ACCELERATED CLIMATE CHANGE: HOW A SHIFTING FLOW REGIME IS REDEFINING WATER GOVERNANCE IN CALIFORNIA

Presented by

ROBERT SHIBATANI
CEO & PRINCIPAL HYDROLOGIST
The Shibatani Group, Inc., Sacramento

There exists an extensive scientific, operational, and technical archive on the potential effects of forced climate change on California's water resources [1, 2, 3, 4, 5, 6, 7]. The effects presented in those works are certainly not new; they have been publicly documented for over a decade with the overall potential effects of global climate change known since the 1960's and 1970's [8, 9, 10, 11, 12]. Attributing the causal mechanisms, however, has been an ongoing debate. This paper does not engage in that discourse. Natural variability, forced climatic drivers or, a varied combination of both all adhere to the physical laws governing radiation attenuation and its effects on the complex oceanic-atmosphere-terrestrial environment that determine our climate hence, our observed weather. These interactions regarding the earth's energy balance have been described previously [13]. This paper assumes that changes are occurring and discusses its immediate implications.

What makes the contemporary challenge regarding climate change increasingly important today is the rapidity with which its effects are being realized. Leaving aside the anecdotal evidence (e.g., sparse snowpack, Valley temperature extremes, dry winters, etc.), recent analytical work point to an accelerated condition that is already upon us. No longer a distant projection, this new evidence is compelling both in its severity and rapid development. While some may refer to this as an "accelerated" condition, this paper included, it is only "accelerated" due to our original reference points. Without delineating the true influence of natural variability, the "accelerated" label is really a matter of convenience since it focuses only on recent multi-decadal changes. It is not representative of the entire climatological record. But if the "accelerated" label can engender greater awareness and concern, then it will have accomplished its objective.

The incontrovertible truth is that our climate has always shifted, sometimes rapidly, often over very long time periods. In fact, a shifting climate is as natural as the systems upon which it affects. The salient point for this discussion is that it continues to shift today and, in the near-term is projected to shift markedly. It is this contemporary shift that is of concern. If left unattenuated, it will impart noticeable and critical changes to the very hydrologic regime we have based all of our institutional, regulatory, infrastructure, and water resource management objectives. We have structured everything around a stationary hydrologic regime that, as we are discovering, is anything but stationary [14]. Water governance in California, whether it involves water rights, permitted federal/State contracts, flood control operations, prescribed environmental flows, NPDES permitting, and yes, even the effectiveness of the federal Endangered Species Act as it pertains to listed aquatic species, all stand to be affected by this shifting regime. The fact that this predicted shift is occurring quicker than what we had perhaps optimistically hoped compels us now to a committed re-examination.

From a hydrological perspective, the fundamental baseline upon which we have developed our entire water resources management framework is shifting – governance needs to shift along with it or risk regulatory irrelevancy

Trends

Recent projections come from numerous sources and illustrate a range of parameters that confirm both the immediacy of these concerns as well as their implications. For example, the U.S. Bureau of Reclamation (Reclamation) released a document titled, **"West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections"**, Technical Memorandum No. 86-682210-2011-01, in March, 2011 that captured the Department of Interior's conclusions as conveyed to Congress. This technical assessment report provides:

(1) an analysis of changes in hydroclimate variables—namely, precipitation, temperature, snow water equivalent, and streamflow across the major Reclamation river basins—and the technical foundation for the SECURE Water Act report and,

(2) documentation for this new hydrologic projections dataset that will be made publicly available over the Western United States.

This is a particularly noteworthy assessment since it represents, in part, the results of Reclamation's commitment to the C-CAWWG or Climate Change and Western Water Group [15]; a multi-federal initiative consists of six major federal entities: Reclamation, the U.S. Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA), U.S. Army Corps of Engineers, U.S. Environmental Protection Agency and the Federal Emergency Management Agency. The Omnibus Public Land Management Act of 2009 (Public Law 111-11) Subtitle F – SECURE Water was passed into law on March 30, 2009. Also known as the SECURE Water Act, the statute enacts various actions supporting Congress' findings that adequate and safe supplies of water are fundamental to the health, economy, security, and ecology of the United States, although global climate change poses a significant challenge to the protection of these resources.

This recent assessment represents the most comprehensive evaluation and projection of the potential future effects from forced climate change on California water resources and one for which all water providers should be aware. It is a process that Reclamation and its federal partners are replicating throughout all of the major watersheds of the Western U.S. (e.g., Colorado, Platte, Columbia, Klamath, etc.). **Tables 1** and **2** show the projected changes from climate modeling for select hydrologic indicators in the Sacramento and San Joaquin river watersheds, respectively [16]. Combined, they represent the primary watershed in the State. Changes reported are relative to those from the 1990's.

Table 1
Simulated Changes in Decade-Mean Hydroclimate for the Sacramento River at Freeport

Hydroclimatic Metric (Change from 1990's)	2020's	2050's	2070's
Mean Annual Precip. (%)	-0.3	0.6	-2.7
Mean April 1st Snow Water Equiv. (%)	-53.4	-75.9	-88.6
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December - March Runoff (%)	9.0	13.6	11.0
Mean April - July Runoff (%)	-11.1	-23.0	-36.1

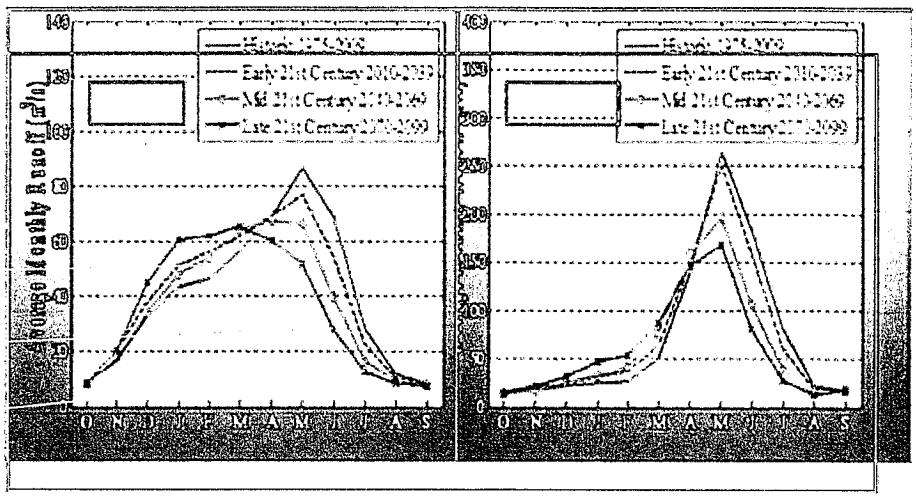
Table 2 Simulated Changes in Decade-Mean Hydroclimate for the San Joaquin River at Vernalis			
Hydroclimatic Metric (Change from 1990's)	2020's	2050's	2070's
Mean Annual Precip. (%)	-1.0	-4.2	-7.7
Mean April 1st Snow Water Equiv. (%)	-27.2	-45.9	-56.3
Mean Annual Runoff (%)	0.8	-5.9	-8.4
Mean December - March Runoff (%)	10.1	10.7	17.5
Mean April - July Runoff (%)	-4.8	-20.6	-25.3

Source: Reclamation, 2011, SECURE Water Act, Section 9503(c) – Reclamation Climate Change and Water, 2011, Report to Congress, April 2011.

