TOWARD CORRELATING CALIFORNIA'S WILDERNESS SNOW SENSORS

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INTRODUCTION

California's automatic snow sensing network is nearing completion. Of the existing 108 snow sensors in California, ten are located in USDA Forest Service (USFS) administered wilderness areas. Additionally, nine more proposed wilderness snow sensor sites are under USFS permit to the State of California, Department of Water Resources (DWR). Following a strict interpretation of the Wilderness Act (P.L. 88-577), the USFS insisted and DWR agreed to correlate the wilderness snow sensors with snow sensors outside USFS-administered wilderness. Further, DWR agreed to install all the wilderness snow sensors granted under USFS Special Use Permit (SUP) by June 1, 1989, and to remove them no later than June 1, 2004. This paper outlines the progress that has been made to date on this correlation effort. The topics reviewed are: 1) background of the USFS/DWR agreement and subsequent events, 2) installation and operational status of the wilderness snow sensors and their proposed correlative snow sensors, 3) techniques for screening and editing snow sensor data, 4) efforts to develop and test a suitable statistical methodology for performing the correlations, and 5) an attempt to estimate the effects of removing the wilderness snow sensors on water supply forecasting, assuming successful correlations. Finally, based on experience to date, the authors speculate on the future of the correlation effort and possible alternatives.

The correlation agreement between the US Forest Service and the California Department of Water Resources is a technical compromise to a political problem. The political problem is that currently automatic snow sensors are not compatible with wilderness in the eyes of the Forest Service, but snow data from wilderness areas is essential to sound water management in California. Indeed, a high proportion of California's snow zone is in wilderness, upwards of 70% in the central and southern Sierra Nevada, including almost all the watershed between 2800 m and 4300 m in elevation. The technical compromise is dependent on some yet unproven features, and this paper focuses mainly on technical feasibility. However, it is worth noting that the legislative landscape has changed considerably since the Decision Notice was signed in December of 1982 inaugurating the correlation agreement. Major wilderness legislation has been passed since 1982, including the California Wilderness Act of 1984. Indeed, much of what was agreed to may already be obsolescent in light of what Congress has legislated and written regarding the intent of this legislation.

In spite of subsequent events, the major strength of the agreement is that it mandates technical work that can form the rational basis for modifying the snow sensing network so that the impact of snow sensing on wilderness is minimized in every way feasible, while still providing for the collection of this critical information. Mitigations such as miniaturized installations, buried components, minimizing the number of wilderness sites, and minimizing the number of trips to each site are all products of this agreement. Even if it is determined that the correlation agreement is no longer needed or that it needs to be renegotiated in light of recent changes, much of the work done on the correlation may prove valuable in terms of further mitigation, and is worth continued full effort.

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BACKGROUND

The correlation agreement actually consists of three parts: 1) an Environmental Assessment (EA) prepared jointly by the USFS and DWR, completed in 1982 and amended 1984, 2) a Decision Notice selecting the preferred alternative, signed by the Regional Forester for USFS Region Five (California) on December 10, 1982, and 3) Special Use Permits authorizing DWR to install and operate the wilderness snow sensors listed in the EA and stating the conditions of the permits. Here is a brief historical perspective.

In the mid-1970's, having completed over ten years of developmental work on an automatic snow sensor, DWR was on the threshold of greatly expanding the sensor network (DWR March 1976). On December 20, 1976 the Regional Forester notified the Director of DWR that in accordance with a new National Direction that DWR would only be allowed to temporarily install and operate snow sensors in the USFS-administered wilderness, during which time they must be correlated to sensors outside wilderness and then removed. The new National Direction cited the Wilderness Act of 1964 as the basis for this requirement, and was signed by Chief of the Forest Service and acting Director of the Soil Conservation Service in September of 1976.

