SPECIALTY CONFERENCE ON POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY
AND CHANGE TO WATER RESOURCES OF THE UNITED STATES
MAY AMERICAN WATER RESOURCES ASSOCIATION 1999

AN ORGANIZED SIGNAL IN SNOWMELT RUNOFF OVER THE WEST

D.H. Peterson[1], R. E. Smith[2], M.D. Dettinger[3], D.R. Cayan[4], and L. Riddle[5]

INTRODUCTION

Climate variability and change pose challenges for water-resource and ecosystem management programs. In the western United States, a realistic assessment must accommodate linkages between climate, water, and energy along river corridors extending from mountain ranges all the way to the coastal ocean. No segment of these corridors is independent of the others and so impacts and responses to climate variability and change in one segment can not be assessed separately from others.

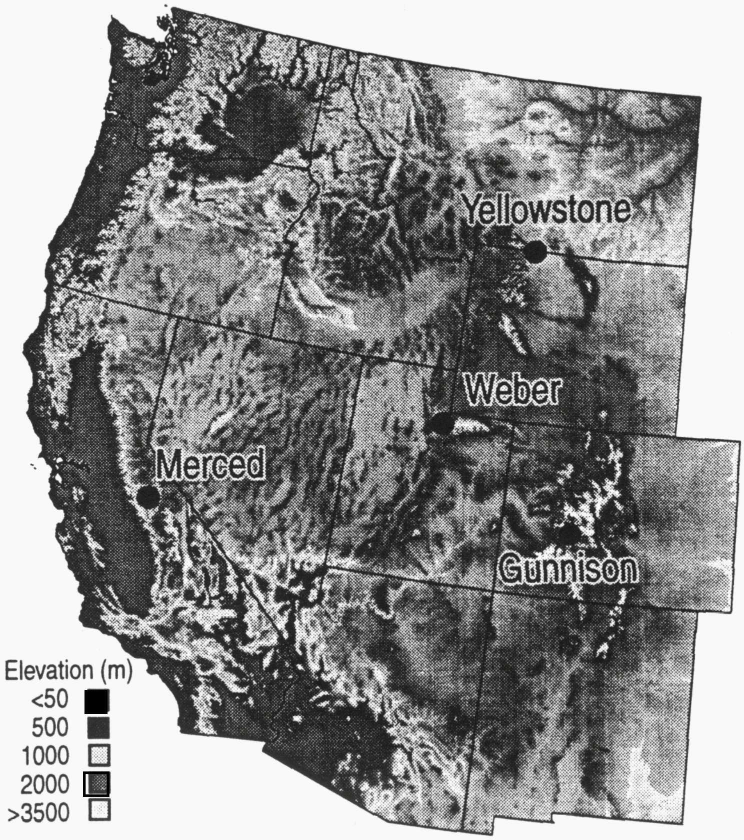


Figure 1. Study area and gaging station locations.

One testimony to the complexity of these linkages has been development of ever more complex models of hydrologic responses to climate variability and change. However, the strategy presented here instead uses simple statistical models to exploit the property that the climate variations are often of such great importance and spatial scale that they serve as cross cutting master variables that make the hydrologic linkages clear and (relatively) simple.

To understand and test the cross cutting role of climate

---

[1] Oceanographer, U.S. Geological Survey, Menlo Park, CA, (650)329-4525 , dhpete@usgs.gov

[2] Oceanographer, U.S. Geological Survey, Menlo Park, CA, (650)329-4516, resmith@usgs.gov

[3] Oceanographer, U.S. Geological Survey, SIO, La Jolla, CA, (619)822-1507, mddettin@usgs.gov

[4] Oceanographer, USGS/SIO, Scripts Inst. Of Oceanography, La Jolla, CA, (619)534-4507, drcayan@usgs.gov

[5] Climatologist, Scripps Inst. Of Oceanography, La Jolla, CA, (619)822-1507, lriddle@UCSD.edu

variations, we investigate here the way in which temperature variations control runoff fluctuations during the critical spring snowmelt season. Taking this one step further we show how predictions of temperature can be translated into river-discharge forecasts at four widely spaced rivers of the western United States. A focus on forecast models ensures that the relations we uncover are sufficient for practical uses and, for example, are not just the over simplified artifacts of statistical overfitting.

