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# Clean and Reliable Water for the 21st Century Paper#69880

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## ABSTRACT

It is well recognized that half the countries in the world will face significant fresh water shortages in the next 20 years, due largely to growing populations and increased agricultural and industrial demands. These shortages will significantly limit economic growth, decrease the quality of life and human health for billions of people, and could potentially lead to violence and conflict over securing scarce supplies of water. These concerns are not limited to the water-poor countries, of course, as many parts of China and the US face similar problems. Such problems can be exacerbated by fluctuating imbalances between need and supply, poor management practices, and pollution. The future is one that will require significant scientific and technological advances in conservation, preservation, and movement of fresh water, as well as in the development of new or alternative supplies. As an example, these issues are discussed in terms of California, and a case study related to the scientific issues associated with a groundwater banking project in Southern California is provided.

## INTRODUCTION

In the past decades, population growth and droughts in California have highlighted and refocused attention on the problem of providing reliable sources of water to sustain the State's future economic development. Specific elements of concern include not only the stability and availability of future water supplies in the State, but also how current surface and groundwater storage and distribution systems may be more effectively managed and upgraded, how increasingly degraded water supplies may be improved or treated, and how legislative and regulatory processes may be used or modified to address conflicts between advocates of urban growth, industrial, agricultural, and environmental concerns.

California is not alone with respect to these issues. They are clearly relevant throughout the West, and are becoming more so in other parts of the US. They have become increasingly important in developing and highly populated nations such as China, India, and Mexico. And they are critically important in the Middle East, especially as they relate to regional stability and security issues. Indeed, in almost all cases, there are underlying themes of "reliability" and "sustainability" that pertain to the assurance of current and future water supplies, as well as a broader set of "stability" and "security" issues that relate to these assurances – or lack thereof – to the political and economic future of various countries and regions. Moreover, water quality is becoming an equally or more important concern in many parts of the world, either as a result of long term agricultural, industrial, or other poor land use activities, or as a result of naturally poor or saline waters being used for routine domestic supplies.

The water supply and quality situation in the United States is replete with many examples of the issues outlined above. Consider, for instance:

- Chemical contamination of surface and subsurface waters, as caused by agricultural, industrial and defense related activities over the past century has been recognized as an important and widespread problem[1] yet one that has proven to be extremely costly to address.
- Biological contamination of drinking water, often associated with isolated septic tank or wastewater discharges, has received more attention recently as a result of water borne illnesses attributed to *Cryptosporidium* in Milwaukee, WI and is now the subject of important changes proposed for the Ground Water Rule in the National Primary Drinking Water Regulations[2].
- Sea water desalination, long thought to be too costly, is now being implemented in Tampa, Florida as part of a master plan designed to provide new water to a region (10% of the overall water supply by 2008) whose groundwater resources can no longer supply the growing urban demand.
- The Ogallala formation in the central plains – an extensive fossil water aquifer with no effective recharge – is being depleted ever so slowly by agricultural and urban extraction, setting the stage for will increasingly more serious water supply problems in the future[3].
- The recent and abrupt reduction of Colorado River water allocated to California by the Bureau of Reclamation that resulted from an inability of competing urban, agricultural, and environmental interests to agree on a comprehensive plan for conservation to achieve the same reduction.

## CALIFORNIA AS A MORE FOCUSED EXAMPLE

In many respects, California serves as an excellent example of many important water supply and quality problems facing the nation and world. Consider, initially, some pertinent facts[4]:

- Direct precipitation provides over 95% of the water input to California each year, with most of the remaining fraction coming from the Colorado River.
- On an average year, of the entire water input – roughly 85 million acre feet (MAF) –

  ~ 28% is captured and used for agriculture,

  ~ 7% is captured and used for urban demands,

  ~ 35% is consumed by environmental allocations (for wild and scenic river flows, California Delta outflow, wetland maintenance),

  ~ 1% is for other uses such as power generation, leaving

  ~ 36% unused and otherwise lost to the Pacific Ocean.
- Urban demands – primarily in the coastal areas – are growing and are basically being offset by surface water transfers from agriculture. Eventually, limitations, delivery restrictions and other political considerations may limit such transfers such that

sources of "new" water must be found.

