ALPINE HYDROCLIMATOLOGY

Exploring the Mystery of Salinity Change in Portions of the Stanislaus and Merced Rivers

By
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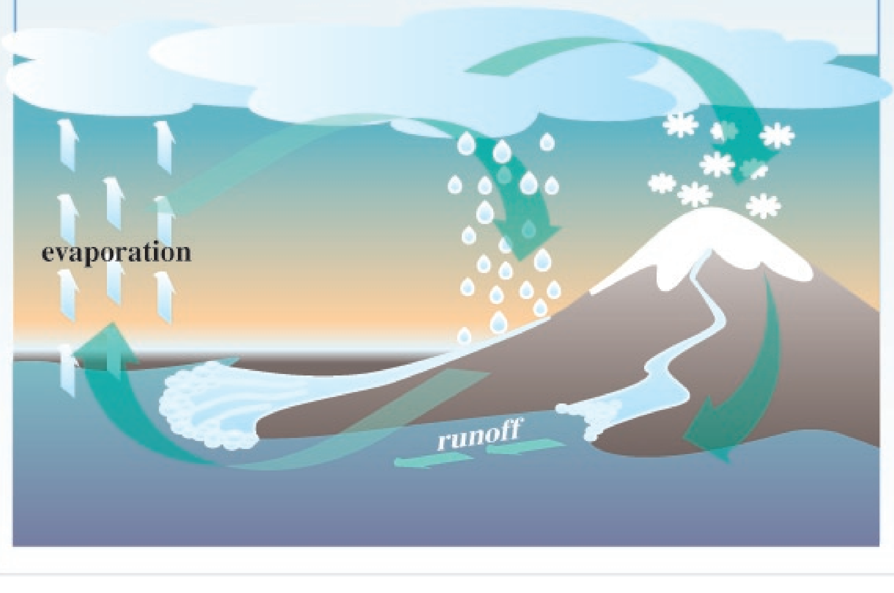

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Merced River in Yosemite National Park.

Preface

A goal in developing an alpine hydroclimate research program in the Sierra Nevada is to connect atmospheric variability to all kinds of hydrologic variability including river chemistry, via a monitoring network and models. To make these connections it is important to monitor river chemistry at the same sample rate (daily, hourly) as the hydroclimate variables such as air temperature and river discharge. Furthermore, it is important to start simple, and river conductivity is among the simplest water chemistry parameters to measure over a long time (months). A surprise in the first years of monitoring was discovery of a strong correlation between discharge variations in the Merced and Stanislaus Rivers. This is a very important simplification in our work defining watershed variability. Another surprise appeared during the transition period from low winter discharge to high spring (snowmelt) discharge. During low discharge, the daily cycles of conductivity in both the Merced and Stanislaus Rivers peaked after the discharge cycle peaked. However, with the onset of spring snowmelt discharge, the conductivity cycle changed in the Merced River, but not in the Stanislaus, even though the diurnal discharge cycles remained similar to each other. In the Merced River, the conductivity peak began arriving earlier and earlier, and after five days, conductivity peaked before and not after discharge peaked.

A tentative explanation of this unexpected phenomenon is the focus of commentary.

INTRODUCTION

The following information is based on our first year, 2001, of inter basin observations and is written for non-specialists. This science mystery started as an intuitive analysis based largely on circumstantial evidence. However, as the detective work progressed, we think we even discovered an intriguing cause and effect relation between salinity and discharge. Part of the story is controversial in that one year of data is not really long enough to draw strong conclusions. In particular, some will question our hypothesis that the observed difference in Merced and Stanislaus River conductivity responses to rising snowmelt discharge is largely due to a difference in watershed soil.

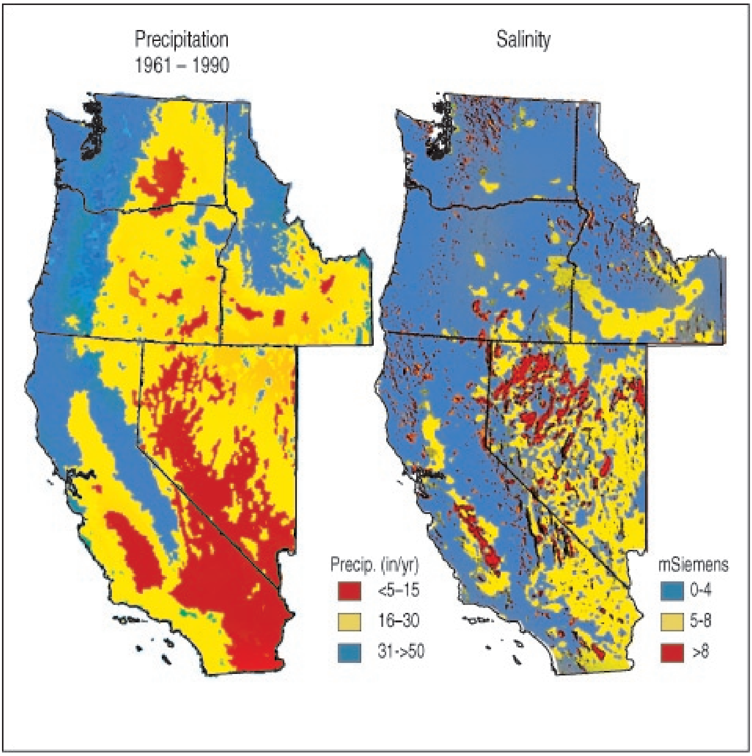

Figure 1. Distribution of precipitation and soil salinity, Western United States.

