Spring Snowmelt Recession

in Rivers of the Western Sierra Nevada Mountains

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Abstract

The hydrographs of rivers flowing from California's Sierra Nevada mountains can be characterized by three distinct components; dry season baseflows, wet season storm pulses, and springtime snowmelt. The springtime snowmelt recession limb occurs as flows drop from snowmelt to summer baseflow. It is a consistent and predictable portion of the annual hydrograph and an important resource to both riverine ecosystems and California's water supply, but reservoir and dam operations commonly eliminate this feature. Environmental flow allocations to promote healthy rivers are have started to include a snowmelt recession limb component, but little research has been conducted to quantify their form in the Sierra Nevada. This study fills this knowledge gap by describing the recession limb and its variability between water years and watersheds for unregulated flows. To do this, I chose eight watersheds without dams or significant hydrologic alterations, and, using historic discharge data, defined the recession period and calculated its magnitude, duration, timing, volume, and curvature. The recession shape, or rate of change, I modeled with an exponential decay curve in two different ways: one to describe the seasonal shape and the other for daily changes. I found that the recession limb typically lasts 75 days, from mid-May until August with differences in timing influenced by different watershed elevations. The magnitude of the discharge changes annually with different water year types, but the curvature is consistent across different water year types. Seasonally, this curvature is between -0.03 and -0.05 (std dev 0.007, NSME 0.64) whereas daily it decreases from 10 to 5 %. This research has important implications for the management of Sierra Nevada rivers in that it will allow for the inclusion of empirical quantitative criteria into the development of regulated flow regimes intended to better mimic natural ones.

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1.0 - Introduction

Freshwater is a precious resource throughout California and the seasonal fluctuations in availability are a critical factor affecting the success of both human and natural communities. California's climate has distinct wet and dry seasons, but environmental conditions during these times can be stressful for organisms. In most of the state, for instance, a handful of passing storms will easily constitute the majority of the annual runoff. The summer months pose a more difficult existence for organisms because, as a rule, rain does not fall and the landscape becomes hot and dry. Spanning these two extremes is the annual snow that the Sierra Nevada Mountain Range receives, which builds up during those few big storms and melts away in the springtime and summer. Lower elevation watersheds of the Sierra receive relatively more precipitation as rain whereas higher ones have more of this spring snowmelt hydrograph (Figure 1). This supply of water fills the rivers for weeks at a time. It inundates the channels and, in big years, it covers floodplains and fills forgotten waterways. As the water percolates through the soil trees suck it up vigorously and spread their seed into the rivers and wet soil. Fish, frogs and insects lay their eggs in the creeks and rivers before the dry season forces everything to a halt.

The systems of reservoirs that humans have built in the Sierra Nevada are designed to capture runoff for flood control, water supply, and hydropower generation, which, most basically, changes the timing of flows downstream. Figure 2 illustrates how the different operational management between systems can have very different effects on flows. Reservoir levels are kept low during the winter to prevent downstream flooding in the case of very big storms, but they are filled to maximum capacity when summer starts and the storms are over. This shift from flood control to hydropower and supply operations is a delicate process and requires reliable snowpack and weather data in order to not overshoot the capacity and cause a late spring spill event. Flows below most reservoirs, regardless of their functions, are therefore commonly reduced during the springtime as the last of the snow is melting.

This spring/summer portion of the annual hydrograph naturally contains the snowmelt recession limb, a period of time when river flows are dropping from the high flows, fed by snowmelt, down to low summer baseflows (Figure 1). The snowmelt recession creates the one time annually where abundant resources are coupled with predictable flows allowing for high reproductive success of native species adapted to this seasonality (Yarnell et al., 2010). These hydrologic alterations by dams result in a loss of flow predictability and a loss of instream habitat that threatens native biodiversity (Bunn and Arthington 2002, Power et al. 1996). There is a growing recognition that one viable option for protecting aquatic species from further degradation below reservoirs is through prescribed flow releases that meet human demands without sacrificing their ecological functions (Jager & Smith 2008, Richter et al. 1997). Restoration of the spring snowmelt recession in particular provides a unique opportunity to return a key ecological component of the natural flow regime, yet to date there has been a distinct knowledge gap regarding how best to prescribe such flows in a quantitative manner.

To this end, I studied the characteristics of the natural springtime recession in the Sierra Nevada and the extent to which it is a constant feature across different years and watersheds. I chose eight United States Geological Survey (USGS) discharge gauging stations below unregulated watersheds across the western Sierra Nevada and measured the magnitude, duration, timing, and volume of spring recession hydrographs for each. I found that the hydrologic properties listed above: magnitude, duration, etc. are proportional to the areas and elevations of the watersheds. Futher, I analyzed the curvature of the recession limbs using two different forms of the exponential decay equation. The first method I used was a regression across the recession period of the hydrograph for each year. This method distills the springtime hydrograph shape to a single coefficient. The other method I used quantifies the ramping rate, or variability on a daily timescale, by measuring the maximum and average percent changes.

Results indicate how streamflows of the Sierra Nevada are strongly autocorrelated and the snowmelt recession is an annual feature whose variation is consistent across water year types, elevations and latitudes. These factors cause the recession limb to be, with the possible exception of the late summer baseflow, the most predictable element of the flow regime. This analysis captures those similarities, provides distributions of the modest regional and interannual differences between hydrologic characteristics, and discusses ways in which a flow regime can be prescribed to mimic a natural one.

2.0 – Background

The idea that watersheds are spatially and temporally correlated with their neighboring basins is as fundamental to hydrologic study as water itself, and background research related to snowmelt in the Sierra Nevada can be understood in these terms. The spatial mechanisms responsible for streamflow characteristics such as topography, geology, soils, vegetation, temperature, and precipitation tend to be strongly correlated across watershed boundaries, making neighboring streams behave in similar ways. Streamflows are temporally autocorrelated, primarily at the scale of days and years. Discharges from one day to the next will tend to be similar because of broad regional weather patterns, but they are also a reflection of the hydrologic travel times in a watershed. In contrast inter-annual autocorrelation occurs as a function of the climate and recurring seasonal patterns. Larger temporal patterns such as El Nino/La Nina- Southern Oscillation (ENSO), decadal oscillations and climate warming also play a role in the snowpack and streamflows of the Sierra Nevada. A suite of previous environmental research contextualizes this question of the predictability of the springtime recession limb; however, few studies have examined the elevation and latitudinal gradients found across the entire Sierran range. This, along with the interannual predictability, is the knowledge gap that this paper will fill.

The geography of the western Sierra Nevada makes it well suited for storing snow all along its 750 km length. The range is a continuous cordillera that extends north to south along the eastern margin of the state. The wet winter storms in this region generally move east to west and when they encounter the Sierra Nevada they are pushed to higher elevations. This orographic lift typically causes the air masses to cool adiabatically which wrings more moisture from them and increases the amount of precipitation that falls at higher elevations. Dettinger et al. (2004 a) also examined the ratio of precipitation at low versus intermediate elevations in the Northern/Central Sierra and found that variations between storms and years were able to influence the balance of rainfall versus snowpack and the timing of the runoff season.

Two important shifts occur along the length of the Sierra Nevada that have contrasting effects on the annual snowpack: relative higher elevations in the south and higher precipitation amounts in the north. In the northern portion of the range, such as around Lake Tahoe and the Yuba and American watersheds, peaks extend to 2,700 meters (9,000 ft) whereas in the southern Sierra, roughly south of Yosemite, there are large areas at high elevations and peaks extend up to the height of Mount Whitney, the highest point in the lower 48 states, at 4,400 meters (14, 500 ft). The southern Sierra is also steeper and more arid than the northern Sierra, where there are much larger areas at intermediate elevations around snowline.

Another geographic characteristic of the Sierra Nevada that contributes to its ability to collect and store precipitation for the state is its gradual western slope. While the eastern edge of the Sierra’s granite pluton has been forced up through hinge block faulting, creating a dramatically steep escarpment, the western side has a large area with wide elevational bands and the space for large rivers to develop. About 14 rivers flow west out of the Sierra into the Great Central Valley. Aside from the three southern watersheds; the

Kings, Kaweah, and Kern, these rivers all converge in the central delta region of the state and flow into the San Francisco Bay.

Weather patterns such as storms and heat waves are spatially correlated across the state so direct runoff and snowmelt rates also cause river discharges to change in unison during the winter and spring (Peterson 2008). Some snowmelt occurs throughout the winter at intermediate elevations. In the spring, a snowmelt 'pulse' indicates the beginning of the melt season (Lundquist 2004, Peterson 2005) and the melt tends to occur within an elevation band that moves upwards through time (Lundquist 2004). Permanent snowfields and glaciers exist in a few places in the southern Sierra, but snow is generally gone from the range by the beginning of July. Figure 1 shows the hydrographs of low versus high elevation watersheds. In the example, the low elevation watershed has a spring recession beginning in May and the higher elevation site starts its recession in July.

As snow disappears from the watersheds and discharges recede, the percent of streamflow that originates from springs and groundwater increases. The streamflow characteristics of groundwater, which are controlled by gravity and the subsurface hydrogeologic characterisitcs, are consistent across the range and contribute to the great similarities between flow regimes across the Sierra (Peterson et al. 2000 & 2005). Granite, which is the dominant rock type in the Sierra Nevada, is functionally impervious to water, so as bedrock it tends to confine the bottom limit of water's movement and contribute to high lateral subsurface flow (Liu et al. 2004 & 2008). The pine duff and shallow, porous soils common here drain quickly and make groundwater a small proportion of water budgets (Kattelmann 1991) at elevations between 2,000 and 3,000 meters. Geology and soil does vary across the range and these variations have implications for low flow periods. Increased soil depth and porous rock types, more common in the northern Sierra, result in increased baseflow during wet years (Peterson et al. 2005). Baseflow discharges have been shown to correlate with precipitation amounts of antecedent years (Peterson et al. 2008, Freeman 2008, Trask & Fogg in progress) indicating deeper perennial storages as well.

A characteristic of baseflow, which is fundamentally different from precipitation or snowmelt, is its high degree of consistency from one day to the next. In other words, groundwater has a strong daily autocorrelation because subsurface permeability buffers flow rates. During the snowmelt peak, partitioning river discharges into snowmelt and groundwater is extremely difficult and typically addressed through isotope and tracer analysis, as discussed below. Aside from the contributions of a few perennial snowfields at high elevation, summer baseflow discharges in rivers are mostly originating from groundwater sources. The snowmelt recession limb therefore encompasses the time when the source flows transition from snow to groundwater.

Native species and ecological communities have evolved to take advantage of the snowmelt peak, the recession limb, and even the difference in flow characteristics between snowmelt and baseflow. The predictable seasonal variation in streams of Mediterranean climates regulates aquatic ecology because summer low flows and winter storms both cause stress on individuals (Gasith and Resh 1999). Springtime, on the other hand, is when abundant resources and habitat are coupled, and organisms rapidly grow and reproduce (Yarnell et al. 2010). Yet snowmelt discharges can be volatile and intense during wet years, thus some organisms, such as the foothill yellow-legged frog (*Rana boylii*), seem to have evolved lifecycles that cue off of the recession limb and the buffering effect of groundwater.

Although interannual precipitation is variable, certain characteristics of a watershed's hydrograph, such as its shape, unit hydrograph, and baseflow are predictable. The ways in which these characteristics remain consistent despite interannual differences in weather are what define a watershed's *flow regime.* Poff (1997) introduced the idea of the *Natural Flow Regime* of any given watershed as the master variable controlling healthy stream ecosystems. Under this idea, the natural range of variability within the flow regime is responsible for the major events that physically restructure river channels and create new habitat. Seasonal extremes caused by early and late storms are capable of wiping out most of a cohort of tadpoles or willow seedlings, while droughts can cause population bottlenecks in which only a few individuals survive such difficult conditions. Species therefore have physical, behavioral, and life history adaptations to the flow regime (Lytle and Poff 2004). The similarity of the flow regimes along the western Sierra Nevada therefore also implies an ecosystem that has evolved and adapted as an interconnected unit.

The highly variable magnitudes of winter precipitation can seem stochastic but scientists have detected a whole hierarchy of atmospheric patterns that influence the amount of winter precipitation. ENSO for instance, is a condition in the tropical Pacific that brings wet/dry winters to California at approximately 5-year intervals (Cayan et al. 1999), decadal oscillations have been observed in climate over the pacific (Cayan 1998) and 14-16 year cycles of runoff have been observed in the Sierra Nevada (Freeman 2002, Trask & Fogg in progress).