In Tables 1 and 2, the first data row shows projected changes in mean annual precipitation. While mean precipitation totals are not expected to change markedly between 2020 and 2070 (e.g., for the Sacramento River; a 0.3% to 2.7% decline is projected, relative to the 1990's, with even an increase projected for the 2050s), the real concern is the precipitation *form*. A warming climate is expected to reduce overall snowfall totals and, thus, snowpack accumulation. Under forced climate change, it is projected that the future will simply be too warm to generate meaningful snowfall totals or, for any accumulated snowpack to be maintained. Accordingly, the mean April 1st snow water equivalent is expected to change radically (second data row), relative to past conditions. For the Sacramento River watershed, these declines in snowpack water equivalent are expected to be in excess of 50% by the 2020s, decreasing to almost 90 percent, relative to the 1990s, by the 2070s. In other words, the snowpack will be half gone in less than a decade and virtually all but disappeared by the 2070s.

An anticipated 50% loss of California's primary snowpack by the 2020's is, in hydrological terms, an event of Katrina-*esque* proportions. The only difference is that it will happen every year and, with increasing severity, representing a permanent change. Most of us in fact will likely see these effects in our own working lifetimes. Such depletion in the snowpack would impart notable temporal changes to watershed runoff (i.e., what we see and manage in our rivers). The last two rows in Tables 1 and 2 show the projected mean December-March and April-July runoff, respectively. The latter row is highlighted as it represents the typical spring "freshet" or spring flood period that is historically typical of California. For the Sacramento River watershed, that runoff is projected to decline by approximately 11 percent, 23 percent, and 36 percent over the 2020s, 2050s, and 2070s, respectively, again relative to the 1990s. This has significant implications to water suppliers since this is the period when agricultural/irrigation and municipal/industrial demands typically increase. Spring excess flows will become increasingly sparse; the corollary that earlier season runoff will increase proportionally. Without a snowpack to "store" accumulated precipitation, what falls during the mid-winter months will simply run off.

Similar results have been reported elsewhere, using variations in assumed forcing ensembles (i.e., GCMs). **Figure 1** shows one such study that focused on the potential effects to hydropower generation in the Sierra Nevada under an assumed forced shift in hydrologic regime. Two watersheds, one each in the northern and southern Sierras were addressed.



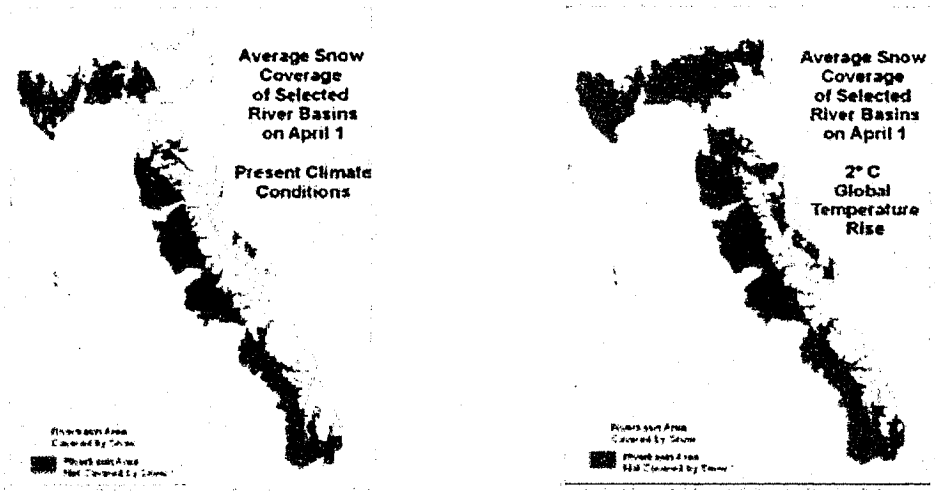
Source: From Vicuna, S., Leonardson, R., Hanemann, M.W., Dale, L.L. and J.A. Dracup, 2008, "Climate Change Impacts on High Elevation Hydropower Generation in California's Sierra Nevada: A Case Study in the Upper American River, Climate Change, 87, 1):S123-S137.

Looking at the left pane, the projected shifts in the response of the upper American River watershed (i.e., above Folsom Reservoir) is compelling. These results depict a more dire condition than Reclamation's West-Wide Assessments but can be explained in that this more directly captures upstream unimpaired inflow. What stands out is the shape change in the hydrograph. The response becomes more muted with less emphasis on the late-spring runoff peak and a shift towards late-fall and mid-winter runoff. Interestingly, when one compares the areas under the curve (i.e., total volume), the differences are much more modest. This supports Reclamation's finding that at least for the Sierra Nevada, total precipitation generated runoff will not change as significantly as the *timing*.

Again, as noted, because air temperatures simply will no longer support an accumulated snowpack, the precipitation-to-runoff response will be more direct. For water purveyors and users, this anticipated shift in timing will have ineradicable consequences. Of significance, the May-July period, especially for the Upper American River Project shows an approximate 33% decrease in projected flows for May, a 66% decrease in June, and about 50% decrease in July by the end of the century with a migration towards these conditions starting today. Based on the hydrograph comparisons, such changes would represent an almost insurmountable challenge to water users; what existing water allocation or instream management scheme can endure a permanent 66% reduction in flows for say, the month of June? Upstream diverters, even those claiming "perfected" pre-1914 water rights will come under significant challenge as they attempt to divert from rivers that experience hydrograph shifts of these magnitudes.

Such hydrologic response is not surprising given our reliance on the snowpack of the southern Cascades and Sierra Nevada. **Figure 2** illustrates the difference in April 1st average snow coverage under current conditions and that projected with a 2° C global temperature rise. Variations of this graphic have been replicated elsewhere [17, 18].