But let's start the story where most scientists agree. There are at least three motivational directions in riverine chemistry research: 1) rock, soil, and water interactions: 2) effects of human activity, and 3) effects of climate variability.

Geochemists can explain the origin and composition of water chemistry by the dissolution of rocks and minerals in water. Human health and ecological concerns motivate studies of the effects of human activity on water chemistry. These two successful approaches towards understanding riverine chemistry are major areas of research. Much less studied is the influence of climate on riverine chemistry. In general, soils in arid and semi-arid regions are more saline than soils in humid regions (Fig. 1), a pattern that often applies to lake salinities. [Note, conductivity (a measure of total dissolved solids), total dissolved solids, salts and salinity are used interchangeably in this text. Also note, that soil salinity is measured by the (electrical) conductivity of a water-saturated soil extract.] Further, riverine total dissolved solids concentrations are largely determined by the salinity of the soils they drain. This relation between soil and water salinities is illustrated by USGS observations from a variety of Western U.S. rivers sampled near the turn of the century (Fig. 2).

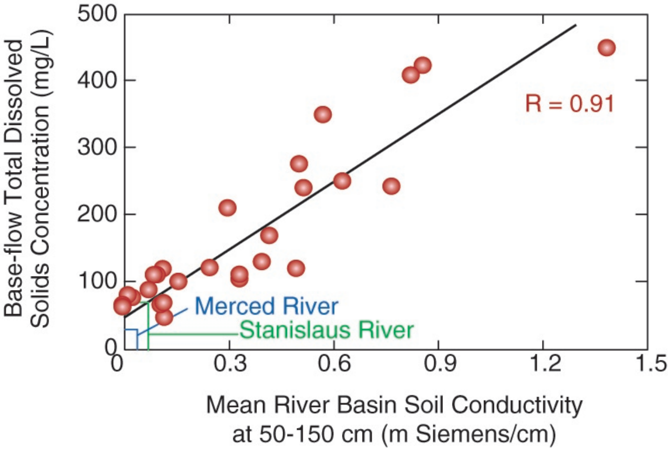

Figure 2. Baseflow (low flow) salinity vs. soil salinity in Western rivers, 1906 to 1911. Note, one milli-Siemen per centimeter is approximately equivalent to 600 milligrams per liter of total dissolved solids.

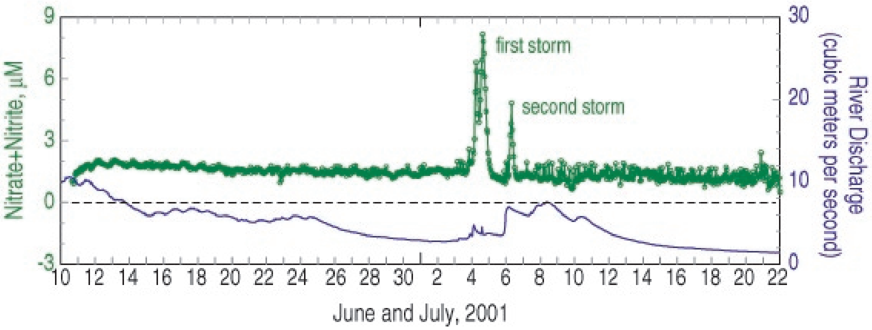

Figure 3. Nitrate-nitrate concentrations compared to discharge for two storms for the Merced River at Happy Isles. A micro-mole of nitrate+nitrite nitrogen is the concentration of nitrogen in micrograms per liter divided by the molecular weight of nitrogen (14).

Humid versus arid soil and river salinity variations across large regions provides a large-scale perspective. What is often overlooked is climate's influence on river salinity over a range of TIME scales. At the short-term storm-event scale, the pulse of streamflow from the first storm after a dry spell is generally accompanied by higher dissolved substance concentrations than from subsequent storms (Fig. 3). In general, salts have more time to accumulate before the first storm. This "first flush" phenomena is well documented throughout California and in other areas in the southwest where salts accumulate and are "flushed" after an extended dry period.

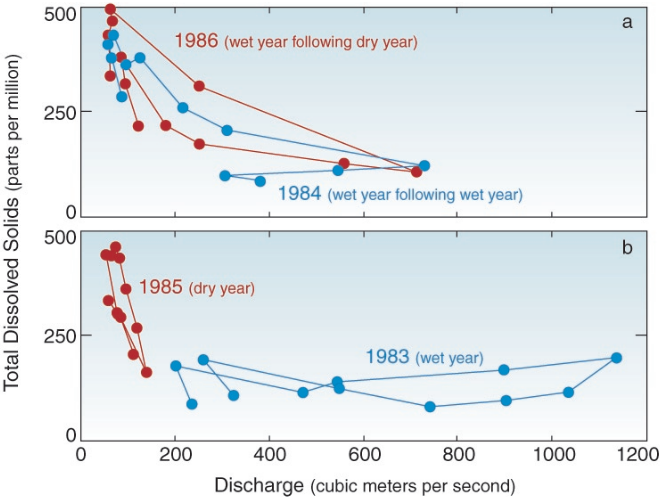

Figure 4. At Vernalis on the San Joaquin River: Top panel shows an example of two wet years with one in 1986 proceeded by a dry year, and the other in 1984 by a wet year. Lower panel shows the dry (red) year and the wet (blue) year which preceeded the two wet years in the top panel.