Two years later, Congress passed the Endangered American Wilderness Act of 1978 (P.L. 95-327). In the House Report 95-540 which accompanies the Act, Congress stated under the heading Weather Modification Special Equipment that "Snow gauges, water quality and quantity measuring instruments, and other scientific devices are located in many wilderness areas and are entirely appropriate to further the scientific, educational, and conservation purposes of wilderness areas as stated in sections 2 and 4 of the Wilderness Act (1964)." The following paragraph goes on to say "The (Congressional) committee hopes the above guidelines will prove instructive in future deliberations on wilderness areas and legislation, and will eliminate much of the confusion and uncertainty surrounding alleged uses, or prohibitions of uses, within wilderness areas." This report and the Joint Explanatory Statement of the Committee of the Conference (Conference Report 95-861) explained further that "Although the issue is discussed on page 7 of House Report 95-540, accompanying H.R. 3454, the conferees would again stress that the snow pillow facilities operated by the City of Los Angeles within the proposed Golden Trout Wilderness are compatible with wilderness designation and may be monitored and maintained in accordance with past practices."

On November 2, 1978, in a memo to DWR, the Western Regional Director of the Park Service recommended for consideration eleven guidelines. Number four read "Attempts will be made to correlate data from temporary automated stations within park wilderness areas. After a transition period not to exceed 10 years or when an acceptable level of correlation has been achieved, whichever is sooner, the temporary automated station will be removed and the site restored to its natural state." In 1979, DWR reached agreements with Yosemite National Park and later with Sequoia & Kings Canyon National Parks on installation and operation of snow sensors, documented in Environmental Summaries (California DWR 1979a & 1979b). The recommendation to attempt a correlation of the wilderness sensors was not adopted by the Parks.

Region Five of the Forest Service continued to press for agreement to correlate and remove wilderness snow sensors. On December 10, 1982 the Regional Forester signed a Decision Notice which requires that sensors be removed after a 10-year correlation period with a possible 5-year extension. The first Special Use Permits authorizing DWR to install and operate these sensors was issued in 1983.

Two years later, Congress passed the California Wilderness Act of 1984. In the accompanying House Report 98-40 under the heading "Weather modification" the Congress reaffirmed that snow gauges are "appropriate to further the scientific, educational, and conservation purposes of the wilderness areas as stated in sections 2 and 4 of the Wilderness Act (1964)."

Congress then passed the Utah Wilderness Act of 1984. The Act itself is very explicit, stating in Title III Section 305 that within eight specified wilderness areas in Utah "the Wilderness Act (1964) shall not be construed to prevent the installation and maintenance of hydrologic, meteorologic, climatological, or telecommunications facilities, or any combination of the foregoing, or limited motorized access to such facilities when nonmotorized access means are not reasonably available or when time is of the essence, subject to such conditions as the Secretary of Agriculture and Secretary of the Interior deem desirable, where such facilities or access are essential to flood warning, flood control and reservoir operation purposes." Accompanying Senate Report 98-581 does make the caveat that "Before such equipment is included in the wilderness it should be determined that such equipment is essential to flood warning, flood control or water reservoir operation purposes." All of this is important to the California situation because the same report states that "the Secretary of Interior and the Secretary of Agriculture are developing a joint policy to provide uniform guidance to federal land managers, forecasters, institutions and other Government agencies involved in the operation of such equipment. The (Senate) Committee urges a prompt development and implementation of such a policy." According to the US Forest Service a joint policy to provide uniform guidance has not been issued yet. The ramifications of such a policy might greatly influence the way DWR and the USFS proceed with wilderness snow sensors.

SENSOR INSTALLATION STATUS

Installing the snow sensors in a timely fashion and getting them to work well is of course a critical part of the correlation effort. All of the currently proposed correlative sensors have been installed, but all of the proposed wilderness sensors have not. Of the 19 wilderness sensors listed in the EA and its Addendum, ten have been installed and two are tentatively scheduled for installation in 1988, for a total of 12 (see Table 1). Of the seven sites outstanding, one site is no longer under consideration for wilderness status vis-a-vis the California Wilderness Act of 1983, two proposed sites may be relocated outside of USFS administered wilderness areas, and four sites are not financed and are yet to be scheduled for installation. Three of these last four are in the high elevation portion of the upper San Joaquin watershed. This constitutes a serious hole in the network, and if not remedied could adversely effect future forecasting on the San Joaquin and adjacent basins. As stated earlier, the Special Use Permits issued by the USFS to DWR stipulate that all the facilities must be installed by June 1, 1989, so time is of the essence.