Researchers have also observed gradual shifts in precipitation and runoff attributable to global climate change (Milly et al. 2008). This includes shifts in streamflow towards earlier runoff, attributed to earlier snowmelt (Steward 2005, Mote et al. 2005) and relatively more rainfall versus snow (Knowles et al. 2006). California is expected to experience increased ambient temperatures of up to 6 degrees in the coming century (IPCC 2007) continuing this trend of reduced snowpack and increased winter stream flows (Miller et al. 2003, Dettinger et al. 2004b). The largest hydrologic changes are expected to occur at intermediate elevations, roughly between 1300-2700 meters (Knowles & Cayan 2004), and result in decreased spring snowmelt and increased air and water temperatures that will likely cause some extirpations and range shifts of aquatic species (Parmesan 2006). Unlike temperature, changes in precipitation due to global climate warming are not presently forecasted. Whether there is an increase or decrease in precipitation, an increase in interannual variability is probable, which would have effects across the entire range of elevations (Cayan et al. 2010).

A more acute force shifting discharges away from their historic flow regimes is the hundreds of dams that have been built along the western Sierra Nevada in the last century. These dams and reservoirs offer flood control, hydropower, and water supply to California. While each reservoir is different because of size, location, age, and intended purpose, they generally consist of large-volume, low-elevation, multi-purpose reservoirs that rim the Central Valley, or networks of smaller, high-elevation reservoirs that are designed for hydropower generation. The lower elevation rim dams are typically under the authority of the state or federal government or local irrigation districts, while the various hydropower projects are mostly owned by publicly traded energy corporations or municipal utility districts. This distinction influences the operation of the reservoirs, what their flow releases look like, and subsequently how they influence downstream hydrology and flow regime. Figure 2 illustrates the difference in flow alteration between a higher-elevation reservoir used to divert water to a different watershed and a mid-elevation reservoir, which saves winter flows to produce hydropower during the summer.

The negative environmental affects of altered flow regimes make natural flow restoration a priority for environmental conservation, and dam management policies remain a perennially low-hanging fruit ripe for contentious environmental politics. While there exist no state or federal laws that comprehensively protect riverine systems from hydrologic degradation in the Sierra Nevada (Viers and Rheinheimer 2011), the hydropower licensing process under the authority of the Federal Energy Regulatory Commission (FERC) is used to prescribe operating requirements for hydropower systems that reflect the values and anticipated demands over the following license term. Thus

FERC licenses provide an opportunity for stakeholders to agree upon ecologically relevant instream flow requirements for below hydropower dams.

Of the many ways in which reservoir operations can alter natural flow patterns (Richter et al. 1996, Magilligan and Nislow 2005), loss of the natural springtime recession, as in Figure 2, is one of the most ecologically detrimental in the regulated rivers of the Sierra Nevada (Yarnell et al. 2010). The spring recession is particularly susceptible to alteration because operators prefer not to overflow reservoir capacity causing spill, yet they want to have a full reservoir after the spring snowmelt. In order to achieve this, reservoir levels are kept low until after the spring peak and operators use the predictable recession inflow to then fill the reservoir. Poff's description of the natural flow regime as the master variable behind healthy stream ecosystems is an observation that addresses this type of flow alteration. Alteration of downstream geomorphology and habitat heterogeneity is one of the common indirect effects by dams that can cause ecosystem shifts (Magilligan and Nislow 2005), reduced ecological integrity (McBain and Trush 1997), and in some instances complete ecosystem failures (Ligon et al. 1995). In California, some species specific studies have shown that both annual and long-term recruitment failure of riverine-riparian dependent species can occur as a result of alterations to the recession limb (Lind et al. 1996, Stella et al. 2006).

As ecologists have learned about the habitat requirements of different downstream organisms in the last century, the possibility of managing flows for the benefit of one species or assemblage has been demonstrated (Marchetti & Moyle 2001). However as the value of water and number of threatened organisms increases, more comprehensive solutions are needed, namely a return to the natural flow regime. Some quantitative methods have been developed for describing degrees of flow regime alteration (Richter et al. 1996, Arthington et al. 2006) and for prescribing flow regimes (Arthington & Zalucki 1998, Jowett 1997). Whatever larger methodological framework is used to prescribe flows in future re-licensings, detailed information about the recession limb characteristics like this thesis, can be incorporated into an improved prescription to restore the natural spring recession limb.

This thesis fits within the context of historical research in the field of hydrology, and hydrograph analysis with quantitative description of any hydrologic recession as a semi-log shape has a 100-year history on both sides of the Atlantic. At the turn of the 20th century, two French contemporaries worked on empirically describing recession limbs. Boussineq used differential equations to describe both linear and non-linear aquifers and Maillet is credited with first using exponential decay a few years later. Horton, a prominent American hydrologist, popularized these ideas in United States in the 1930's. Hall (1968) provides a nice overview of these analyses and points out that similar social (water pollution and limited resources) and geographic factors (geology and climate) were what drove early interest in baseflow and aquifer characteristics, and these factors persist in driving today's research.

Continued work has been done describing recession limbs with various forms of the exponential decay equation. This has most commonly been applied to recessions of individual precipitation events, but it can also be useful for recessions of diel signals (Lundquist 2002) or seasonal snowmelt (Singh 2000).

$$Q = Q_0 \times e^{kt}$$

In this equation, Q is discharge, Q_0 is the initial discharge, e is the root of the natural logarithm, t is time, and *k* is an exponential decay coefficient (and thus negative). That this equation distills the recession shape into just two coefficients, Q_0 and k, is its redeeming quality and makes it useful for generalized characterization.

Another interesting aspect of this equation is its physical meaning as the solution of the differential equation for a linear aquifer:

$$Q = K \times S$$

where discharge, *Q*, which is also *dS*/*dt*, is linearly related to the storage, *S*, of a system by a constant *K* (Brutsaert 2005). Despite the appealing and intuitive nature of a linear aquifer, the characteristics upon which it is predicated (i.e., time-invariance, proportionality, and superposition) are rarely observed in nature and are thus less credible for a massive seasonal signal.

Another commonly applied method of recession characterization, based on this same formulation, is to further differentiate and compare *dQ*/*dt* to Q. By plotting discharge against its derivative, *k* is found as the slope of the regressed line.

$$Q = -\frac{1}{k} * \frac{dQ}{dt}$$

This method can be a straightforward but in time-variant systems it does not capture the changes that might be affecting k across the recession period.

Various approaches have been used to devise ‘Master Recession Curves’, which are generalized expressions for a basin’s drainage behavior. These methods result in ‘average’ recession shapes with more visual or qualitative methods (Nathan and McMahon 1990) but they can also be inaccurate due to high interannual (and intra-annual) variability (Tallaksen 1995) and non-linearity during different periods (Nathan and McMahon 1990).

In this study I used a novel approach, daily percent change, to further describe dicharge patterns. This concept also stems from a combination of the above approaches and, as modeled by the exponential decay equation is synonymous with the decay coefficient (k) and has the expression:

$$-k = \frac{\frac{dQ}{dt}}{Q}$$

This expression of a recession shape can be calculated for daily increments and provides insight into the pattern across the season whereas master recession curves provide a more broad and general characterization.

Daily percent change, as a method of calculating and prescribing a recession curve has certain benefits over an expoential method, especially under conditions when the hydrology is responding to the effects of various mechanisms. One benefit is that percent change can be calculated for daily increments. In this case, looking at an incremental calculation of curvature values is useful because it shows when in time changes in the curvature happen, and changes in the curvature can be an indication of how and when snowmelt is gone and baseflow is the dominant sreamflow source.

Separation of baseflow into age classes and from younger sources such as rain and snowmelt is an active topic of research that includes more specific descriptions of hydrologic pathways, storage, and streamflow generation in seasonal montane and alpine watersheds. Tools exist for baseflow separation of storm runoff but many of these methods lack mechanistic explanations or justifications for the distinction between baseflow, interflow, and overland flow. Similarly, the question of how to conceptually (and practically) partition hydrologic components of a seasonal recession exists at a larger scale, when trying to distinguish between snowmelt input and groundwater release (baseflow). If these two can be separated, then the groundwater release can be thought of as a predictable geologic basin parameter (Tague and Grant 2009) while the snowmelt component is driven by daily weather patterns and experiences greater interannual variability (Kattlemann 1991).

Another benefit of using daily percent change to work with seasonal recession curves is that is does not depend upon when the start and end dates are picked, as does the regression method. In the case of using environmental flow allocations to prescribe a recession limb below a reservoir, the starting magnitude, or intercept date might have to be reduced depending on the existing infrastructure such as gates and valves. This measure would allow licensees to say 'the percent downramping is naturally ***x*** percent during these two weeks of June', where ***x*** represents an empirically derived flow recession rate.

Previous modeling of the springtime recession limb of Sierra Nevada hydrographs has been couched in either basin studies or broader regional studies, but these studies were not intended to isolate this portion of the hydrograph correct and thus do not discuss what that means about flow sources and mechanisms. Instead of calibrating snowpillow data or artificially partitioning the groundwater component into depleting storages, this study takes the opposite approach and looks from the gauge upstream at what changes to the flow, and specifically the first derivative, tells us about where the water is coming from.

3.0 –Methods

I selected eight USGS stream gauges below undammed watersheds in the Western Sierra Nevada to work with for this study (Table 1). Despite the overarching similarity between Sierran basins described above, I selected watersheds that reflect the diversity of basin locations and within the range in order to describe the diversity of hydrologic characteristics conservatively. The locations of these gauges extend latitudinally from Indian Creek in the Feather River drainage south to the Kern River (Figure 3). On average, they have 70 years of available daily average discharge values and the watersheds are all relatively large- mostly 5th and 6th order. The elevational variation between the watersheds also reflects the diversity that is possible for watersheds of this size; from the Cosumnes, which is mostly below 2,000 meters to the Merced and Kern which are mostly above that. I used ArcGIS (v. 9.3) and digital elevation files to graph the hypsometry, or area- elevation relationships, of each watershed by breaking them into 20 evenly spaced elevation bands. I calculated the elevation centroid as an index of basin elevation. I also summarized the geologies of each watershed using a state geology map by Jennings, 1977.

I calculated the magnitude, duration, timing, volume, and curvature of the recession limb hydrograph using the full available historical record for each gauge. I used the daily average discharge, called a *synthesis* hydrograph, to define a fixed, average recession beginning and end date for each site. The recession start date was defined as the day of maximum discharge of the synthesis hydrograph after April 11. The end date was defined as the point when the daily change in discharge (dQ/dt) (cms) became less than 0.1 after applying a 5-day moving average. This definition of the recession period was therefore unique to each watershed, but static across each year's individual hydrology. Magnitude is the discharge at the start and end dates of the recession limb. Duration is the number of days within this period. Timing is the dates of the recession start and end. Volume is the average amount of water contained within the recession limb, which I calculated as a fraction of the average annual flow.

I used two related methods to quantify the recession limb shape, or curvature, both of which are based upon the exponential decay model and use daily discharge data instead of the synthesis hydrograph. The first method I used provides an exponential decay coefficient for the recession shape of each year of record. I did this by modeling the recession period with a best-fit exponential function by semi-log transforming the recession hydrograph and regressing a straight line to the recession portion. The slope of this line is by definition the exponential decay coefficient (k). Using this coefficient and the initial discharge, I modeled recessions for each year and evaluated the goodness of fit to the observed recession with the Nash-Sutcliffe Model Efficiency (NSME) index (Nash & Sutcliffe 1970). I also separated these results into different water year types to look for relationships between the annual precipitation and the recession curvature.

My second method of quantifying the recession limb shape was to calculate the annual hydrograph's daily percent change, which is equivalent to the decay coefficient k but provides an incremental look at the hydrology. According to this method, a period of receding discharge has a negative percent change, and a recession with true exponential decay shape will have a constant negative daily percent change. For the second half of every water year of record, for the eight sites, I calculated the forward-looking percent change between each day and analyzed the times in which discharge went down. I calculated the average and maximum percent downramping through time to see trends across the season as well the cumulative distribution of all percent downramping values during the recession limb. Finally, I calculated the percent of the time downramping occurred at every day of the water year for each site in order to assess the consistency.

4.0 - Results

Results of this study show that the factors controlling the springtime hydrology of the Western Sierra Nevada combine in a way that makes the recession limb a predictable feature at each site despite the variability of winter storms. Basin size and the precipitation amount both scale the recession magnitude and duration, and basin elevation dictates the timing, but the shape of the recession, particularly during the second half, is extremely consistent from year to year. The distributions of coeffiecients for the curvature at each site overlap over a narrow range of values and basins appear to have recession coefficients related to their elevations.