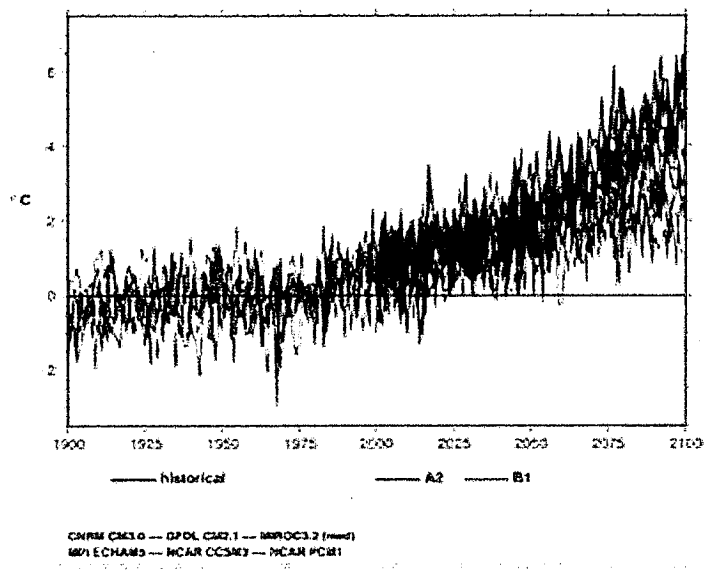
Figure 2
California's Average Snow Coverage under Present and Future Temperature-Forced Conditions



These projections corroborate Reclamation's predictions for more robust changes in the Sacramento River basin, relative to its southern valley counterpart, the San Joaquin River basin. Much of the northern Sierra Nevada snowpack is projected to ablate under forced warming including much of the Pit and McCloud river watersheds, the Lassen Plateau and significant portions of the Feather River upper basin.

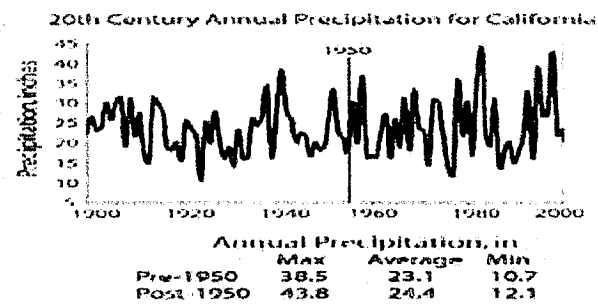
Such changes in near-term snowpack coverage and accumulation totals are consistent with projected air temperature increases likely to affect California in the future. **Figure 3** shows the projected changes in air temperature for the Sacramento area under two future modeling scenarios compared against the historical temperatures for the 1961 to 1990 period. Air temperatures from the turn of the century are anticipated to increase and continue to increase significantly through the end of this century. These temperature projections conform with the snowpack coverage estimates shown in Figure 1. A 2° C departure, relative to the 1961-1990 baseline according to Figure 2 is likely to occur in the next decade.

Figure 3
Annual Temperature Projections – Sacramento Area
SRES A2 and SRES B1
Departure from 1961 to 1990 Historical Mean



For precipitation, historic trends reveal an earlier threshold crossing that occurred sometime in the last half century. **Figure** 4 depicts an arbitrary line set at 1950 for illustrative purposes. Clearly, increased variability in inter-annual precipitation occurred in the last half of the preceding century, relative to the earlier half of the century. While the averages were similar (e.g., 23.1 versus 24.4 inches), the maximums varied between 38.5 and 43.8 inches. Both the maximum and minimums during the latter half of the past century was greater implying an increased variability (e.g., more extreme yearly temperatures).

Figure 4
20th Century Annual Precipitation Trends for California



Source: J. Anderson, DWR Bay-Delta Office, 2012

With such changes in atmospheric variables occurring in the past and projected to occur in the future, one might ask how current river flows and watersheds are responding. So, where is the evidence? Long-term hydrological shifts, by nature are subtle. Outside of multi-millennium scale catastrophic events such as natural impoundment failures on large glacial lakes (e.g., Lake Agassiz) [19], a shift in hydrologic regime occurs slowly in response to the influencing stressors. Often, only by plotting the hydrologic response and applying statistical metrics can one quantify and readily discern that changes are indeed occurring. Figure 5 is a well acknowledged graphic showing how the portion of flows in the American River between April and July (i.e., spring peak), as a percentage of the total annual river flow, has changed over time. Between 1905 and 2004, this portion of the river's annual flow has declined about 13%. In other words, the spring peak (recall the hydrograph peaks from Figure 2) has decreased by approximately 13% over the past 100 years in the lower American River. Forced climate change, by these results, suggest that it has already initiated its influence on this river's annual flow regime.

Figure 5
American River Runoff at Folsom Dam
April – July Runoff in Percent of Total Water Year Runoff

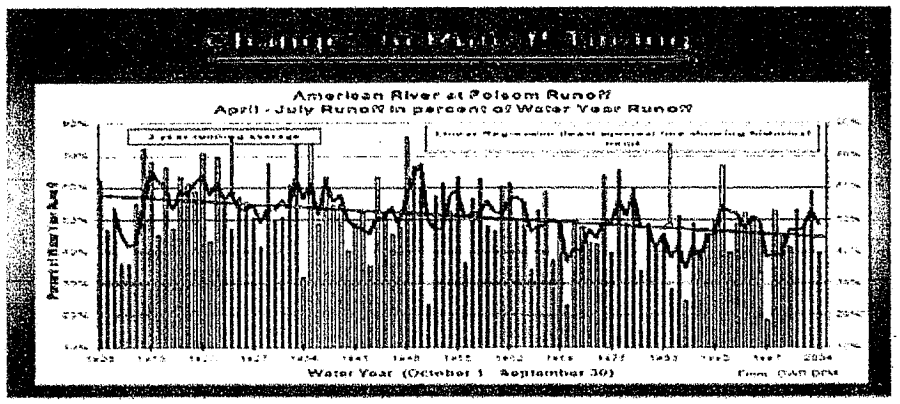
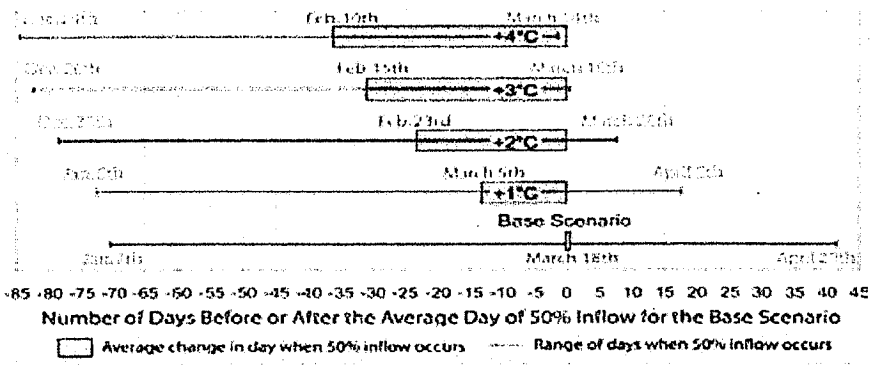


Figure 6, shows the sensitivity of shifted hydrographs to projected temperature changes in one typical snow-dominated watershed, the Feather River basin. Relative to the base scenario, increasing air temperatures will have noticeable effects on the date at which half of the watershed's annual runoff will have been passed.