Wilderness sensors with correlative pairs that were installed and operational prior to the 1983 season provide something that may be hard to obtain in the future. They have recorded upper and lower decile April-July runoff events (AJROs), since 1983 was very wet and 1987 was very dry in California. In order to ensure that the correlation period spans both a very wet and very dry year, the agreement stipulates that correlation include at least one AJRO that falls in the upper decile and at least one that falls in the lower decile. In fact, however, it is uncommon to get an upper and lower decile AJRO in a 10-year period, and far from certainty for a 15-year period. Assuming randomness, the probabilities are 41% and 62% respectively. However, AJRO's are not completely random, and wet years and as well as dry years have a slight tendency to be bunched. Historically for the watersheds in question, getting an upper and lower decile AJRO in a 10-year period happened about 34% of the time, and for a given 15-year period about 58% of the time. This poses a potential problem that was not addressed in the EA.

Table 1. Proposed and existing wildernesss snow sensors involved in the DWR/USFS correlation agreement and their tentative correlative snow sensors.

Directly Affected Watershed	California Number & Name WILDERNESS SNOW SENSOR (W) TENTATIVE CORRELATIVE SENSOR	Sensor Site Elevation (m)	Average April 1 SWEQ (cm)	Approx. Distance Apart (km)
Trinity River	10W RED ROCK MTN.	2040	111	24
	838 BONANZA KING	1970	***	
Trinity River	12W SHIMMY LAKE	1890	127	19
	838 BONANZA KING	1970	***	
Trinity River	311W MIDDLE BOULDER 3	1890	69	12
	850 SCOTT MOUNTAIN	1800	12	
Yuba River	~ **390W SUNNYSIDE MDW.** *	1890	160	17
	575 GOLD LAKE	2060	105	
American River	847W LAKE LOIS	2500	***	14
	365 ALPHA	2320	91	
Stanislaus R.	138W LOWER RELIEF	2470	100	17
	345 DEADMAN CREEK	2820	94	
Tuolumne River	162W HORSE MEADOW	2550	123	9
	345 DEADMAN CREEK	2820	94	
Mono Lake	282W GEM LAKE	2790	78	17
	157 DANA MEADOWS	3000	79	
San Joaquin R.	~ **189W AGNEW PASS**	2880	80	17
	205 MAMMOTH PASS	2900	108	
San Joaquin R.	~ **182W MONO PASS**	3490	82	28
	205 MAMMOTH PASS	2900	108	
San Joaquin R.	~ **186W VOLCANIC KNOB**	3080	77	21
	190 KAISER PASS	2775	97	
Owens River	~ **524W PIUTE LAKE EAST**	3350	52	14
	834 SOUTH LAKE	2930	41	
Owens River	~ **213W SAWMILL**	3140	47	3
	834 SOUTH LAKE	2930	41	
Kings River	224W UPPER BURNT CORRAL	2960	90	22
	570 WEST WOODCHUCK MDW.	2680	83	
Kings River	~ **223W BLACKCAP BASIN** **	3140	87	15
	570 WEST WOODCHUCK MDW.	2680	83	
Tule River	~ **576W SUMMIT LAKE** **	2750	71	5
	518 WET MEADOWS	2440	55	
Kern River	~ **257W BIG WHITNEY**	2970	45	12
	253 CRABTREE	3260	53	
Kern River	830W TUNNEL G.S.	2730	***	28
	253W CRABTREE	3260	53	
Kern River	262W CASA VIEJA	2560	50	35
	569 PASCOE	2790	35	

~**BOLD TYPE** Indicates sensor is not yet installed.
* Site no longer in wilderness or wilderness study area (California Wilderness Act of 1984.)
** Alternative site outside of USFS-administered wilderness may be possible.
*** Indicates insufficient data to estimate an average April 1 snow water equivalent (SWEQ) for the site.

DATA EDITING

The most critical feature of the correlation effort is establishing and preserving the most complete set of noise-free sensor data possible. Though the raw (unedited) sensor data contain a great deal of information about individual snow sensor performance and therefore comprises an essential part of the record that must be preserved, adjusted (edited) data more closely reflect the actual snow water equivalents encountered by each sensor. Consequently, adjusted data is better suited to correlating sensor-to-sensor and, eventually, sensor-to-runoff. This data-editing is well underway for all of DWR's snow sensors. Ultimately, the California Data Exchange Center (CDEC) will retain both a raw and an edited set of daily snow water equivalent data for each snow sensor.