Watershed Properties

The geographical properties of the watersheds which I looked at in this study; geology, area, elevation and latitude, most exhibit covariation in ways that make their individual influences on hydrology tricky to isolate, but certain relationships are distinct.

Bedrock geologies, as shown in Figure 4, have very strong latitudinal autocorrelation, but bear little relationship to hydrologic properties at this scale. The southern Sierra watersheds are predominately granitic, but a mix of granitics, volcanics, and marine rocks occurs in the North. This gradual shift, as a percentage of each watershed, is very consistent across the range. Volcanic and marine geologies have higher porosity and transmissivity than granite and this relationship to late summer baseflow magnitudes has been shown, but the other characteristics tended to overwhelm the runoff patterns for most of the year. The baseflow magnitude results are more influenced by wetness of the previous water year and tectonic faults than geology.

Watershed elevations are also strongly correlated to latitide, but most of the elevations encompassed by these watersheds are concentrated between 1000 and 2500 meters as illustrated by the hypsometric profiles in Figure 5. The Cosumnes and NF American have large areas below 1000 meters; while the Merced and Kern are mostly above 2500 m. The higher elevation watersheds, which store more of their precipitation as snow and have later recessions (Figure 6), have a greater proportion of their annual runoff encompassed by the snowmelt recession limb (Figure 7). The effect of orographic precipitation on runoff would lead us to expect elevation to influence annual runoff volume (Figure 8), but with the exception of a few sites, latitude plays a visibly larger role.

The areas of the watersheds vary from about 200 to 2000 square kilometers. Watershed area is positively correlated to average annual runoff and the recession limb magnitude

(Figure 8). NF Yuba and NF American annually receive three to four times as much water per unit area as the lower and/or drier Indian Creek, Cosumnes, SF Kaweah, and Kern (Figures 8 and 9).

Synthesis Hydrographs: Magnitude, Duration, Timing, Volume

The synthesis hydrographs in Figures 10 a & b show the periods of the snowmelt recession used in calculating magnitude, duration, and timing, and volume for each watershed. The magnitude of the recession, as measured by the initial discharge, was largely controlled by the watershed area. The Kern is the largest watershed and had the highest initial discharge of 67.8 cms with an average date of May 29 (See Figure 10a and Table 2). The Kaweah is the smallest watershed and had the lowest magnitude, at 7.3 cms two days later. The other sites all started within the range of 20-60 cms. The baseflow 'magnitudes' were all within the range of 2-3 cms except for the NF Yuba and Kern, which were at 6 and 9 cms respectively.

The average recession period timing of all sites was from mid-May (14th) until the end of July (28th). Recession start dates were generally clumped into three time periods: The lowest elevation sites began in mid-April, the three intermediate sites began in mid-May, and the three high-elevation (southern) sites began at the end of May. End dates ranged from the end of June until the end of September and largely followed the pattern of start dates, although the smaller watersheds tended to earlier end dates. The range of the recession limb timings, between earlier-low elevation sites and later-higher ones is about 50 days. Figure 11 also shows when period of recession are the most common for each watershed and that the flows in many can be expected to be dropping about 95 percent of the time during July.

The average duration was 75 days, with the Kern having the longest (99 days) and the Kaweah having the shortest (29 days). These are the largest and smallest basins, but otherwise the duration was not well correlated with area alone.

Results showed that watershed area controls the recession magnitude, but by normalizing the synthesis hydrographs to area, some deeper similarities between basins emerge (Figure 10c). Shapes of the high, medium and lower elevation watersheds overlie each other very closely, and deviations from these patterns become clear. For instance, the NF Yuba and NF American have identical winter flows per unit area, but after April 1 the Yuba has much more snowmelt, and the American matches the Clavey's recession. Similarly the Kern and Kaweah have very similar hydrographs except the Kern's recession is shallower, like the lower elevation Indian Creek and Cosumnes.

Recession Limb Curvature

Results from the regression method used to quantify the recession limb shape were that average exponential decay coefficient for all sites ranged from between -0.03 and -0.05, with an average NSME of 0.63 (Table 2 and Figure 12 & 13 a). Each site has approximate normal distribution of values. The NF American had the fastest decay rate (-0.05, NSME= 0.72) of the eight sites and the Cosumnes had the slowest (-0.03, NSME = 0.50). The Cosumnes and Indian Creek both had less curved recessions and lower NSMEs, while the intermediate elevation sites, NF American and Yuba, both had higher *k* values and NSMEs. The Kern was unique in having a less negative *k* (less curvature) but high NSME.

Interestingly, most *k*-values were the same across all different water year types, indicating a symmetrical scaling across discharge magnitudes (Figure 13 b). These results were not statistically different by water year type (Table 2, mean $p = 0.016$) except at the Kaweah gauge ($p = 0.056$), which has the smallest number of years on record (31 years).

Daily percent change results indicate that downramping averages were between 2 and 10 % during the recession limb periods (Figure 14 a) and never greater than 15 %. Five of the eight watersheds show an increasing (less negative) percent change over the course of the recession period, which represents changes to the exponential decay shape through time, indicated by negative slope of downraming rate. This pattern is also clearly visible in individual years, as in Figure 15. Indian Creek was the one site where the recession limb developed steeper average curvature through time. Neither the Cosumnes nor Kaweah had any appreciable shifts.

The maximum daily percent downramping values have similar trends as the averages during the springtime but higher percent changes during the winter associated with storms and during the late summer as baseflow discharges get very low. Aside from a few cases where the Cosumnes River went dry, these maxima never exceeded about 70 percent (Figure 14 b). Another way of looking at the distribution of daily percent downramping results is through a cumulative distribution function as in Figure 16. This figure shows that downramping values are between 0 and -0.1 roughly 90% of the time and greater than -0.3 roughly 99% of the time.

For each day of the year at each site I calculated the percent of the time that discharge decreases from one day to the next. Results from this analysis, shown in Figure 11 indicate that 80 to 90 percent of days are receding during the spring, with lower sites receding consistently earlier. Since rivers reach baseflow every year, the volume of water represented by upramping must equal the volume of downramping, however an average annual inequality in upramping rate versus downramping rate is a coefficient that has meaning about the character of the watershed.

5.0 – Discussion

Watershed Properties

The eight watersheds I used in this analysis were chosen to encompass the diversity of unimpaired basin types in the western Sierra Nevada, and results from both the basin and hydrologic analyses suggest they do, while the hydrologic results all tend to fall within a narrow range of results and the variation among them can be largely explained by the physical differences between watersheds. These physical differences are controlled by the gradual latitudinal changes across the range, which supports the idea that the Sierra has a predictable hydrologic signature with strong spatial autocorrelation. Within this hydrology, the recession limb is a particularly predictable portion of the annual hydrograph because it is so directly tied to the physical watershed.

Watershed area, which varied across an order of magnitude in this study, played the most obvious role in differences between hydrographs. When I normalize to watershed area to eliminate its effect, as in figure 10c, the hydrographs cluster into three different types, with respect to the relative volume and timing of the recession limbs. These types can roughly be catergorized as representative of low, intermediate, and high elevation watersheds.

Indian Creek and the Cosumnes River are the two sites that exhibit low-elevation characteristics of having a relatively small amount of snowmelt and reduced recession limbs. Both of these sites occur in the Northern Sierra where the range is not as steep and more area occurs at lower elevations. The Cosumnes has large area at low elevation (Figure 5), which is why it has the earliest centroid timing (Figure 6). Indian Creek, on the other hand has a large area at intermediate elevation but this area doesn't reliably accumulate much snow. Indian creek has the lowest average annual runoff (Figure 8), so its low-elevation character might be because it is in a rainshadow.

The sites that exhibit characteristics of intermediate elevations of having both winter storm runoff and significant spring snowmelt are the NF Yuba, NF American, and Clavey. The Yuba and American sites have similar winter hydrographs, and the Clavey and American have similar spring hydrographs. The Clavey and Yuba are very similar in terms of basin elevations, (Figure 5) and runoff timing (Figure 6) except the Clavey receives a bit less precipitation.

These intermediate elevation sites are interesting because they lie across the rain-snow boundary and the weather patterns of a given year can cause them to retain or lose the snow very differently. These are also the sites that will be expected to have the greatest hydrologic changes as a result of climate change because they span the ‘critical’ elevations (as in Steward et al. 2005) With climate warming producing relatively more rain and earlier snowmelt, hydrographs of these sites could shift to look like their low-elevation neighbors in time.

The Merced, Kaweah and Kern represent high-elevation type watersheds, with runoff occurring later in the year as snowmelt. This snowmelt ‘pulse’ or onset occurs when the weather warms in the spring and snow begins to melt, which means that the timing of the annual flows occur at a more predictable point in time than sites inflenced by rainfall. These three watersheds are all very different and they do not accumulate rainfall for unique reasons. The Kaweah and Kern are both relatively dry (Figure 8), possibly because of rain shadow effects or because they are the farthest south where the climate is warmer, drier, and relatively little precipitation falls in the low elevations. The Merced contains the highest elevations, with very little area below 2,000 meters, and it has a high average annual runoff.

Peterson et al. (2005) found that during wet years the Merced River Happy Isles gauge is representative of snowmelt patterns across the Sierra Nevada as controlled by uniform distributions of air temperatures across the range. Snowmelt patterns do appear to correlate among my sites, but the Merced represents the highest elevations of these and therefore the latest runoff (Figure 10c).

Peterson et al. also found that the geology and subsurface properties of a watershed such as soil depth have an effect on the amount of baseflow in wetter years. Although they did not discuss the recession limb of the snowmelt season, these findings also hold true for the portion of the hydrograph I am looking at. Watersheds with more soil have more of a baseflow component to the recession limb than bedrock dominated watersheds and these patterns are spatially distinct because of the topographic layout of the Sierra Nevada. High-elevation hydrologic behavior is visible in the Merced River's recession limb, as temperature driven variations in discharge occur while the flows are dropping.

Watersheds with more groundwater storage in the uplands, such as the northern and central Sierra, have recession limbs as a result of the travel time of water through the soil (See example in Figure 1).

While the Merced might be representative of the Sierran snowmelt during wet years, this study is more concerned with the watersheds that span the range of elevations down to the Central Valley and patterns across all water year types. Therefore I consider the intermediate sites such as the Yuba, American and Clavey, whose recession limbs exhibit a shift from snowmelt to groundwater, to be more representative of rivers from the western Sierra.

Magnitude Duration and Timing

The magnitude, or average discharge, of the recession limb start is influenced by the watershed area, precipitation, and elevation of each watershed. This definition of the magnitude is discharge at the snowmelt peak. The recession in a given year is rarely continuous directly after this point. Instead the discharges go up and down with snowmelt patterns, declining gradually into baseflow that has a more continuous recession pattern.

There was considerable variation in the baseflow magnitudes, especially the NF Yuba and Kern, which were significantly higher than the others (Figures 10 a & c). The NF Yuba has an elevated baseflow throughout the summer low-flow period but the same recession shape as the majority of other sites. In other words it has significant baseflow contributions that come from such a 'slow' source that the hydrograph has an almost vertical shift. The Kern's average recession is longer than most but discharges ultimately reached a level similar to others per unit area, indicating storage that releases much faster.

The average recession duration of all sites studied was from mid-May until the end of July, meaning that June is typically the heart of the recession period, but each watershed elevation type exhibits a characteristic start and end timing. The higher elevation sites studied here tend to have a snowmelt peak in late May, as much as two months later than the low elevation sites. According to annual hydrographs, high elevation sites also tend to have a more distinct snowmelt peak, with temperature-driven peaks that occur within a few weeks of one another. The rainfall-dominated sites, Cosumnes and Indian Creek, make determination of the recession start very difficult because the snowmelt occurs with rain events and often does not form a distinct peak of its own. These sites tend to have a start date of around April 15, the point immediately after the rain signal subsides. The intermediate elevations, NF Yuba, NF American, and Clavey, all have start dates right around May 20. The timing and character of the annual snowmelt peak at these locations can be highly variable because, at intermediate elevations they are more affected by interannual temperature fluctuations. Warm springtimes melt enough snow all at once to create a distinct peak and quick recession, while wet years and colder springtimes can keep snow in the mountains longer so that a distinct hydrograph peak never occurs and the recession begins as much as a month after the mean, as in 2011 or 1995 (Figure 1).

