWS station is highly desired for fire danger and other purposes.

Figure 6 raises the important issue of station proximity. It may graphically appear that some stations are close together, and this could lead to a temptation to remove one solely based on horizontal distance. This appearance may be misleading because of plotting stations on a 2-dimensional map. A closer examination of each station's environmental characteristics may show substantial differences in elevation, slope, aspect, and fuels, even with relatively short distances. In order to determine if two stations were effectively measuring the same values, a detailed statistical analysis would have to be performed. This would provide an empirical comparison of the two data sets and allow for an objective assessment of the two sites to determine if one could be removed. However, one should also consider each variable being measured, the purpose of each site, and the decisions made based on information from each site. For example, each site might measure similar hourly temperature values, but very different wind speed and direction. If the sole purpose of each site was for fire danger monitoring, perhaps one could be removed (presumably the one with the shortest historical record). However, if one station is used for other purposes, such as fire behavior, it would be undesirable to remove it since its measurements has high relevance to its particular location and uses. It is noteworthy that no respondents mentioned the removal of an existing site to facilitate the establishment of an additional desired site.

To provide an example of measurements taken from two closely spaced stations, a simple correlation analysis was performed on six sites to investigate how distance may or may not affect climate characteristics. Correlations for July monthly mean temperature, relative humidity and wind speed for 3 pairs of RAWS sites with relatively close distances were generated. Each station had to have at least 9 years of data to be included in the analysis. Table 1 shows the station pairs, elevation, distance between each pair, and the Pearson correlation. In the first case, Juniper Springs and Fox Mountain are separated by a straight line distance of approximately 12 miles with an elevation difference of around 1500 feet. All three correlations are high, suggesting close correspondence between the two stations. This might initially suggest removal of one of the stations. However, further analysis of the original data shows that there is a monthly average temperature difference of 5 degrees, a relative humidity difference of approximately 2%, and a wind speed difference of 1 mph. These differences may be large enough (especially temperature) to effect dissimilar outcomes of fire danger and fire behavior between the two sites. In the second case, Twin Buttes and Horse Butte are separated by nearly 1600 feet of elevation, but only a straight line distance of approximately 7 miles. Though the relative humidity correlation is high, there is an approximately 4.5% difference between the two stations. The correlation for temperature is only moderately high (an approximately 7 degree difference) and wind speed is even less though the monthly median values are nearly the same. These values clearly show substantially different climate characteristics within a short straight line distance. The third example, Jensen Spring and Brimstone Reservoir, shows that a substantial climate difference can occur with relatively short straight line distance and similar elevations. In this case, both temperature and relative humidity have high correlation values (and similar monthly median values for temperature, but an approximately 4% difference in humidity), but the wind speed correlation is quite low and there is a large difference in the monthly median value, especially important for fire behavior. These examples highlight a danger of correlation statistics alone for the purposes of determining station relevancy; other summary and comparative statistics should also be analyzed.

In the past, decisions of RAWS placement or removal have been placed rather solely on looking at a map similar to Figure 6, with a simple focus on station proximity as the primary criteria. We must think in three dimensions rather than just two when topography affects climate as dramatically as it does in this region. It can be concluded from the above discussion that many factors should be considered, with emphasis on analyzing data where available, developing a good understanding of the various uses of the information, and an assessment of how the decision-making process might change with the addition or removal of a station.

Table 1. Correlation of July monthly mean temperature, relative humidity and wind speed for three pairs of closely spaced RAWS sites. Also shown are the monthly median values corresponding to each variable. The left value refers to the first station in the pair, and the right value the second listed station.

Station pair	Elevation (feet)	Distance (miles)	Climate variable	Correlation	Median values Lo Elev	Hi Elev
Juniper Springs	5348	12	Temperature	.92	70.8	65.8
Fox Mountain	6890		Rel. Humidity	.92	32.6	34.9
			Wind Speed	.89	7.1	8.1
Twin Buttes	3350	7	Temperature	.77	70.7	77.5
Horse Butte	5000		Rel. Humidity	.98	32.2	27.6
			Wind Speed	.54	10.1	10.2
Brimstone Res.	5620	19	Temperature	.93	75.8	75.8
Jensen Spring	5744		Rel. Humidity	.88	33.6	29.1
			Wind Speed	.32	7.5	10.3

Survey question 3. Do you have any geographic areas or topographic settings where weather sampling overlaps significantly and why?

Virtually all of the respondents indicated that no significant overlap exists. Only 2 respondents noted that there might be some overlap in their area. This suggests from the user perspective that their areas of responsibility are unique from a geographic or topographic setting. This further suggests that based on this unique setting, distant RAWS sites may be unsuitable for local purposes. There will likely be other reasons for this suitability, as discussed later.

Survey question 4. How important is it to have a backup station near enough to help give at least an indication of weather at a desired station for situations when data are missing?

The majority of the respondents (83%) indicated that having a backup station was very important. The reasons were varied, but can be generalized as follows:

-Backup used for loss of data or cross-reference to questionable station data
-Operational safety
-Outages caused by vandalism
-To ensure necessary information for fire danger and fire behavior calculations
-Improve overall climatology information

The phrase “near enough” in the original question was left for the respondents to interpret as they wished. In one response, the nearest “backup” station was indicated to be approximately 100 miles away from the local point of interest. Later in the climatology section of this report, station separation distance will be discussed in more detail. In this example, 100 miles is likely an unsuitable distance for most purposes despite the fact that it may be the closest station. One would have to closely scrutinize and compare data from the two sites to develop confidence in their interchangeable use.

In an ideal situation, for every station there exists another station that is somewhere between perfectly correlated (complete overlap) and poorly correlated (no overlap). Complete overlap is desired when a station is absolutely crucial and data gaps are unacceptable. No overlap means that a station is in a unique setting and no external information is useful for checking data quality or providing backup. In general, the desire is for some degree of correlation of each station with a subset of surrounding stations that serve as proxies, so that missing data can be reconstructed. Depending upon the time scale (i.e., hours, days, or months), this may or may not work. Nearly always, climatological similarity between separated stations is greater for monthly mean temperature or precipitation totals than it is for shorter time scales, such as on a daily or hourly basis, like the specific 1300 local time wind speed and direction used by NFDRS. For many sites, a statistical relation (e.g., regression) could be sought to allow for one station to describe another. But again this may be highly dependent upon the time scale chosen (i.e., a stronger relation is usually found for monthly versus daily versus hourly data).

As a network property, redundancy implies that nearby backup stations can be found for most stations in the network. However, it could also be in context of providing immediate maintenance or replacement of a station whose data appear in error or are missing. In fact, it is often only by means of partly redundant stations that one is able to identify data problems. Otherwise only the most obvious and egregious bad data are spotted. Maintenance and replacement can be facilitated by establishing a mechanism for fast response to known instrument problems, and by maintaining a suitable replacement equipment inventory. In some cases, it may be highly desirable to temporarily install a portable RAWS station with identical RAWS equipment, to act as a data "bridge" or overlap, until the permanent instruments can be repaired or replaced.

One area not explicitly noted in the survey, but nonetheless highly important, is quality control. In any dataset, there must be a mechanism in place to ensure that data are of the highest quality, and erroneous values corrected or removed. A description of this process and actions taken should also be part of the metadata.

Survey question 5. What is the typical date range of weather data collection for your stations?

Many RAWS in the Great Basin operate year round, though it is widely known that daily precipitation during the cool season is problematic due to the lack of heated precipitation gages. Based on the responses to the survey question, the users basically defined the prescribed burning and wildfire seasons in the Great Basin. Two-thirds of the respondents indicated a range of March through November. The remaining one-third indicated all months. There may have been some confusion regarding this question. Some respondents may have indicated primarily when they *use* the data, which is generally March through November, rather than confirming or identifying their stations as year round collection. Based upon RAWS records at the Western Regional Climate Center, virtually all of the RAWS sites noted in this study record data year round.

Survey question 6. Which hourly observations do you use regularly?

The 1300 observation appeared in all responses in one form or another. This is not surprising since NFDRS is designed around this particular time of day. Nearly 75% of the respondents indicated using all 24 hours for a variety of purposes, even though the 1300 time is used specifically for fire danger. Examples of additional usage included prescribed fire, weather tracking for initial attack periods, humidity recovery, wind speed and direction, fire behavior, red flag condition monitoring, and input to general fire management decision-making. This indicates in general that availability and usage of 24-hour RAWS data is important, as will be further substantiated in the general usage section below.

Survey question 7. Which elements are of most value for your uses?

Virtually all of the respondents indicated usage of all standard NFDRS sensors. Four respondents indicated having soil moisture at their site that is used regularly. Of the sensors listed as being desirable at a particular site, solar radiation and soil moisture were the top two priorities. Maximum and minimum values of temperature and relative humidity, wind speed gust, and precipitation totals and durations were all commonly mentioned as being important element summaries.

Manual Stations

There were eight respondents to four questions regarding manual stations. The primary purpose of the brief section was to determine some indication of how many manual stations are in use, for what purposes, and whether there is a desire to convert them to RAWS.

Survey question 1. List all manual fire weather sites you work with on a regular basis.

Sixteen manual stations were listed as being used on a regular basis. Again, since not all potential users of manual stations were surveyed, this number may be fewer than the total number of stations in practice. With the exception of one, all are being used for NFDRS purposes. All are being used for fire behavior, and eleven of the 16 stations are being used for fire use. Only one station does not meet NFDRS standard requirements.

Survey question 2. What is the typical date range of weather data collection for your sites?

Nearly all stations are operated from May to November. A few stations begin earlier in April, and one station as early as March. Not surprisingly, these months represent the primary prescribed burn and wildfire season in the Great Basin.

Survey question 3. Do you take observations other than 1300? If so, when?

All but two stations take observations at 1300. One station takes a 0900 observation for primary use by the National Weather Service (NWS). Another station also incorporates a 1600 observation (in addition to 1300) that is primarily used by the NWS.

Survey question 4. Where do you have manual stations that you would like to upgrade to RAWS?

Of the 16 manual stations reported, respondents indicated a desire to upgrade 12 of these to RAWS. The locations of the manual sites desired for conversion are also indicated as solid triangle symbols in Figure 6.

General Usage

General questions were included in the survey to gather information regarding other aspects of weather and climate data usage. The responses indicate a large number of uses of RAWS data. All respondents consider the value of weather and climate data to be very high. General improvements could be made to the RAWS network, including installing additional sensors and providing for easy access to hourly observations. The uses of data and the types of decisions made with the information are numerous and varied.

The value of RAWS data to the users to make informed decisions is extremely high. This is apparent based upon the responses indicating so many different uses of the information, and the large number of different types of decisions that take place in consideration of the data. There were no indications that RAWS data are not useful.

Survey question 1. What non-fire weather stations are located on your unit or in your area of responsibility? What are they used for?

All but two of 27 respondents indicated one or more non-fire weather stations in their areas. Many of these were NWS, METAR or COOP stations. METAR (in primary support of aviation applications) measures many of the same elements as RAWS, but does not meet the NFDRS standards. The COOP sites are typically either daily temperature or precipitation. SNOTEL stations were another commonly noted source of weather data. Many of these sites provide hourly temperature and precipitation related information.