Figure 6
Projected Runoff Changes Feather River

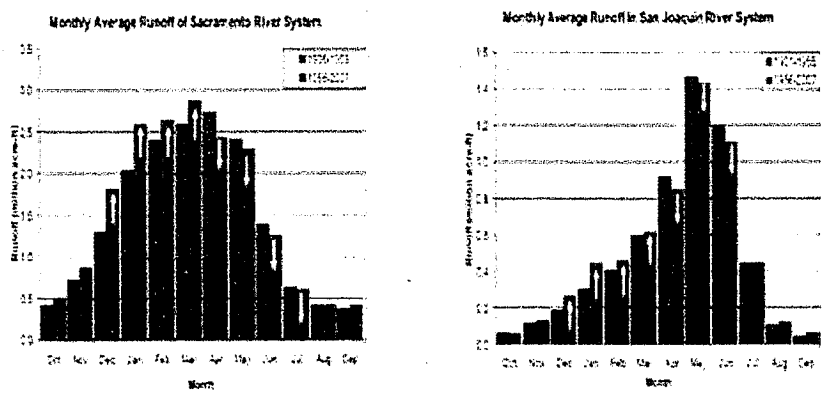


Source: M. Anderson, Climatologist for the State of California, Department of Water Resources, February, 2012, Preliminary results from DWR Bay Delta Office Watershed Modeling

The graphic displays the period of the spring where half of a watershed's runoff has passed. The overall range of possible days shows a shift covering more of the previous year and ending earlier. The average change in the actual day where the 50% flow occurs also extends earlier to February 10th, relative to March 18th under the base scenario. Again, this is consistent with the graphics presented previously showing how the overall hydrographs are muted (in their typical late spring peaks) with a greater portion occurring earlier in the mid-winter time periods.

Figures 7a and **7b** show the monthly average historic runoff within the Sacramento and San Joaquin River systems over the last approximate 100 years, distinguished between flows occurring before 1955 and that occurring after. The yellow arrows depict how mean monthly flows during the latter period (i.e., 1956-2007) changed, relative to the earlier period.

Figures 7a and 7b
Monthly Average Runoff for the Sacramento and San Joaquin River Systems
Depicting Pre- and Post-1955 Conditions



Source: M. Anderson, Climatologist for the State of California, Department of Water Resources, February, 2012.
Note: Variation in Y-axis scale.

The temporal pattern difference between the two primary Central Valley watersheds is notable. The Sacramento River basin is more mid-winter and spring dominated in flow responses, compared to the San Joaquin River basin which is more late-spring dominated. Note also the differences in flows in the earlier part of the century, relative to the latter half. This categorization was an attempt to illustrate how our federal/State water project facilities (i.e., dams) have had an effect on resulting river flows. What is particularly noteworthy, however, is the change in seasonal flows in both basins across the two timeframes. In both watersheds, early season flows have increased during the latter part of the last century, relative to the first part of the century. In addition, later season flows have decreased. Again, these data confirm the earlier discussions regarding the inexorable migration of the hydrographs towards representing a new flow regime across California.

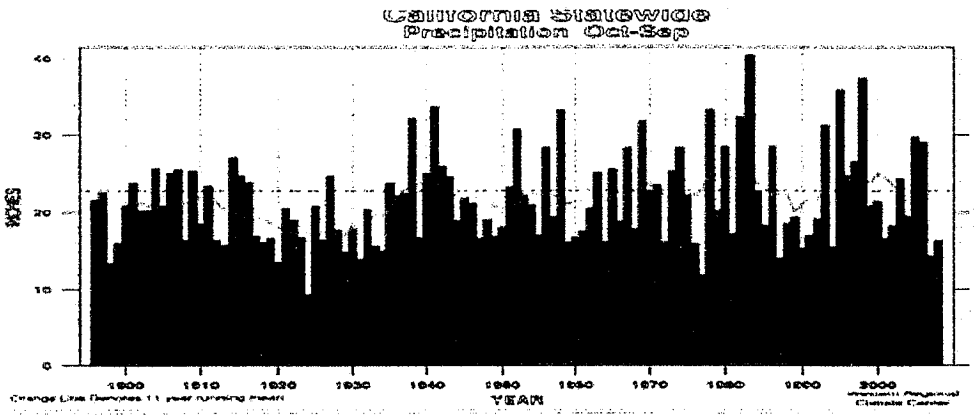
Normality – The Question of Vernacular

While the current shifts in hydrology across California are undeniable and the projected changes convincing in their legitimacy, the metrics we use to describe such conditions also bear some discussion. Focusing on terminology or vernacular may, in some circles, appear offhand or even irrelevant. Consider, however, that much of what we characterize, manage, regulate, and plan for in water resources management depends on a set of broadly accepted terms. Many in fact, have been codified in long-standing legal documents. These terms have (or at least had) meaning and when based on assumed hydrologic conditions can have significant implications to water managers if those conditions no longer depict their original meaning.

For example, what is a "normal" water year? What thresholds define the difference between "wet" and "dry" years, since even in "dry" years it is wet. The answer of course lies in the quantitative labels we have attached to these conditions based on our statistical assessment of the historical hydrologic record. **Figure 8** illustrates California's historic precipitation record from 1895 to present day. The lower panel presents summary statistics over select periods of time. Observe how the linear trends vary depending on time period selected. Additionally, standard deviations over those same selected periods also vary widely. Taking the entire historical record, a positive 3.52 inch trend increase with a standard deviation of 3.30 inches is revealed. Focusing on a more recent period, however, shows a markedly different result. From 1975 to present, a negative 1.97 inch precipitation linear trend with an extremely high variation (suggesting, and perhaps confirming the shift towards a more extreme climate) is evident. The last 35 years have included the top 3 precipitation years, interspersed with extended drought periods.

So, what is "normal"? A "normal" water year in 2030 may look very different than what we term "normal" today. Again, much will depend on our reference point. All current terminology was developed based on a statistical depiction of the past historic record. With an aggressively shifting climate, however, not only will the long-term trends continue to distance itself from historic norms but also the frequency and magnitude of individual annual events. As we will discuss in more detail, these extremes (e.g., increased standard deviations) are much more difficult to assess, model, let alone appropriately incorporate into our contemporary planning frameworks. One of the most egregious examples of vernacular misuse in water resources is the flood term, 100-year "protection". All this indicates is that an event of a certain size occurred once in the last 100-years. It offers no assurance (usually to the unsuspecting homeowner) that a 200- or 500-year flood will not occur in the year immediately after. Again, the 100-year label is based on an examination of the past historic record which, by our standards of data assimilation, is quite limited, relative to the overall historic period.

Figure 8
Precipitation Trends in California 1895 to Present



Linear Trend 1895-present	+ 5.52 ± [illegible] in.	(+ 15 ± 14%) per 100 yr		
Linear Trend 1945-present	+ [illegible] in.	(+ 4 ± 44%) per 100 yr		
Linear Trend 1975-present	- 1.97 ± [illegible] in.	(- 5 ± 124%) per 100 yr		
Wettest Year	40.44 in. (176%)	in 1983	MEAN	[illegible] in.
Driest Year	9.23 in. (40%)	in 1924	STDEV	6.55 in.
Oct-Sep 2008	16.40 in. (71%)		RANK	21 of 119

What does this all mean to water governance?