The timing of the recessions that I measured from the synthesis hydrographs is a generous portion of time considering variations in the snowmelt portion. The method I used to demarcate the end of the recession limb – using a slope threshold for the hydrograph – is not dimensionally homogenous, so smaller watersheds such as the Kaweah have relatively earlier end dates than other watersheds of the same elevation-type. Timing of the recession limb end at the Merced and Kern sites were later than others because of high elevation snow persistence, but as mentioned above, there seems to be another factor at play within the Kern watershed. Figure 10 c, the area-normalized synthesis hydrograph, and results from the exponential regression method in Table 2 indicate that the Kern's recession shape is significantly longer and more gradual than other sites. The Kern's primary difference between from the other sites is that it is oriented north to south along a tectonic fault, so the different rate of recession might be attributable to the aspect or hydrologic storage in the fractured bedrock.

The volume of water below the recession limb of the synthesis hydrograph is another measure of magnitude and, as in Figure 7, is influenced by elevation. The high-elevation Merced River has almost 50 percent of its flow beneath the recession limb. The Kaweah is unlike the others because its duration is so short. Otherwise the mid-elevation sites have the smallest percent of annual discharge during the recession (~20 %) and the low elevation sites have an intermediate amount (~30%).

Recession Limb Curvature

The first method I used for measuring the curvature of the recession limbs, regression a line across the recession portion, yielded values of between -0.03 and -0.05, which is equivalent to a daily downramping of between 3 and 5 percent. Each site has a slightly different distribution of values, but the overall degree of similarity is remarkable given the simplicity of the method. Years with a large precipitation event shortly after the recession start result in greater curvature (more negative values), while years with storms in the late spring or summer have less curvature. Interannual temperature variability also plays an important role in the recession limb shape. As Lundquist (2005) describes, some years have different melt patterns in space and time. Rapid spring warming and complete snowmelt across the higher elevations causes a more distinct peak and a faster initial recession rate because inputs to the channel are exhausted. Slower melting can have the opposite effect, with a less distinct peak and protracted recession duration.

The NSME values recorded for each site are essentially a measure of how well the hydrograph fits an exponential decay shape. NSME equaling 1 indicates a perfect fit, while an NSME of zero or lower indicates an entirely worthless fit. Results were that the rain dominated (Indian Creek and Cosumnes) and higher elevation sites (Merced Kaweah) tend to have poorer fits while the NF American and Yuba and the Kern have the best fits.

All sites tend to have both more predictable and smooth recession shapes during the latter half of the recession, when discharges are lower. In rain-dominated systems, the variability during the early recession is likely to be due to precipitation events. In snowmelt-dominated systems, variability during the early season is caused by temperature-driven melt fluctuations. This portion of the hydrograph can appear very stochastic, which in synthesis hydrographs gets smoothed to a convex-up shape. The Kern, which is also high-elevation, has a higher NSME because, due to its large size source areas, the variation gets damped out. That the NF Yuba and NF American have the best fits would indicate that the snowmelt peak is more consistent in time, as with the higher sites, but containing fewer major snowmelt or precipitation induced discharge fluctuations.

I found no clear relationship between water year type and exponential decay value (Figure 13 b), which is potentially an important result. The lack of such a relationship would indicate that during years with less snowpack, the hydrograph is reduced in a way that scales the shape accordingly.

Since the recession shape is capturing melt patterns at the end of the snow's elevational retreat, this pattern might mean that the snow maintains a constant storage gradient across elevations despite different water years. The specific contribution of snowmelt versus groundwater is unknown, and average groundwater ages have been shown to vary by decade at different points during the recession (Rademacher et al. 2005), but the consistent exponential decay across water year types supports the idea that a system can have a linear relationship between its storage and discharge regardless of whether the storage is above or below ground.

The second method I used to assess the recession limb curvature was to calculate the average daily percent change in downramping during spring and summer. While the regression method of calculating curvature is useful for characterizing the entire spring recession shape, the daily percent change method provides a more detailed view. This incremental approach helps explain why certain sites do not have good exponential decay fits by showing shifts in the decay rate over the course of the season. For instance, earlier in the season snowmelt can fluctuate depending upon temperature and can apparently drop at faster rates than later in the recession, when more of the water is travelling to the channel via groundwater pathways.

Although the exponential equation is an expression for the gradual release of a linear aquifer by gravity, snowmelt is being added to the recession in diminishing amounts as the springtime proceeds. Results and observations of individual years, as in Figure 15, indicate that the tradeoff between these two is linear and gradual over a few weeks. In the winter and early spring, saturated soil at low and intermediate elevations provide steady ‘winter baseflow’ which reduces its contribution to streamflow later, as snowmelt at higher elevations begins. Higher elevation sourcewaters travel through little soil. Instead discharge fluctuations are buffered by percolation time through snowpack, variable source areas and travel times. That the contributions from the range of elevations unite to create a recession so consistently close in shape to an exponential is surprising, especially considering the total number of variables at work.

Baseflow magnitudes at the end of the recession are also an interesting and complex issue that affects the curvature results of both methods. While it is standard mathematical practice in regressing across logarithms to do a vertical adjustment to a fixed known minimum before calculating slope, I did not do this because it would be making assumptions that the curvature and baseflow are two independent things. A greater knowledge about the mechanisms and sourcewaters might allow justification of a fixed point. Without any adjustment, sites and years with higher baseflows have slightly higher k values than they otherwise might. This helps to explain why the Yuba and American sites have slightly different decay rates, despite their very similar hypsometries at higher elevation.

The three sites with poor exponential fits (NSME < 0.60) from the regression method were the same three sites that did not exhibit a decreasing recession rate. These sites are the low elevation sites and the SF Kaweah, which has a small area, so I believe that these sites do not have enough interannual consistency to see the shiff a shift in the percent change. The other five sites, which had better fits, all exhibited the same general trend of a shift from about 10% to 5% daily change per day. This is the opposite of what Singh

(2000) found to be the case in the Austrian Alps, which was a trend toward a faster recession rate over the course of the melt season.

Broader Applications

This research has direct applications for prescribing restorative recession limb flows in managed systems and additionally describes a portion of the annual hydrograph that is a controlling variable for many processes in healthy rivers.

Geomorphic implications of the study are that magnitude of the recession limb start is important, which is controlled by area and the interannual variability, but the relative amounts of channel restructuring and sorting also depends upon watershed elevation. Lower elevation sites have brief, but much greater magnitude winter flows which do the most restructuring, while the sustained influence of the snowmelt peak and recession limb do more for sorting materials. Higher elevation sites like the Kern or Merced do not have high winter flows and therefore both the sorting and restructuring occurs during the snowmelt portion.

The ecological implications of this study are species specific, but each of the hydrologic parameters quantified in this study can support the entire assemblage of native species that live in and along Sierran rivers. Fish are sensitive to water volume and temperature restrictions, but other species that use edgewater habitat, such as foothill yellow-legged-frogs, benthic macroinvertebrates, and vegetation, are often more sensitive to changes in stage and velocity than actual discharge. Stage change patterns during this time depend upon how the recession limb hydrograph engages with the river cross-section at viable or breeding sites. Stage-discharge rating curves are also commonly modeled with exponential funtions, so something that merits more inquiry is the possibility that an exponentially decaying recession, consistent across different water year types as is the case here, produces a linear stage drop across the entire springtime recession limb.

Information within this study can be used to prescribe a recession limb that mimics a natural one in a variety of watersheds in the western Sierra Nevada, but the extent to which any application approaches the natural recession will depend upon the alignment of many other factors. Infrastructural limitations are one important consideration. Many reservoirs do not have gates or values that can control the amount of water that spills over during wet years, so a managed recession could only begin after discharges drop below a certain level. The volume of an environmental flow allotment might be another limiting factor, forcing a decision between a longer recession at a lower magnitude, or a shorter one that peaks at higher flows. The ability of reservoir operators to accurately predict springtime inflow to reservoirs in any given year is another critical piece of the solution, and possibly one of the most tractable. They must know the upstream volumne of snow storage and be able to predict the final snowmelt peaks in order to avert late-season spills.

All of these challenges require continued research in the emerging area of ecohydrology however the findings presented here should form the basis for improved river management that better incorporates observations from natural systems.

6.0 – Conclusions

The springtime snowmelt recession limb of rivers in the western Sierra Nevada is an annual hydrologic feature that provides important habitat to native aquatic and riparian species, but through the construction of hundreds of reservoirs along the range humans have eliminated this aspect of the natural flow regime in many stretches of river. Environmental flows from reservoirs have consisted primarily of minimum instream flows to this point, but there is a growing recognition that restoration of the recession limb would have enormous benefit to helping conserve and restore healthy downstream ecosystems. To this end, this paper is a quantitative description of recession limbs in undammed watersheds. I analysed historical hydrology of eight unimpaired gauges in the western Sierra Nevada between the Feather and Kern basins by defining the recession limb and calculating its magnitude, duration, timing, and shape. Magnitudes of the recession starts were positively correlated to watershed sizes, but the volume of water beneath the hydrograph as a percent of annual flow was positively correlated to the watershed elevation. Duration was variable between sites, but the average recession lasted 75 days, between the middle of May and the end of July. I used two different methods to quantify the recession limb shape, both of which are mathematical variations of the exponential decay equation. Results from the first method, which describes the seasonal shape with a modeled best-fit curve, were that the average decay coefficients are between -0.03 and -0.05 across all watersheds independent even of water year types. The second method describes the recession shape at daily intervals in order to see shifts in the average curvature over the recession period and the greater distribution of values. I did this by calculating the percent change between days of downramping. Results from this method indcated a shift from greater to lesser curvature over the recession period at five of the eight sites. The distributions of results from this method also show that the daily percent downramping is between 0 and -0.15 approximately 90 percent of the time during the spring recession. These calculations as measures of the recession limb where chosen to cover a range of variables important to riverine ecosystems and results have implications for the conservation of healthy rivers and direct application to reservoir management as protective flow guidelines.

7.0 – References

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8.0 – Figures

Watershed	Gauge Name	UGSG Gauge No.	Gauge Elev. (m)	Elevation Centroid (m)	Area (km^2)	Latitude	Years of Record
Feather	Indian Creek nr Crescent Mill	11401500	1067	1714	1914	40.08	63
NF Yuba	Goodyears Bar	11413000	748	1732	647	39.53	77
NF American	North Fork Dam	11427000	218	1328	886	38.94	66
Cosumnes	Michigan Bar	11335000	51	933	1388	38.50	100
Clavey	Buck Meadows	11283500	724	1801	373	38.90	34
Merced	Happy Isles Br.	11264500	1224	2746	469	37.73	93
SF Kaweah	Three Rivers	11210100	246	1579	223	36.42	31
Kern	Combined Kern & No 3	11186001	831	2500	2191	35.95	96

Table 1. Watersheds, USGS gauges, and basin attributes used in this study.

	Indian Creek	NF Yuba	NF American	Cosumnes	Clavey	Merced	SF Kaweah	Kern
Start Date	18-Apr	19-May	20-May	13-Apr	19-May	28-May	31-May	29-May
End Date	13-Jul	6-Aug	28-Jul	10-Jul	20-Jul	20-Aug	29-Jun	5-Sep
Start Discharge (cms)	41.1	60.0	55.8	30.5	21.4	42.8	7.3	67.8
End Discharge	2.0	5.8	2.9	2.2	1.7	2.3	2.9	8.9
Percent of Annual Discharge	32	25	16	26	23	47	20	41
Duration (Days)	86	79	69	88	62	84	29	99
k	-0.04	-0.05	-0.05	-0.03	-0.04	-0.04	-0.05	-0.04
NSME	0.58	0.73	0.72	0.50	0.64	0.61	0.57	0.74
WYT ANOVA P-value	0.0002	0.0329	0.0332	0.0001	0.0013	0.0038	0.0551	0.0003

Table 2. Hydrologic results of the recession limb description.