The study area is four stream flow gaging stations (Fig. 1) with primary focus on the Merced River at Happy Isles Bridge, Yosemite National Park, California (Fig. 2).

The following presents the data and statistical method, an example of forecast results including a measure of forecast skill, examples of temporal/spatial variations in air temperature and snowmelt discharge, and some future research directions.

METHODS

Data

Air temperature observations are from the National Climatic Data Center's cooperative station data. Air temperature forecasts are provided by the National

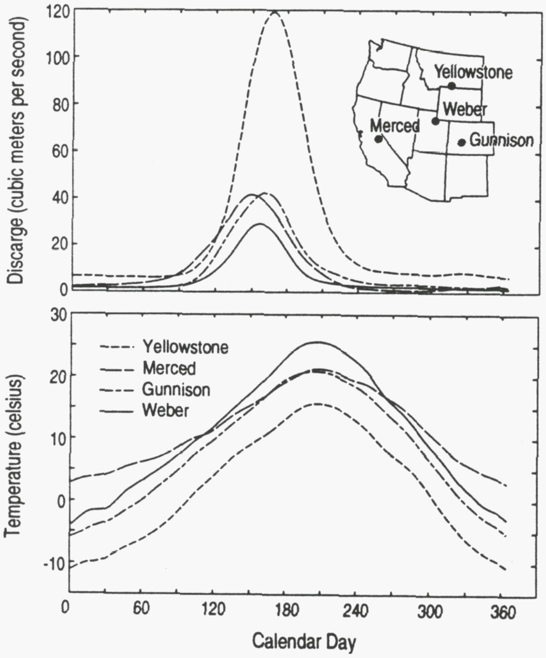


Figure 3. Upper panel, seasonal climatology of discharge. Peak value day, Merced 149; Weber 157; Gunnison 162 and Yellowstone 168. Lower panel, seasonal climatology of air temperature, all values peak after day 200. Fifteen-day times two boxcar low pass filtered mean daily observations.

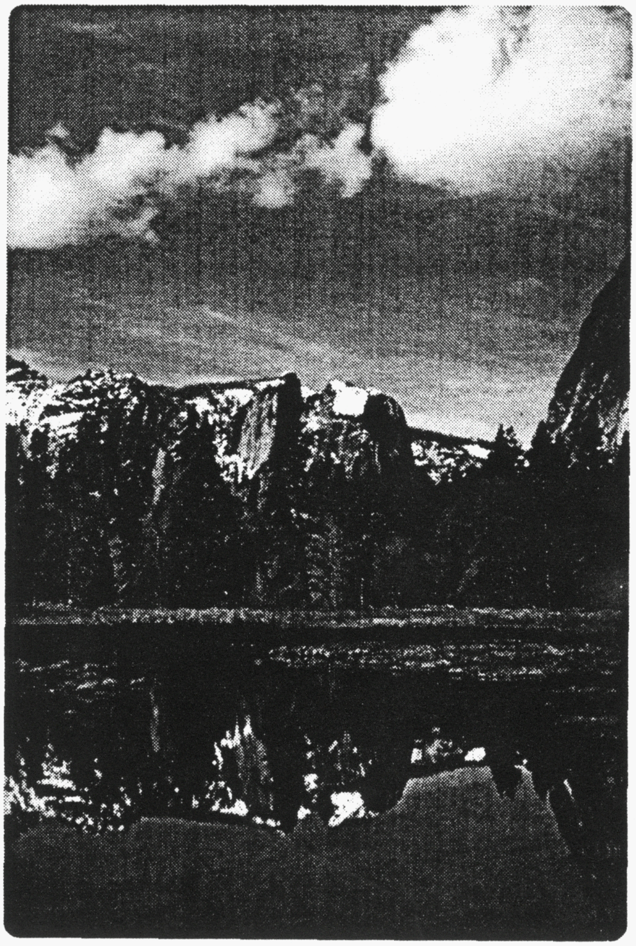


Figure 2. Yosemite National Park

Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Predictions. Discharge measurements are from the U.S. Geological Survey. Hydroclimate statistics are in Table 1 and Fig. 3.

