Forecasting Spring Discharge in the West: A Step towards Forecasting Stream Chemistry

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ABSTRACT

By linking climate to hydrology, correlations emerge that may be overlooked when studying hydrology alone. Forecasting the spring snowmelt discharge of the Merced River, Happy Isles, Yosemite National Park, is a first step towards that linkage. Once climate and stream flow are linked, stream flow-chemistry relations will become clearer as, indeed, will climate-chemistry linkages. This approach looks promising for synthesis/interpretation of simple and complex chemical variations, including “pollutants”, atmospheric or otherwise.

INTRODUCTION

A Conceptual Hydrological Cycle

One of the goals in hydrology is to be able to predict the behavior of dissolved substances (conservative, reactive, toxic, etc.) in the watershed/estuary/coastal ocean. This is often a source/transport/fate problem.

In the riverine transport part of the problem, to the extent that concentrations are related to river discharge, if we can predict river discharge, we can predict concentration. Similarly, if the major control on discharge is climate, which it is, if we can predict climate, we can predict discharge. Taking this a giant leap further, if the state of the ocean is a major control on climate, to the extent we can predict the state of the ocean, we can predict climate.

Our goals are deceptively simple, to link atmospheric circulation to discharge and discharge to chemistry. For reasons given below, we have started with the snowmelt discharge process. For reviews of this subject, see Morris (1985) and Gray and Prowse (1992).

YOSEMITE NATIONAL PARK

It may seem odd to pick as a starting point a relatively pristine region, Yosemite National Park (Fig. 1 photo of YNP), distant from obvious toxic problems. We have this luxury because, as stated earlier we are taking a simplified view of the entire system and asking what are the linkages.

Figure 1. Merced River Yosemite National Park.

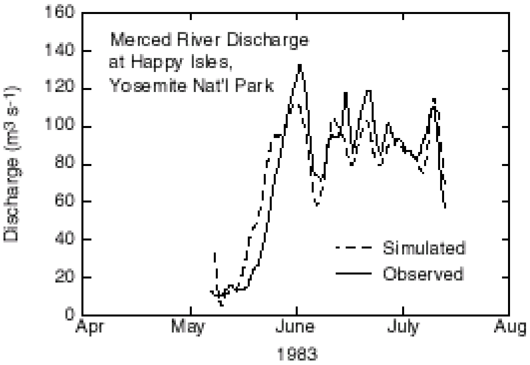


Figure 2. Merced River discharge, note abrupt rise in discharge (the spring pulse).

For a variety of reasons, the Merced River at the Happy Isles Bridge gage site, Yosemite National Park, is an excellent laboratory for studying high elevation hydrological processes. The discharge records are long and there is little human influence; discharge is largely snowmelt (simplifying the climate connection); and Yosemite is an apparent bellwether site for the spring pulse (Fig. 2) with large-scale atmospheric temperature correlations (Cayan and others, 1997) that have biological (S. Kammerdiener, University of California, San Diego, written communication, 1999), as well as hydrological implications (Dettinger and Cayan, 1995). The adjacent Tuolumne River (Fig. 3), a close twin of the Merced, is the major water resource for the city and county of San Francisco via the Hetch Hetchy reservoir. As is typical of most reservoirs, there are water quality concerns associated with Hetch Hetchy. Because the pre-development major ion chemistry “finger print” of the Tuolumne and Merced are a close match (not shown), we can exploit their historical similarities. For example, changes in the chemistry of the Tuolumne can be measured against unmolested constant Merced chemistry. Further, the Merced River is upstream of one of the most important agricultural regions in the United States that is the source area for many contaminants.

Figure 3. Tuolumne River before and after Hetch Hetchy reservoir, 1922.

WHY CLIMATE?

This may be best answered by example. Understandably, toxic research is focused on the source and disposition of toxic substances, natural or otherwise, and much less focused on the role of climate factors. One of the best documented examples of overlooking the role of climate was the use of a numerical groundwater salinization model to predict long-range salinization resulting from agriculture (Konikow and Patten, 1985). In revisiting their predictions some years later, the authors found they were off the mark. This led to the discovery that they had tuned their model with data collected in the middle of a three-year period of declining discharge which contributed to the an overstimate of the rate of salinization (both human and climate effects were present). Climate variations, no doubt, make toxic problems more complex; thus toxics researchers often attempt to work around, or neglect them. The thesis here is that we may also learn by putting climate back into the water quality equation (Peterson and others,1996, note, for purposes here weather and climate are used interchangeably).