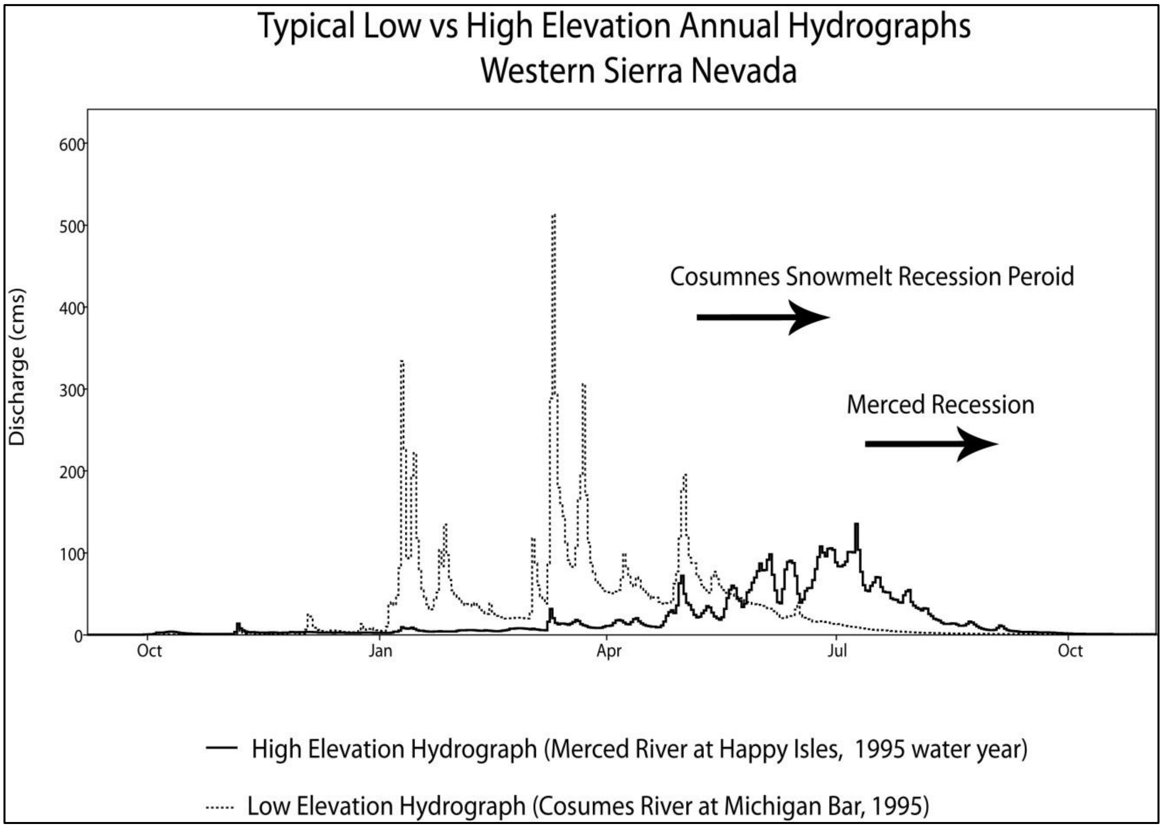


Figure 1. The influence of watershed elevation on runoff timing.

Despite the same weather patterns on these two watersheds, the Cosumnes River ran at high flow after storms while the Merced River had higher flows during the spring snowmelt. Notice the different character of the springtime recession limbs: the Cosumnes exhibits a gradual recession after May but the Merced's is shorter and more jagged (Note 1995 was a wet year).

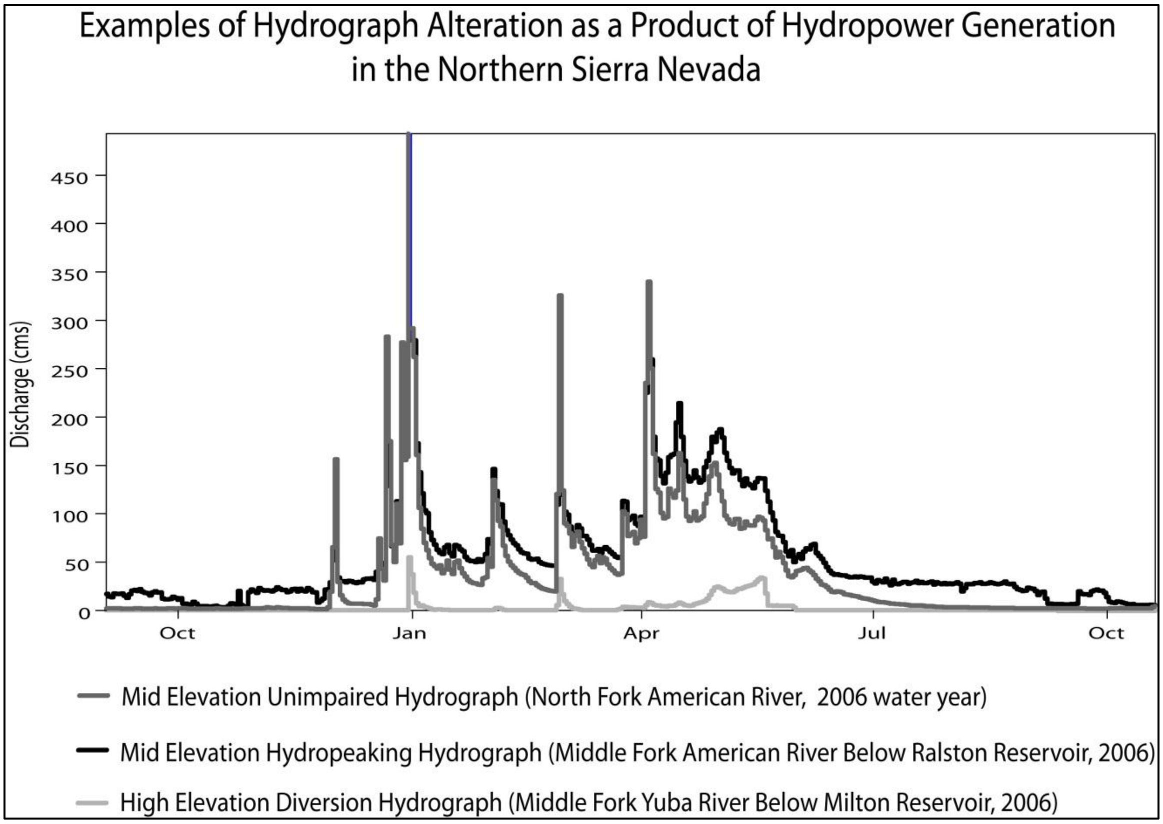


Figure 2. Example alterations to the springtime hydrology in the central Sierra Nevada. The spring recession of the Middle Fork American (black line) begins a daily pattern of controlled hydropower release before the discharges reach baseflow while the Middle Fork Yuba (light grey line) has all of its spring recession limb diverted to another watershed for power generation. The North Fork American gauge (dark grey) is an unimpaired watershed used in this study.

(Note 1993 was a wet year)

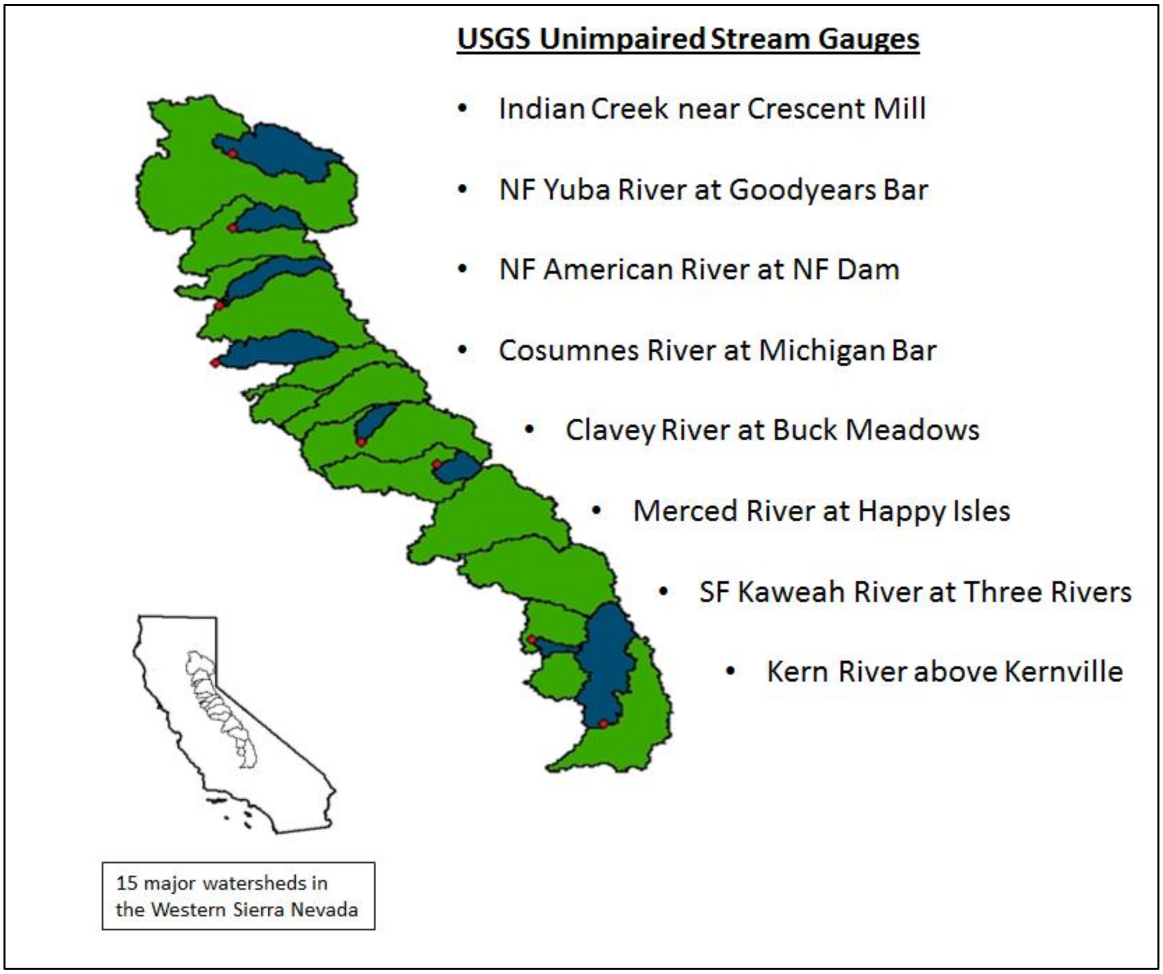


Figure 3. Site location of the fifteen major watersheds of the western Sierra Nevada and locations of the eight unimpaired basins within these fifteen that I used in this study.

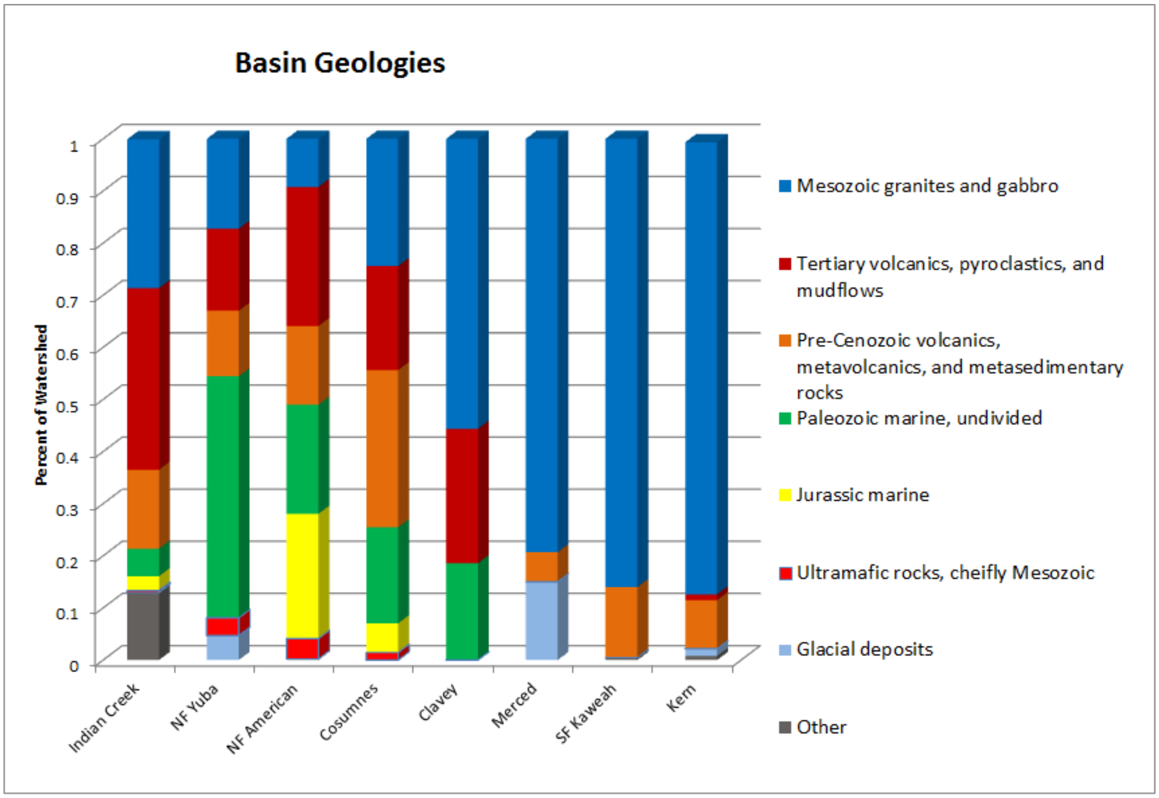


Figure 4. Major geologic classifications of the eight basins used in this study, organized from North to South. Granites, in blue, dominate in the southern Sierra, while volcanics and marine sedimentary rocks dominate in the North.