Table 1. Description of gage sites.[1]

Location	Gage Elevation meters	Area above Gage square kilometers	Record
MERCED RIVER at Happy Isles Bridge USGS gage number (11264500)	1,220	470	1916 - 1922 1932 - Present
GUNNISON RIVER near Gunnison USGS Gage number (09114500)	2,330	2,620	1911 -1921 1935 - present
YELLOWSTONE RIVER near Belfry Mountain USGS Gage number (06207500)	1,220	2,990	1924 - present
WEBER RIVER near Oakley, Utah USGS Gage number (10128500)	2,020	420	1935 -1987

[1] Air temperature is from an average of four observation stations centered on each region except for the Weber River with a single site from Salt Lake City.

Forecast Model

Recent developments in the area of hydroclimate forecasting have been mostly in the direction of detailed multi-parameter physically based numerical models of rivers and watersheds. But to focus directly on some of the climate-stream flow linkages, we use here a much simpler statistical discharge model. In this model the present and previous three days of air temperatures, T_i, i =O, are input and river discharge, Q_i, is output.

The discharge model, then, is simply:

$$Q[n] = \sum_{i=0}^{3} b(t) T[n - i]$$

where b_i's are the present and past temperature coefficients. The coefficients b_i are estimated using a Kalman filter, feeding daily forecast discharge back into the correlation calculation (Peterson and others, in press). The model uses a recursive difference equation (Ljung, 1988, 1989) modified for forecasting with lead times to 11 days.

RESULTS/DISCUSSION

Discharge Forecasts

Our earliest experimental forecasts, spring 1997, used a constant-parameter version of the model (Dettinger and others, 1997). Variable-parameter forecasts started in spring 1998; and these forecasts will be continued in 1999 and beyond. Yellowstone and Weber Rivers are not yet included in the www site forecast. Preliminary results show that they exhibit broad scales of correlation similar to Merced and Gunnison Rivers (see below).

Fig. 4 shows an example 6-day forecast from 1998 for the Gunnison River. Typically, forecasts maintain a close match in phase (both air temperature and discharge) but not in amplitude (Fig 4). Thus the correlation coefficient (Fig. 5) is perhaps an exaggeration of skill as it is most sensitive to differences in phase. Also, including the seasonal cycles will improve the correlations. We are studying why the forecast skill for 1998 differed between the Merced and Gunnison rivers. One factor appears to be that the observed fluctuations in air temperature arrived sooner than predicted for the Merced region.

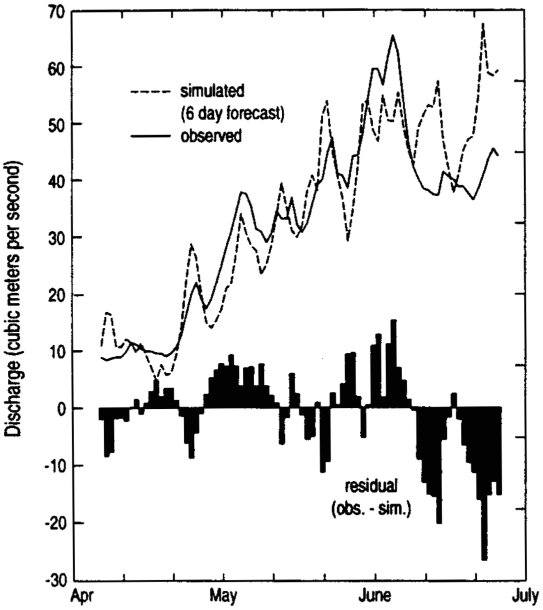


Figure 4. Observed and 6-day forecast of discharge, Gunnison River, Colorado, 1998