With the above in mind, the Pacific Northwest and Southwest hydrology provides an introduction to our theme because this region is strongly influenced by the well-studied ENSO (El Niño Southern Oscillation) phenomena (see for instance Cayan and Peterson, 1989 and references cited). Not surprisingly, the strong ENSO-discharge correlation also includes a strong river chemistry correlation (simplified here as specific conductivity or total dissolved solids, Fig. 4).

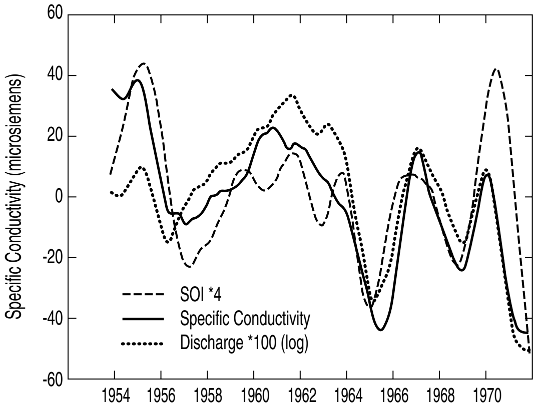


Figure 4. Low-pass filtered mean-monthly ENSO, Snake River discharge and specific conductivity, King Hill Idaho, deviations from long-term mean and discharge times minus one.

Our study area, central and northern California, lies between these two centers of oscillating wet/dry ENSO patterns. In central and northern California, wetness or dryness in ENSO years varies, going with the northern regime in some years and the southern in others. This ambivalence tends to cancel out much of the atmospheric-hydrologic ENSO correlation for northern and central California over the period of instrumental record. Therefore the resulting atmospheric-discharge correlation is more regional in scope and is better indicated by the atmospheric pressure anomaly index, the California Pressure Anomaly, or CPA, (Cayan and Peterson, 1989). CPA correlates with Merced River discharge, (Fig. 5). On a regional scale, then, Merced River chemistry, although sparsely sampled, tends to follow CPA just as the Snake River discharge/chemistry follows ENSO to the North (Fig. 4).

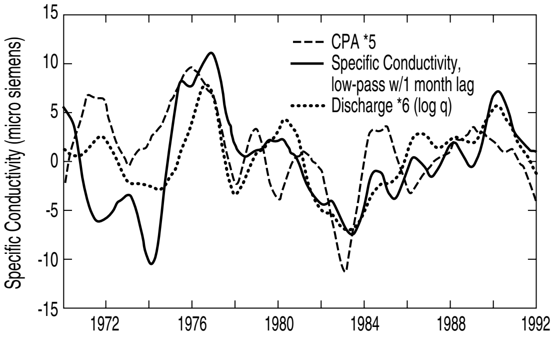
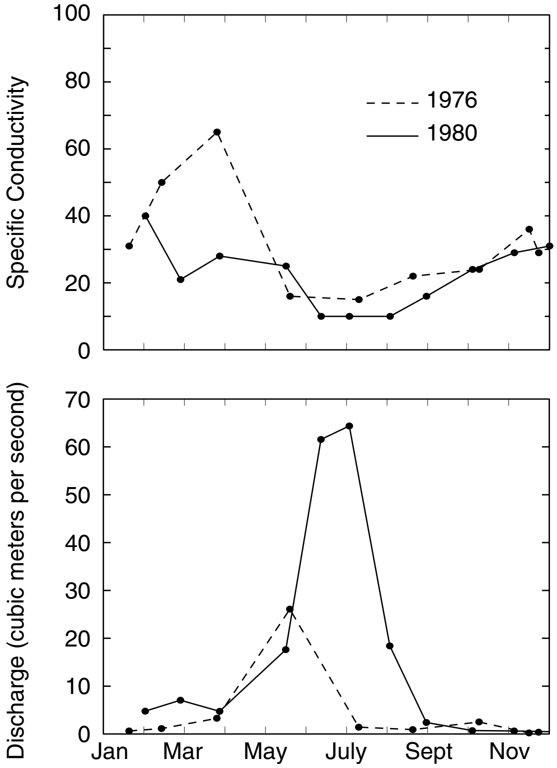