Similarly, at longer time scales, such as inter annual time scales or beyond, wet year salinities following a dry year, or a series of dry years, are generally higher (for a similar discharge) than wet year salinities following a wet year, or a series of wet years (Fig. 4). This phenomenon can be very important in saline river management where salinity is being maintained below a specific concentration.

Further, because riverine substance concentrations, such as salinity, are functions of the rate of salinity supply, removal, and dilution, evapotranspiration (a negative dilution) from agricultural irrigation in arid and semi-arid climate, artificially increases soil and river salinity concentrations. For example, because the semi-arid San Joaquin River valley runoff does not have the flushing capacity of the more humid Sacramento River valley, the San Joaquin River salinity and chemistry are more vulnerable to climate variations and human activities that increase the rate of salinity supply and decrease the rate of salinity dilution and removal. As a result, the San Joaquin River salinity has increased over the period of record (Fig. 5).

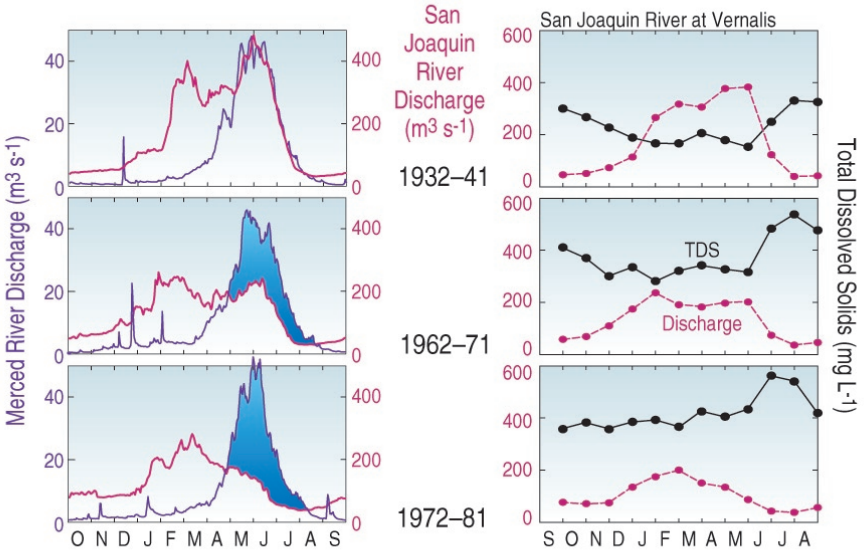

Figure 5. Decadal demise of spring snowmelt discharge peak in the San Joaquin River at Vernalis, accompanied by the rise in total dissolved solids. Vernalis is located near the Sacramento-San Joaquin River Delta, north of the San Joaquin River.

Our observations of temporal variations of salinity that are long enough to show long-term climate-forced changes are rare. However, after a long wet period, the long-term mean salinity/discharge relation in the Snake River watershed in Washington shifted to a lower salinity for the same level of discharge (not shown), suggesting a decrease in the soil salinity over the wet spell similar to the example in Figure 4, but over a longer time scale.

The Merced River watershed above Happy Isles, Yosemite National Park represents a combination of supply, removal and dilution rates that produce very low total dissolved solids concentrations. The soils are thin and patchy due to several glaciations. In general, the underlying granite bedrock weathers slowly (low rate of supply) compared to other rocks and minerals; precipitation is moderate to high (high rate of dilution) and the rate of downstream transport of dissolved solids is relatively fast. The cumulative result of these three factors is that the Merced River at Happy Isles is one of the most dilute rivers in the world in terms of salt concentration. From the discussion above, if riverine total dissolved solids concentrations are largely determined by the salinity of the soils they drain, then the soils in the Merced watershed and associated interstitial soil water must also have a low salinity (i.e., near zero on the horizontal axis, Fig. 2).

To understand just how dilute the upper Merced River is, we compare it to a slightly less dilute, deeper soils of the Stanislaus River watershed. The following is an example of the complexity of research linking variations in climate-driven snowmelt discharge to variations in river chemistry. At this point in our discussion, our reasoning and conclusions depart from common knowledge.

The most controversial part is use of the terms salt-limited and salt-saturated. From our perspective, the upper Merced River watershed (above Happy Isles) is described as salt-limited (relatively under-saturated with salt) and the upper Stanislaus River watershed (above Clarks Fork) is described as salt-saturated (relatively saturated with salt, at least for much of the year 2001, a year with a below average snow pack). In interpreting our observations we note that: 1) The differences in glacial history

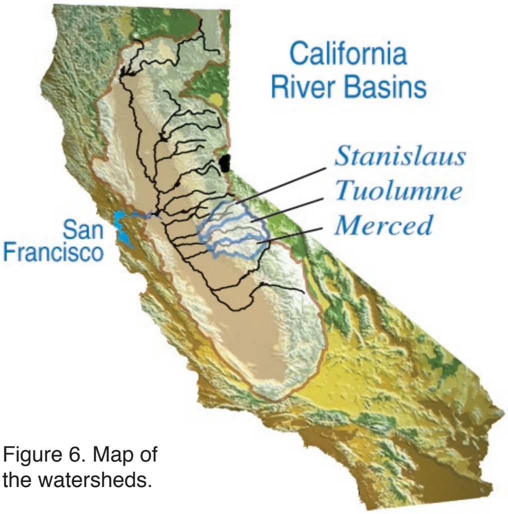

Figure 6. Map of the watersheds.

of the two watersheds largely determine the difference in soil salinity above the gages. 2) The temporal and spatial precipitation, evapotranspiration and runoff (discharge per unit) areas are similar for both watersheds (we only know this for runoff). 3) The Merced watershed has had more recent glacial episodes than the Stanislaus, leaving it with less soil compared to the upper Stanislaus. 4) The difference in the amount of soil and its salinity above the gage determines differences in salinity response to rising snowmelt discharge. In the Merced watershed, as snowmelt discharge rises, the soil salinity cannot sustain the discharge and salinity pattern observed during low flow. In the Stanislaus watershed, the soil salinity is sufficient to sustain the low discharge pattern (for most of the record).