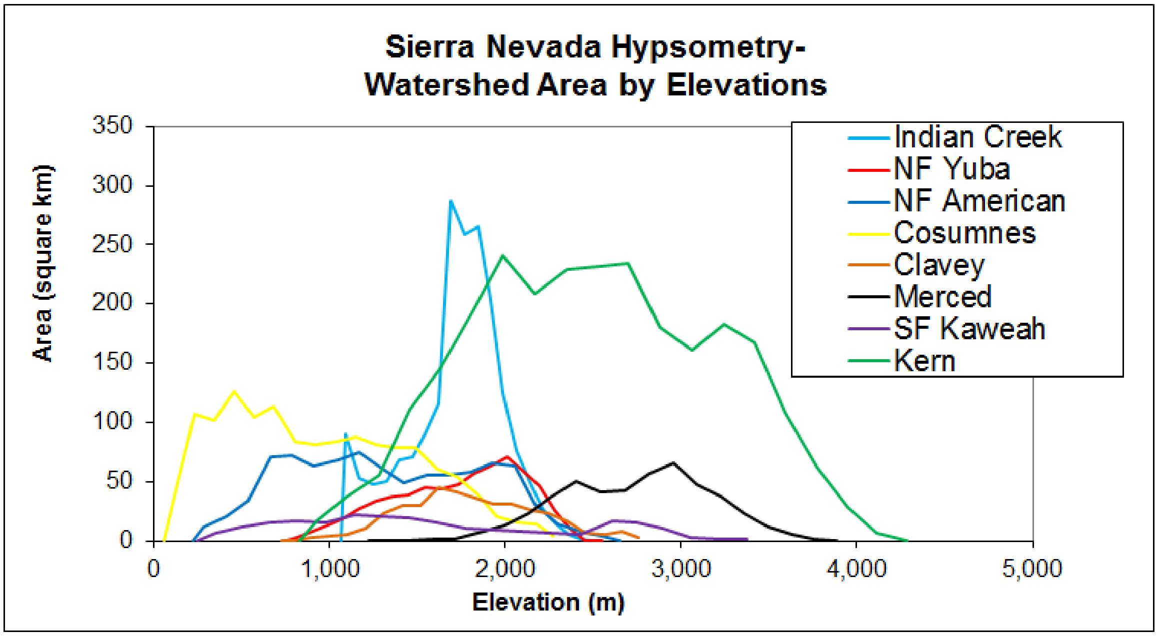


Figure 5. Hypsometric profiles of the eight watersheds, based upon 20 elevation bands per basin. Most of the area is concentrated between 1000 and 2500 meters elevation.

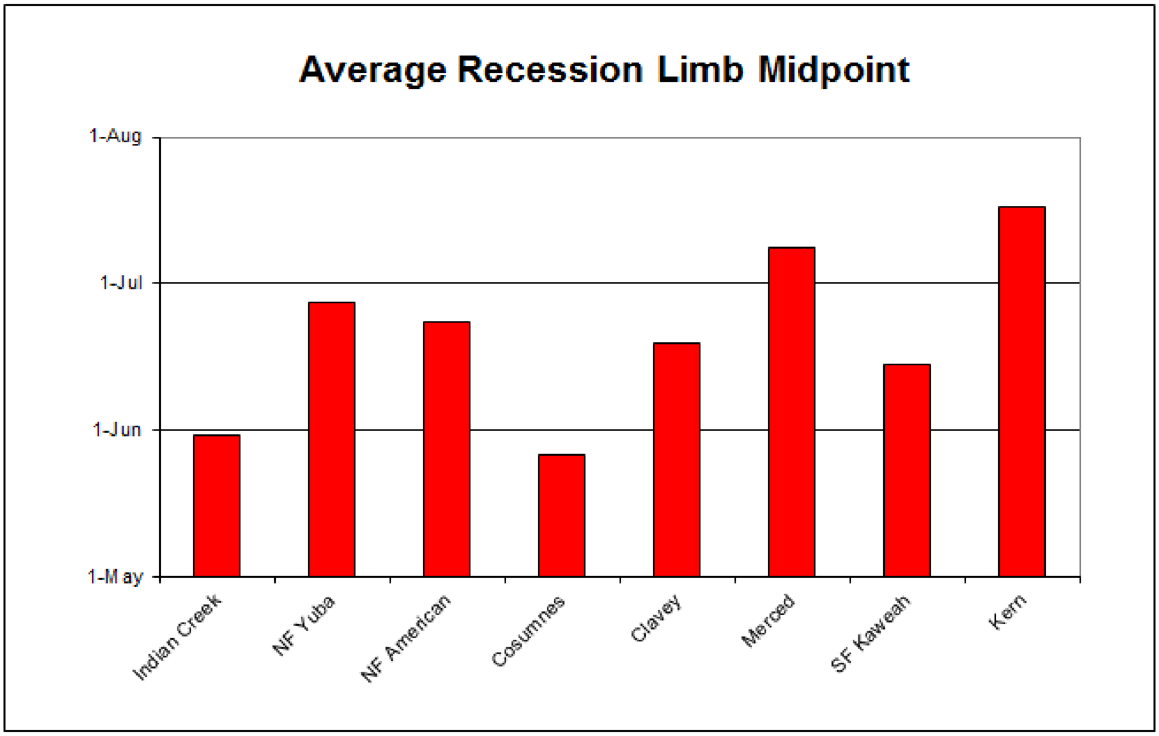


Figure 6. Midpoint timing of the recession limb at each site. Indian Creek and Cosumnes are low elevation sites with smaller recessions. The SF Kaweah is earlier than its neighbors because of its small size.

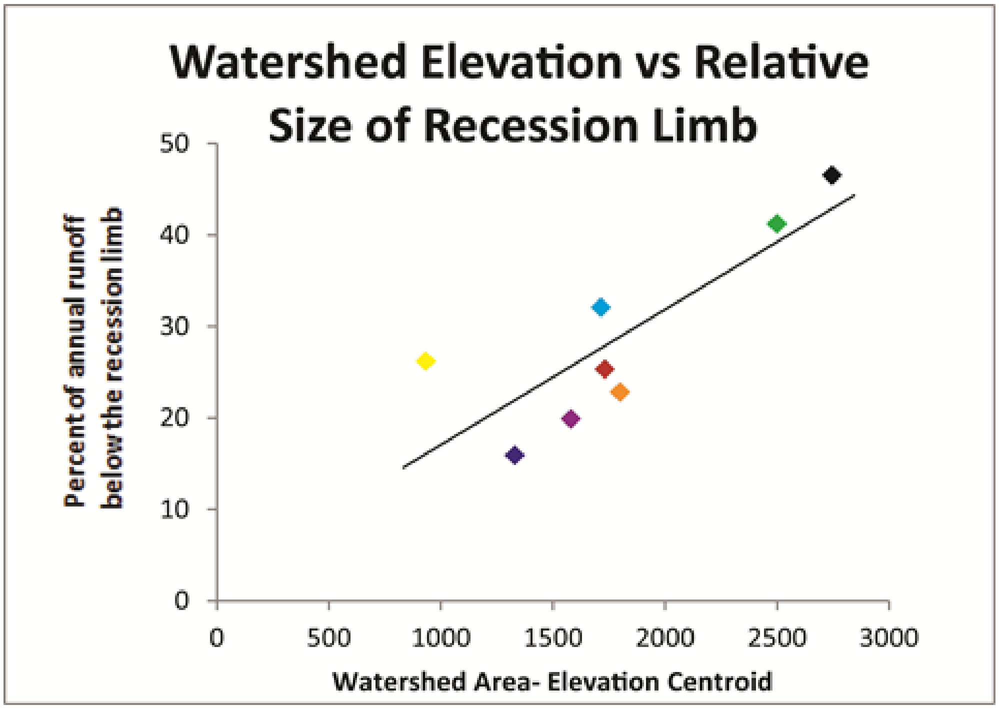


Figure 7. Percent of the annual flow encompassed by the recession limb, versus the basin's centroid elevation (m). Recession periods on the Cosumnes (yellow) and Indian Creek (light blue) begin early and contain a greater proportion of direct runoff from precipitation, which explains their deviation from the otherwise linear relationship.

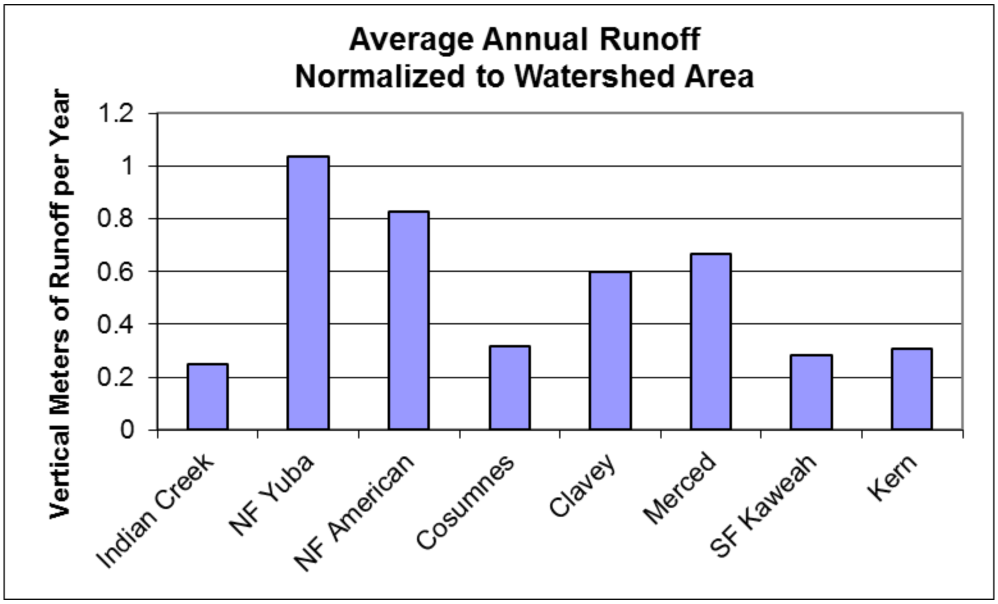


Figure 8. Annual watershed runoff per year per unit area.