The uses include general weather information and fire management. Some responses were more specific indicating river levels, precipitation, prescribed fire, historical climate, military chemical weapons monitoring and avalanche conditions.

Survey question 2. Do you have any non-NFDRS weather stations (e.g., DOT, NWS, FAA, SNOTEL) that fire or other disciplines could take better advantage of?

The general indication is that, yes, there are other stations that fire or other disciplines could take better advantage of. Over 40 stations were listed, most from the question 1 response. Many of the sites are NWS or SNOTEL, but a few other types were noted. The responses to questions 1 and 2 indicate that it is likely several non-NFDRS sites are available to a particular unit or district. These data can provide a valuable supplement to RAWS information for certain applications.

Survey question 3. Do you have other users of your weather stations that you know of?

The responses clearly indicate that other users of the information could be identified beyond those directly involved with RAWS. This further supports what is generally known, that is, RAWS information is used by a substantial number of individuals, many outside the "traditional" in-house or agency setting. Also, based upon other questions in this section, the use is for a large number of reasons. Unfortunately, this particular survey question was not worded in the detail necessary to extract this type of information. It was hoped to be able to distinguish different types of users, such as biologists, hydrologists, etc. However, little information of this type was provided in the responses, and thus, no comment can be provided on the general occupations of users.

From the requests for RAWS data received by WRCC, a number of uses are coming from environmental consultants, university researchers, state regulatory agencies, grazing councils, and non-governmental organizations. Many of these are in disciplines or topics such as wildlife mortality, endangered species, rangeland ecology, hydrology, riparian studies, forest health, forest entomology, and related areas. The general field of environmental consulting seems to be exhibiting the fastest rise of requests for RAWS information, followed by research and regulatory groups.

Survey question 4. How important is it for your uses to measure weather and climate in a consistent way during the station's existence?

Based on the 25 answers to this question, the overwhelming response was “very important”. Some individual responses are paraphrased below:

“similar amount of confidence throughout the station’s existence…data should be gathered from same site with no major changes that might effect the readings”
“important during high fire danger periods for the safety of field personnel”
“if not consistent, difficult to track historical trends”
“better results achieved if observations are consistent over long periods of time from the same location”
“garbage data is just garbage”
“non-consistent data can impact all of our fire planning and adversely affect localized forecasts”
“important for analysis, fire growth and simulation projections, and fire management planning”
“important for season comparisons”
“all fire and many non-fire related decisions are based on high-quality, consistent weather and climate data”
“very important to obtain a good baseline of information”
“extremely important for long-term analyses”
“critical to examine trends”
“important for historical and trend analyses”

These are clear statements indicating that consistent observational procedures (e.g., maintenance, station location, instrument type, etc.) must be maintained throughout the station’s existence. In other words, data homogeneity is critical for operational use and historical studies.

Survey question 5. How do you rely upon historical or climatological information for purposes other than fire danger?

There were 24 responses to this question indicating a variety of purposes other than fire danger. Three of the respondents indicated that they only use the information for fire danger purposes. One additional respondent indicated that they do not use the information currently for purposes other than fire danger, but are anticipating increased usage in the future for prescribed fire and resource benefits. The various purposes indicated in the responses are provided below:

-predict or assume fire severity based on historical information
-related to fire history
-fire investigations
-court cases
-erosion
-historic season ending events
-risk appraisals for wildland fire use
-prescribed burn planning
-rehabilitation
-budget analysis
-fire behavior
-fire severity funding requests
-develop programmatic fire management plans
-ground water and hydrologic assessments
-summaries to visitors and visitor guides
-wildlife impacts
-forest health
-soils studies
-vegetation change and response

This list demonstrates the wide variety of uses of RAWS information for longer-term data applications and climatological purposes. While fire danger may be an important and original component of RAWS sites, it clearly is no longer the only one. The uses range from physical (e.g., erosion, soils), environmental (e.g., wildlife, vegetation) and social (e.g., court cases, budget analysis) components. It is important to be aware of these various uses when decisions are made to remove or add a station.

Survey question 6. What improvements would you suggest related to your weather stations?

There were 23 responses to this question. The three general categories of improvements included 1) instruments, 2) telemetry, and 3) other. These are summarized below:

<u>Instruments</u>
-Add soil moisture
-Add solar radiation
-Add air quality monitor

Telemetry

-Add radio or phone system to receive data real-time
-Change to hourly output rather than 3-hourly
-Change to 15-minute output rather than 3-hourly

Other

-Improve security
-Improve data access; make data available via internet
-Provide fire danger indices more often than just 1300 (e.g., 0900, 1700)
-Provide training on data input of manual observations
-Improve station coverage

The inclusion of additional instrumentation at each site, especially those noted above, is beneficial for a number of reasons. Soil moisture is an important factor in vegetation stress. The monitoring of soil moisture can provide information on live fuel moisture, and provide measurements for input into NWS weather prediction models. Models that incorporate coupled atmosphere-terrestrial physics require soil moisture information. More reliable data generally improves forecasts. Also, a reliable soil moisture network would provide a much needed database for regional climate studies.

It is planned to install solar radiation at RAWS sites based on an NFDRS standard. For many of the sites, this has already been accomplished. These data will provide the state of weather for NFDRS calculations of 10-hour fuel moisture. However, these data will also provide a valuable database for regional studies such as ecosystem analyses, climate change and climate variability.

Air quality measurements would be valuable at many of the RAWS sites not only for monitoring prescribed burning emissions, but also for validation of particulate dispersion and transport models. These data would also be useful for numerous types of studies concerned with regional air quality and haze. However, given the many aspects and uses of air quality information, considerable thought would be required to determine one or more standard sensors, and how those sensors would be operated and maintained.

The telemetry issues are relevant to oversight committees concerned with setting standards and the processes of disseminating and archiving RAWS data. The issues noted in the survey should be a priority topic for such committees.

Regarding other improvement factors, security is clearly a concern. An important consideration in locating a weather station is ease of access, but also accounting for a secure location. The other aspects noted in this category, such as improving data access, more frequent fire danger indices, more training, and improved station coverage, are also highly relevant. These issues will hopefully be addressed in the near future by appropriate individuals and committees.

Survey question 7. Do you have needs other than direct fire management for fixed weather stations?

Twenty responses were provided for this question. Approximately half of the respondents indicated that they did not presently have special needs for RAWS beyond fire management. This is due in part to the fact that many of the individuals contacted were primarily responsible for fire management issues. For those that did indicate a need, the responses are summarized below:

-Prescribed fire and air quality monitoring/forecasting
-Rehabilitation
-Forest health monitoring
-Fuels monitoring
-Avalanche forecasting
-Restoration
-Rangeland monitoring

This list is basically a broad generalization of many of the factors noted in question 5. Again, it highlights the importance of a multitude of uses that ultimately must be considered when establishing or removing a station.

Survey question 8. Describe in general what decisions you make that utilize weather and/or climate data and information? At what times of the year do you make each of these decisions?

All 27 respondents provided information for this question as summarized below. The decisions can generally be placed into two categories – short-term (e.g., daily) and long-term (e.g., weekly, monthly, seasonal). This is an important question as it ultimately identifies why the weather and climate information is pertinent. The list of responses is summarized below:

Short-term decisions

Tactical
Prescribed fire go/no go
Fire danger assessment
Staffing levels; duty hours
Fire restrictions/closures
Determination of prescribed burn windows
Agricultural burning
Fire behavior predictions
Pre-positioning of resources
Monitoring fuels conditions
Providing weather related warnings and situations to incident commanders and crews
Planning levels
Fire crew safety
Initial attack preparedness levels
Initial attack priorities

Long-term decisions

Pre-suppression planning
Fire prevention planning
Budgetary decisions
Resource needs
Monitoring fuels conditions
Rehabilitation
Planning levels
FARSITE simulations
Severity money requests
Fire risk assessment
Determination of probabilities for season ending events
Seasonal drying/drought events
Seasonal fire danger analysis
Forest health planning (beetle flight and planting timing)
Pre-positioning of resources
Fire slowing events
Prevention patrols
Seeding times
Animal turnouts or removal
Restoration and range management (greenup periods/dormancy; frost/freeze)

These two lists highlight numerous decisions requiring weather and/or climate information. Clearly, the various decisions extend well beyond those strictly related to fire danger, and justifies additional assessment when a station installation or removal is being considered.

Long-term Applications - Climatology and Other Uses

As the period of record at a station lengthens, its usefulness for long-term applications increases. The uses of climatological data are numerous and varied, such as providing a basic understanding of climate characteristics at a particular location, and serving as input for the development of value-added products. Various uses indicated by the survey respondents show the need for climate information across the Great Basin in relation to fire and resource management. Climate information can be used as input for resource and budget planning, risk assessment, monitoring fuels conditions, and ecosystem health among others. Virtually every item noted in the long-term decision list in the previous section requires some climate information. Thus, this section addresses the network in terms of climatology, which is also an indicator of fire danger as previously discussed.

Designing a climatological network requires consideration of a number of factors. The goals of the network must be well-defined, and resolve questions such as the types of users the network will serve and the elements that will be most appropriate to measure. Locating a station within a network can also be problematic, especially in complex terrain. Two stations a mere mile apart could ultimately measure two very different environments, especially if the elevation change over the mile distance is substantial. Identifying all of the potential uses of the network data, both current and future, can also be a challenge. Budgetary constraints limit the number of stations that can be feasibly installed and maintained. Thus, the goal is usually to achieve representative sampling. But the question we face is "representative for what?".

As a general comment, atmospheric data measured for "climate" purposes must adhere to a higher standard than data measured for "weather" purposes. Chief among these is the need for temporal consistency. Across the board, the need for measurements that meet climate standards is rising rapidly. The RAWS network could play a major role in the western states as this need further crystallizes. Most respondents (see question 4) were keenly aware of this need.

Network Standards

In 1996 Tom Karl, director of the National Climatic Data Center, and co-authors published a scientific paper on critical issues for long-term climate monitoring in a book related to long-term climate monitoring. The key points made in this paper, listed as items 1 through 10 below (often referred to as the "Ten Commandments for climate monitoring"), are applicable to the Great Basin RAWS network (as well as other regional land management agency data networks). One of the primary purposes in providing these protocols is to suggest that they be incorporated into the Great Basin RAWS network planning. As a federal expenditure, the RAWS program is one of several major observing networks that should be managed to serve the largest public interest. This list is applicable to the entire national RAWS network, and should be incorporated into the standards along with NFDRS specific items.

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 measurements, both in terms of physical location and changes in the nearby environment, should also be a key criterion in site selection.

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. 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.

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. Regions that are data poor, 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 operational or research-oriented needs or programs. A lack of stable, long-term commitment to these observations is a frequent limitation in the development of adequate long-term monitoring capabilities.

10. Data management systems that facilitate access, use and interpretation are essential. Freedom of access, low cost, mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata, etc.) and quality control should guide data management.

All of these points should be considered with the establishment and operation of the Great Basin RAWS network. It seems that historically, the RAWS network was traditionally thought of by many as a daily weather network strictly suited to operational needs, in particular fire danger and fire behavior. This follows item 8 above. However, it is clear from the survey responses that many other uses have arisen over the years.