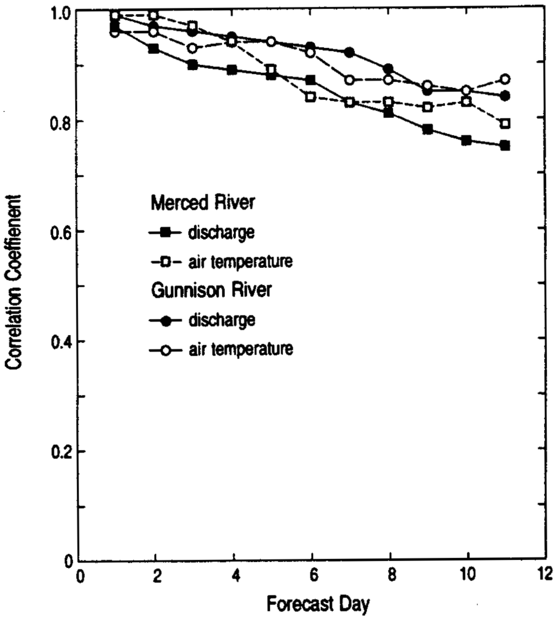


Figure 5. Correlation coefficients of observed air temperature and discharge as a function of forecast horizon.

Air Temperature Correlations

Several lines of evidence show that air temperature is a useful master variable in prediction of the timing of snowmelt discharge (Cayan, 1996). Of course the seasonal discharge is controlled by the amount of snowpack. What we are talking about are the fluctuations in discharge. Each watershed has unique characteristics of topography, soils, and vegetation, and it might be assumed that distant high elevation watersheds would yield different sequences of discharge. What is unexpected is that distant high elevation watersheds often display very similar discharge fluctuations, down to the level of a few days. The reason for this remarkable result is the broad scale nature of synoptic features in the atmospheric circulation, which provides anomalous temperature forcings that often span the entire western U.S.

Several examples provide a good illustration of the correlation in temporal variability among the four distant watersheds. In the next three figures the daily hydrographs and temperatures were adjusted for lead-lag relations for the same variable but not for cross variables. That is, no adjustment was made for the delay between air temperature and snowmelt. The Merced is assumed to always lead the Weber and Yellowstone temperature/discharge by one day and the Gunnison by two

The first example (Fig. 6a), 1951 shows a low frequency snowmelt "cycle" (approximately days 140 (May 20) to 170 (June 19). That is obviously driven by two warm spells separated by an interlude of cool weather that invaded the west. Also evident is an early response for the Merced and fading snowmelt for the Gunnison, Weber, and Merced with continued snowmelt at Yellowstone. The next example (Fig. 6b), 1979 is similar with higher frequency temperature and discharge fluctuations. Again, the snow at Merced is probably preconditioned to a higher temperature giving a earlier higher discharge response and the Weber River snowmelt is fading before the other three. The last example (Fig. 6c), 1980 is similar to the first (Fig. 6a) except the second major peak is less for Weber and Merced presumably because their remaining area of snowpack is significantly diminished.