While ongoing efforts involving key water management initiatives continue throughout the State, a rapidly shifting climate is literally changing the very hydrologic regimes for which we are attempting to manage. The reason why this change or shift in hydrology has such dire consequences is due to the manner with which traditional hydrology has relied upon this timing. Remember that all of our existing water storage infrastructure, operational rules (for reservoir operation), allocation metrics for water contracting, permitted diversions under existing water rights, instream flow standards, etc., were all developed based on the premise that the springmelt period would remain our primary hydrologic event of the year. We thought, somewhat understandably, that hydrology was *stationary*; and that the historic record was a good indicator of what we could expect under future conditions. Under a changing climate, however, nothing could be further from the truth. This most recent and comprehensive analysis by the U.S. Department of Interior, as one of a continually growing archive of studies [20, 21, 22], would seem to confirm this thesis.

Water Rights

Long-standing water rights were established based on the hydrology of the day and were assumed permanent, if not in the legal sense, then certainly in their physical sense. It was presumed that water was always to be present in those watercourses where rights were established. Even today, few pre-1914 water right holders, for example, admit

or attach depletion factors to their long-standing water rights. For example, in urban water management plans, senior water rights are seldom, if ever, shown to possess a deficiency potential. In other words, they are rarely shorted as part of long-term water supply planning exercise. They are assumed firm, reliable, and sacrosanct.

While this optimistic viewpoint is certainly understandable and perhaps legally correct, it ignores the long-standing though simplistic rule that says, "*one cannot divert what is not there*". A revisit to Figure 2 provides clarity to this ignominy. While the area under the curves (i.e., area under the hydrographs) may not vary impressively, the skewed timing shift can impose significant challenges to water users claiming diversion rights during these times. Diversion periods, at specified diversion rates, are specifically set within the water right permits. For the most part, these were developed in response to the needs of the water right holder at the time and followed use requirements of the day as well as anticipated future needs (e.g., agricultural, municipal, industrial, etc.). A considerable shift (e.g., 66% decrease by 2070) in the long-term baseline hydrograph such that river baseflows would no longer be present at the flow rates necessary to sustain the permitted cumulative water diversions would critically impair water user reliability. Consider, for example, the Sacramento River mainstem during the month of May which, over the past half century, averaged about 2.3 MAF of runoff. If a 66% depletion by 2070 is applied (using the Upper American River forecasts from Vicuna et al., 2008), long-term runoff in the Sacramento River may be as low as 760,000 AF for the month of May.

This imbalance is significantly complicated by the fact that the other permitted requirements for those same river reaches would still be present (e.g., by-pass flows, hydropower, maintaining stream wetted perimeter, etc.). Added to that are the potentially numerous other requirements that may have since been imposed (e.g., Endangered Species Act requirements, SWRCB Decisions regarding minimum flows, etc.). So, while the instream requirements would still be in place, diversions for consumptive purposes would be notably inhibited. In some ways, this is an inequality that goes against the oft espoused principle of co-equal objectives. Instream water resources, whether they are designated for environmental, hydropower, recreation, or consumptive uses should all ascribe to the same baseline hydrology.

CVP/SWP Allocations

Similar to the water rights discussion above, all federal/State contractors would likely experience notable changes in their inter-annual contract allocations under a shifting hydrologic flow regime. Depending on how both water systems (CVP/SWP) adjust their reservoir operations to accommodate these shifts, without compromising flood control mandates, would dictate how significant these changes in anticipated deliveries would be. Contractors would likely face an even more dire situation since much of their acquired supplies must be conveyed through the Delta; this would include all of the exporters (sea level rise is discussed later). Contractor deliveries would likely face closer oversight since they must rely on Reclamation and/or DWR to obtain their annual allocations. In many cases, Reclamation holds control over the conveyance and facilities that allow the contractors to obtain water at their turnouts. The urban water supply intake at Folsom Dam, for example, provides water from Folsom Reservoir via the North Fork Pipeline/Natoma Pipeline to Placer County Water Agency, San Juan Water District (including its retail water districts), City of Roseville, Sacramento Suburban Water District, and the City of Folsom. Water rights holders would not necessarily face that same *outside party influence* if diverting directly with their own facility intakes (e.g., City of Sacramento).

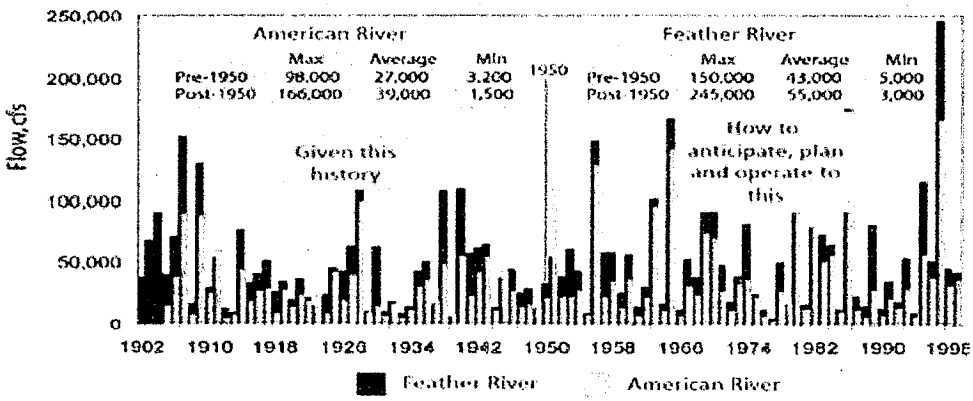
With such significant reductions in instream flows, or yield, can the CVP/SWP expect to continue to meet their obligations both as annual delivery totals and as monthly scheduled exports? It must be remembered that these projected reductions are long-term averages, essentially representing the new "normal" water year; they do not take into account

inter-annual variability such as droughts or extended droughts which would be superimposed onto this new baseline. An extended drought on top of a new baseline that is already 33-66% lower than the 1990s during future late-spring months would represent a drastic challenge for CVP/SWP allocations. Simply put, if the growing database of climate change modeling is accurate, there will not be the yield within the system, *at the times required*, to meet CVP/SWP delivery expectations to the same degree as they are allocated today. This puts most existing drought reliability analyses on tenuous ground, since the reality of the next 20-50 years may be considerably more constraining to water supplies than what current drought analyses are showing.

Reservoir Operations

California's contemporary hydrology is largely dictated by a coordinated reservoir system that defines our CVP and SWP primarily operated through the complex and multi-faceted Operations Criteria and Plan (OCAP), Coordinated Operations Agreement (COA), and to a lesser extent the Monterey Amendments. Hydrology has been forcibly modified through the construction of reservoirs; hence, the oft used metric, unimpaired flow. **Figure 9** shows the annual flows for the American and Feather rivers over the last century. The potential effect that the primary reservoirs in these watersheds (i.e., Folsom and Oroville) may have imparted to overall watershed response, can be observed and compared.

Figure 9
20th Century Annual Peak 3-Day Flows
With and Without the Influence of Reservoirs



For both rivers, the average annual flows have markedly increased during the post-1950 period, relative to the pre-1950 period. In both rivers, the maximum flows significantly increased after the construction of the reservoirs, while the minimum flows over the same period decreased from the pre-1950 period.