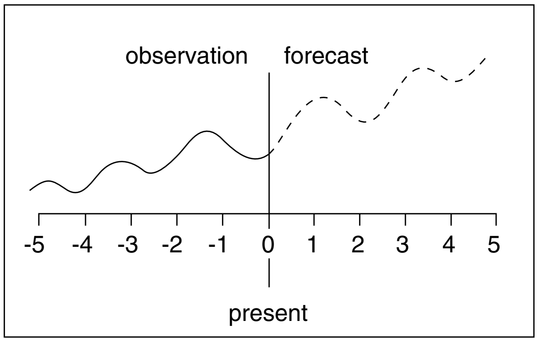
Figure 5. Low-pass filtered mean-monthly CPA and discharge with interpolated specific conductivity, Merced River, Happy Isles, Yosemite National Park, deviations from long-term mean and discharge times

FORECASTING SNOWMELT DISCHARGE

At the time of this writing we do not have time series of chemical variations to clearly link water chemistry to discharge for the Merced River (Fig. 6 shows a gappy pattern). We can however, provide initial results in the climate-discharge step, which of course preceeds the discharge-chemistry step.



Our approach is to exploit the correlation between air temperature and snowmelt via statistical methods. Consider a time series of discharge observations and imagine discharge projected into the future (Fig. 7). To the extent that the observed and forecast wiggles in discharge correlate with the observed and forecast wiggles in air temperature (Fig. 8) we can predict discharge.



By predicting discharge in addition to measuring it, we may think about the system in ways we otherwise would not. Obviously, riverine toxic research will more fully benefit from a much more detailed knowledge of the riverine physics (and vice versa) than given here. Such research is proceeding by Dettinger, vanWagtendonk, Cayan, and others (Dettingers and others, 1998 and 1999).

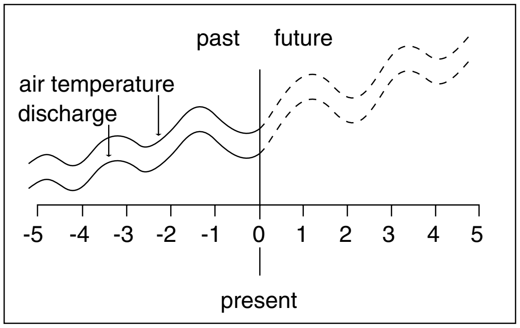


Figure 8. Cartoon of air temperature/ discharge correlation in the observational and prediction domains.

Constant Parameter Snowmelt Model

A seasonal snowmelt cycle may be simplified into four phases (Fig. 9). In the first phase, discharge shows little response to changes in temperature (it's too cold). The second phase follows after the snowpack has stored sufficient heat. The snowpack is then ready to more strongly respond to an increase in temperature (resulting in the spring pulse and rises in discharge). However, in phase three, the system is near temperature saturation, and the discharge response to temperature is nearly constant (the snowpack is warm enough throughout the basin and solar isolation becomes the limiting factor). Beyond this, phase four, discharge declines and air temperature is replaced by snowpack size as the major controlling factor. A major limitation of the simple temperature-driven model used here is that it does not describe phase four.

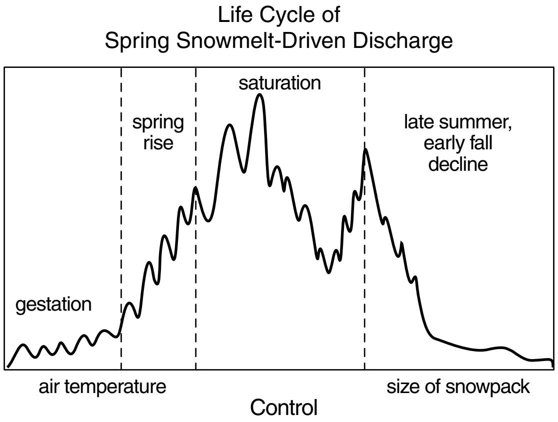


Figure 9. Cartoon of spring snowmelt discharge cycle.

Considering only the first three phases of the cycle, then, the discharge response to air temperature is first small, then increases, and last is nearly constant. To understand this more clearly, it is instructive to start with a constant parameter method. For response parameter estimation (air temperature as input, discharge as output) we used the instrumental variable method (Ljung, 1988, 1989). This method gives the average of response coefficients over the length of record (the response coefficients are constant). This method first overestimates and then underestimates the discharge when applied to the first three snowmelt phases (Fig. 10).