Because precipitation is dominant in the North and in the wintertime, an elaborate interconnected infrastructure has been built to store snowmelt water in surface reservoirs and to redistribute water to users in along the central and southern coastal areas from the northern runoff and from the Colorado River. The California Delta forms the heart of this system. Water flowing through the Delta is subject to many forms of degradation, increasingly stringent environmental outflow and quality constraints, potential interruption from earthquake and levee failures, and a finite throughput capacity. This system is separate from – yet augments – groundwater use in the state, which is significant (~16 MAF/yr) and satisfies between 40 and 50% of the agriculture and urban demand. Groundwater storage capacity is quite large, roughly 850 MAF, as compared with the surface reservoir capacity of 43 MAF, but may be limited by quality, sustainability, and other production constraints.

Although it has been said that there is "enough water in California" to meet future population (urban) demands for some time, capacity, water quality, and environmental constraints in the system are seen by many to prevent the kinds of redistribution and capture necessary to satisfy all demands in an economically feasible manner.

## Where are things headed in California?

Significant trends in population growth are likely to aggravate water shortages – today's average may be tomorrow's drought – and reduce overall reliability of the system. Although water transfers from agriculture to urban use are here to stay, there will be growing pressure to reallocate more water from agriculture to the environment – all of these will be subject to the overall capacity of the water system to move the right water around to the right places. Increasing the capacity of the surface water system (dams, aqueducts) is being limited by real estate and cost concerns. The Delta, its long-term environmental health, and the myriad of complicated factors that influence its water quality will continue to influence how it is used in the California water system.

Persistent shortages in the urban areas will become the norm unless broader and more aggressive strategies for developing reliable sources of "new" water are pursued. In truth, there are only two real sources of water in California: (1) that derived from the hydrologic cycle and (2) seawater. Sources of new fresh water must either be derived from reallocations or more efficient use of the hydrologic input, reuse of impaired water (wastewater, agriculture drainage, polluted or non-potable groundwater), or seawater.

In the near term, water reuse, as derived from wastewater treatment and agricultural drainage sources, will be particularly popular, yet subject to increased concerns with respect to water quality that are related mainly to salt and human pathogen loads (see example in next section). Water banking in underground aquifers, using fresh or reused water, is being used successfully in many areas, and is being considered for many others – especially when the capacity issues noted above are considered. These, too, have to be evaluated with respect to water quality concerns, especially if reclaimed water is used, if existing underground water is of poor quality in the first place, or if unhealthful natural minerals such as arsenic and selenium are leached into the water the process. In addition, the viability and quality of existing groundwater supplies in agricultural (or former agricultural) areas are being threatened by the legacy of fertilizer (nitrate) and pesticide inputs. Applied for decades at the surface, they are only now beginning to reach and contaminate deeper supply wells. Accumulations of arsenic and selenium, leached from natural minerals, also threaten groundwater and surface waters, and are the focus of increasingly stringent regulated concentration limits.

Over the longer term, the consensus of many is that desalination of ocean water or aggressive treatment of marginal, brackish, or otherwise unusable water – typically quite expensive – will become a routine source of "new" water, especially if more robust and economically viable treatment methods are found. The ability to predict long term changes in climate or and the ability to predict multi-year droughts on the 1 to 5 year time scale are becoming increasingly important to many, especially as it relates to forecasting changes in overall inputs to California water system or the conversion of precipitation from snow to rain[5]. Increased and more concentrated runoff from "increased rainfall" scenarios will undoubtedly lead to floods, the need for higher capacity in water runoff and storage systems, or just smaller amounts of water that can ultimately be saved in existing reservoirs. This, in turn, which may accelerate the need for developing reliable sources of "new" water, as described above and below.