Three items are essential for adequate editing of snow sensor data: 1) data from comparable snow sensors, 2) snow water equivalent (SWEQ) control measurements, and 3) complete maintenance records. Precipitation and temperature data, particularly on-site data, are also very useful for editing historic data and sometimes essential for interpreting current SWEQ data (Suits 1985). As the network nears completion, data from comparable snow sensors is readily available in most cases. As their usefulness becomes increasingly clear, the taking of monthly SWEQ control measurements (monthly Federal cores taken contiguously to the sensor pillow or tank) is becoming more common. Of the installed sensors involved in this correlation effort, all but three are now scheduled for monthly control measurements. Two sensors, Horse Meadow on the Tuolumne River and Casa Vieja on the Kern River, are scheduled for February 1 and April 1 controls, which will probably prove adequate. The last one of the three, Scott Mountain on the Scott River, is only scheduled for an April 1 control measurement, which is a potential problem that should be closely watched. Incidentally, SWEQ control measurements should be adjusted to discount snow sampler over-measurement (Peterson 1976). Snow sensor maintenance records are inadequate and this record keeping process needs to be upgraded, not only for the purpose of data editing, but also to evaluate and improve sensor performance. Finally, while all the sensors report temperature, the wilderness installations do not have precipitation gages, a concession to making these installations as unobtrusive as possible. This is a definite handicap. However, since the majority of sensors to which we are attempting to correlate wilderness sensors have precipitation gages, the problem is somewhat mitigated.

In snow sensor data editing there are basically four types of problems that we are trying to eliminate: erroneous data, bad datums, missing data, and chatter. Erroneous data is generally due to either system malfunctions such as fluid leaks or trapped air in the hydraulic line, or difficult hydrologic conditions such as snow bridging or flooding. Each kind of erroneous data leaves telltale signs that can often be detected when sensor SWEQ data is plotted against time. What appears to be early melt with an ablation curve that is concave like the falling-limb of a hydrograph very often indicates a leak. When the sensor tanks are inundated by local flooding, the plot of the SWEQ sensor data often resembles the shape of a storm hydrograph, with a steep rising-limb and a concave recession-limb. Rain-on-snow events often causes the sensor data to rise, then dip sharply below the pre-storm SWEQ, and then recover over the course of a few days to approximately the pre-storm level or slightly higher (Buer, Spence & Marchant 1984). Bad datums are not hard to spot and correct, with the exception of undocumented mid-season datum changes. These are difficult to detect and correct unless they are large and sufficient control data is available. The ultimate solution is to not make undocumented mid-season datum corrections. Missing data are self-explanatory and a fact of life. Chatter, defined as minor oscillations in the data not representing actual changes in water content, is easy to identify and smooth. Familiarity with these types of data errors is a great help in editing the data accurately and efficiently.

DWR's current practice is to group two to five comparable sensors, and then to plot the SWEQ sensor data and the SWEQ control measurements versus time for each group. Most of this plotting is done by computer. Then plots are inspected for possible erroneous data and bad datums. Once identified, the validity of the suspect data is confirmed or denied using maintenance records, precipitation and temperature records, SWEQ control measurements, recollections of eyewitnesses or any other source of information available. Once confirmed, erroneous data is deleted from the adjusted data set, and bad datums are rectified. Missing data as well as deleted erroneous data are replaced by synthetic data to the extent possible. These synthetic data are generated using SWEQ control data, precipitation and temperature data, and data from comparable snow sensors. Chatter with an amplitude greater then 5 cm is deadened. At the end of this process, the raw data set remains unchanged, and an adjusted data set is produced. This editing process has been made considerably easier by a computer program titled SD_EDIT, written in 1988 by Stein Buer and Marco Bell, both DWR engineers.

STATISTICAL METHODOLOGY DEVELOPMENT

Oddly enough, the correlation agreement does not prescribe a statistical methodology. According to the Environmental Assessment, a successful correlation depends on reaching a correlation coefficient of 0.95 with at least one April-July runoff event falling in each the upper and lower decile. However, the only reference to methods is in the Special Use Permit, which states: "Standard statistical techniques acceptable to the Forest Service will be used in making this determination."