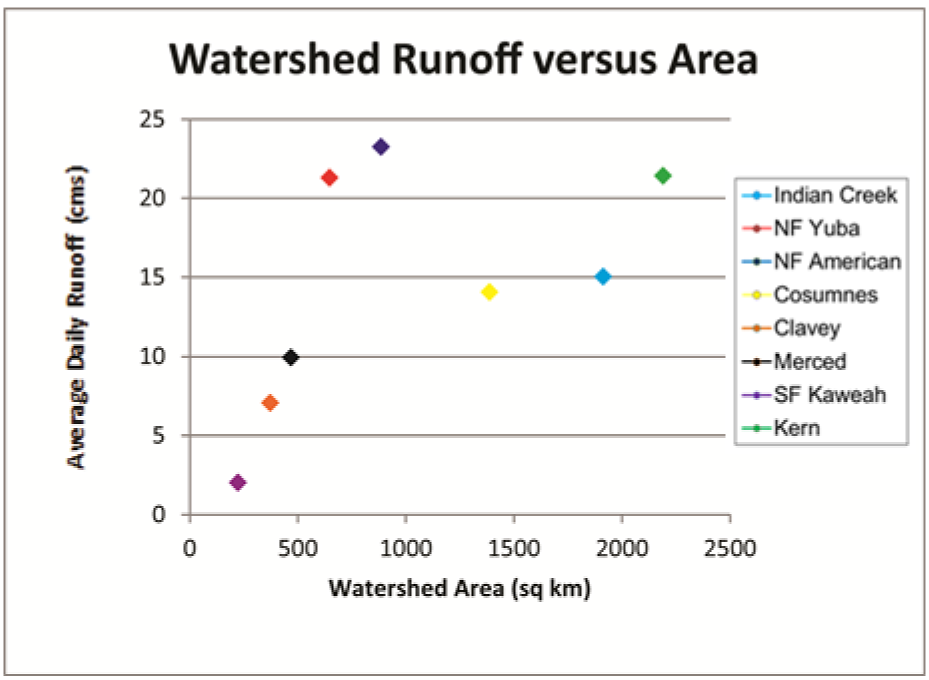
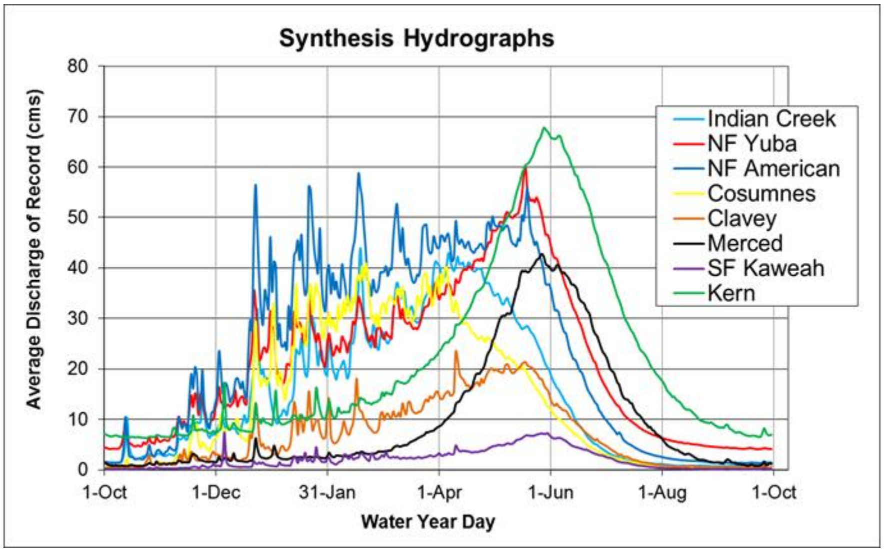
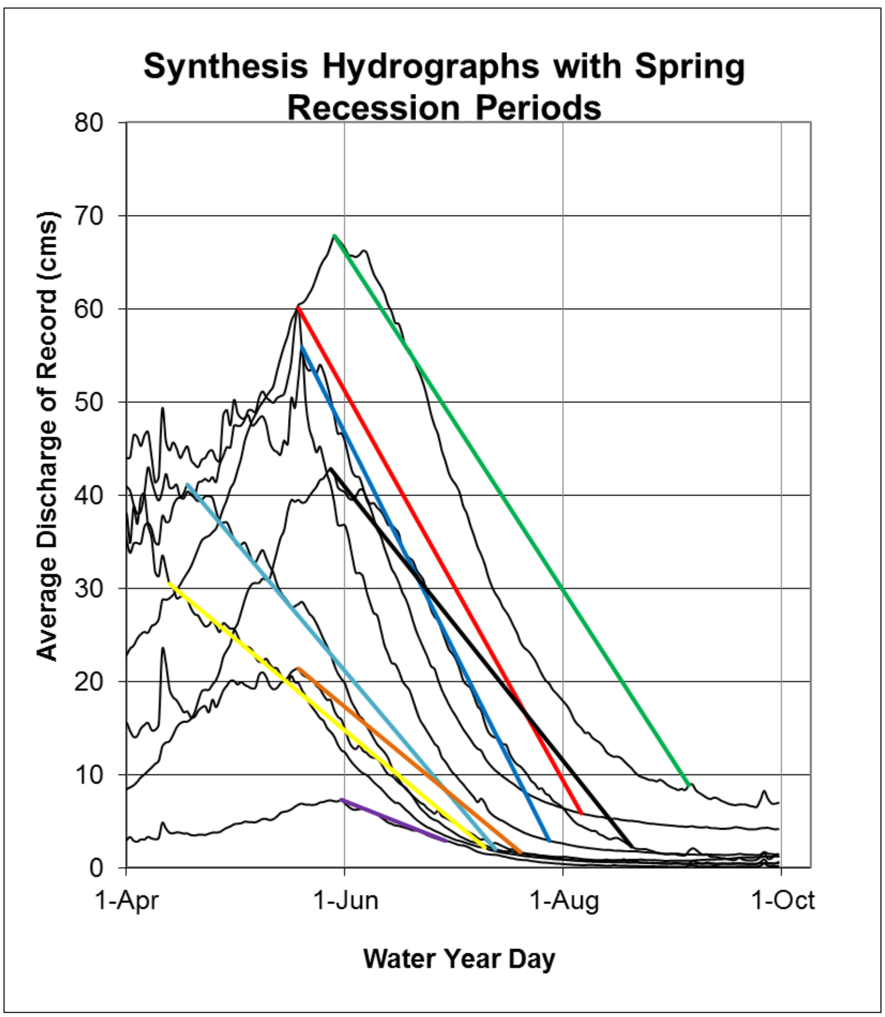


Figure 9. Watershed area versus average annual runoff.

Indian Creek, the Cosumnes and Kern Rivers seem to be exceptions to the other five watersheds because they experience rainshadows (IC & Kern) or are at lower elevations (Cosumnes).


Synthesis Hydrographs
Average Discharge of Record (cms)
80
70
60
50
40
30
20
10
0
1-Oct
1-Dec
31-Jan
1-Apr
1-Jun
1-Aug
1-Oct
Water Year Day
Indian Creek
NF Yuba
NF American
Cosumnes
Clavey
Merced
SF Kaweah
Kern

10 a


Synthesis Hydrographs with Spring Recession Periods
Average Discharge of Record (cms)
80
70
60
50
40
30
20
10
0
1-Apr
1-Jun
1-Aug
1-Oct
Water Year Day

10 b

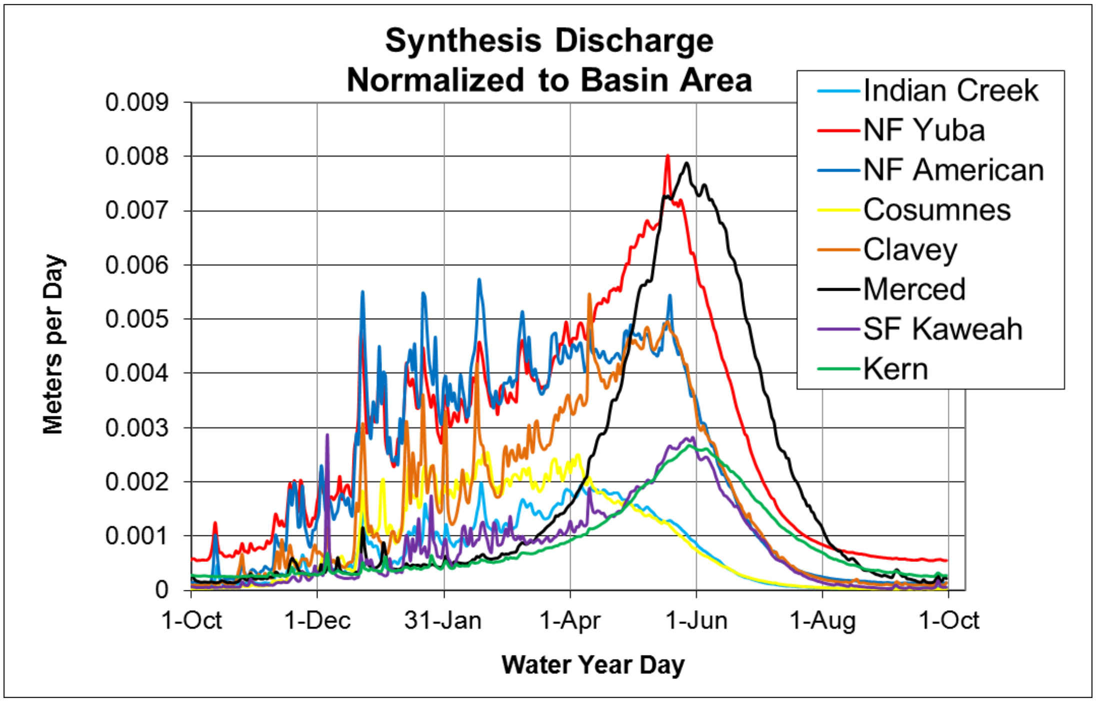


Figure 10. (a) Synthesis hydrographs, calculated from daily average discharge values, **(b)** with recession limb periods indicated, **(c)** normalized to basin area.

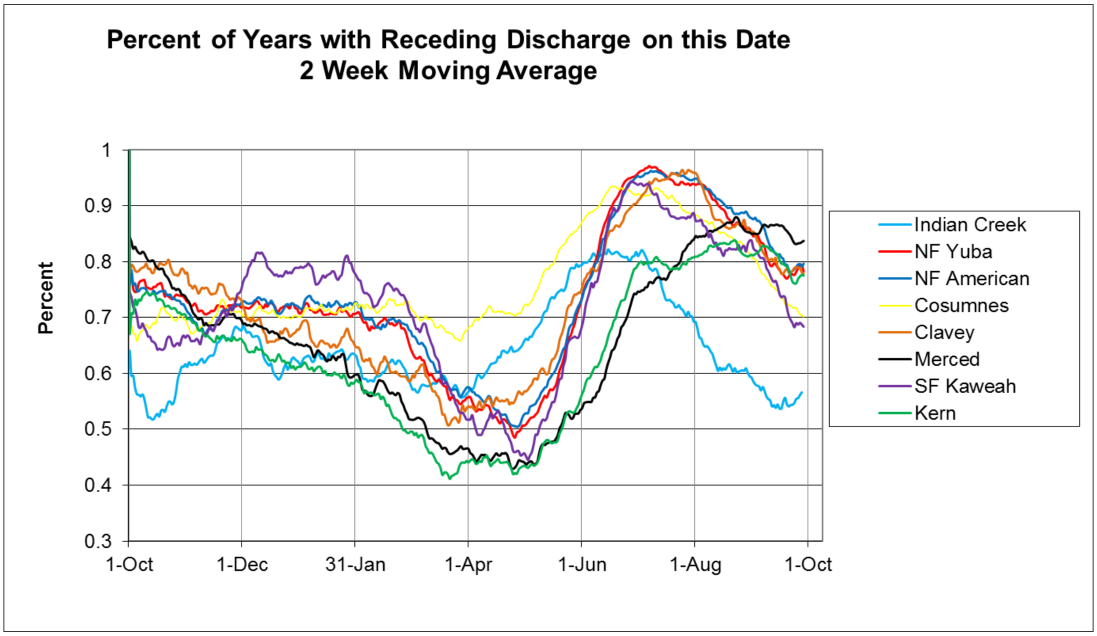


Figure 11. Increasing discharge rates tend to be significantly faster than decreasing ones, meaning that relatively more days of the year have receding flows. This figure shows the percent of the years on record which have receding flows at each day. During June, July, and August flows are dropping more than 90% of the time at five of the eight sites.

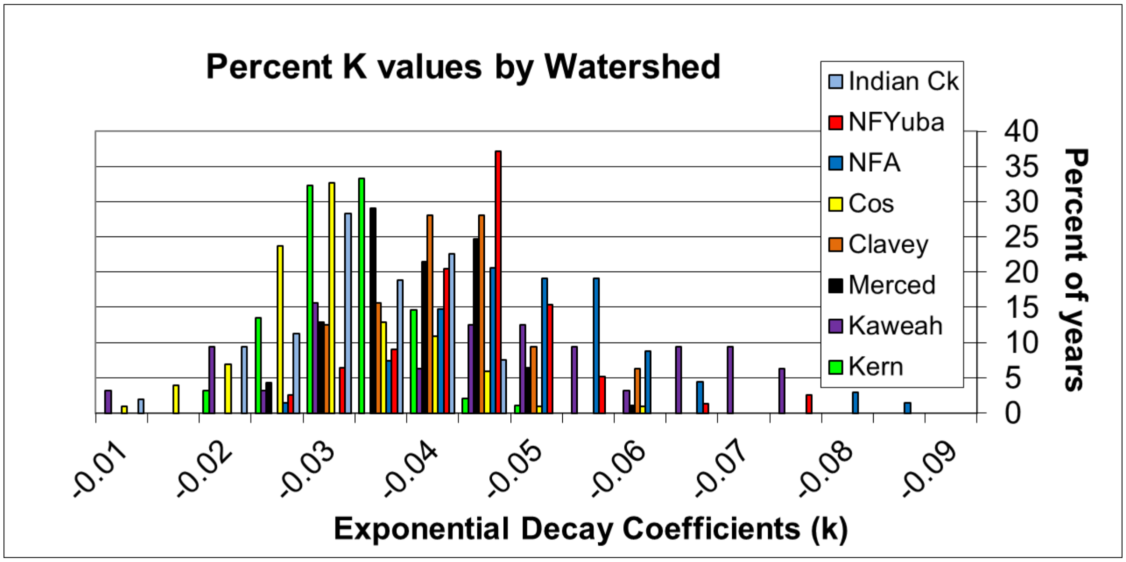
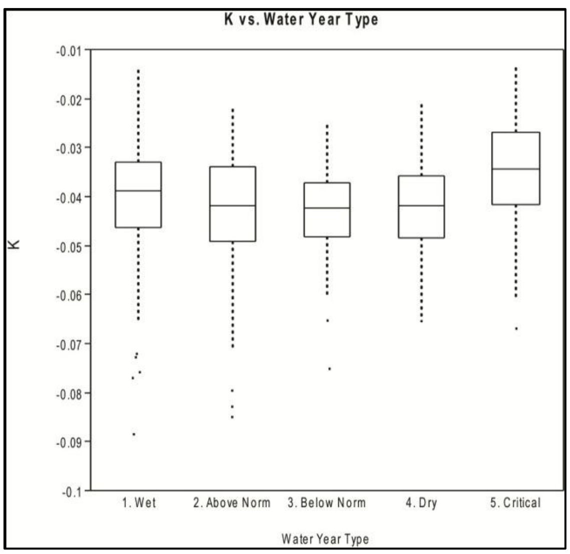
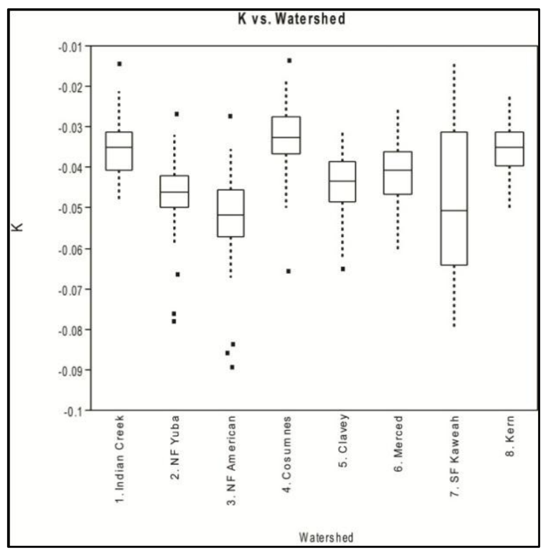