## What kinds of key, wide ranging Science and Technology can make a difference in California?

At this stage, it would appear that three or four closely-connected areas for Science and Technology (S&T) development can be identified that could have a noticeable and meaningful impact on water in California (and by extension, elsewhere):

**New Water: Improved water treatment technologies.**

Here, we are concerned with the development of more cost efficient methods for water treatment and purification, as it relates to seawater desalination, removal of salts and fertilizers from non-potable brackish groundwater or agricultural drainage, filtration of viruses or other pathogens from treated wastewater, or removal of other kinds of industrial or organic waste stream contaminants. The S&T issue here may involve the development of more efficient reverse osmosis (RO) membrane or filtration designs, for example, new deionization techniques, point-of-use techniques, cheaper sources of energy, or some suitable combination of these or similar processes. If effective and viable at large enough scales or in a widely-distributed sense, such processes would serve to add "new" potable water into the California equation where it otherwise did not exist – through the effective reuse of wastewater or development of new water from seawater – thereby adding more reliability to the immediate users of this water and greater flexibility to other parts of the California water system.

**Future Water: More reliable assessments of future climate variability.**

Here we are concerned with achieving a greater understanding of the future climate in California through prediction and observation, as it relates specifically to long term changes in precipitation and temperature, or shorter term fluctuations, typically manifested as droughts. Long term trends or changes in climate may result in more or less precipitation coming into the state, longer or shorter wet seasons, or warmer temperatures that minimize accumulation of snow. Precipitation changes will alter the water balance in the state and change the way water is used, reused, moved, stored or procured – as, for example, through desalination. Even if precipitation amounts remain the same, less snow means that runoff will be more concentrated and lost unless, for example, new forms of storage or alternative sources of water are found. The S&T issue here really is one of developing (i) climate predictions at a fine-enough spatial resolution for use in California and over specific types of relevant time scales, (ii) the ability to reduce or quantify uncertainties that are involved in such predictions, and (iii) the ability to translate or propagate the results of such predictions into hydrologic variables such as runoff and groundwater recharge rates. Many types of these activities are already ongoing, but specific, well-focused tasks pertinent to other parts of this proposal can be identified.

**Banking Water: Impacts on groundwater quality.**

Here we are concerned with the use of groundwater basis for the storage of excess or reclaimed water, as recharged artificially through injection wells, infiltration basins, or ephemeral streams, or in the development of groundwater from degraded or low quality aquifers. Active water banking is already being used in many parts of the state (e.g., Kern, Los Angeles, and Orange Counties) and is being considered in some others (e.g., near Cadiz in the Mojave Desert). Many currently viable aquifers are being threatened with widespread salt loads from agriculture, while many others are naturally of poor quality – yet might be used if effective treatment techniques could be employed. The S&T issue here is really one of understanding mechanisms that degrade or threaten groundwater quality, especially as they relate to the more aggressive uses of groundwater basins that are being considered or are in use. Issues to be addressed may include understanding the fate and migration of viruses in groundwater systems, developing gross balances of introduced or dissolved salts from agriculture or recharge practices, understanding the impacts of surface water – groundwater interactions on water quality, and so forth.

**Delta Water: Understanding complex ecological trends and balances.**

Here, we would be concerned with the Delta water quality and its interactions with aquatic ecology, as affected by the quantity and quality of water moving into the Delta from inland sources or the San Francisco Bay, groundwater interactions between the channels and Delta islands, and other more complicated land use issues, both in the Delta and along the rivers that feed it. The S&T issues here would really focus on trying to understand complex chemical and ecological cycles, especially as they are influenced by a combination of anthropogenic and natural forces, and their relation to the increasingly complicated and limiting environmental constraints being imposed to protect the Delta ecological system. The charter for addressing many of these issues lies with the recently established CalFed Program, a cooperative effort of more than 20 state and federal agencies working with local communities to improve the quality and reliability of California's water supplies and revive the San Francisco Bay-Delta ecosystem.