Geostatistical analysis

For the first part of the geostatistical analysis in this study (described in the methodology section), all 116 RAWS sites were used and a number of initial lag distances (~ 7 to 62 miles) were examined. A lag distance of approximately 27 miles produced the most optimal correlogram based upon exploratory analysis, visual inspection and mathematical function fitting. The pattern of correlation values indicates in part whether or not the lag distance is appropriate; a smoother curve will allow for a better fitting mathematical function which yields overall better results. The initial lag number provides a starting value for the calculations necessary to search for relevant point pairs and perform the correlation computations. The starting value does not imply a fixed separation for every lag (i.e., 27, 54, 81, etc.). It should also be noted that in all of the original analyses, decimal degrees were used for lags. These have been converted to miles in this report for more convenient application of the results. The general formula that 1 degree latitude is equal to 69.057 statute miles was used.

Figure 7 shows the correlation versus distance for the case of using all stations. Each solid circle on the plot represents a correlation for lag distance given along the x-axis. The first lag correlation of .45 can be interpreted as quite low. The plot overall shows a general downward trend of values indicating that the correlation decreases with distance as expected in this type of physical data.

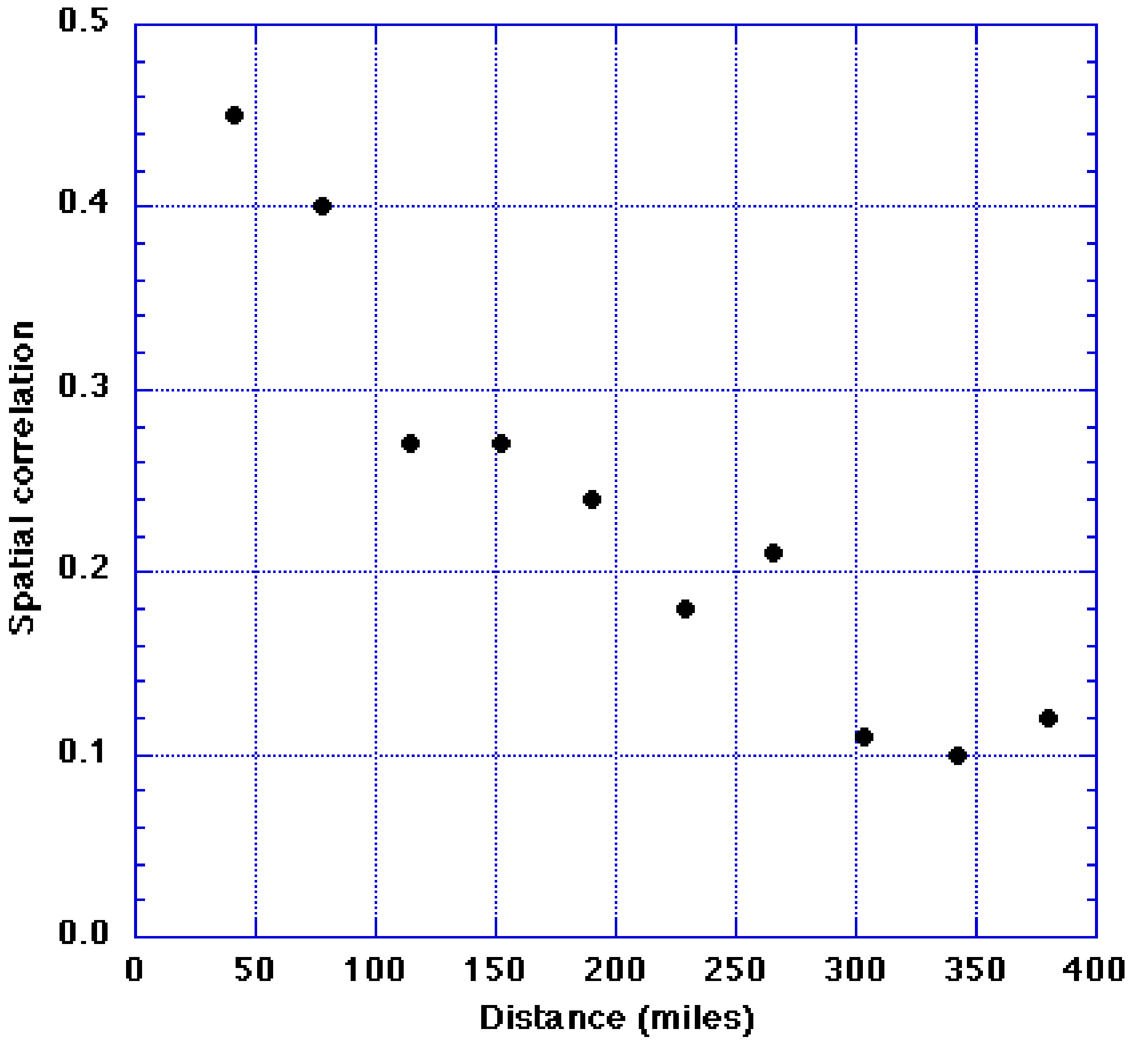

Figure 7. Correlogram showing spatial correlation structure versus distance in miles for July monthly average temperature using 116 RAWS sites across the Great Basin (see Figure 4).

At first thought, the low correlation value of .45 for the first lag-1 seems surprising. A value based on .70 was anticipated based on experience. But after consideration of possible reasons, the most obvious explanation is elevation differences. As discussed earlier, the extreme elevation changes across the Basin can create substantial climate differences across the region. More importantly in this case, changes in topography are causing significant climate differences between lower and higher elevation sites, and the current set of RAWS is capturing that difference. The shape of a histogram of RAWS elevations (and subsequent exploratory analysis) initially suggested that three terciles of elevation ranges should be examined – less than 5,000 feet; greater than or equal to 5,000 feet and less than or equal to 7,000 feet; greater than 7,000 feet. Subsequent analysis using the empirical variogram indicated these ranges were reasonable choices.

Figure 8 shows an example variogram fit for middle elevations (≥ 5,000 and ≤ 7,000 feet) sites. Distance is given in 1 degree increments. Basically, the points exhibit a linear pattern through which a straight line can be fit. How well the fit is determines in part how large the error variance will be across an estimated grid (the better the fit, the smaller the standard errors). In this case, a geostatistics spherical function was used, but with parameters such that basically a straight line appears. This fit (mathematical function) is then used to estimate point values across a grid.

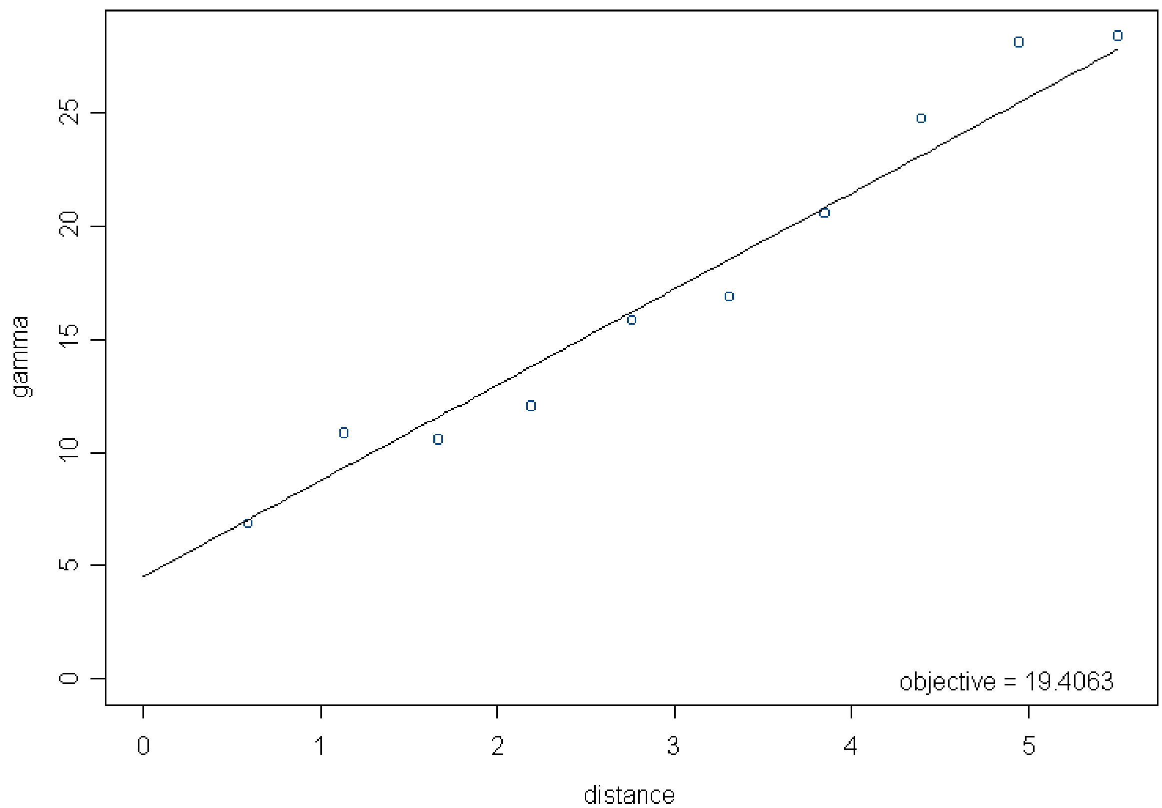

Figure 8. Variogram modeling fit for stations within the ≥ 5,000 and ≤ 7,000 feet range. The objective value is a measure between the model fit and empirical variogram, with zero indicating perfect agreement.

Estimates for the original values will yield the lowest standard errors, with increasing error values retreating away from the original value until the next observed value is approached and the errors begin to decrease again. An example of this pattern is given in Figure 9, which shows standard errors across a grid using three RAWS sites from the middle elevation group. Each 0.1 degree grid cell is color coded to a standard error, hence giving the block appearance. Smoothed contours are added to show the actual standard error values. The darkest areas represent a standard error value of approximately 1.8, with the very center of the area having an error value of 0.8. If grid cells having values of approximately 0.8 to 1.8 are counted in the north-south direction, 7 cells are seen around all three original locations. Using the conversion from degrees latitude to miles yields approximately 50 miles for station spacing. That is, beyond 50 miles from a station, the standard errors begin to get large, suggesting that if another station were located 50 miles away, the error would be substantially reduced again. From this we can suggest a maximum distance of 50 miles between stations, which holds for the three elevation ranges examined. This does not suggest that there should be a station spaced every 50 miles apart in a grid (though this might be desirable for some applications), but does indicate that as new stations are added to the network, that they should be spaced no further than 50 miles from an existing station where possible and feasible.