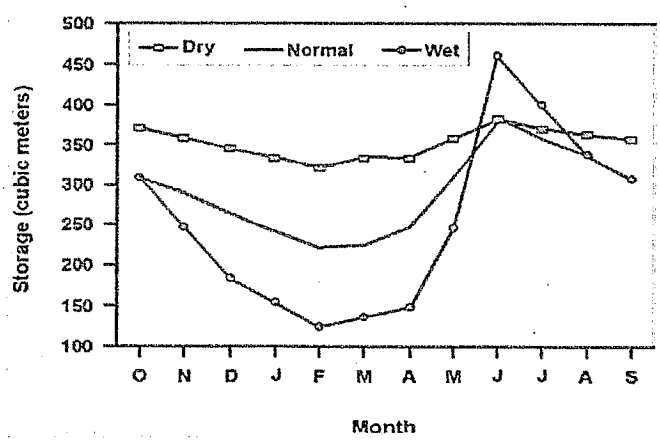
On the one hand then, reservoir operations provide water managers with increased flexibility to capture and release water in line with the needs at the time (e.g., water supply refill or flood retention) staving off what could have otherwise been an adverse effect for that water year. The challenge is to discern, from these operations in the latter half of the past century, how much was operationally induced or climatically driven. We have already seen how the linear trends

in precipitation (from Figure 7) vary depending on the period of assessment, but the variability clearly has increased in the latter half of the last century. From Figure 7, the pre-1950 period generated 15 years with annual precipitation above the long-term mean (i.e., 22.9 inches), compared to the post-1950 period that produced 20 such years. As Michael Anderson, Climatologist for the State of California notes, the challenge will be to both anticipate and plan for a future that includes a diverse reservoir system, subject to accelerated climatic variables, but also taking into consideration past historic hydrology. This author takes a slightly different approach relying less on historical hydrology and relying more on empirical, real-time monitoring.

Flood Control Operations

Figure 10 illustrates a conceptual array of flood curves, or encroachment curves for a hypothetical reservoir. Note that the degree of empty space reservation (i.e., steepness of the curve) becomes greater, the wetter the year. Reservoirs must maintain an adequate empty space volume where frequent and intense storm tracks are anticipated. This requirement become vital whenever a large snowpack exists upstream of the reservoir. Where this snowpack matures and ripens (i.e. possesses a higher snow water equivalent), that need increases.

Figure 10
Conceptual Variable Reservoir Flood Control Diagram



Under a forced climate and the reduction in the anticipated snowpack, the timing of the historical empty space requirement will change. As described earlier, reducing and ultimately removing the natural upstream storage reservoir (i.e., the snowpack), would generate a runoff-response that is more immediate. There would be no snowpack attenuation delay. Precipitation would more directly result in a temporally in-phase runoff response.

Comparing the projected hydrographs from Figure 1 under a future forced climate, the shift in the anticipated runoff peak from late-spring to early- to mid-winter suggests that reservoir evacuation should accommodate that shift. With anticipated late-spring runoff lower, the ability to retain and supplement carryover becomes that much more important in reservoir flood operations. No longer can operators rely on the late-spring refill (after early-spring evacuation).

The importance of prediction and managing for current year carryover becomes essential to maintain supply reliability under a shifting hydrologic regime.

Coldwater Pool Management – Biological Opinions

One the most demanding instream management prescriptions related to anadromous fish survival and recovery is that associated with establishing optimum in-river thermal conditions. As noted above, with a riverine system that is largely "managed", that is, controlled by reservoir releases as opposed to unimpaired run-of-the-river flows, the ability to moderate and control the hypolimnion or coldwater pool assets becomes critical for downstream temperature management. The recent and ongoing discussions and documentation associated with Reclamation's *"Long-Term Operation of the Central Valley Project and State Water Project, California"*, including its continuing jurisdiction under various Biological Opinions (aka Wanger decisions) [23] provide ample proof of this biologic necessity. Flow releases for both temperature (and habitat) requirements are governed by water availability (water year type) and species life-cycle requirements.

Linked to reservoir operations, the management of reservoir coldwater pools involves an intricate process of gauging reservoir carryover balance with a seasonally adjustable hypolimnitic profile as well as downstream life-cycle needs of the target fish species. Temperature management is sensitive to the acute thermal sensitivity ranges of various species such as fall-run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) [24] that inhabit many reaches downstream of terminal reservoirs. Two issues are relevant here. First, low temperature snowmelt and the associated peak inflows traditionally enjoyed by most terminal Sierra/Cascade reservoirs during the spring freshet will, in the future, no longer provide the same benefit as they do today. Second, as reservoir operations re-adjust to accommodate a larger shift to late-fall and mid-winter peak inflows, the coldwater pool volumes available may also not be what they are today.

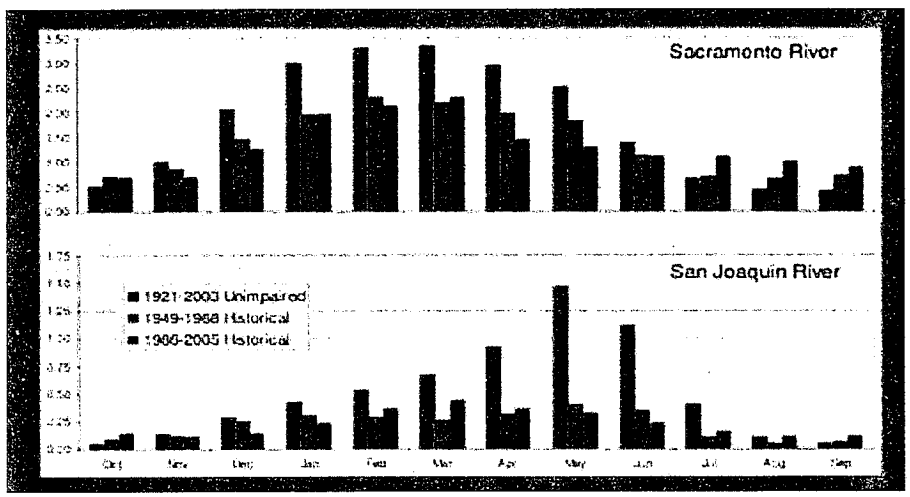
It is likely that the late summer requirements of thermally sensitive anadromous fish species will be more difficult to meet with depleted coldwater pool assets in the upstream reservoirs. For example, the thermal requirements set out in the Fall Actions of the RPAs from NOAA/National Marine Fisheries Service's Biological Opinion on Reclamation's OCAP will be more difficult to attain. These RPA prescriptions were based on a projected baseline hydrologic and in-river thermal condition using hindcasted hydrology (i.e., CALSIM II's historical record) and did not include, for example, bias corrected and spatially downscaled climate data run through empirically-based runoff models (e.g., VIC Model) as Reclamation did for its West-Wide water supply assessments under the SECURE Water Act mandates [25]. To date, no definitive study has linked how a depleted snowpack, when combined with adjusted reservoir operation, will affect long-term thermal conditions and the risk boundaries for meeting existing water temperature conditions at key target locations within the coordinated CVP/SWP.