These assumptions help to resolve a scientific mystery that arose when we first began to compare conductivities in the two rivers at hourly resolution for many months at a time. As described in the preface, prior to the onset of rapid snowmelt discharge in the winter of 2001, the discharge rates of the two rivers rose and fell each day in remarkable unison, as did their conductivities. Over the first few days of rapid snowmelt, the similarity of the diurnal conductivity variations disappeared while the flows continued to echo each other without fail. Here is a description of what was observed and what it tells us about the basins, step by step.

WHAT IS DRIVING DIURNAL SALINITY VARIATION IN THE MERCED VERSUS STANISLAUS RIVER

(What we think we know and what we assume):

1. Watershed soil salinity varies within and between watersheds. The Merced and Stanislaus watersheds are shown in Figure 6.

2. The soil salinities of the two watersheds are unknown.

3. We can, however, describe qualitatively how the soil salinity responds to the seasonal variations of discharge. During the dry season, salts accumulate (increase) in soil due to atmospheric sources and soil weathering. During the wet season, soil salts decrease as they are flushed into the rivers by runoff and percolation (river transport). The same applies for longer periods such as wet and dry years, decades, etc.

4. These are climate-dependent dynamic systems with watershed salinities continuously adjusting up or down in response to dry or wet climate regimes.

5. For simplicity, elevational and seasonal patterns of evapotranspiration are assumed to be the same in both watersheds. The long-term average precipitation and the soil to bedrock ratio largely determine average salinity (soil and bedrock composition is also a factor). Therefore, for simplicity, we assume that the climate variations of the two watersheds are the same, and only the soils differ.

6. Over geologically short time scales (decades), the watershed soil and rock properties are also assumed to be constant.

7. Snowmelt discharge in the Sierra Nevada has a remarkably strong correlation over large spatial scales (>200 km) and fine (daily) temporal scales.

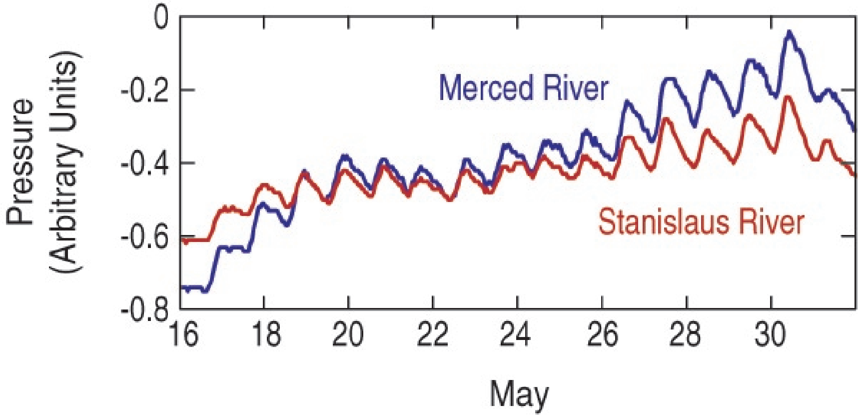

Figure 7. Merced River at Happy Isles and Stanislaus River at Clarks Fork dirurnal pressure variations (pressure is a measure of water height and water height is a measure of discharge).

8. Remarkably, the Merced and the Stanislaus Rivers respond similarly at hourly time scales (Fig. 7) even though the Tuolumne River watershed separates them (Fig. 6).

9. Interestingly, the Merced and Stanislaus Rivers have a different diurnal salinity response to snowmelt despite their high correlation in discharge variations.

10. The Merced bedrock is granite and the Stanislaus bedrock is a mixture of granite and volcanic deposits.

11. The ratio of soil to bedrock is much greater above the gage in the Stanislaus River than in the Merced River due to more recent glaciation of the upper Merced Basin.

12. In 2001, the Merced River conductivities (related to salinity) ranged from 46 to 5.6 µ Siemens per cm and from 90 to 42 in the Stanislaus River. An approximate conversion from µ Siemens to total dissolved solids in milligrams per liter is 0.6 (i.e. 5 µ Siemens per cm times 0.6 = 3 milligrams per liter total dissolved solids), and 5µ Siemens per cm is about the concentration of rainwaters.

Happy Isles site on the Merced River in Yosemite National Park.

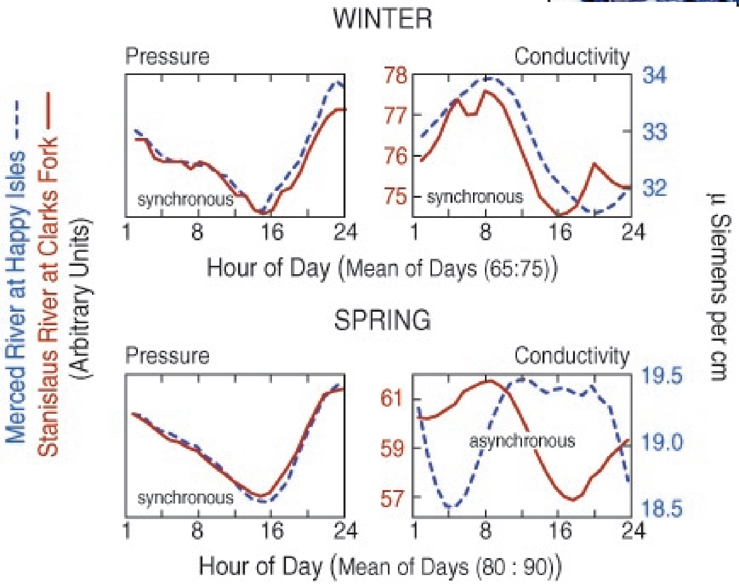

Figure 8. Diurnal variations in discharge (measured as pressure) and conductivity. The bottom panel shows the winter/spring conductivity shift for the Merced River.