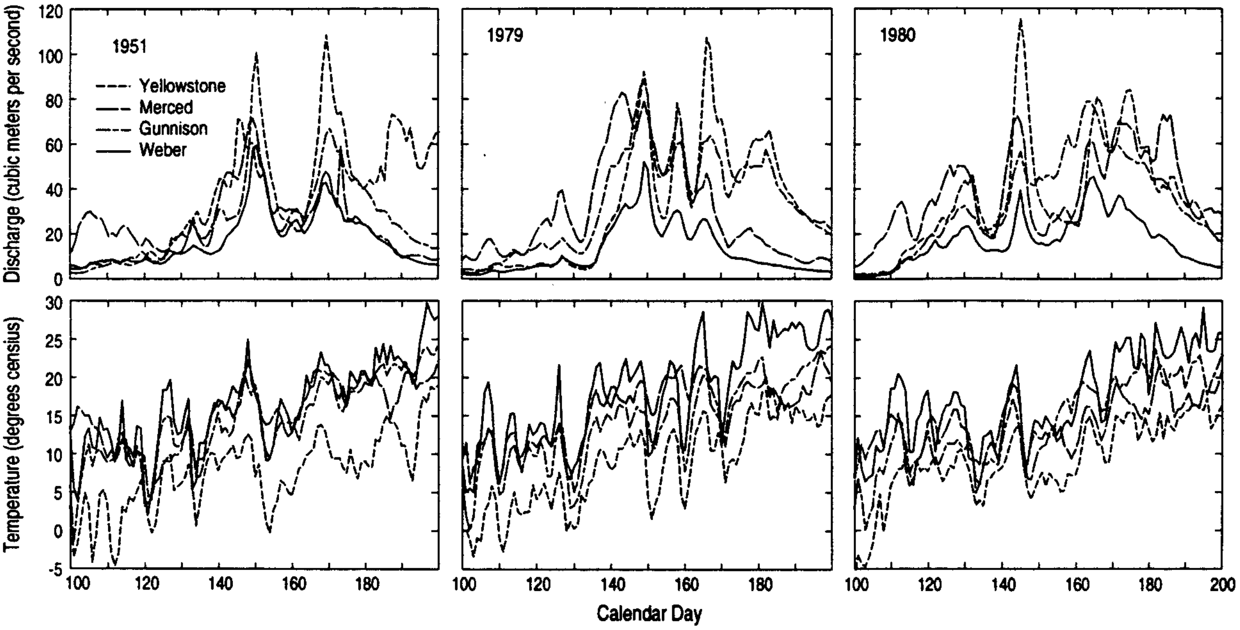


Figure 6. Daily variations in discharge (upper) and air temperature (lower) Yellowstone, Merced, Gunnison and Weber Rivers, for years 1951(a), 1979(b), and 1980(c). Yellowstone discharge divided by two.

Figure 6a, 6b, and 6c include the seasonal and daily variations. The seasonal cycles (Fig. 3) are approximated by filtering the mean-daily values with a 15-day boxcar filter times two (forward and backward to preserve phase). Examples of deseasonalized daily fluctuations are shown in Fig. 7 for the Merced and Weber Rivers. These fine structure variations seem remarkably in-phase (Merced plotted as a one-day lead) for such distant watersheds. The forecast "skill" correlations (Fig. 5) included both seasonal and daily cycles as do the long term average spatial air temperature correlations in Fig. 8.

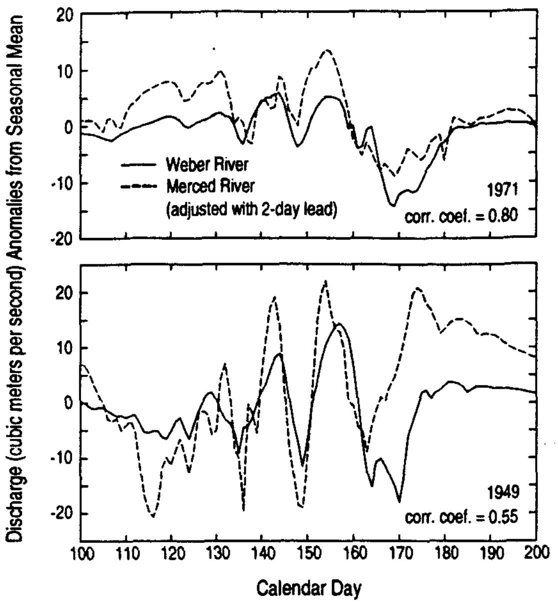


Figure 7. Examples of daily correlations in Merced and Weber River daily anomalies from seasonal climatology (in Fig. 3). Upper panel 1949. Lower panel 1971.

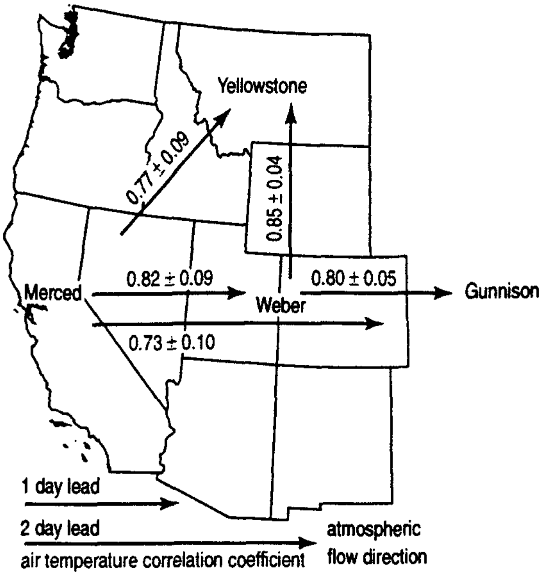


Figure 8. Long-term mean (1935-1987) spatial correlations in daily air temperature between distant watersheds.