## AQUIFER BANKING IN ORANGE COUNTY, CALIFORNIA

As a more illustrative example, we now review some recent and ongoing work to more scientific insight into the groundwater banking processes in a large urban setting.

The Orange County Water District (OCWD) manages a groundwater basin that provides 70% of the domestic water supply for approximately 2 million residents in the northern part of Orange County, California[6]. The remaining 30% is purchased and imported from outside the district. On an average annual basis, roughly 270,000 acre-feet (af) of water are extracted from several hundred production wells located within the middle production aquifers of the basin. To sustain this rate of withdrawal, OCWD maintains an artificial recharge program that returns about 205,000 af of water, on an annual basis, to the groundwater basin. This is achieved by diverting large portions of the base flow of the Santa Ana River into a series of infiltration basins and abandoned gravel pits along or nearby the upper reaches of the river. Because of the higher permeabilities in these areas, recharged water readily percolates into the main production aquifers.

Although the principal source of recharge comes from the Santa Ana River, additional supplies are occasionally imported from the Colorado River and California State Water Project sources. Future plans also call for direct use of reclaimed water from a nearby wastewater treatment plant to increase the overall recharge. Interestingly, much of the base flow in the Santa Ana River today is already reclaimed in the sense that it is partially composed of discharges from upstream wastewater treatment plants in Riverside County.

Reclaimed wastewater may contain organic and microbiological contaminants like viruses that, upon recharge into an aquifer, may later be captured in production wells, especially in the absence of tertiary or other advanced forms of wastewater treatment. Because dilution, natural degradation and other transformation processes may lower these contaminant concentrations along travel pathways, state regulators in California have proposed a nominal set of standards to govern how production wells and recharge practices involving reclaimed water are operated. In terms of the Orange County basins, they would require that (1) Reclaimed water have a groundwater residence time of one year before reaching production wells, as a way to ensure that degradation or dilution mechanisms occur; (2) No more than 50% of production well water may be reclaimed in its origin, regardless of residence time; and (3) Production wells be located more than 2,000 ft. from recharge basins.

Because these regulations are tentative, additional scientific study may be needed for their refinement. There have been no conclusive monitoring or epidemiological studies relating to the introduction and fate of viruses into the OCWD aquifer system, although viruses derived from similar artificial recharge operations have been observed in a nearby aquifer in Los Angeles County[7]. As a means to assess compliance with the proposed regulations, however, isotopic and modeling analyses have been used in the Orange County system to infer migration patterns of groundwater and estimate the ages and sources of groundwater in production and monitoring wells near the spreading basins[8-11].

Figure 1 shows a figure from a modeling study[11] that shows approximate flow pathways from three production wells, labeled as 'P5', 'P6', and 'P7', back to their surface water sources. These sources are represented, primarily, by three artificial recharge basins (Anaheim Lake, Warner basin, and the Santa Ana River). Other production wells exist but, for clarity, are not shown.