Together, DWR and the Forest Service have commenced development of suitable statistical methodology. The ultimate goal is to be able to predict the SWEQ at each wilderness sensor from the SWEQ at a sensor located outside USFS-administered wilderness, so that the wilderness sensor can be removed without affecting the ability to forecast water supply. Paradoxically, it may be possible to meet the correlation criteria but not be able to reliably predict the SWEQ at a wilderness sensor from one outside the wilderness. More on this later. While this statistical methodology will undoubtedly continue to evolve during the life of the agreement, work to date has uncovered some lurking problems and some potential solutions.

Based on professional judgement and familiarity with the data, it was decided that a minimum of seven years of record was needed to get a reasonable spread of water year (WY) types. Since none of the sensor pairs involved in the agreement yet meets this requirement (the earliest pair dates back to 1983), surrogate sensor pairs with longer records were selected for the purposes of developing a statistical methodology. This scheme has the added advantage of allowing the development of a statistical approach using one set of data (the surrogate pairs) and eventually testing it on another set of data (the actual pairs).

Initially, nine surrogate pairs were selected. Pairing of the surrogates was based on their mutual proximity, their elevational relationship, and how well their co-located snow courses correlated. This is similar to the way sensors were chosen for potential correlation to sensors in USFS-administered wilderness. The elevational relationship is a somewhat special case. In many instances it is not possible to find a correlative site for a sensor outside of USFS-administered wilderness. In these cases the wilderness sensor must be paired with a sensor that is significantly lower in elevation. This problem is particularly acute in and around the Trinity and San Joaquin watersheds. Because of the importance of this problem, some of the surrogate pairs were selected to reflect this situation. Finally, in choosing the surrogate pairs, we were careful to establish at least one pair for each of the provinces that are involved in the correlation agreement: Trinity, central Sierra, southern Sierra, and eastside Sierra.

After editing the data, a simple regression of the SWEQ daily data was performed for each of the nine pairs. No synthesized data was used. All the data sets included the upper decile water year (WY) of 1983. Five of the nine pairs had records that spanned the 1976-77 California drought. Both WY76 and WY77 were lower decile runoff years for all the watersheds involved in the correlation agreement. WY87 was and WY88 will probably be lower decile years, but the data was not available when this early developmental work was done. This data, as well as that of WY83, will be very useful in some of the wilderness correlations. The results of the first attempt to correlate the nine surrogate pairs are listed in Table 2. The R-squared values range from 0.49 to 0.94. Unexpectedly, the pair with the longest record produced the highest R-squared value, and the pair with the second shortest record produced the lowest. As a general rule, other things being equal, shorter records should result in higher R-squared values. What this case illustrates is the importance of securing a good match when pairing sensors for correlation. Also, in Table 2, note the large standard errors. Their size presents a key problem, which will be discussed later.

Table 2. Correlations of nine surrogate snow sensor pairs using full data sets.

Snow Sensor Pairs	Period of Record	N	R^2	Standard Error (cm)
BIG FLAT & BONANZA KING	1981-84	214	0.68	9.1
VAN VLECK & ROBBS SADDLE	1972-86	2137	0.75	23.9
DANA MEADOWS & TUOLUMNE MEADOWS	1980-86	978	0.77	20.3
MITCHELL MEADOWS & STATE LAKES	1955-85	3994	0.94	9.9
UPPER TYNDALL CREEK & PASCOE	1971-85	3551	0.78	18.8
PASCOE & WET MEADOWS	1973-85	1998	0.83	13.2
WET MEADOWS & UPPER TYNDALL CREEK	1968-85	2310	0.61	23.1
WET MEADOWS & TUNNEL GUARD STATION	1984-85	435	0.49	17.8
COTTONWOOD LAKES & SOUTH LAKE	1980-85	733	0.74	9.6

N = Number of daily snow water equivalent (SWEQ) values used.