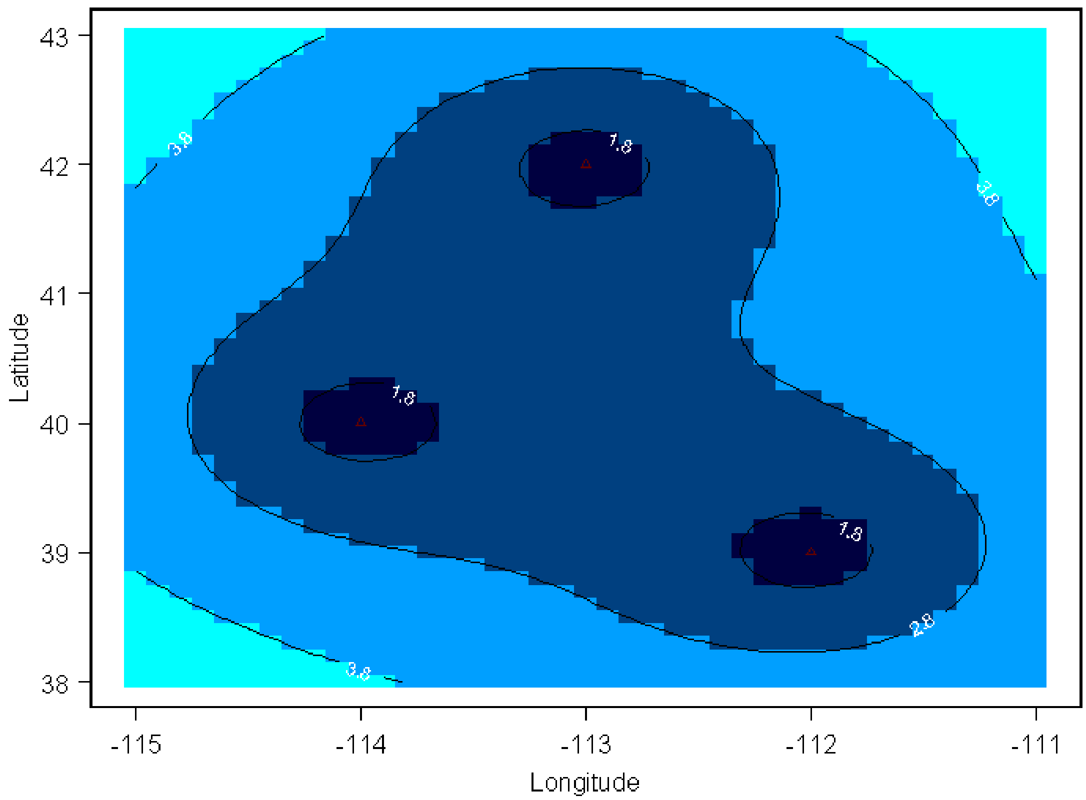

Figure 9. Standard error example using three stations from the kriging point estimation of the middle elevation range (≥ 5,000 and ≤ 7,000 feet). Contours indicate standard error values, and shading range is from lowest error (dark shading) to highest error (light shading), respectively.

How well the current network is represented by the distances determined by the standard error analysis can be examined by plotting maps of elevation and RAWS locations using the 50 mile maximum distance criteria. Figures 10a through 10c show RAWS locations for the elevation ranges of < 5,000 feet, ≥ 5,000 and ≤ 7,000 feet, and > 7,000 feet, respectively. While coverage in Figure 10a appears to be generally good, there does appear to be some areas that are not well represented by a RAWS site. However, some of these areas may not necessarily be prone to fire danger, such as the eastern Snake River valley, some portions of northwestern Nevada and northwestern Utah for example. Though vegetation type maps are provided at the end of this section, managers at the local level will be able to best determine if there are data coverage gaps for fire danger strictly based upon this map. Though fire may not be a critical issue for some of these areas, the addition of a RAWS site might add value for other purposes.

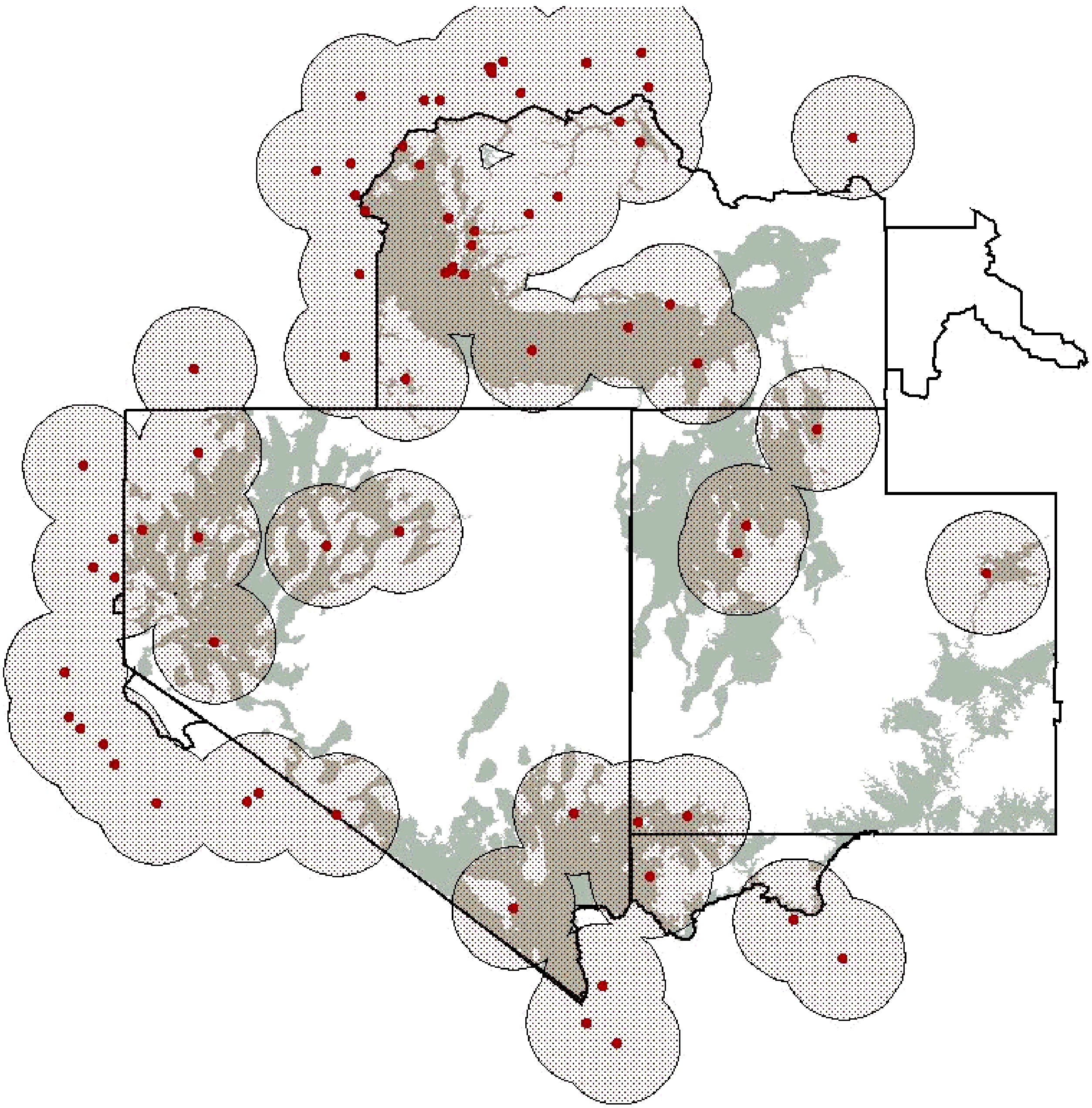

Figure 10a. Great Basin RAWS sites used in the spatial correlation analysis for elevation < 5,000 feet. Solid dots indicate RAWS location, gray shading regions of elevation < 5,000 feet, and shaded circles indicate 50 mile radius around the respective RAWS location.

Figure 10b shows a similar map except for the middle elevation range of ≥ 5,000 feet and ≤ 7,000 feet. It seems that coverage using a 50 mile radius may be considered quite good for the current RAWS network. There are some areas lacking coverage which might be desirable to have a station. Also, there may be numerous sites with local topographic and meteorological influences where a new RAWS would be desirable.

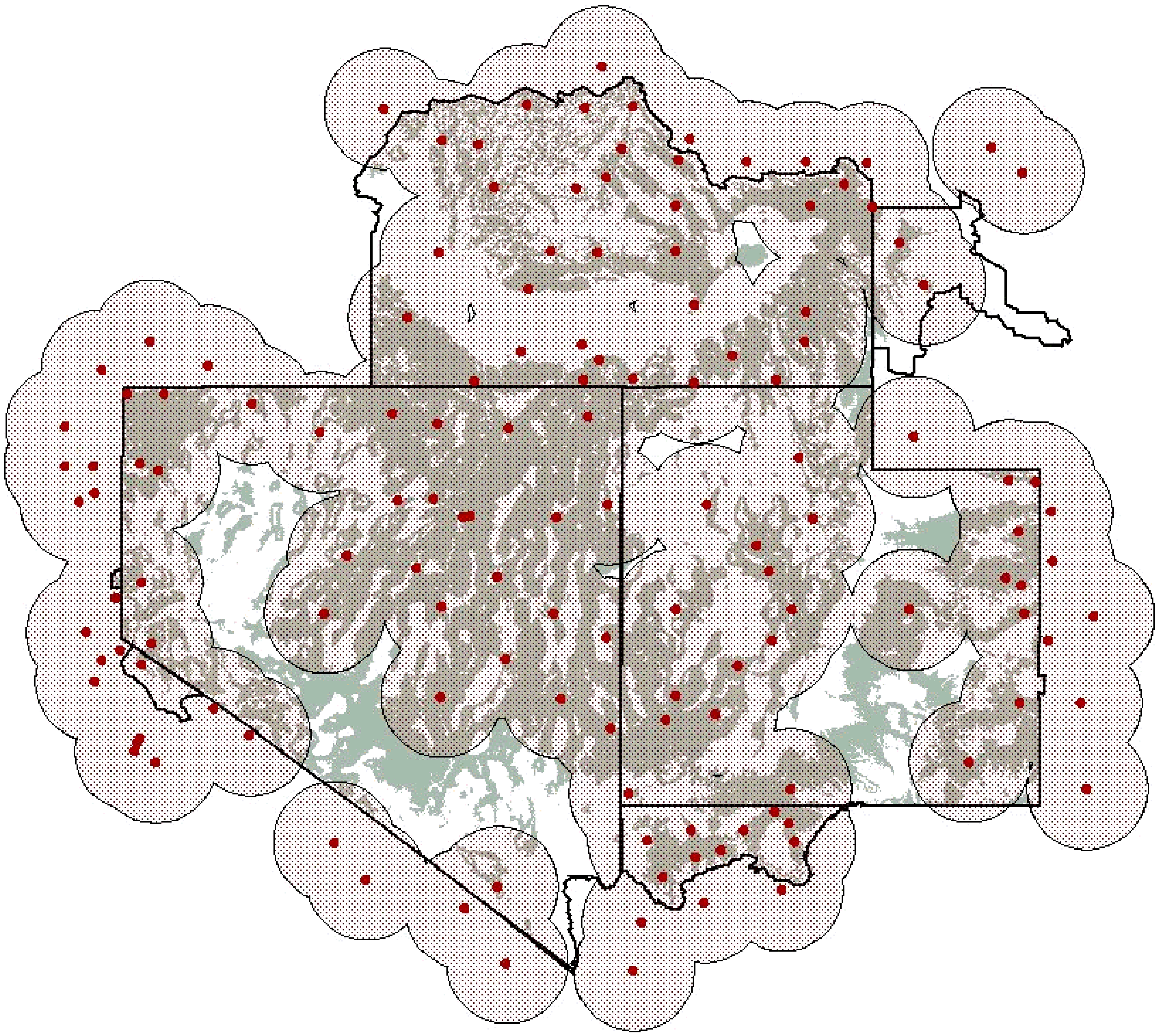

Figure 10b. Same as Figure 10a, except for elevation ≥5,000 feet and ≤ 7,000 feet.