The success of the simple model above (Equation 1) argues for air temperature as the master variable. When this model is augmented with past discharge (on the right hand side of the equation) little is gained in the correlation between observed and forecast discharge (it may even degrade). This indicates that for the short period (1-10 day) fluctuations in runoff during spring, the air temperature-discharge correlation is so strong it captures almost all of the predictable signal. It seems, then, as temperature goes, so goes discharge, and temperature "goes" in very large spatial patterns.

Watershed Air Temperature

Climate variability and change issues are centered on precipitation and air temperature. Below are some research directions relevant to these issues and to hydrologic forecasting.

In comparing some of the Merced/Weber River results the distant Merced discharge correlates better with Weber discharge than do their respective air temperatures (Fig. 9, upper panel). The air temperature/discharge correlation is also stronger for the Merced than Weber watershed (Fig. 9, lower panel). The Merced temperature is a composite from four locations (Cayan, Riddle, and Aguado, 1993) and may better represent "average" temperature above the gage site, compared to data from a single location used in the Weber River example (Salt Lake City). Also, snow melt integrates energy inputs (we used four days of temperature) and this is not as sensitive to high frequency noise – discharge "sees" the lower frequencies and ignores higher frequency noise in temperature. These differences in correlation suggest a need for better high elevation air temperature networks.

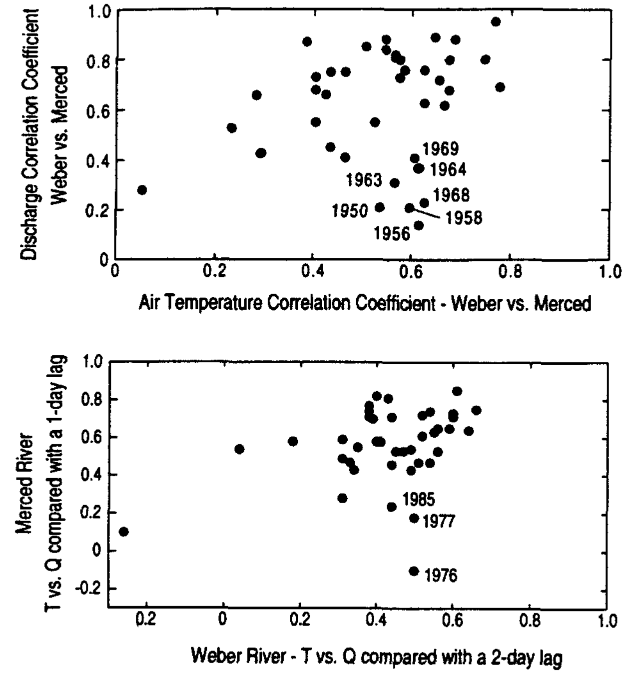


Figure 9. Correlation in Weber and Merced discharge versus correlation in Weber and Merced air temperature (upper panel). Note red dots represent years when one watershed ran out of snow before the other within the 100 to 200 day window. Correlation in Merced air temperature and discharge versus correlation in Weber air temperature and discharge (lower panel) outliers in red were drought years in California.

The Snowmelt Air Temperature Response

In the context of global warming and also natural interdecadal climate fluctuations such as the Pacific decadal oscillation (Mantua, and others, 1997; Gershunov and Barnett, 1998), it would be useful to determine the empirical air temperature – snowmelt discharge response surfaces for high elevation snowmelt watersheds. In West Coast winters, the day-to-day mixes of rain or snow that fall are determined by the general temperature within a storm and the rate of decrease in temperature with increase in elevation (temperature lapse rate). As a result, low elevation precipitation is more often rainfall (warm), high elevation precipitation is most often snow (cool), and at an intermediate elevation a mixture of the two falls (Cayan, Riddle, and Aguado, 1993). At high elevations, for similar snowpack (estimated here from their cumulative discharge but also measured directly), the timing of snowmelt (early or late) is largely determined by seasonal air temperature variations (Cayan and others 1997). Figure 10 is a comparison of Merced River discharge between warm-wet (1986) and cool-wet (1967) years. Both discharge totals were higher than the long term mean, but importantly, the timing of peak discharge was 30 days earlier in 1986 in response to having much warmer spring-early summer temperature. The mean day-100 to day-200 temperature difference between the two years was 2.3 degrees centigrade (Fig. 10; the cartoon, Fig. 11; see also Cayan and Peterson, 1993)