13. We hypothesize that the observed difference in salinity is an important clue to explain why the Merced and the Stanislaus salinities differed when subjected to the same sequences of snowmelt discharge, as described in items 14 and 15.

14. Before the onset of rapid snowmelt around day 75 of 2001, the diurnal variations of discharge and the salinities of the two watersheds were synchronous (Fig. 8, top panels).

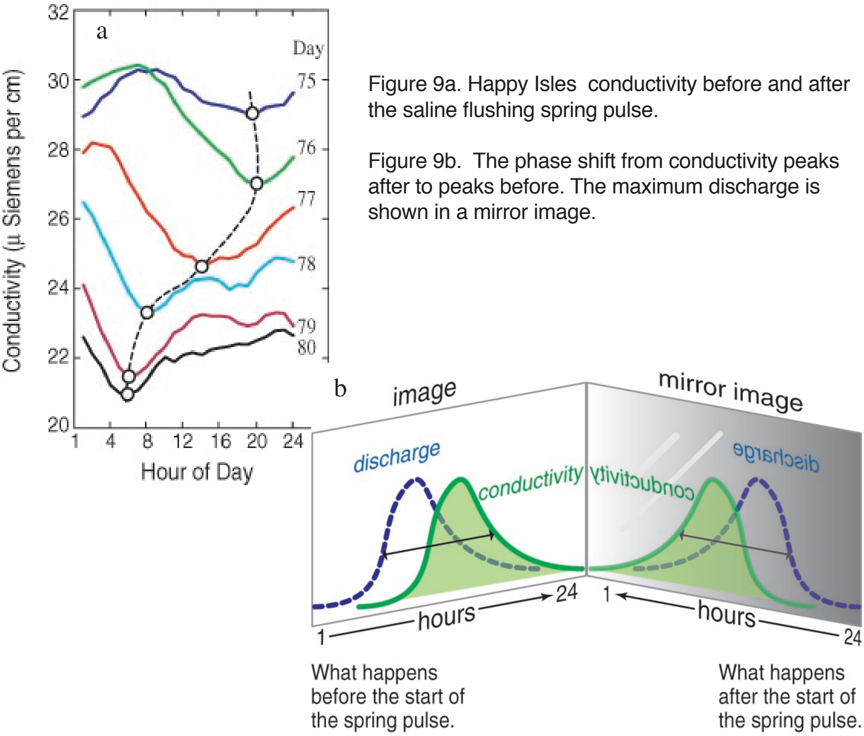

Figure 9a. Happy Isles conductivity before and after the saline flushing spring pulse.

Figure 9b. The phase shift from conductivity peaks after to peaks before. The maximum discharge is shown in a mirror image.

15. After the winter/spring transition, defined here by the change in timing of the spring salinity pulse (Fig. 8 bottom panels and Fig. 9a), the diurnal cycles of salinity were approximately 180° out of phase (appearing on opposite sides of the discharge peak, shown in Fig. 9b), even though the discharge fluctuations remained in phase with each other.

16. The average salinity of Merced watershed is only about a tenth of the Stanislaus per unit area (a rough estimate combining likely soil patchiness, thickness and low flow salinity).

17. Ultimately, the Merced River conductivity drops to the level of rainwater at 5µ Siemens per centimeter, or approximately 3 parts per million total dissolved solids. A mere 12% of the maximum conductivity value. Whereas, the Stanislaus River only depresses the conductivity to 47% of its maximum value. Thus the salinity response is more sensitive to snowmelt discharge in the Merced than in the Stanislaus.

18. The rate of salinity decrease (around the beginning of June) is larger as a percentage of its winter value (during March) in the Merced River than in the Stanislaus River. For purposes here, we define the Merced watershed as a "salt-limited" system because of its sparse soil with a very low salinity whereas the Stanislaus is a salt-saturated system (relative to mean precipitation).

19. Thus in the salt-limited Merced River system, during spring snowmelt, the diurnal salinity cycle peaks before discharge, and in the salt-saturated Stanislaus River system, the diurnal salinity peaks after discharge. In the salt-limited system, snowmelt discharge plays a stronger role in defining the salinity variations than in the salt-saturated system. For example, the diurnal salinity peak in the Merced River not only shifts in phase (timing) but also diminishes in amplitude (height). Over the same period, the diurnal salinity peak in the Stanislaus not only maintains its timing, but even increases in amplitude while the seasonal salinity decreased (Fig. 8). In addition, after the seasonal salinity reaches a minimum and begins to increase, the increase is slower in the Merced River than in the Stanislaus River (Fig. 10).