Delta Management

The decline in Delta ecosystem function, habitat, and species has been thoroughly documented and continues to be exhaustively reviewed by numerous public trust resource agencies, universities, and interested stakeholders [26]. While the causal factors in this decline are several and complex, increased diversions upstream of the Delta and, their collective long-term effect on freshwater flows into the Delta have been identified as one significant contributor to the observed decline in Delta health. It should be clearly noted, however, that while export pumping and upstream depletions represent two of several factors that, collectively, have resulted in adverse environmental effects on the fragile Delta ecosystem, no one factor is solely responsible.

Since the Delta represents the terminus point for the Central Valley mainstems, it will incur the collective effects of the other rivers and streams. Probably the most significant change to be experienced in this estuary will be in the magnitude and timing of Delta inflow. So much of the Delta's inherent and managed function depends on the inflows that sustain the Delta's many purposes. **Figure 11** shows the yearly average Delta inflows from the Sacramento and San Joaquin rivers by month.

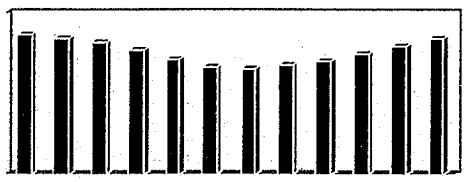
Figure 11
Delta Inflow from Central Valley Mainstem Rivers
Historical Period Trends Yearly Average by Month (MAF/Month)



This Figure mimics Figures 7a and 7b shown earlier. In Figure 11, however, the unimpaired historic flows are also shown. Note, however, the scale differences between the Sacramento River (upper panel) and the San Joaquin River (lower panel); the northern Sacramento River basin contributing significantly more to Delta inflow than the San Joaquin River watershed. Moreover, the temporal distribution is also skewed with the Sacramento River basin contributing more during the mid-winter and spring months than the San Joaquin river basin. Note the effect of the managed reservoirs in the San Joaquin River watershed which has significantly muted the unimpaired runoff pattern (e.g., green versus blue/red histogram bars). In both watersheds, the effects of the CVP/SWP terminal reservoirs and other local reservoirs are clearly depicted by the difference in unimpaired flows and recorded instream flows.

A changing future hydrology will affect the manner with which Delta inflow will be generated. As we have discussed, an altered upper basin runoff pattern will affect how the terminal reservoirs (e.g., Shasta, Oroville, Folsom, etc.) fill and, ultimately, how effectively they can continue to meet downstream release requirements. Depending on adjusted reservoir operations, the overall potential exists that traditional Delta inflow requirements will be increasingly challenged. **Figure 12** shows the mean monthly long-term position of X2 (near bottom 2 ppt isohaline) in the Delta. X2 is used as one of several parameters to gauge the volume of freshwater inflow to the Delta and so, provide one measure of the effectiveness of freshwater inflow to the Delta in maintaining the position of saline intrusion from San Francisco Bay.

Figure 12
Mean Long-Term Position of X2 – 1922-1992
(Distance in km from Golden Gate Bridge)

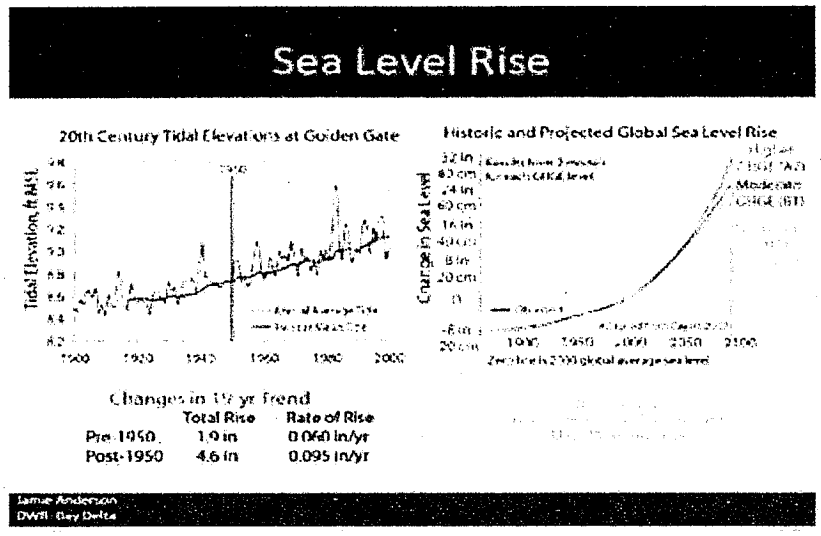


It is assumed to be equivalent to an electrical conductivity (EC) of 2.64 mmhos/cm. Since seawater is denser than freshwater, the measurement targets the near bottom isohaline. As more freshwater is available from the Delta tributaries (e.g., Sacramento and San Joaquin rivers), the saline interface (X2) is "pushed" farther away from the central Delta towards the Golden Gate. As freshwater inflows decrease, X2 migrates upstream into the Delta. Typically, during the late-spring when tributary runoff is at its highest (e.g., due to spring snowmelt), freshwater inflow maintains X2 at approximately 66 km [27]. During the latter part of the summer when diversions increase and into the winter months when reservoirs attempt to re-establish carryover, freshwater inflow to the Delta is reduced. The position of X2 during this period correspondingly adjusts.

Potential impacts on delta smelt, splittail, striped bass, and other Delta fishery resources are of concern if a substantial shift in the long-term monthly mean X2 position occurs (i.e., more than one kilometer (km)), or if Delta export/inflow ratios are increased to where allowable export limits would be exceeded. The USFWS and Reclamation have in past documents (i.e., *Draft Trinity River Mainstem Fishery Restoration EIS/EIR*) applied a 10 percent modeled exceedance in changes in X2 position during the February through June period to determine potentially significant impacts on fish populations in the Delta. Under an accelerated shift in hydroclimatic response, this is the exact period when it is anticipated that the historical hydrograph will shift. From Figure 1, it was shown that the traditional spring peak flow period will abate, shifting to a more mid-winter response. The ability to maintain X2, Delta outflow, export/inflow ratios (E/I ratios), salinity measurements, and other in-Delta flow requirements (e.g., Rio Vista and Vernalis flows) will all encounter a changing hydrologic regime that will test the ability of water managers to meet existing requirements. Moreover, how current initiatives establish a new Delta operating regime under the aegis of anticipated accelerated climate forcings remains uncertain. These include initiatives such as the Bay-Delta Conservation Plan (BDCP) or the State Water Resources Control Board's (SWRCB) Delta Flow Criteria. The regulatory challenges extend beyond just Delta-specific actions and include other broad CVP/SWP efforts that will also affect overall yield management (e.g., Reclamation's new CVP Shortage Policy).