Water managers are concerned about differences in spring discharge timing because an early snowmelt shortens the season of natural water storage. Reservoir management would require more artificial reservoir volume to account for this loss of "free" storage capacity. There are also concerns about spring snowmelt floods in some watersheds. This temperature affect is at the heart of the long-term global warming issue (Jeton and others, 1996; Gleick, 1987; Lettenmaier and Gan, 1990). And, it is probably even more significant because over the last several decades, spring snowmelt at intermediate elevations has been declining (Roos, 1987) due to increasingly warmer winters (December, January, February, March; Dettinger and Cayan, 1995).

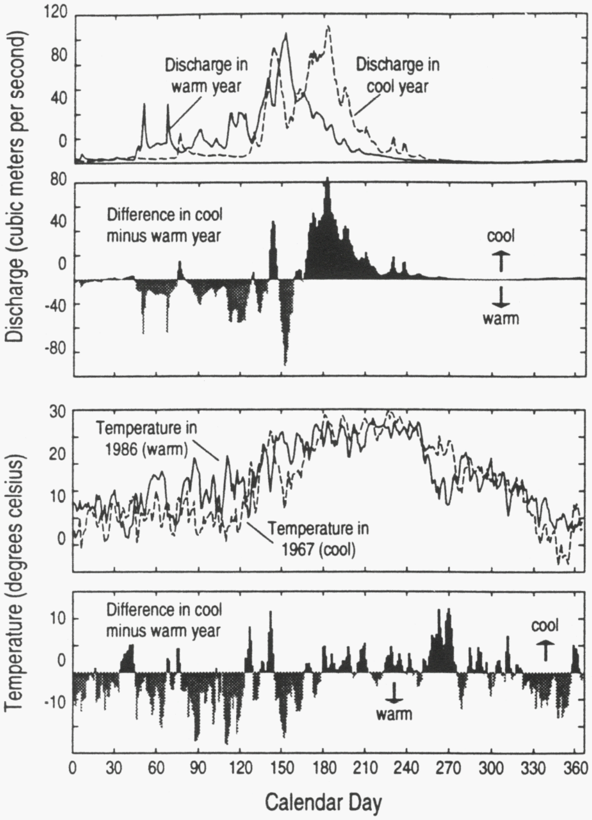
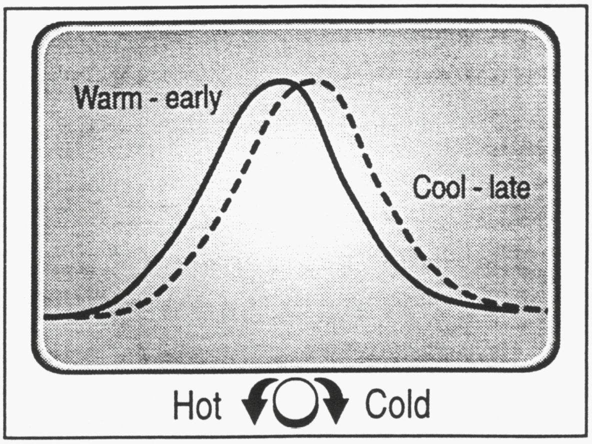


Figure 10. Example of a cool spring (1967) delay relative to a warm spring (1968). The mean day-100 to day-200 air temperature in 1967 is 13.9o centigrade, and in 1968, 16.2o centigrade; mean discharge for the same period, in 1967 is 54.5 cubic meters per second, and in 1986, is 39.5 cubic meters per second. Day for start of spring pulse in 1986 is 108, and in 1967 is 126; day of peak discharge, in 1986 is 152; and in 1967 is 182.