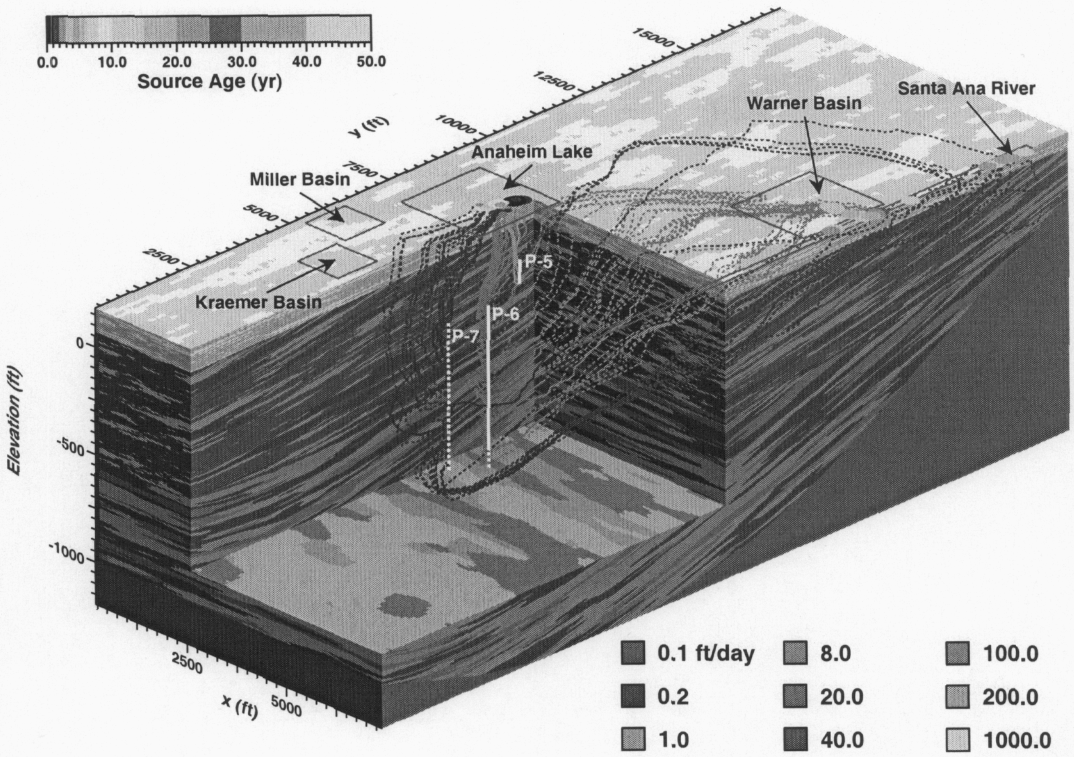


**Figure 1:** Perspective showing of simulated travel pathways from wells P5, P6, and P7 to their surface sources. Streamlines are color-coded to indicate the relevant capture well, and white areas along each well bore indicate their open intervals. The background block is color coded to indicate complexity in the geology, hydraulic conductivity distribution. Dots represent intersection of streamlines with recharge surface and are color coded to travel time (after ref. 11).

Note that wells P6 and P7 are deep and have large open intervals, while P5 is shallow and only has a small open interval. For each well, the travel pathways envelop a distorted "capture zone" around a body of water that flows uniquely into each well through a complicated geological setting. The point is that the "age" of the water entering each well is not unique, but, rather, distributed as a function of the recharge pathways for each well. Small and shallow wells such as P5 would tend to have younger ages, while deeper wells like P6 and P7 will have older ages. This is obvious in Figure 2, which shows the distribution of groundwater age in each of these wells.