Sea level rise also represents a notable concern. Again, the data and trend analyses are not new. **Figure 13** shows the tidal elevation trends at the Golden Gate during the past century. A clear trend over the past 100-years is evident where total tidal elevation rise was 1.9 inches between 1900-1950, but has increased to 4.6 inches from 1950-2000.

Figure 13
20th Century Tidal Elevations at Golden Gate
Historical and Projected Global Sea Level Rise



Source: J. Anderson, DWR, Bay-Delta Office

The 19-year mean tide is used since it represents the periodicity of the lunar cycle. The right side panel in Figure 12 shows the projected changes in global sea levels. Note the particular escalation from now to the end of the century depending on assumed GHGE (greenhouse gas emission) loadings. The curves are not linear, again confirming the accelerated potential of sea level rise under some exponential function. This pattern is consistent with the IPCC "hockey stick". Long-term tidal shifts (i.e., permanent sea level rise) can, depending on overall magnitude, result in drastic consequences within estuarine systems. For California's Sacramento-San Joaquin River Delta, these risks have broad ranging implications. Their physical effects have been documented in the literature [28, 29, 30, 31]. But apart from the physical risks (e.g., levee stability, island inundation/shoreline encroachment, saline intrusion, etc.), the regulatory framework that has been overlaid upon the Delta ecosystem must also change. Why? Because the fundamental nature of the hydrologic system that has been the focus of long-standing regulatory prescriptions is no longer what it was when those original prescriptions were set.

Simply mapping out a new "shoreline" with a new inundation zone only provides part of any long-term assessment. An encroached Delta will impart changes in hydrodynamic function that we have only begun to appreciate, let alone attempt to simulate. Inter-island and inter-tidal flow patterns, altered potentiometric surfaces (e.g., groundwater tables) and their interaction with a new free standing water surfaces, bedload and suspended sediment transport, not to mention the water quality effects from an extended saline wedge and how this may affect riparian/estuarine vegetative communities, are all unknowns at this point. Moreover, while this new baseline generates its own challenges and uncertainties, the added effects from extreme events under a future condition with elevated tides only complicates the outlook.

Sea level rise, combined with a new long-term temporal Delta inflow/outflow regime will undoubtedly result in marked changes to Delta function. While sea level change will focus on baseline levels, upper watershed function and response will dictate the quantity and timing of potentially available Delta inflow. It is highly likely that the existing regulatory framework (e.g., Bay-Delta Water Quality Control Standards, Biological Opinion RPAs, etc.) and pending new initiatives (e.g., Delta Flow Criteria, BDCP, etc.) will each have to continually adjust in order to dynamically stay synchronized to changes we know are upon us, but have not yet seen the magnitudes and frequencies with which those changes will impart.

Water Quality - NPDES

From a water quality perspective, California's natural hydrology plays an unquestionably vital role within our complex established water quality regulatory framework. Like the other water resource management responsibilities discussed previously, water quality regulation also is driven by ambient hydrology. Should that hydrology change, as it is anticipated to, what are the implications to all of the existing water quality standards, permitted constituents, daily discharge limits of treated effluent, that were developed based on an assumed, and static, hydrologic regime? How will those changes affect specialized assessments such as toxicity reduction evaluations (TRE) or trace metal water-effect ratios (WER) studies? Where dilution is relied upon as one key element in setting water quality discharge limits, should existing permits be re-assessed given that the assumed dilution coefficients originally assumed may no longer represent an accurate depiction of instream ambient flows? Finally, how would a future changed hydrologic regime affect, adversely or positively, current State Water Quality Control Plans (such as the Basin Plan), the Policy for the Implementation of Toxics Standards for Inland Surface Water, Enclosed Bays and Estuaries, the California Toxics Rule, or the State 303(d) List and TMDLs?

Conclusions

The evidence of a rapidly shifting climate is indisputable. Again, putting aside the causal mechanisms, water managers today are faced with the reality that the once assumed static hydrologic environment is really anything but. Operating within a regulatory framework that is still based on historical hydrology with little or no provision for mandated adjustment or balancing, risks compromising long-standing understandings and agreements and will compel water managers to unilaterally change many of their operations. Where those changes conflict with existing regulatory requirements is where the incompatibility will become evident. In light of climate imposed changes to the hydrologic system, both the regulatory system and water users must strive to develop a more dynamic and amenable system of regulatory compliance; one that is 21st century sensitive.

In many ways, this represents one of the most significant challenges facing California's water resources industry today. The entire hydrologic environment is evolving and, in many ways, much quicker than earlier estimates had predicted. Adopting fixed prescriptions, in a non-fixed, rapidly changing world, is no longer appropriate given the extent to which climate change will alter the fundamental hydrology of the State. Indeed, if California genuinely accepts the notion of climatic shifts, future flow management must be as dynamic as the environment for which it is attempting to manage and regulate. To be sure, any imposed changes will not be easy, nor necessarily quick. For we are talking of revisiting long-established and entrenched concepts (and yes, even legal principles) in water resources management (e.g., water rights). To do nothing, however, and watch the incompatibility escalate over the next several decades is not a responsible strategy.

Several immediate actions could be embraced and ultimately implemented by the regulators. First, using historic hydrology as the basis for analysis of future conditions must be discarded. Hydrologic *stationarity*, under a rapidly climate change is no longer an accepted edict in all leading hydrologic circles. Second, the concept of normality must also change. This includes our labeling of what constitutes an above-normal, wet, normal, dry and critically-dry water year, since so much of our regulatory, institutional, and administrative vernacular is still based on this rather unfortunate practice. Third, scaling factors could be adopted that recognize both positive and negative biases in year-to-year hydrology. In other words, rather than set prescriptions solely on annual hydrology within assumed water-year classifications, water use should be flexibly applied based on current needs of water ecosystem functions, including consumptive uses. For example, if monitoring and forecasts show a low returning year-class of adult salmonid spawners, there is no legitimate fisheries basis to maintain high flow requirements during the upstream immigration season. Alternatively, where a higher than projected returning year class is observed, flow prescriptions could be adjusted higher. There should be no minimum.

Finally, and perhaps most importantly, in the interim, while water users, regulators, and the scientific community work towards re-defining the current and projected future hydrologic baselines, actions and operations should be flexible and cast in real-time or, at least to the closest extent possible. A rapidly changing climate and all of the hydrologic implications associated with such change require that adjustments to flow prescriptions be made constantly or, *dynamically*. Essentially, this takes the long-standing *adaptive management* principle and simply elevates it to the next level. To do so, however, significantly increases the need for real-time monitoring and the establishment of extensive iterative feedback mechanisms. The magnitude and immediacy of anticipated climatic perturbations, however, leave us with little alternative. The status quo will not work under a rapidly changing climate. A dynamically changing climatic environment is compelling us to look at hydrological response and associated ecosystem and user needs in an equally dynamic manner. The quicker we realize that our existing water governance structure must change along with the environment for which it was designed to regulate, the more effective we will be at attaining the many objectives that will continue to define operational water resources management in California.

NOTES