There is is a problem with doing the correlations using all of the daily data points: serial correlation. In correlating sensors, the goal is to predict the change in SWEQ at one sensor from the change at another. So far, the correlations have been of total daily SWEQ. Since, the daily changes in SWEQ are much smaller than antecedent SWEQs (except in the first and last weeks of the season), changes in SWEQ tend to be overpowered. For example, the importance a 10 cm SWEQ snowstorm is underrated if it fell on a 100 cm SWEQ snowpack. Likewise, data from winter fair-weather periods, when there is no change in the snowpack SWEQ, tend to be overrated. Since all the daily values are weighted equally, a 15-day dry period in midwinter carries about five times the weight of a 3-day storm. This problem is aggravated by the fact that in all but the wettest winters, fair-weather in the Sierra Nevada is more common than foul-weather. Serial correlation artificially raises R-squared values and undermines our predictive capabilities. To reduce this problem, daily SWEQ data points that had not changed from the prior day were eliminated, and the regressions were run a second time. This technique reduced the sample size by as much as half in some cases, but the R-squared values were only slighty lower, and the standard error only slightly larger (Table 3). This technique does not eliminate the serial correlation problem, but it does reduce it. Eventually, more work may be needed to fully address this problem.

Table 3. Correlations of nine surrogate snow sensor pairs using reduced data sets in order to reduce the problem of serial correlation.

Snow Sensor Pairs	Period of Record	N	R^2	Standard Error (cm)
BIG FLAT & BONANZA KING	1981-84	182	0.66	9.9
VAN VLECK & ROBBS SADDLE	1972-86	1998	0.74	24.4
DANA MEADOWS & TUOLUMNE MEADOWS	1980-86	774	0.72	22.1
MITCHELL MEADOWS & STATE LAKES	1955-85	1842	0.93	12.2
UPPER TYNDALL CREEK & PASCOE	1971-85	1623	0.66	22.3
PASCOE & WET MEADOWS	1973-85	978	0.81	14.0
WET MEADOWS & UPPER TYNDALL CREEK	1968-85	1179	0.51	28.2
WET MEADOWS & TUNNEL GUARD STATION	1984-85	330	0.49	18.3
COTTONWOOD LAKES & SOUTH LAKE	1980-85	603	0.74	9.9

N = Number of daily snow water equivalent (SWEQ) values used.

After talking with Jack Hannaford of Sierra Hydrotech and after working with the SWEQ data plotted against time, it became apparent that the SWEQ relationship between any two snow sensors is different during the winter than it is during the spring. To obtain better R-squared values and perhaps improve our predictive capabilities, the data from each sensor pair were split into an accumulation phase and an ablation phase (Hannaford 1987). Given the historical record, the actual dividing date between SWEQ accumulation and ablation could be identified for each year. Operationally, however, such a dividing date could not be predicted, and the water-supply forecaster would not know when to switch from the accumulation function to the ablation function. Therefore, we decided to adopt the convention of using April 1 as the fixed dividing date. We reduced the number of surrogate pairs from nine to six for convenience, split the data into accumulation and ablation phases, and ran two sets of regressions. The first run used all the data points, and the second run used only the daily SWEQ values that showed a change from the previous day. The results of the latter are shown in Table 4.

Table 4. Correlations of surrogate six snow sensor pairs using reduced data sets, and separating accumulation and ablation phases. (Period of record for each pair same as in Tables 2 & 3.)

		ACCUMULATION			ABLATION		
Snow Sensor Pairs	Average April 1 SWEQ (cm)	N	R^2	S.E. (cm)	N	R^2	S.E. (cm)
VAN VLECK & ROBBS SADDLE	91 54	1318	0.91	11.2	519	0.76	29.4
DANA MEADOWS & TUOLUMNE MDWS.	70 57	544	0.95	8.4	176	0.84	20.1
MITCHELL MDWS. & STATE LAKES	84 74	930	0.98	5.8	825	0.93	11.9
PASCOE & WET MEADOWS	63 77	566	0.94	7.1	250	0.94	9.1
WET MEADOWS & UPPER TYNDALL CR.	77 70	728	0.87	14.4	342	0.51	30.5
COTTONWOOD L. & SOUTH LAKE	29 41	397	0.75	8.9	189	0.74	14.4

S.E.= Standard Error.
N = Number of daily snow water equivalent (SWEQ) values used.