Figure 12. Distribution of annual exponential decay values for each watershed from the regression method.





13 a

13 b

Figure 13. Results from the regression method: distributions of exponential decay values by watershed (a) and water year type (b)

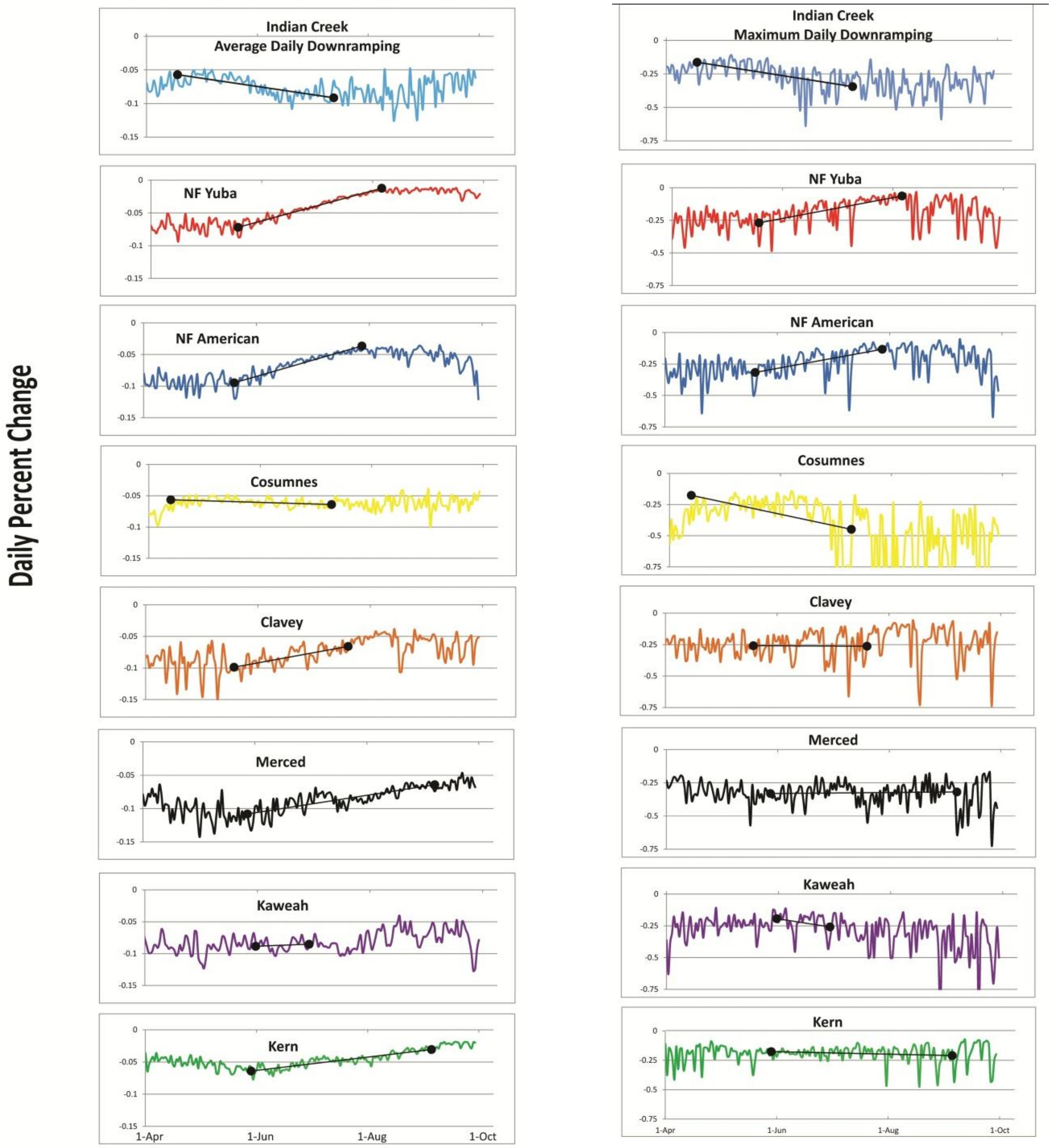


Figure 14 a. Figure 14 b.

Figure 14 a. Average daily downramping rates for all eight sites, the bar indicates the recession period. Notice the increasing trend in five of eight locations, indicating a shift toward shallower curvature.

Figure 14 b. Maximum percent downramping rates per day of the water year for the available period on record. Notice the different scale of the vertical axis. Downramping rarely exceeds 50 percent and these higher rates are only associated with storm events and very low flow periods. The Cosumnes, for instance, has repeatedly gone dry in late summer.

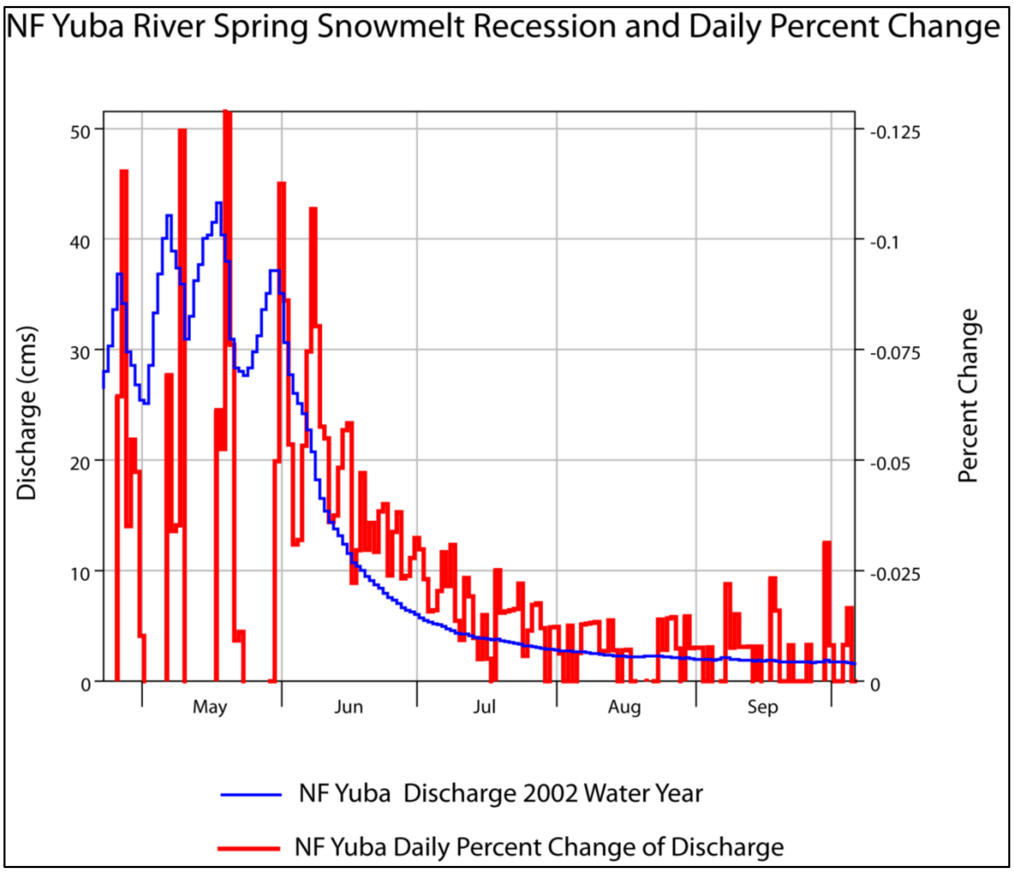


Figure 15- Example daily discharge during the snowmelt recession and associated negative daily percent changes. Notice how daily precent change values shift to more positive values, as seen in sites across the Sierra Nevada.

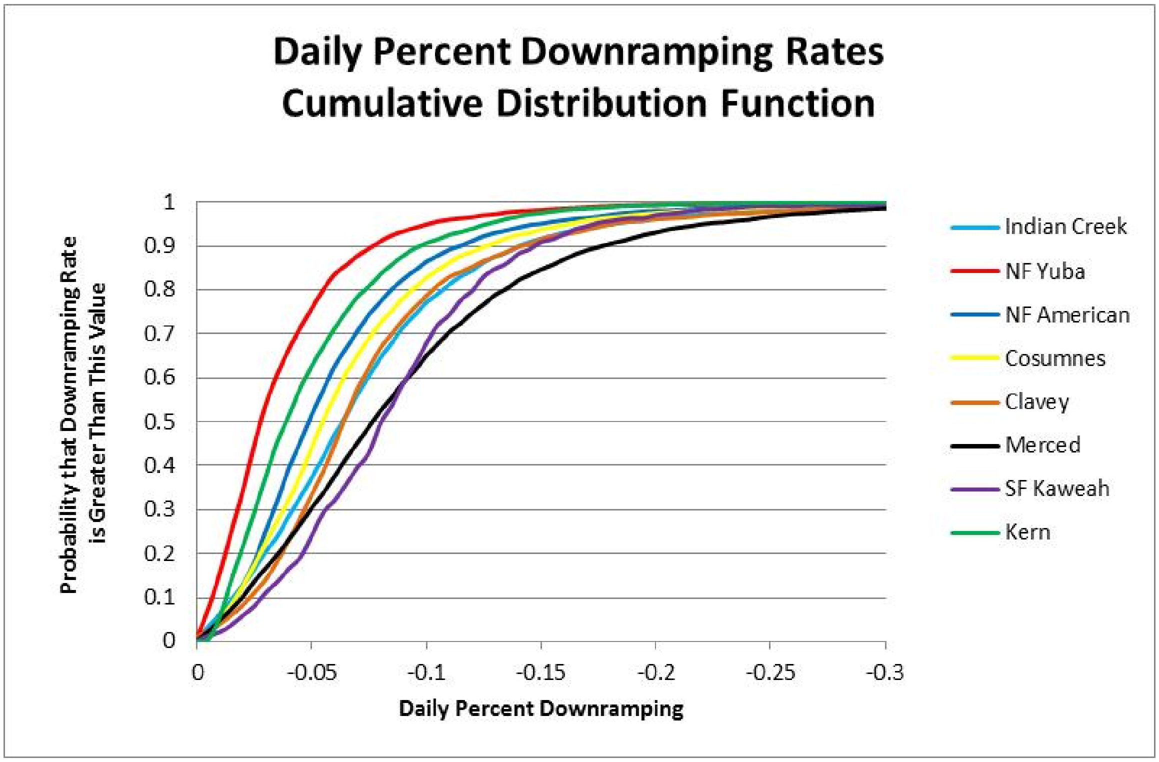


Figure 16. Cumulative distribution of daily percent downramping rates during the recession period of each year. On the North Fork American for instance, the daily downramping rates observed from May 20 to July 28 (Table 2) are greater than -0.15 90 percent of the time.