Figure 10c shows the same type of map except for the high elevation range of > 7,000 feet. While the higher elevations in the eastern Great Basin seem to be fairly well covered, there are numerous locations in Nevada and northern Idaho that seem to be lacking coverage. Again, some of these areas may not necessarily be critical for fire danger monitoring and assessment, but it is likely that there are some important areas lacking coverage at this elevation. Also, this is the elevation region where local influences on measurements will be most pronounced, and thus desirable to have more sites. On the other hand, this is an elevation range where access and maintenance of sites can be more difficult.

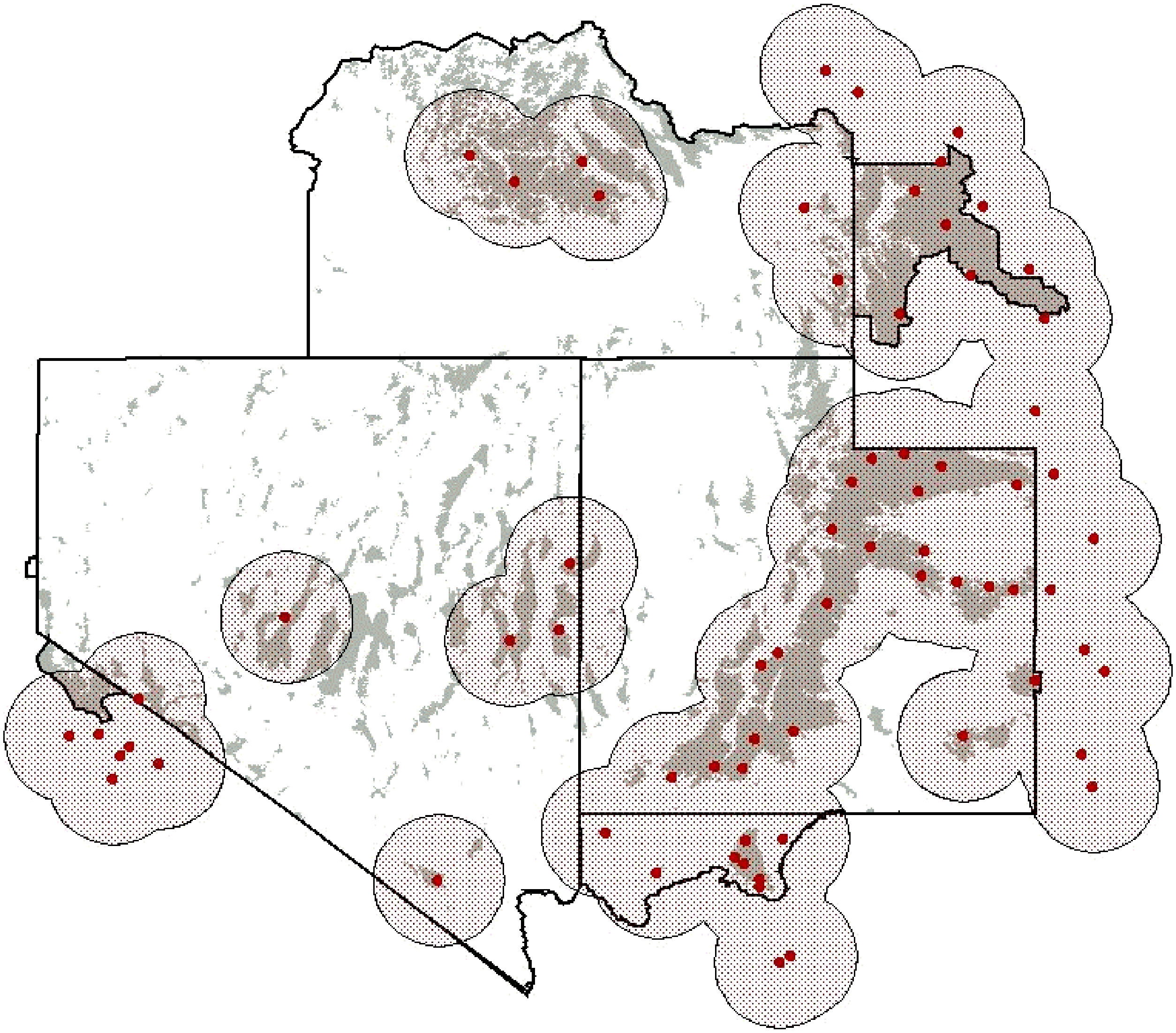

Figure 10c. Same as Figure 10a, except for elevation > 7,000 feet.

There are several caveats that should be considered with this analysis. First, just because radii overlap, does not imply adequate coverage, though this is highly dependent on the use. In the broad spatial sense of climate and fire danger, the network as configured does a pretty good job of capturing the relevant information. However, due to many local influences, there may likely be a strong desire to add stations to the network to increase the coverage and represent the variety of uses discussed earlier. Second, the distances given for the three elevation cases does not imply that a uniform grid should be constructed based on those values. Third, it should not be assumed that all climate features within the given mile radius will be captured by a single monitoring station. While these distances may capture general climate features of valley and mountainous environments, localized terrain effects will strongly influence weather elements, especially precipitation and wind.

Relative humidity and wind speed were also analyzed in a manner similar to temperature. For relative humidity, the spatial autocorrelation values were .66, .66 and .64 for sites at elevations < 5,000 feet, ≥ 5,000 and ≤ 7,000 feet, and > 7,000 feet, respectively. Basically, the relative humidity spatial correlation structure is similar at all three levels. This result is similar to the temperature findings. Wind speed exhibited spatial correlation structure in the low and mid-elevation ranges (.69 for both < 5,000 feet and ≥ 5,000 and ≤ 7,000 feet). However, for stations above 7,000 feet the correlation was only -.34, indicating little spatial structure at the higher elevations. This is likely due to localized terrain effects on wind speed, that are not so influential on temperature and relative humidity. Though precipitation was not analyzed for this study (due largely to the fact that middle and high elevation historically observed precipitation data are not available), the PRISM map of Figure 3 suggests that much closer spacing for precipitation climatology purposes would also be required.

One could either visualize the results shown in Figures 10a through 10c in terms of linear separation, or in terms of area covered. For example, the 50 mile distance may be thought of in terms of equivalent areas in acres. Squaring 50 yields 2,500 mi^2, which is equivalent to 1,600,000 acres. This has the perception of a very large area being represented by a single station, and the users and managers of RAWS information should assess whether or not a single RAWS site is representative of this size acreage for their particular purpose. For comparison, the relatively flat State of Oklahoma (68,656 mi^2 or 43.9 million acres) has a network of weather monitoring stations with an annual operating budget of approximately $1 million. A total of 114 stations are located across the state with a mean distribution of one every 24.5 miles, or 385,437 acres. This distance/area is substantially less than what exists in the Great Basin and our recommended maximum spacing distances. To establish a similar density network in Nevada alone would require a total of 182 stations.

For strictly fire danger purposes, a single station within 1 million acres may be sufficient, as long as fire danger characteristics occur across this acreage in a homogeneous manner at a given time. However, differing vegetation types within such large areas may affect the uniformity of fire danger, thus requiring a denser network of stations. As noted earlier, the number of potential uses and a good understanding of the decision-making processes should also help determine the station density.

Great Basin Climate and Vegetation

Vegetation types do tend to occur fairly uniformly across large areas. In a natural setting, this occurs because particular climate characteristics also tend to occur across large areas. Climate regions can be classified by a number of methods, but a widely adopted one that can serve as a proxy for coarse ecosystem representation is the Köppen classification system. First introduced in 1928, this classification uses average monthly temperature, average monthly precipitation and total annual precipitation to establish spatial categories and boundaries. In reality the boundaries represent transition zones of gradual change. A general discussion of the Köppen classification system can be found in Christopherson (2000).

In this study we show an updated Köppen classification for the Great Basin from the Idaho State Climate Services Office. These are shown for two reasons. First, to determine how well the current network represents general climate features of the Great Basin. Second, to provide managers with climate background information when planning for a new RAWS acquisition, and the manager wants to make sure that a certain climate classification is being represented. Specific details of the classification can be found at the web site **http://snow.ag.uidaho.edu/Clim_Map/koppen.htm**. Table 2 indicates the basic climate properties associated with each category.

Figures 11a through 11c show the classification applied to different regions of the Great Basin. For purposes of presentation in the maps, we have simplified the categories slightly by combining the temperature subsets "h" and "k" under category "B", "a" and "b" under category "C", and "a", "b" and "c" under category "D". It can be seen that this classification somewhat delineates the complex terrain of the region. Since these classifications are somewhat representative of ecosystem classes, they could also be thought of as broad based fire danger areas, particular if one is working with larger spatial scales of fire danger rather than site specific analysis.

Table 3 provides the climate classification percent occurrences within each state's portion of land area representing the Great Basin, and percent occurrences of RAWS sites located within each climate classification. In general, the higher percentages of area indicated by the climate classification also contains the larger number of RAWS sites. For example, in Nevada the BSk climate classification accounts for 59% of Nevada's land area, and 43% of all Nevada RAWS sites are located somewhere spatially within this classification area.

In a coarse sense, the Köppen classifications in Figure 11 matches vegetation zones. Figures 12a through 12c shows current coverage at a 1 km resolution from a Joint Fire Sciences Program project "Fire Regimes for Fuels Management and Fire Use" (JFSP 1999). Details of this project can be found at the web site **http://www.fs.fed.us/fire/fuelman/**. The following description of the vegetation maps below is taken directly from this web site:

> The data presented in this map depict the vegetative cover types currently present across the conterminous United States. These data were first developed by integrating two pre-existing remotely sensed vegetation classifications. The 1990 Land Cover Characteristics database (LCC) developed by USGS EROS Data Center was used for all non-forest cover types, and the 1992 Resources Planning Act map of Forest Types of the United States developed by the Southern Research Station, USDA Forest Service, was used for all forest cover types. The two remotely sensed classifications were based on biweekly composites of the Normalized Difference Vegetation Index (NDVI) derived from daily Advanced Very High Resolution Radiometer (AVHRR) satellite images collected during one vegetative growing season. These biweekly NDVI composites were clustered into areas of similar seasonal profiles, then classified into vegetation classes. Seven regional expert panels then integrated the biophysical classification of Potential Natural Vegetation and the Historical Natural Fire Regimes with the Current Cover Types data to create generalized successional pathway diagrams. These successional pathways diagrams and local knowledge were used to refine the integrated Current Cover Type map.

Table 2. Climate properties associated with Great Basin Köppen categories based on Critchfield (1983). See the Idaho State Climate Services web site for further details on the classification.