Note that the R-squared values for accumulation are higher than those for ablation, in some cases very much higher. This could prove to be a problem in correlating the wilderness sensors in some cases. In the cases were it is found that the wilderness sensor consistently retains snow longer than its correlative partner, the problem of predicting the SWEQ at the wilderness sensor becomes particularly difficult. We have been working on ways to handle this case. The solution will probably involve modeling the late season ablation at the wilderness sensor. The major failing of this approach is that the prime uses for ablation information are to track the performance of hydrologic models, and to provide water-supply forecasters with real information about what is taking place hydrologically on the watershed. Using model-generated numbers to check other model-generated numbers may often result in big, unpleasant surprises during and after the April-July runoff season.

The ability to predict the SWEQ at one sensor from the SWEQ at another, as alluded to earlier. is the key to success, and it is not addressed by merely reaching an R-squared value of 0.95. The standard error plays a significant role. For example, for the accumulation phase the R-squared value for Dana Meadows and Tuolumne Meadows sensors is 0.95 and the standard error is 8.4 cm of SWEQ. Say that given a certain SWEQ at Tuolumne Meadows, that the regression equation predicts that the SWEQ at Dana Meadows is 51 cm. A prediction of 51 cm is, in fact, only good to within about twice (1.96 times) the standard error (at about a 95% confidence level). Therefore, the actual snow water equivalent at Dana could be as high as 67.5 cm or as low as 34.5 cm. Moreover, there is about a five percent chance that the actual SWEQ would fall outside of even this broad range. Adding this much uncertainty to the data would seriously impede accurate water-supply forecasting, where the goal is to have SWEQ data with an accuracy of plus or minus 5% or better. When SWEQ data, or data of any kind, is cranked into hydrologic models and water-supply regression equations, the errors tend to be compounded. And that bring us to the final topic of this paper.

EFFECTS OF REMOVAL

No one can fully estimate the effects of removing the snow sensors from USFS-administered wilderness, simply because no one can with certainty predict all the future uses of the data. But we can look at the current water-supply forecasting situation and the expected future trends. The snow sensor data base is young; the oldest reliable data starts in the mid-1960's. The snow course data base is much longer; Rubicon Peak 1 and Mount Rose snow survey courses date back to 1910, just five years after Teddy Roosevelt established the Forest Service. At present, the California Department of Water Resources is heavily dependent on snow course data to make their monthly forecasts of water-supply. However, there is an increasing reliance on snow sensor information to update these forecasts weekly. Moreover, many private concerns are beginning to incorporate sensor data, particularly ablation data and temperature data, into new hydrologic models for optimizing hydro-power production and reservoir operation. Snow sensor information is even used in some cases to help predict backcountry avalanche hazard. Clearly, the use of snow sensor data is growing and becoming more diverse.

As the ability to forecast water-supply improves, eliminating uncertainty from the data will become more and more critical. However, removing wilderness sensors may add a great of deal uncertainty to the data. In the example given previously of a sensor with a 51 cm SWEQ, we could only predict that the SWEQ is between 34.5 cm and 67.5 cm (at about a 95% confidence level). That is plus or minus 32%. In light of this, let us look at our current water-supply forecasting equations and see how sensitive they are to errors in their SWEQ term(s).

DWR has two sets of regression equations for water-supply forecasting. The old equations were written in the early 1960's, and the new set was written in the early 1980's. To estimate the sensitivity of these equations to errors in the snow-term (an index of SWEQs in a watershed), we computed runoff for basins involved in the correlation agreement, using data for a wet year (WY83), a nearly average year (WY84), and a very dry year (WY87), having perfect knowledge of future weather. These are called hindcasts. Next, holding everything else in the equation constant we varied the snow-term, thus simulating snow-term errors ranging in steps of 10% from a snow-term that was 100% too high to one that was 100% too low. The output is too large to display here, but some important generalizations can be made. With regard to whether the new equations are more sensitive to errors in the SWEQ then old equations, there is no uniform trend. Some of the new equations are more sensitive some are less. However, all the equations are sensitive to errors in the snow-term. In a nearly average year, such as 1984, a 10% error in the snow-term produces anywhere from an 8% to 3% change in the computed runoff. In dry year, such as 1987, a 10% error in the snow-term influenced the computed runoff from 18% to 3%, and in a wet year, such as 1983, this influence ranged from 11% to 4%. In summary, the equations used in water-supply forecasting are sensitive to errors in SWEQ.