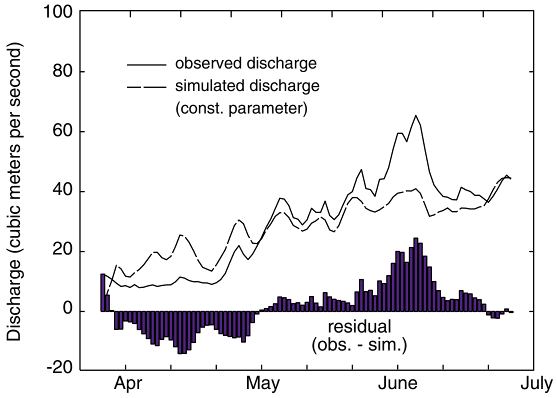


Figure 10. Observed and simulated discharge using a constant discharge response parameter to air termperature, Merced River, Happy Isles, Yosemite

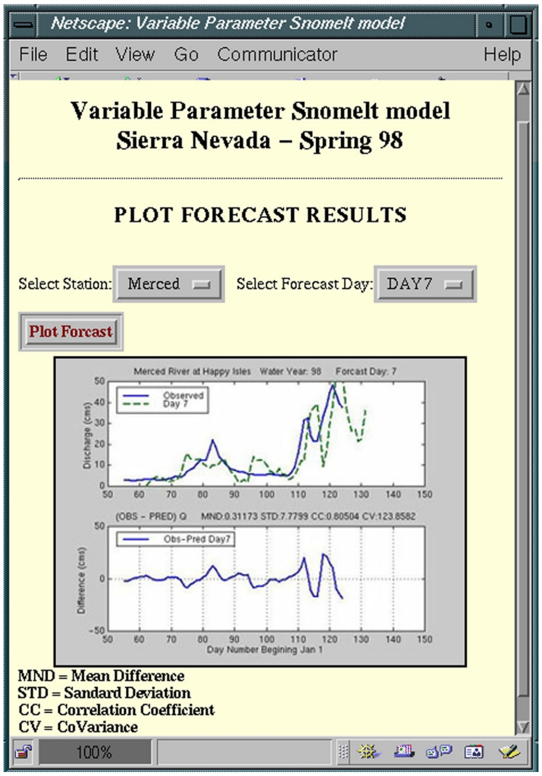
Variable Parameter Model

The simplified phases given above is better characterized by a model using variable response coefficients. The details of the model are beyond the scope of this paper. Briefly the model uses air temperature as input (forecasts provided by the National Oceanic and Atmospheric Administration Agency) and discharge as output. The model includes a Kalman filter to estimate the variable response coefficients (of discharge to temperature). In essence, the Kalman filter is a predictor/corrector scheme. The system model estimates the next discharge value and the time-equivalent discharge observation corrects the estimate. With various assumptions the optimal correction is estimated by minimizing the prediction error (the difference between observed and predicted value). An obvious difficulty, not discussed here, is the bootstrap nature of the method – we are feeding past forecasts into the loop under the guise that they are observations to extend the forecast horizon beyond one time step (one day). Examples of Kalman filtering in hydrology are given by Wood and O'Connel (1985) and Lettenmaier and Wood (1992). A step by step mathematical derivation of the Kalman filter is in Dutton and others (1997).

RESULTS/DISCUSSION

A variable parameter method experimental forecast website was maintained for the Merced (CA) and Gunnison (CO) Rivers in 1998 and will be continued in spring 1999 and beyond. For several reasons, still under study, in 1998 the Merced forecasts (Fig. 11) were not as good as for the Gunnison (Fig. 12). The most important reason was that the Gunnison air temperature forecasts were better. In other words, as air temperature forecast skill increases, which it will, discharge forecast skill will follow.

Although we will be testing an in-situ continuous chemical analyzer this spring, 1999, we do not expect to get year-around records until the year 2000. This analyzer will then provide the data needed for an experimental chemical forecast driven by the discharge forecast model. Never-the-less, insight from our initial findings may be relevant to toxic researchers even without the chemical observations.