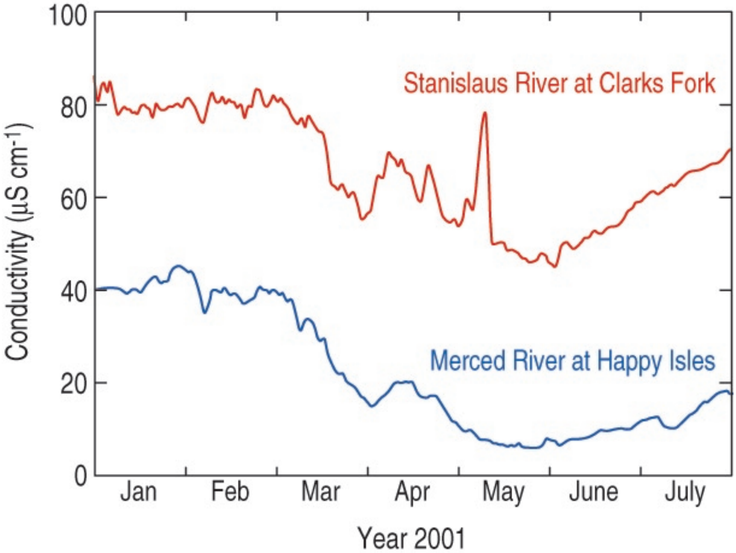

Figure 10. Note the increase in the Merced and Stanislaus Rivers' conductivity towards the end of the snowmelt cycle.

When scientists have a lot of interesting and, especially unexpected results (like these), and have concocted some plausible explanations (like ours), their work is not yet done. The next step is to try to reduce their description of the observations to a mathematical model - a simple mathematical model, if at all possible. If they can produce such a model, and if it reproduces the observations well, the scientists can consider their explanations to be viable; if the model produces predictions that can be tested with new observations, then they can even trust their explanations.

Thus our next step was to describe the conductivity-cycle differences with some (SIMPLE!) equations. We used a very simple mixing model with two equations and two unknowns for each watershed:

Happy Isles: $Q_{HI} = Q_{H1}\ \text{soil} + Q_{H1}\ \text{snowmelt}$

$$Q_{HI} \bullet C_{H1} = Q_{H1}\ \text{soil} \bullet C_{HI}\ \text{soil} + Q_{HI}\ \text{snowmelt} \bullet C_{H1}\ \text{snowmelt}$$

Clark Fork: $Q_{CF} = Q_{CF}\ \text{soil} + Q_{CF}\ \text{snowmelt}$

$$Q_{CF} \bullet C_{CF} = Q_{CF}\ \text{soil} \bullet C_{CF}\ \text{soil} + Q_{CF}\ \text{snowmelt} \bullet C_{CF}\ \text{snowmelt}$$

Where Q is discharge and C is conductivity converted to TDS concentration; Q_{HI} is the observed hourly discharge at Happy Isles; Q_{CF} is the observed water pressure at Clarks Fork transformed to discharge (a description of the transformation procedure is beyond the scope of this discussion); and Q_{HI} soil and Q_{CF} soil are the unknown inputs from soil reservoirs to the rivers; Q_{H1} snowmelt is the rate of direct snowmelt. We assume that the concentrations of Total Dissolved Solids (TDS) in soil waters into the Merced River C_{H1} soil is 25 parts per million and C_{CF} soil is 48 parts per million TDS (based on the low flow TDS concentrations). The snowmelt concentration C snowmelt is 3 parts per million TDS in both watersheds. By solving the above equations (you figure out how), the unknown Q soils and Q snowmelt values are estimated (Fig. 11).