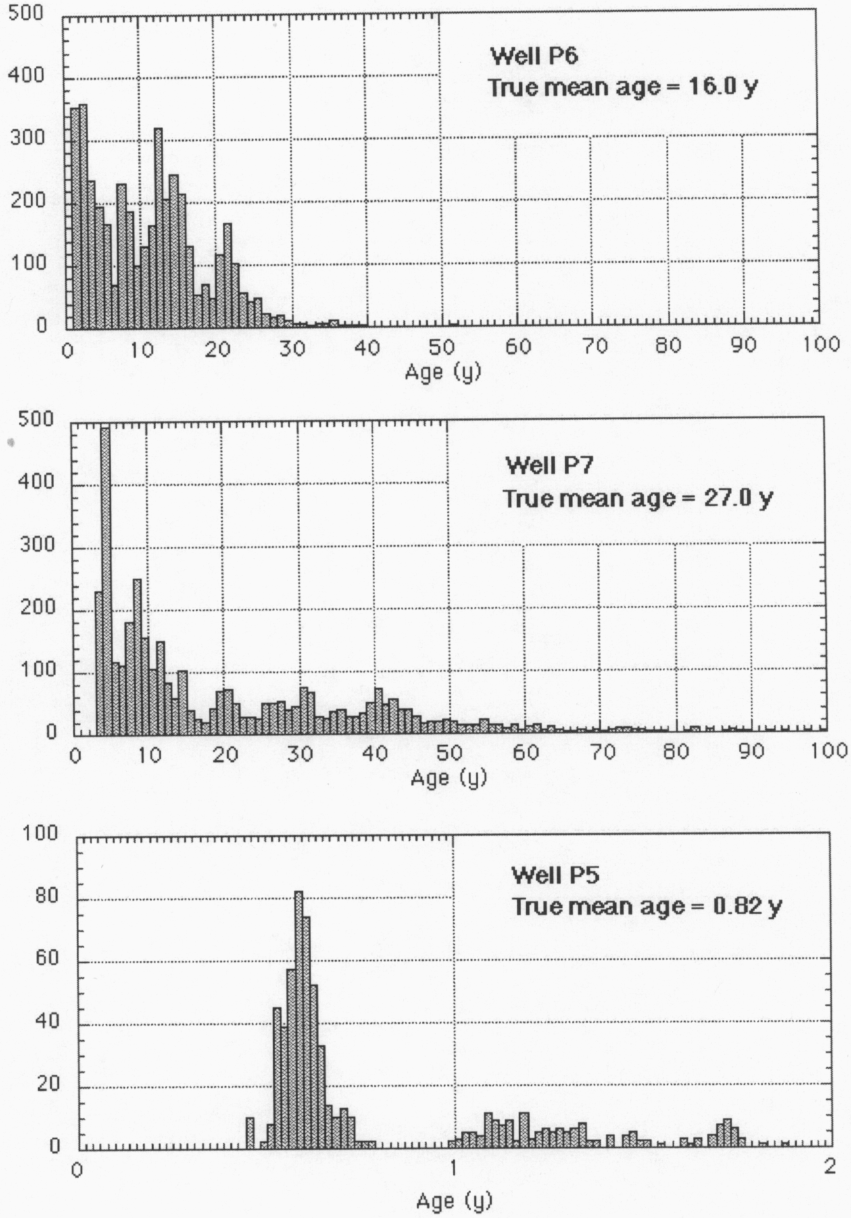


**Figure 2**: Distribution of model-predicted groundwater ages for wells P6, P7, and P5. One-year intervals shown for P6 and P7 histograms; one week intervals shown for P5 histogram (after ref. 11).

The mean ages in each well were similar to tritium/helium age dating estimates determined for "average water" extracted from the entire open interval of each well. Although the age estimates were useful in calibrating the simulation model, they were not wholly indicative of the age distribution in any of the wells, and thus were not as completely useful for demonstrating compliance with the aforementioned proposed regulations as originally envisioned. Notably, from the simulation results, no water entering wells P6 and P7 is younger than 1 year in age, although more than half of the water entering well P5 is.

As a result of these observations, a tracer test was conducted during a recharge event in nearby Anaheim Lake to see whether any "first arrivals" would appear in any of the various production wells surrounding the lake within a 1-year time period (Davisson et al., 1998). A small amount of a Xenon isotope ($^{124}Xe$) was introduced in the lake as the tracer. Figure 3 shows measurements of $^{124}Xe/^{132}Xe$ ratios observed in three deep wells (P6, P7, and P8) surrounding the lake over a 400 day period following the recharge event. Although there was no appreciable arrival of the tracer in wells P6 and P7 during this time (apparently consistent with the results in Figures 1 and 2), there was an obvious arrival in well P8.