Category	Climate properties
B	70% or more of annual precipitation falls in warmer 6 months
	70% or more of annual precipitation falls in cooler 6 months
	Neither half of year with more than 70% of annual precipitation
S	Precipitation > 1/2 potential evapotranspiration but not equal to it
h	Mean annual temperature > 64.4 F
k	Mean annual temperature < 64.4 F
B	70% or more of annual precipitation falls in warmer 6 months
	70% or more of annual precipitation falls in cooler 6 months
	Neither half of year with more than 70% of annual precipitation
W	Precipitation < 1/2 potential evapotranspiration
h	Mean annual temperature > 64.4 F
k	Mean annual temperature < 64.4 F
C	Average temperature of warmest month > 50 F and of coldest month between 32 and 64.4 F
f	Precipitation not meeting conditions of driest summer month < 1.57” and < 1/3 the amount in wettest winter month or driest winter month < 1/10 of amount in wettest summer month
a	Warmest month > 71.6˚F
b	Warmest month < 71.6 F with 4 months > 50
C	Average temperature of warmest month > 50 F and of coldest month between 32 and 64.4 F
s	Precipitation of driest summer month < 1.57” and < 1/3 the amount in wettest winter month
a	Warmest month > 71.6 F
b	Warmest month < 71.6 F
D	Average temperature of warmest month >50 F and of coldest month <32 F
s	Precipitation of driest summer month < 1.57” and < 1/3 the amount in wettest winter month
a	Warmest month > 71.6 F
b	Warmest month < 71.6 F
c	Warmest month < 71.6 F and 1 to 3 months > 50 F
D	Average temperature of warmest month >50˚F and of coldest month <32 F
f	Precipitation not meeting conditions of driest summer month < 1.57” and < 1/3 the amount in wettest winter month or driest winter month < 1/10 of amount in wettest summer month
a	Warmest month > 71.6 F
b	Warmest month < 71.6 F
c	Warmest month < 71.6 F and 1 to 3 months > 50 F
H	Average temperature of warmest month < 50 F

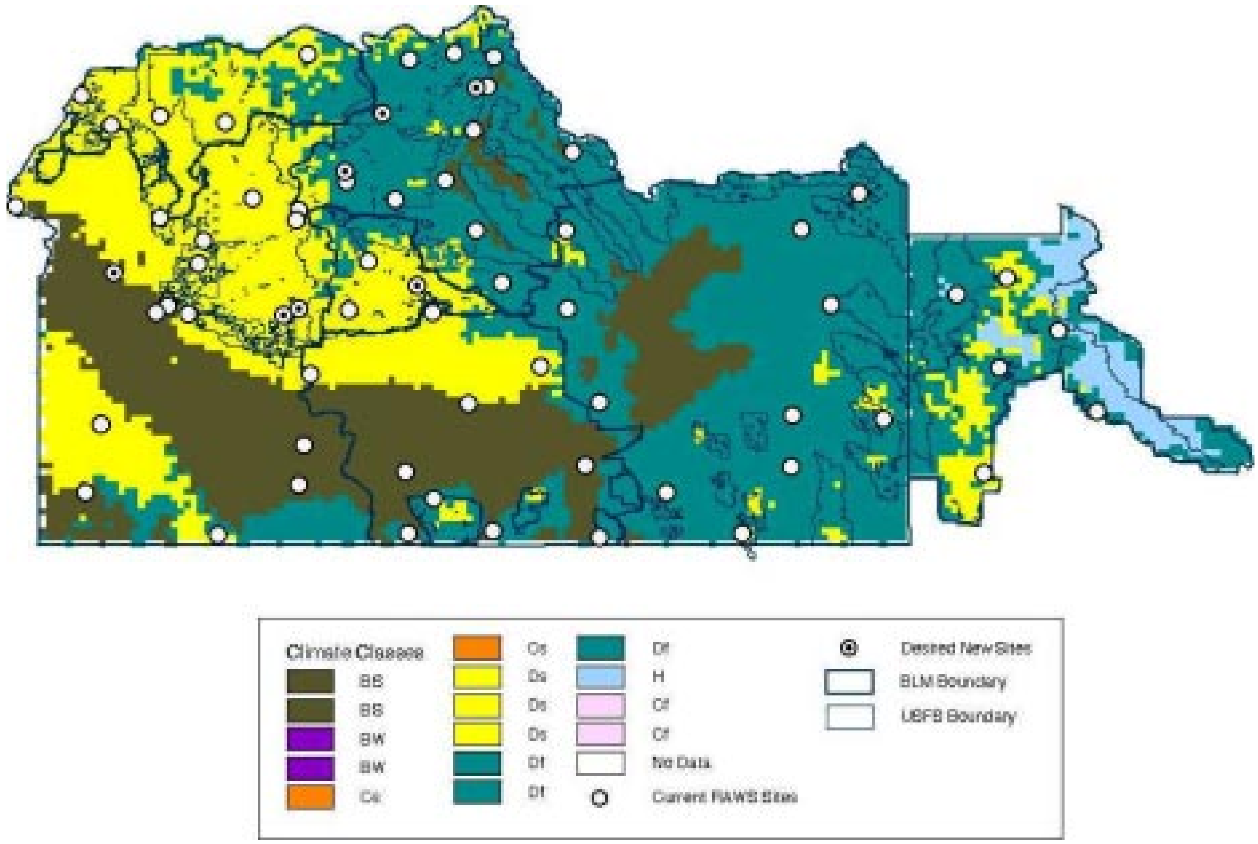

Figure 11a. Köppen climate classification (see legend) from Idaho State Climate Services for the Idaho and Wyoming regions of the Great Basin RAWS network analysis study. RAWS sites as of August 2000 are indicated by an open circle, and desired (based on survey) new site locations are given by circle with central dot.

Table 3. Percent occurrence of Köppen climate class and RAWS sites within each class by state area representing the Great Basin.

	Nevada		Utah		Idaho		Arizona		California		Wyoming	
Climate Class	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %
BSh	0	0	0	0	0	0	1	0	0	0	0	0
BSk	59	43	58	36	24	22	71	50	11	0	0	0
BWh	3	0	0	0	0	0	6	0	4	0	0	0
BWk	3	2	0	0	0	0	4	0	7	0	0	0
Csa	0	0	1	0	0	0	4	11	0	0	0	0
Csb	0	0	0	0	0	0	1	0	3	100	0	0
Dsa	1	2	1	0	2	4	1	6	0	0	0	0
Dsb	18	32	6	6	22	29	11	27	41	0	0	0
Dsc	1	0	1	0	6	5	1	6	34	0	19	17
Dfa	0	0	5	12	0	0	0	0	0	0	0	0
Dfb	14	21	24	36	37	35	0	0	0	0	54	0
Dfc	0	0	4	8	10	5	0	0	0	0	27	83
H	0	0	0	2	0	0	0	0	0	0	0	0

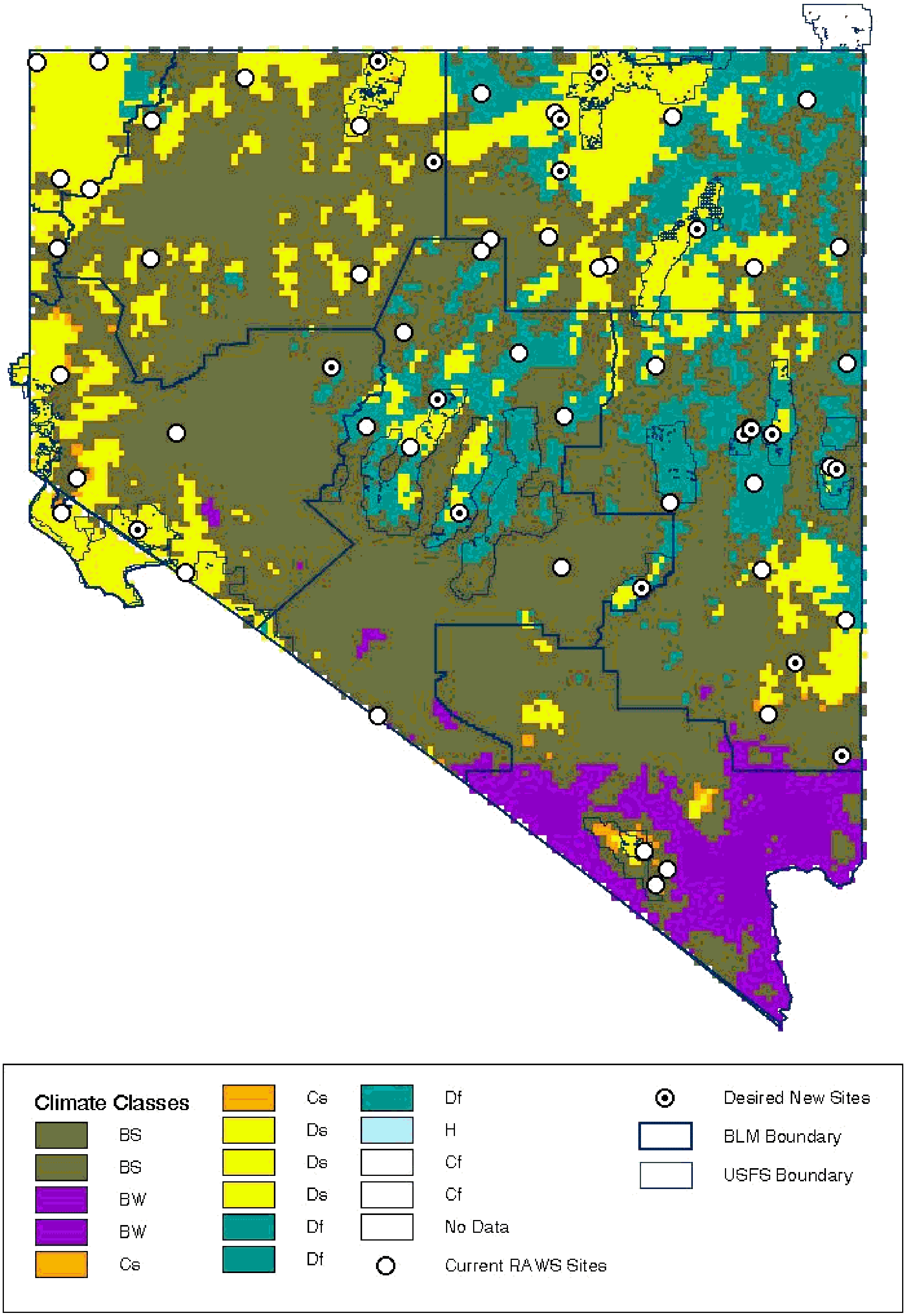

Figure 11b. Same as Figure 11a except for Nevada and California areas.