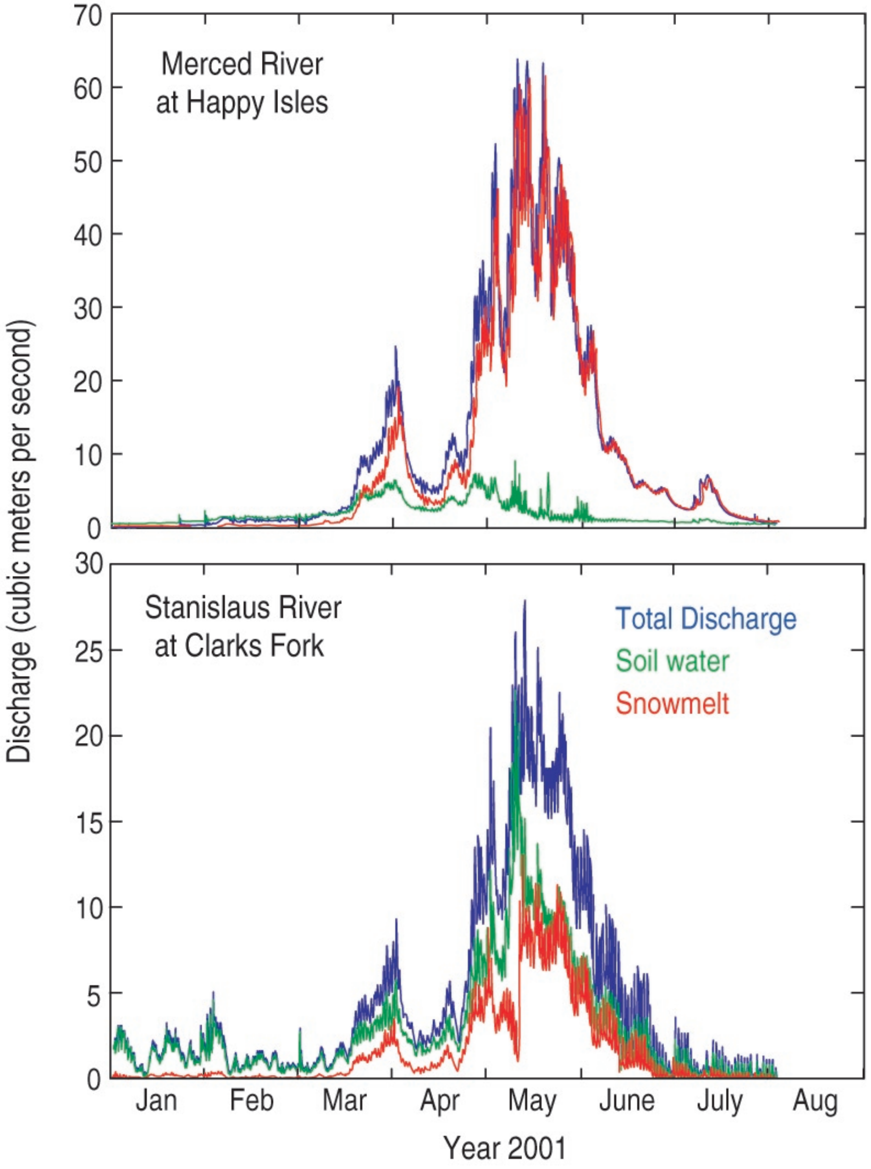

Figure 11. Estimated contribution of soil and snowmelt water to discharge for the Merced and Stanislaus Rivers based on the equations given in the text.

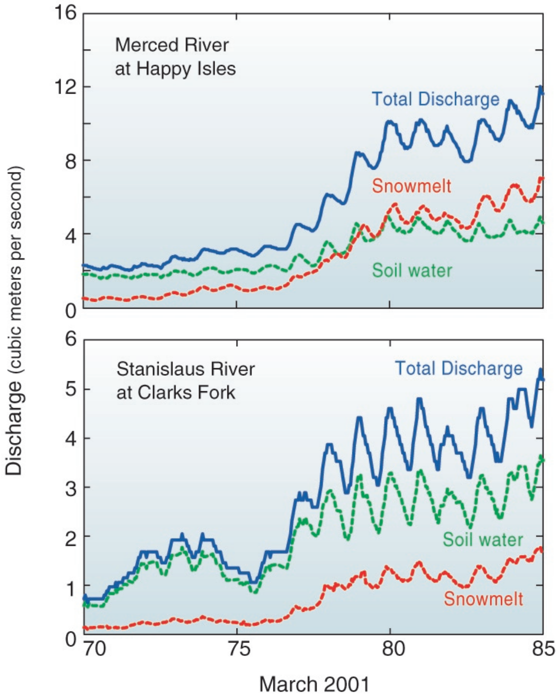

Figure 12. Merced River and Stanislaus River discharge showing estimated (dashed) soil and snowmelt discharge, based on the simple two-component mixing model described in the text.

In the Merced, after the start of the snowmelt pulse (Fig. 8, lower panel), the TDS always peaked before discharge peaked. This corresponds exactly to the period when snowmelt contributions in the Merced were larger than the soil water contributions. During the same (post-day 75) period in the Stanislaus (Fig. 12 lower panel), the soil water contributions remain larger than those from snowmelt. Indeed, only for a brief time around day 150 (Fig. 13) did snowmelt contribute more to the Stanislaus, and (as predicted by our model) the diurnal cycle of conductivity switched briefly then. Thus, we find that when

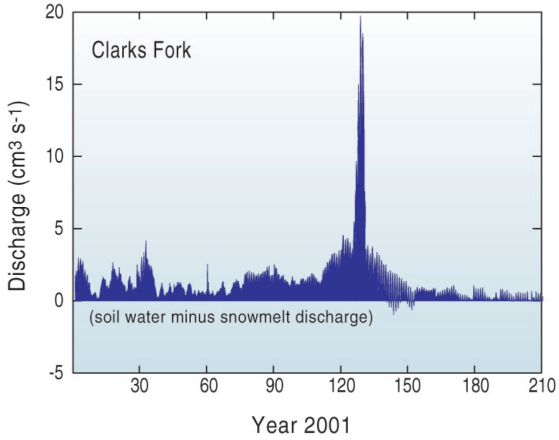

Figure 13. Difference in estimated sources of river discharge between soil water and snowmelt in the Stanislaus River at Clarks Fork. The soil water and snowmelt components of discharge are shown in the lower panel of Figure 11.

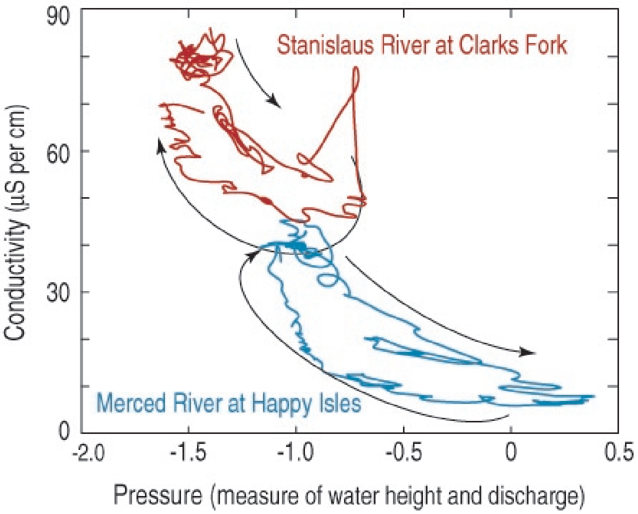

Figure 14. Merced and Stanislaus River discharge vs. total dissolved solids. Both views show the same pattern, a higher total dissolved solids concentrations during the rise in discharge and a lower concentration (at the same discharge) during the decline in discharge. However, this pattern is clearer for the Merced River.

the river is snowmelt dominated, the conductivity peaks before the discharge each day (as in the Merced after the spring pulse), and when the river is soil water dominated, the conductivity peaks after discharge. We believe that because the Merced is soil and salt-limited; it settles more quickly and persistently into the snowmelt-dominated pattern than does the salt-saturated Stanislaus. In essence, the simple mixing model explains the phenomena in question.

