Capstone Project

A Policy Response to the Water Supply and Flood Control in Changing Climate

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EXECUTIVE SUMMARY

CAPSTONE SUBJECT: The Policy Response to Water Supply and Flood Control in Changing Climate

CAPSTONE DELIVERABLE: Policy Brief “Recommendations on executive actions on the water supply and flood control”

AUDIENCE: California Department of Water Resources

ALIGNMENT WITH CLIMATE SCIENCE & POLICY: climate science – the link between climate change and extreme weather events, the role of atmospheric rivers in water supply and flood control; policy – recommendations on supporting scientific research targeting fulfilling informational gaps which will foster more reliable weather forecasting with an ultimate goal to be prepared for uncertainties associated with climate change effect on water availability and, subsequently, on reservoir operations.

APPLICATION: The project has a direct effect on policy associated with climate change adaptation. The findings to be presented on the North Coast Regional Water Quality Control Board (RWQCB) meeting on June 16, 2016 in Santa Rosa, CA as well as on the Sonoma County Grape Growers board meeting in Petaluma, CA.

In hindsight, what used to be a highly polarized topic within the scientific community, the consensus behind man-made climate change has become increasingly uniform. In 2014, the Intergovernmental Panel on Climate Change (IPCC) released a ‘Fifth Assessment’ report citing “unequivocal” evidence of rising average air and ocean temperatures (Graphic 1).

Graphic 1: Temperature and Precipitation at Santa Rosa, CA, from 1890 to 2014 (Data source: National Climatic Data Center, NOAA).
Given the multiple and dire effects projected from the rise in global temperatures, especially increasing frequency of extreme weather events, ignoring the topic is simply too grave and could come at a significant economic cost. For example, California averages $370mm/year in flood damages, the third highest of any other state in the U.S. This project’s deliverable – policy memo to Director of California Department of Water Resources, proposes a number of policy recommendations towards adopting a Forecast-Informed Reservoir Operations (FIRO) strategy for long-term climate change adaptation. This strategy would provide water managers and reservoir operators responsible for flood control with the necessary tools to deal with wide ranging cause and effect relationships pertaining to climate change. Most importantly, it aims to empower these critical actors to better face the many uncertainties associated with reservoir operations, thus mitigating challenges both today and in the future.

Although the federal government has funded billions of dollars’ worth of climate change research, when it comes to projecting extreme precipitation events with the aim of circumventing potential economic damage, there undoubtedly remains a considerable amount of research and development needed in the field. The simple “do nothing” option, which remains a popular ‘fall back’ approach to many policy scenarios, is not only reckless but no longer viable given the potentially catastrophic effects of extreme weather events, like flooding. At present, many avenues exist for key executives to consider and address these issues. Most importantly, it would be prudent to support a collective scientific effort aimed at filling information gaps which would facilitate the adoption of FIRO, thus empowering decision makers engaged in reservoir operations with critical data sets to better manage the nation’s reservoirs. There are several information requirements for improved reservoir operations:

- Accurate quantitative precipitation estimates (QPE) in complex terrain.
- Accurate quantitative precipitation forecasts (QPF) for extreme events.
- Accurate collection and monitoring of hydro-meteorological data, including soil moisture conditions, snow pack, existing stream flow, base flow, precipitation inputs, temperature and evapotranspiration.¹
- Better understanding of atmospheric river (AR) landfall positions, strength, orientation, timing and duration.²

Armed with the aforementioned data sets and research produced from the scientific community whose work is dedicated towards addressing the effects of rising global temperatures, policy makers can minimize their environmental and economic costs while expanding the infrastructure required to continually monitor and learn from extreme weather events going forward.

² Ibid., p.24.
TO: Mark W. Cowin, Director of California Department of Water Resources
FROM: Nataliia Zadorkina, Scripps Institution of Oceanography
DATE: 06/02/2016
RE: Recommendation on Executive Action on the water supply and flood control

The purpose of this policy brief is to provide recommendations to assist California Department of Water Resources to support scientific research required to adopt Forecast-Informed Reservoir Operations (FIRO) for long-term climate change adaptation. FIRO aims to assist reservoir operators in determining the best response to prevent flooding while maintaining adequate water supply during normal weather. The focus of this document is to present relevant information on the link between climate change and extreme weather events, how to be prepared to uncertainties associated with the global rising temperatures affecting water availability. The brief recognizes the progress in scientific knowledge regarding atmospheric rivers which provide up to 50% of California’s water supply and are responsible for most severe floods. This document also provides detailed information on the progress and challenges associated with prediction of the extreme weather events and gives a number of recommendations to the officials to address this challenges.

Introduction

In hindsight, what used to be a highly polarized topic within the scientific community, the consensus behind man-made climate change has become increasingly uniform. In 2014, the Intergovernmental Panel on Climate Change (IPCC) released a ‘Fifth Assessment’ report citing “unequivocal” evidence of rising average air and ocean temperatures. Given the multiple and dire effects projected from the rise in global temperatures, especially increasing frequency of extreme weather events, ignoring the topic is simply too grave and could come at a significant economic cost. For example, California averages $370mm/year in flood damages, the third highest of any other state in the U.S. This memo proposes a number of policy recommendations towards adopting a Forecast-Informed reservoir operations strategy for long-term climate change adaptation. This strategy would provide water managers and reservoir operators responsible for flood control with the necessary tools to deal with wide ranging cause and effect relationships pertaining to climate change. Most importantly, it aims to empower these critical actors to better face the many uncertainties associated with reservoir operations, thus mitigating challenges both today and in the future.