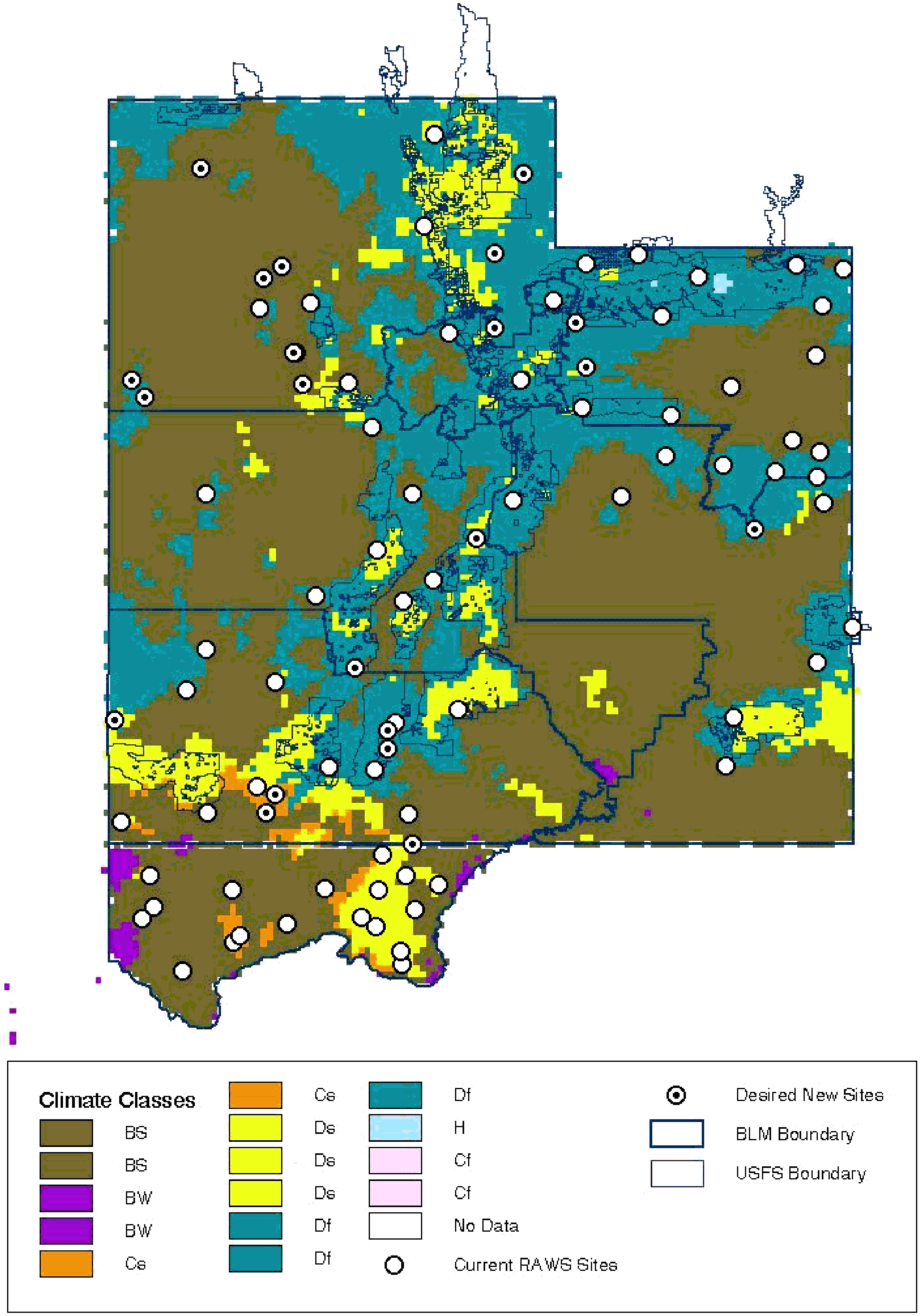

Figure 11c. Same as Figure 11a except for Utah and Arizona areas.

Also shown on each Figure are the August 2000 RAWS sites (open circle symbols) and desired (based on survey) new ones (open circle symbols with dot). The vegetation maps are included in this report generally for the same reasons as the Köppen climate maps. First, to determine how well different vegetation types are represented by the current network, and second, to provide managers with at least a coarse map of vegetation for new RAWS acquisition and planning purposes.

Table 4 provides a list of percentage area of land classification based upon the vegetation zones from JFSP (1999) and the percent occurrence of RAWS sites somewhere spatially within each classification area. As with the climate classification, it is found that generally the highest percentages of land class occurrence also have the highest percentage occurrence of RAWS sites.

Table 4. Percent occurrence of vegetation class (from JFSP 1999) and RAWS sites within each class by state area representing the Great Basin.

	Nevada		Utah		Idaho		Arizona		California		Wyoming	
Veg Class	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %	Class %	RAWS %
Agriculture	2	0	4	0	17	24	0	0	1	0	2	0
Grassland	4	11	3	4	10	11	0	0	1	0	1	0
Desert Shrub	23	18	18	6	1	0	28	6	0	0	0	0
Other Shrub	40	56	28	40	23	22	37	39	4	0	0	0
Aspen-Birch	1	2	2	0	0	0	0	0	0	0	0	0
Western Hardwood	0	0	4	6	1	0	0	0	1	0	1	0
Ponderosa Pine	1	0	2	6	6	16	4	22	21	100	0	0
Douglas Fir	0	0	1	4	13	11	0	0	0	0	14	33
Lodge Pole Pine	0	0	1	4	12	4	0	0	15	0	42	0
Fire-Spruce	0	0	2	2	5	0	0	0	2	0	26	17
Pinyon-Juniper	11	11	17	21	4	7	30	33	50	0	0	0
Alpine Tundra	0	0	0	2	1	0	0	0	3	0	4	0
Barren	16	2	9	0	0	0	1	0	0	0	0	0
Water	1	0	4	0	0	0	0	0	0	0	1	0
Urban	1	0	5	6	7	5	0	0	2	0	9	50

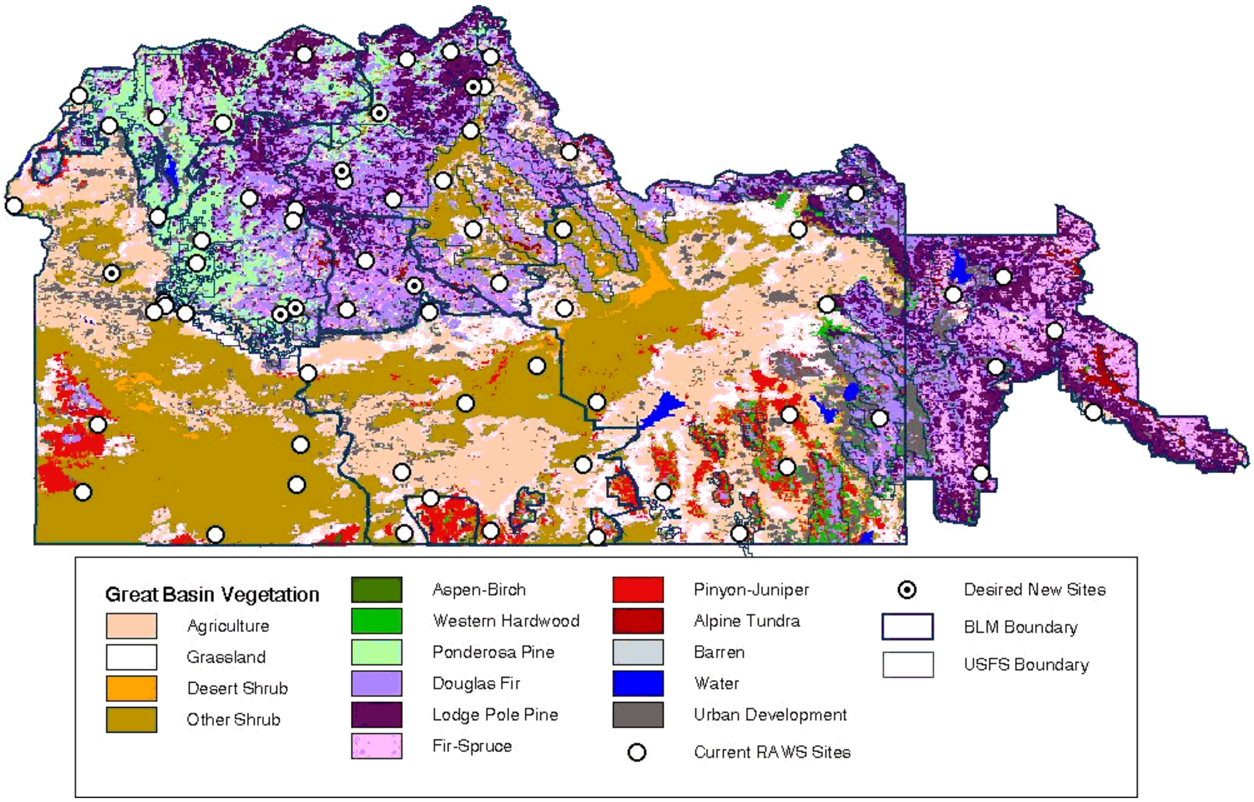

Figure 12a. Current coverage vegetation classification at 1 km resolution for the Idaho and Wyoming areas of the Great Basin RAWS network analysis. Source: Joint Fire Sciences Program.

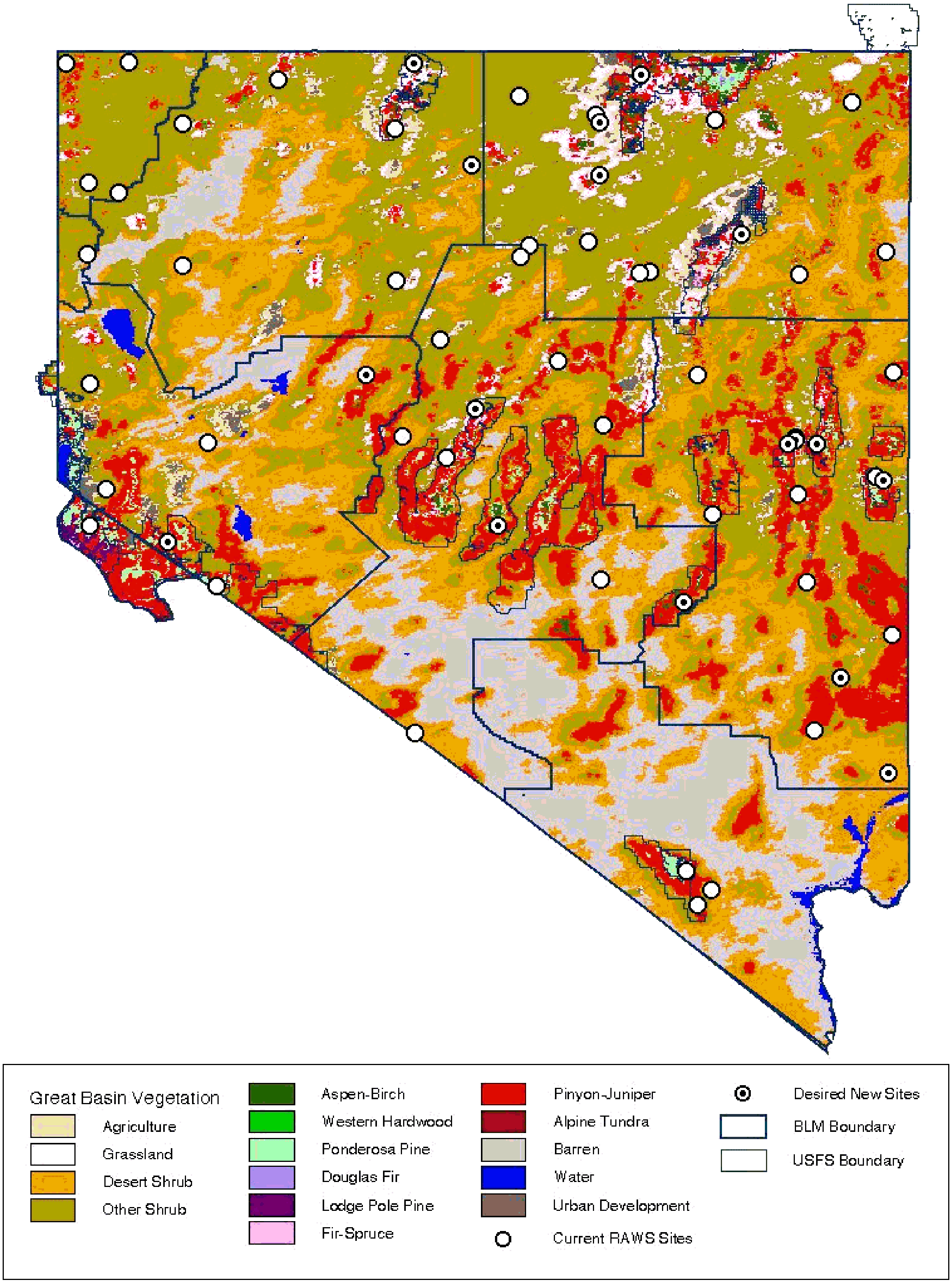

Figure 12b. Same as Figure 12a except for Nevada and California areas.