SO WHAT?

Although the above variations are diurnal, the more prominent pattern is seasonal (Fig. 14). The seasonal pattern is similar in both watersheds, and is similar to the diurnal pattern when the snowmelt discharge is greater than the soil discharge (clockwise when TDS is plotted versus discharge). Using conductivity, we can study how watersheds respond to inter annual variations in the snowpack (Fig. 15). However, we have shown here that even the shortest-term conductivity variations depend on the soils and bedrock they are drained from. Thus, while discharge is often controlled by climate, water chemistries are affected from both above and below.

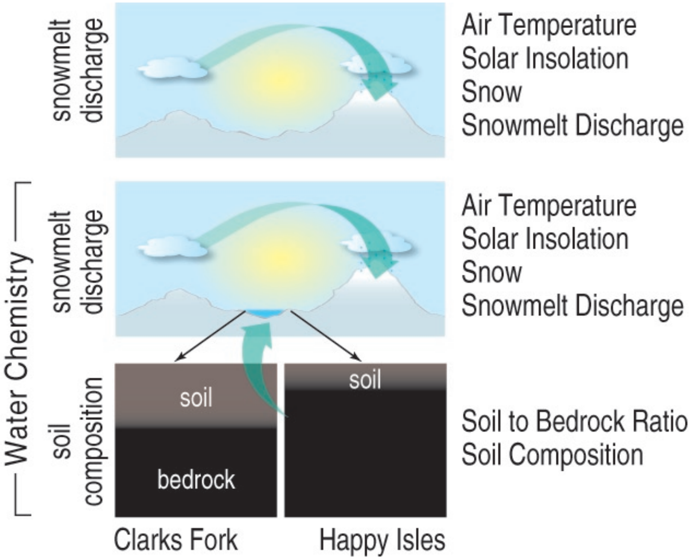

Figure 15. Variables linked to snowmelt discharge are largely climate variables such as air temperature and solar insolation. Variables linked to water chemistry, however, are both climate and soil variables such as soil cover and composition.

This study also identifies a potential sampling pitfall for these kinds of systems, because how and when you sample could influence your results. If we were comparing the chemistries of the two rivers knowing that there is a diurnal snowmelt cycle, but we could only sample the two rivers once per day, then we would probably decide to sample the two at the same time of day. Unintentionally then, the rivers would be sampled at opposite salinity phases (high for one and low for the other). Thus, when asked, “why do we want to sample so often?” The answer is that we need to sample often to avoid misunderstanding our observations.

When studying riverine chemistry, river discharge (Q) variations have often been considered as noise. In this study, however, climate is the signal and, therefore, we do not average out the effect of discharge variations (generally caused by climate variations) on concentration.

Some chemistry is difficult, costly, or impossible to measure as often as conductivity. For such chemistry, we believe that hourly salinity observations provide a framework for interpreting the more complex chemical properties.

Beyond this, observing salinity at the same time scale as discharge (hourly, daily) provides valuable control in numerical simulation experiments of river discharge and, vice versa, numerical simulation experiments of river discharge provide insight into interpreting the salinity variations. In this study, for example, soil differences were shown to result in important differences in the sources and pathways of runoff that were not evidenced at all from the discharge measurements alone.

Studying the upper elevation watershed salinity is a starting point for defining downstream evapotranspiration and other effects on riverine and soil salinity. The estimates of soil and snowmelt discharge are simple approximations, to be refined with more detailed models and "tracer" chemistries.

LESSONS

Many papers have been written on the value of long-term monitoring for understanding how hydrologic systems work. What seems to be relatively unknown in alpine watershed studies is that the hydrochemistry of the snowmelt-driven watersheds are greatly simplified by the strong correlation of discharge variations between multiple watersheds. This simplification is what makes linking chemistry to discharge in these watersheds seem doable and exciting, so that scientists don't end up starting their research on each watershed from scratch.

Also interesting are the observations of water chemical variations at sampling rates compatible with hydroclimate variables, such as air temperature and snowmelt discharge. This makes linking riverine chemical variations to climate more straightforward because climate is the major source of variability in river discharge.

Soil in arid and semi arid regions is defined as saline when the soil salinity is greater than 4000 μ Siemens per cm, or two orders of magnitude higher than in this study. In general, chemical concentrations in snowmelt-driven river water are extremely low.

For example, a diurnal variation of only 1 µ Siemens per cm and TDS concentrations approaching precipitation concentrations were observed. Measurements in the variations in these micro-concentrations in the watershed river chemistry pulse may not only detect the variations and change in climate, but also the effects on river chemistry of forest fires, logging, etc.

As a closing comment, what makes this work special is that this is a small part of a much larger effort to understand and predict alpine hydroclimatology in collaboration with scientists from: The Scripps Institution of Oceanography, Yosemite National Park, The California Department of Water Resources, The National Oceanographic and Atmospheric Agency, The USGS (Menlo Park, Denver, Sacramento and San Diego, and El Portal).