Variable Parameter Snomelt model
Sierra Nevada – Spring 98

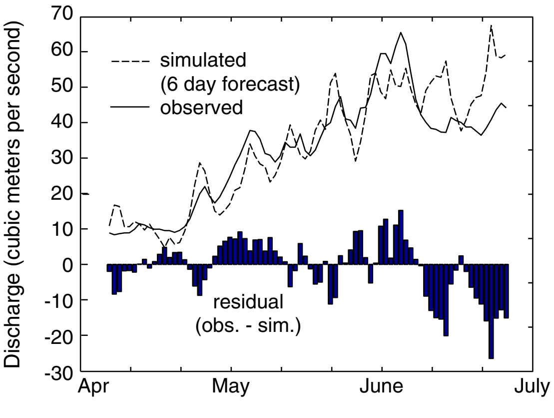
PLOT FORECAST RESULTS

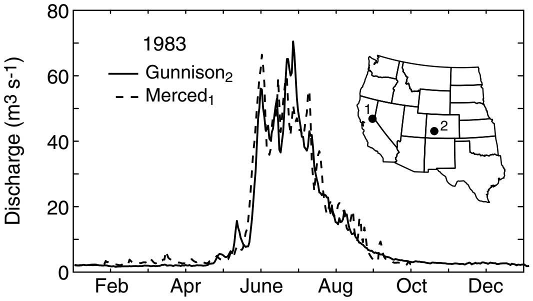
Select Station: Merced

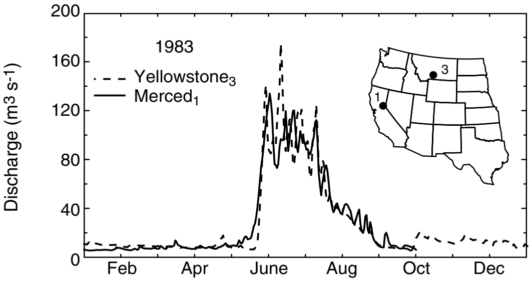
Select Forecast Day: DAY7

MND = Mean Difference
STD = Sandard Deviation
CC = Correlation Coefficient
CV = CoVariance

Figure 11. Observed and simulated discharge using variable discharge response parameters, Merced River, Happy Isles, Yosemite National Park.

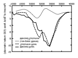






REGIONALIZATION

Understandably, because each basin is unique, hydrologic researchers often are slow to transfer their findings from one watershed to another. However, individual basin characteristics/complexities may be less critical for snowmelt than for rainfall discharge regimes, when interpreted in a broad climate context. For example, snowpack was unusually the correct location thick and widespread in wrong, locations in the western United States in 1983. This, plus the fact that air temperature patterns usually are quite large in scale (air temperature fluctuations at distant locations are often similar, and produce



a remarkable synchronization of discharge history (time shifted and amplitude scaled) for three remote watersheds (Figs. 13 and 14).

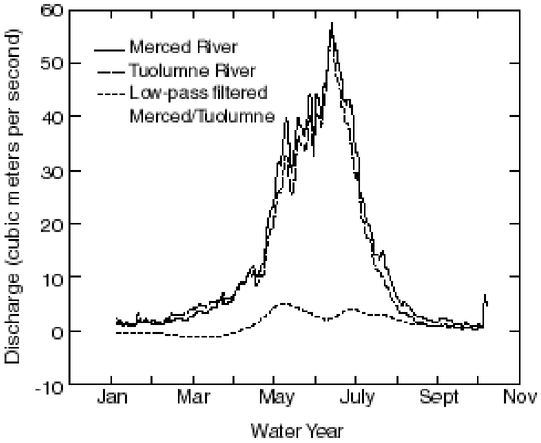


Figure 15. Daily average discharge over the annual cycle, 1916-1922 Merced River, Happy Isles and Tuolumne River, Hetch Hetchy, Yosemite National Park (Tuolumne, discharge scaled by 1/3.2, and their low-pass filtered difference.

Over smaller distances, the matching detail in the average 1916-1922 daily discharge records Merced and Tuolumne River (Fig. 15) is also striking. Even the low-pass filtered residual, (the mean discharge differences between the two basins) appears to contain hydrologic information. In fact, much of this residual may be explained by inter-basin differences in area vs. elevation (Fig. 16).

Figure 16. Areas of Merced and Tuolumne rivers as a function of elevation above the gage sites for discharge in Fig 15 and their low-pass filtered difference.

In closing, we expect that similar or new subtleties in chemical signatures also will be found when chemical hydrology is interpreted in the context of climate, with direct implications for the behavior of toxic substances.

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