Turn the knob to your left, make the temperature warmer and the plot will show an early snowmelt.

Turn the knob to your right, make the temperature cooler and the plot will show a late snowmelt.

Figure 11. Cartoon version of results in Fig. 12 for constant discharge values. A similar interactive program could be designed for constant temperature values with discharge as the variable (high discharge is a late and low discharge is an early spring snowmelt).

In northern and central California, early snowmelt also means downstream summer discharge is less (all other things being equal). Salinity encroachment into the northern San Francisco Bay/Delta, a freshwater source for 20 million people, is exacerbated following warm versus cool springs (Cayan and Peterson, 1993). Therefore warm springs put even more pressure on management in balancing agricultural, urban, and environmental water needs.

In closing it appears that there is a much stronger regionally organized signal in snowmelt runoff than has been appreciated. These coherent runoff fluctuations would seem to have application to water resources and hydropower concerns among others. Even using relatively simple statistical methods, forecast results are encouraging and model refinement will continue. Also, the results infer that if air temperature forecast skill continues to increase discharge skill will follow.

REFERENCES

Cayan, D.R., 1996, Interannual climate variability and snowpack in the western United States, Journal of Climate, 9, 928-948.

Cayan, D.R., Peterson, D.H., Riddle, L. Dettinger, M.D. and Smith, R.E., 1977, The spring runoff pulse from the Sierra Nevada, Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary Newsletter, Summer, p. 25-28.

Cayan, D.R. and Peterson, D.H., 1993, Spring climate and salinity in the San Francisco Bay estuary, Water Resources Research 29,293-303.

Cayan, D.R., Riddle, L.G. and Aguado, E., 1993, The influence of precipitation and temperature on seasonal streamflow in California, Water Resources Research, 29(4), 1127-1140.

Dettinger, M.D. and Cayan, D.R., 1995, Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California, Journal of Climate, 8, 606-623.

Dettinger, M.D., Peterson, D.H., Diaz, H. and Cayan, D., 1997, Forecasting spring runoff pulses from the Sierra Nevada Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary Newsletter, Summer, p. 32-35.

Gerhunov, A. and Barnett, T.P., 1998, Interdecadal modulation of ENSO Teleconnections, Bulletin of the American Meteorological Society, 79, 2715-2725.

Gleick, P.H., 1987, The development and testing of a water balance model for climate impact assessment: modeling the Sacramento Basin, Water Resources Research 23(6) 1049-1061.

Jeton, A.E., Dettinger, M.D., and Smith, J.L., 1996, Potential effects of climate change on streamflow eastern and western slopes of the Sierra Nevada, California and Nevada:U.S. Geological Survey WRI Report 95-4260, 44 p.

Lettenmaier, D.P., and Gan, T.Y., 1990, Hydrologic sensitivities of the Sacramento-San Joaquin River basin, California, to global warming, Water Resources Research, 26(1), 69-86.

Ljung, L., 1988, System Identification Toolbox User's Guide for use with Matlab, The Mathworks, Inc., 21 Eliot St., South Natick, MA, 59 p.

Ljung, L., 1989, System Identification: Theory for the User, Prentice-Hall, Inc., lnglewood Cliffs, N.Y., 515 p.

Mantua, N.J., Hare, S.R., Zang, U., Wallace, J.M., and Francis, R.C., 1997, A Pacific interdacadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78, 1069-1079.

Peterson, D.H., Smith, R.E., Dettinger, M.D., and Cayan, D.R., in press, Forecasting spring discharge in the West: A step towards forecasting stream chemistry, In: D.W. Morganwalp, and H.T. Buxton, eds., U.S. Geological Survey Toxics Substances Hydrology Program – Proceedings of the Technical Meeting Charleston, South Carolina, March 8-12, 1999 – Volume 2- Contamination of Hydrologic Systems and Related Ecosystems: U.S. Geological Survey Water Resources Investigations Report 99-4018 B. 8 p.

Roos, M., 1987, Possible changes in California snowmelt runoff patterns, Proceedings of the 4th Annual PACLIM Workshop, Asilomar Conference Center, Pacific Grove, CA March 22-26, 1987, pp. 22-31.