While the uncertainty of future weather is the predominant source of forecast error during the accumulation phase--particularly in early winter, during the ablation phase, forecast procedure error and basic data error become the predominant sources of forecast error (Hannaford 1976). Water-supply forecasting involves not only deriving the most likely April-July runoff volume (AJRO), but also describing and narrowing the range of probabilities. For example, in practice, median AJRO forecasts are often accompanied by 10% and 90% exceedence levels. Simply stated, while median forecasts represent the most likely AJRO, these two exceedence values define a range in which the actual AJRO will fall 80% of the time. Accounting the other 20% of the time, the extreme future weather situations, 10% of the time the actual AJRO will be higher than the upper demarcation (the 10% exceedence value) and 10% of the time it should be lower than the lower demarcation (the 90% exceedence value). As the remainder of the wet season grows short and the snowpack builds, these demarcations narrow around the median forecast. In short, the water-supply outlook becomes more clear. Consequently, adding additional uncertainty into the SWEQ data could potentially adversely affect water management in California, by adding significant error and uncertainty to the water-supply forecasts.

Moreover, extremely light or extremely heavy snowpacks present the most difficult forecasting situations, particularly when the season is so extreme that it falls outside of historical precedent. Because these truly extreme years may not be represented in the data used to do the correlations, the upper and lower AJRO requirement notwithstanding, the agreement may effectively truncate the record at the sites removed after a successful correlation. This would have the effect of making it even more difficult to forecast water-supply during extreme droughts and runoff volumes during extreme spring floods.

Misunderstanding or misinterpretation of the nature of forecast error may be one of the most critical problems faced in water management at the present time (Hannaford 1976). In view of California's highly variable runoff, this is certainly also true when it comes to evaluating the effects of eliminating snow sensors from USFS-administered wilderness. Modifications in the agreement should reflect the increased understanding in this area.

CONCLUSIONS

The goal of the correlation agreement is to eventually exclude snow sensors from USFS-administered wilderness. Based on recent Congressional reports and legislation, this is not Congress's intent for wilderness generally, and, perhaps with some reservations, for California wilderness specifically. It is clear that Congress wants the environmental impact of snow sensing minimized in wilderness. The work done to fulfill the correlation agreement can serve as the technical basis for minimizing the impact of snow sensing, and should, therefore, continue. However, the basic premise for the agreement has changed, and our knowledge of the technical underpinnings has grown. Based on what we have learned so far, it appears unlikely that snow sensors can be excluded from USFS-administered wilderness without adversely affecting improvements in water-supply forecasting and ultimately improvements in California water management. In light of this, the authors recommend that the agreement be reviewed and updated to reflect a change of objective from eventual total exclusion from USFS-administered wilderness to minimizing the number and impact of the sensors. Doing this now instead of later, will help the implementers to focus on the right technical questions as the work progresses.

We have demonstrated, using surrogate sensor pairs, that a 0.95 R-squared value is possible in some cases. However, the corresponding high standard errors indicate that getting to the point where we can reliably predict the SWEQ at a wilderness sensor from the SWEQ at another sensor miles away is going to be very difficult and in some cases probably impossible. More statistical developmental work needs to be done; however, it is important that the USFS and DWR continue to meet and update the agreement as our knowledge of what is possible and what is not possible grows. It is important to keep the work focused on the feasible.

It is equally important that the wilderness sensor network be completed in a timely fashion. Delays beyond the 1989 deadline may have severe and lasting effects on the program, particularly in the upper San Joaquin River basin. Further, it critical that DWR ensure that each year each sensor involved in the correlation produces a complete and accurate set of data, and that this data along with sensor maintenance records and other pertinent information is carefully archived.

Finally, snowpack information from wilderness has been an essential part of water management in California for over seventy-five years. Its loss would have an adverse effect on present water-supply forecasting and would inhibit our ability to use our water resources more wisely in the future. This could potentially affect everything from preserving instream flow values to the water that comes out of our taps. It is ironic that eliminating snow sensors from USFS-administered wilderness could in the end aggravate environmental problems elsewhere, particularly where the the environmental mitigations are dependent on accurate and timely hydrologic information.

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