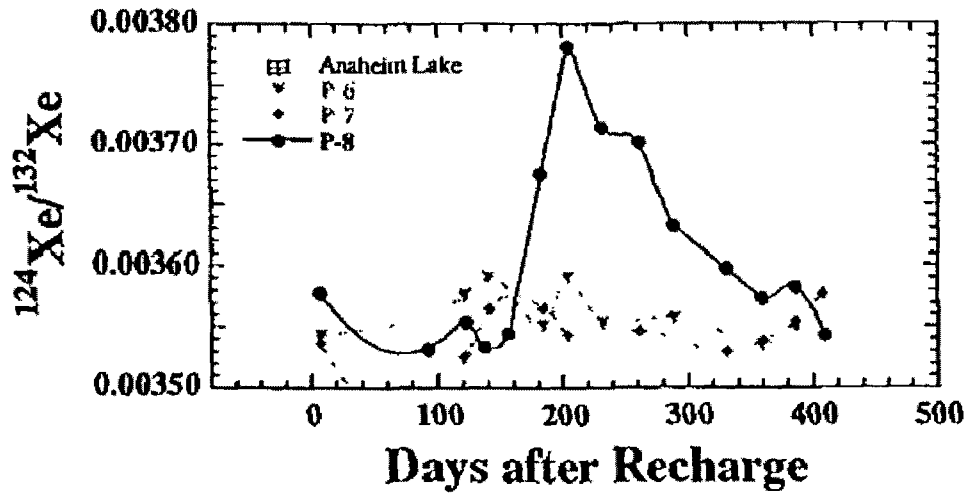


**Figure 3:** $^{124}Xe/^{132}Xe$ ratios observed in deep wells P6, P7, and P8 following tracer injection during a recgharge event in Anaheim Lake (after ref. 9). Observations suggest a < 1 year travel time component to the well P8, but nothing so short to wells P6 and P7.

Now, although age and travel time data for P8 were not included in the information in Figures 1 and 2, it should be noted that all three wells are similar in their deep penetration into the aquifer, their large open intervals, their close proximity to one another, and a mean groundwater age that is over ten years for each well. Neverthelesss, the tracer test indicated a relatively fast travel pathway between Anaheim Lake and P8 that is not apparent in the other two wells. Our interpretation of this observation is that it reflects the complicated nature of the geologic system that controls groundwater flow in relatively small areas, and that "statistically" different results of this sort are reasonable to expect in such natural systems. In a broader sense, the results indicate that the current wells, or even nearby "untested" wells of similar design have a plausible chance for having 1-year old water components, and that the relationship of these findings to the proposed regulations and the more fundamental concerns about pathogen transport may deserve additional consideration.

## CONCLUSIONS

The problems and difficulty in providing clean and reliable water to the world's population in the 21$^{st}$ century remain among the most challenging tasks for the human race. In addition to the important role that the world's political, social, and economic institutions play in addressing these issues, there will always be a correspondingly strong and focused role for the world's science and technology establishments in this effort.

In this paper we have discussed several scientific challenges that face the State of California with respect to securing reliable water supplies in the future. These concern, primarily, understaning impacts of future climate change and climate variability, the long term effects on water quality and ecological health produced by industry, agriculture, and various land use practices, primarily over the past century, and the technical challenges we face in developing "new" water through advances in treatment, purificatiuon, and reuse practices.

As an example reviewed, albeit briefly, a detailed modeling an isotopic study related to a water banking operation in an urban setting in Southern California. The ultimate water quality concerns here are related to the potential introduction of viruses and other pathogens from treated wastewater into the aquifer and the ultimate viability of several proposed "surrogate" regulations designed to protect the quality of water produced from the aquifer. The model – albeit complicated – and the the tracer tests proved to be powerful tools to examine the behavior of the system and provide insights related to compliance with the proposed regulations. We believe, in addition, that these techniques may continue offer a strong scientific basis to explore more directly the fate of viruses and pathogens introduced in to such systems, the concern that motivated the regulatory interest in the first place[12].

## ACKNOWLEDGEMENTS

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