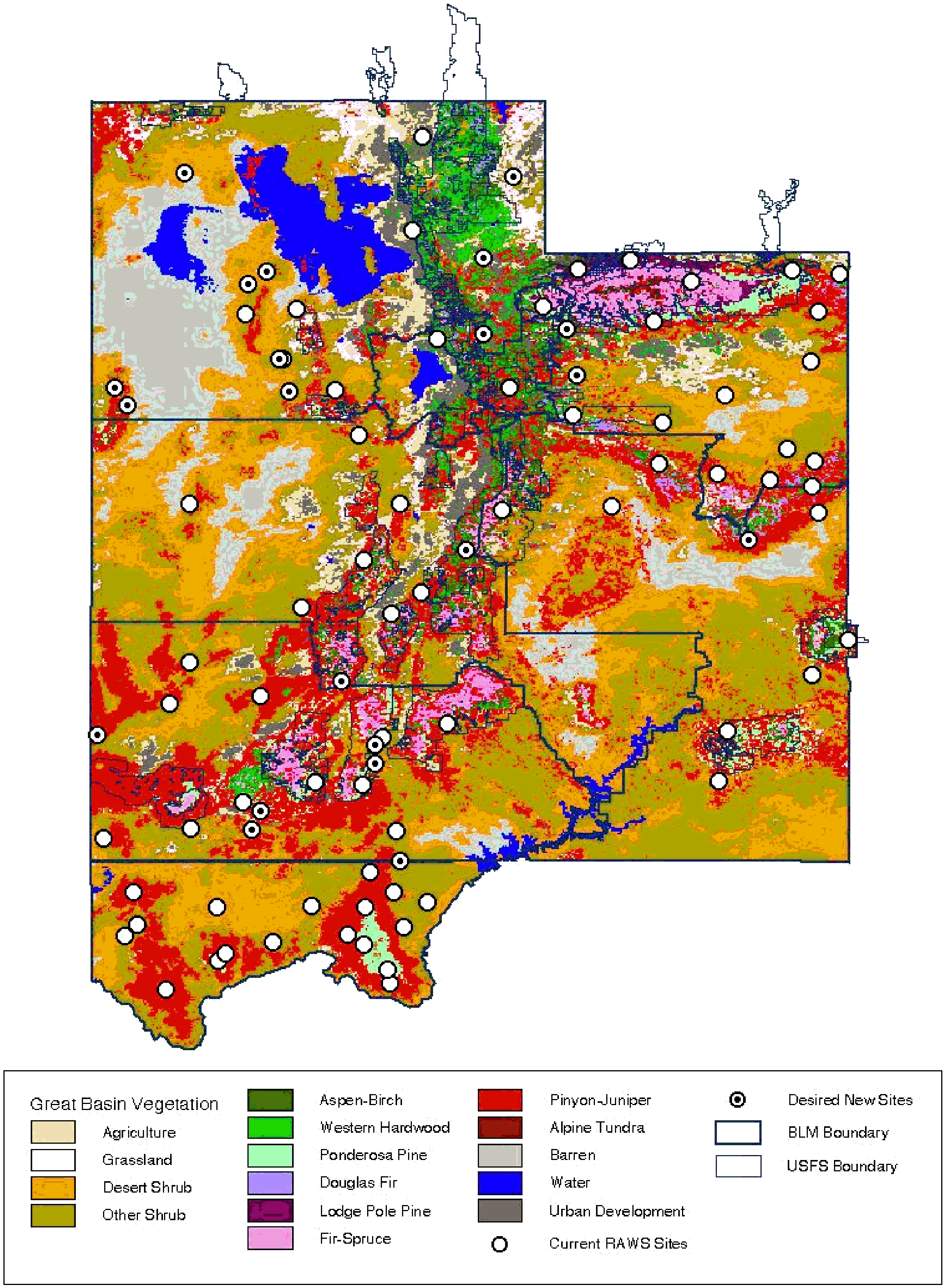

Figure 12c. Same as Figure 12a except for Utah and Arizona areas.

Recommendations

Based upon the survey responses and the spatial correlation analysis, a number of recommendations can be made regarding the Great Basin RAWS network. It is found that generally, the existing Great Basin RAWS network is good for larger scale fire danger and climate information, and adds much value to the management decision-making process. There remain some data poor regions, which should be addressed by future acquisitions. Several respondents to the survey indicated a clear desire to add new sites, which would address local issues and add overall value to the network. A denser network would obviously provide more spatially detailed information. It would be especially desirable to add more stations to improve meteorology requirements for spot weather forecasts and red flag watches/warnings. Data from an increased RAWS network can be used as part of the input into National Weather Service forecast models, which generally should improve the forecasts, and provide necessary observations for forecast evaluation. These stations might also serve in the future a source of information for fire danger models.

Fire behavior and fire use typically require more localized information, especially since wind is a critical factor for these wildfire management components. While the network is generally adequate for addressing larger scale fire behavior and fire use, additional stations would no doubt begin to respond to local needs. Other non-fire uses were prevalent in the survey responses, and the addition of new stations would be beneficial to these needs. In fact, RAWS information now has so many uses, perhaps the time has come for non-fire divisions and branches of agencies to consider providing funding to the RAWS network for new acquisitions and continued maintenance.

One of the most important considerations of the network is to assess how decision-making will change by the addition or removal of stations, and how overall agency objectives will be affected. It is often far too easy to make management decisions based solely on bottom line budget data, and without a good sense of the overall impact of the change.

The list below provides the primary recommendations by objective based upon the results of this study.

To develop guidelines for more optimal decisions regarding future acquisition and placement of stations.

- No stations currently in the network should be discontinued, unless it is determined by a specific site analysis that the data quality is so poor that data analyses would be severely comprised by misleading results.

- Every effort should be sought to appropriate sufficient budgets to maintain existing sites without compromise, and to establish new sites. The budget should include the necessary funds for equipment maintenance and replacement, archive and retrieval, metadata and relevant personnel. Given the number of uses for information, non-fire resources should also contribute support to the network, either through direct dollar amounts or staff.

- If, in the worse case scenario, stations have to be discontinued strictly for budget purposes, those with the shortest records should be removed first, while keeping intact sites with the longest historical records. Mountain-valley station pairs should be retained whenever possible. Another important factor is the number of uses for a site. Stations with multiple uses should get priority over a single use site.

- The international protocol for network design and operation as outlined by Karl et al. (1996) should be incorporated in the design and operation of the Great Basin RAWS network.

To develop parameters for the optimal placement and operation of weather stations within the Great Basin that have area-wide importance as well as interagency support and value.

- The priority of new installations should go to the sparse coverage and "data poor" regions. However, keep in mind that given the complex terrain across the Great Basin, simply looking at a 2-dimensional map may not be sufficient to determine spatial gaps.

- A maximum distance between stations should be 50 miles for larger scale fire danger and climatological analyses. A caveat with the higher elevation sites is that a denser network may be required to address localized effects such as wind channeling through canyons, orographic precipitation (e.g., rain shadows), slope and aspect, etc.

- All stations should be instrumented with additional non-standard fire danger instrumentation including soil moisture and air quality sensors. A committee should be formed to begin evaluating appropriate air quality needs and required measurements.

- Resource management applications are growing rapidly and will continue to. Many of these would be better served by upgrading the network to year-round all-weather status, and particularly the ability to deal with snow. Strong consideration should be given to upgrading the network to meet this need, and to meeting climate standards such as temporal consistency. In much of Great Basin region, the influence of winter continues to be experienced during the following spring and summer, especially—but not only—at more elevated sites.

To identify user needs for both climatological (regional assessment) and operational weather (suppression and prescribed burning) information.

- The various aspects of decision-making should be taken into consideration with plans to add or remove a station. This includes how decisions will change given the presence or absence of RAWS information, and to what extent management objectives will be affected in either a positive or negative manner as a result of the station change.

- When new station installations are being considered, the various uses should be taken into account when determining the site location. For example, a specific location might be appropriate for fire danger, but another location just 10 miles to the south would cover the same fire danger issues, and also allow for fire use, forest/range health and restoration for example.

- Data quality, usage, and access are inextricably interwoven. A number of comments received as part of this study, and independently during the course of the study, especially during the very active 2000 fire season, strongly advocated the development of a web-based network-wide access system. This access system should be able to dynamically access the entire historical RAWS database, and be capable of generating products ranging from simple data listings to complex user-defined summaries. This will have two important effects: 1) making the data more useful for more purposes; and 2) developing the constituency needed to support the continued operation of the entire network. Web-based access to WIMS is anticipated in Spring 2001, and the Western Regional Climate Center plans to have web-based access to hourly RAWS and related climate information by Summer 2001 contingent upon funding.

- It is recommended that all new station requests indicated in the survey be accepted. Many of these are re-establishing stations that were removed for budget reasons, and converting manual sites to fixed RAWS. In our view, the users of the information have the best insight as to whether or not a new station is needed, especially at the local level. There are probably some additional new sites desired that were not accounted for in this survey either from not contacting all of the appropriate individuals, or for some reason a response to the survey was not received. Another list of desired new sites should be established by contacting all appropriate individuals in a district or unit before a station priority list is developed.

- Users of RAWS information might also want to consider other sources of weather and climate information, such as NWS and State Department of Transportation sites. The use of non-RAWS data was noted in some of the survey responses.

- Environmental managers should try to acquire the habit of placing themselves in the future, 10-15 years hence, and ask "what will we wish then that we had started observing now?" This frame of mind greatly facilitates the establishment of successful and popular monitoring programs.

Acknowledgements

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