Although the federal government has funded billions of dollars’ worth of climate change research, when it comes to projecting extreme precipitation events with the aim of circumventing potential economic damage, there undoubtedly remains a considerable amount of research and development needed in the field. The simple “do nothing” option, which remains a popular ‘fall back’ approach to many policy scenarios, is not only reckless but no longer viable given the potentially
catastrophic effects of extreme weather events, like flooding. At present, many avenues exist for key executives to consider and address these issues. Moreover, it would be prudent to support a collective scientific effort aimed at filling information gaps, thus empowering decision makers engaged in reservoir operations with critical data sets to better manage the nation’s reservoirs. There are several information requirements for improved reservoir operations:

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Armed with the aforementioned data sets and research produced from the scientific community whose work is dedicated towards addressing the effects of rising global temperatures, policy makers can minimize their environmental and economic costs while expanding the infrastructure required to continually monitor and learn from extreme weather events going forward.

**Background**

Climate change increases the frequency of extreme weather events ranging from intense droughts to severe floods. Approximately fifty years ago, the number of new record high temperatures was almost equal to the number of new record lows. In contrast, today the number of documented record highs is at least twice the number of record lows per year. Not only is this an alarming indication of global warming (see Appendix A for the graphic of temperature and precipitation variations from 1890 to 2014), but also a clear example of how rising temperatures positively affect the frequency and severity of extreme weather.

The risks associated with the effects of climate change on the water cycle and atmospheric processes include, but are not limited to, reduction of the snowpack, shortening snow seasons, expansion of the flood season in areas most susceptible to flooding such as the west coast and increased flood risk in warmer areas with more intense storms. In addition, weather variability and unpredictability can be extremely costly. One estimate finds that total U.S. economic output varies by as much as $485 billion per year owing to extreme weather. According to the National Center for Environmental Information (NCEI), since 1980, the U.S. has sustained 188 weather and

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climate disasters where total economic damage reached or exceeded $1 billion. The sum total of just these 188 events exceeds $1 trillion, which does not take into account those events that did not reach the $1 billion threshold to be recorded. As for California, it averaged $370 million/year in flood damages, the third highest in the nation. According to the ArkStorm, an emergency preparedness scenario for California, projected damage and losses will exceed $750 billion in the case of AR events similar to the 1961 and 1982 floods.

Based on numerous research studies, the primary meteorological cause of same scale extreme precipitation and flooding in California are the narrow corridors of moisture transport within an atmosphere, called atmospheric rivers. These ARs are responsible for some of the largest historical floods in the region. For example, one major AR event in December 2012 recorded 33% of the entire year’s precipitation (i.e., 15 inches out of 46 inches) over just a few days. Therefore, predicting AR storms will undoubtedly help mitigate the risks of major floods while improving the management of water resources. Understanding the effects of ARs on the overall water cycle as well as regional water supply can play an important role towards increasing the efficiency of reservoir operations and other water management activities.

Warming climate and extreme weather

Climate plays a pivotal role in water supply management, flood control, and environmental stewardship. Our expectations of the timing and form of precipitation, magnitude and distribution of runoff for beneficial use are based on our understanding of the climate system and our familiarity with hydrological and meteorological events. Attribution of extreme weather events to a changing climate is a challenging topic and one that is now undergoing significant development. Specially in the western United States, which has historically faced the greatest challenges for water management, the link between extreme weather and climate change is being studied in great depth by a number of prominent scientists. Droughts, floods and resource wars are a part of California’s history and sit at the very core of acute future challenges. Much of California has warmed in the last few decades by about 1.5°C compared to the historical norms from 1901-1960. Therefore, changes in climate and its effect on extreme weather events must be accounted for within the water resource planning process.

According to Michael Dettinger, a research hydrologist for the U.S. Geological Survey, “climate change threatens water resources in California to an extent unparalleled anywhere else in the country”. Based on current conditions, California’s overall water demand for agriculture, municipalities and power plants exceeds 40% of available supply. This is an alarming sign for
water managers and officials at both the regional and national levels. Specially in the Golden State, where the budget for water resources is skewed heavily towards agriculture due to the state’s multi-billion dollar agricultural sector which accounts for 80% of all water use. As for the future, projections are for a continued vigorous trend toward higher mean and extreme temperatures that will play a highly important role in 21st century hydroclimate. Averages of a number of recent projections of future temperatures have the western United States warming by between about 2.5°C and 5°C by end of century. Some predictions are even higher depending on the level of greenhouse gas emissions factored into the models. Conversely, annual average precipitation totals are expected to decrease during the same period.

Current projections suggest extreme precipitation events are going to increase throughout California. In southern California, heavy storms which historically occurred once every 20 years are now projected to occur as often as every 12 years. In northern California, the projection is for every 15 years. Moreover, although average precipitation projections show a decrease in ensuing years, the frequency of extreme weather occurrences is likely to increase. Managing and capturing rainfall from these events will therefore be crucial for minimizing economic costs as well as improving the overall water supply in a state with a massive agricultural economy as well as a rapidly growing urban population. With heavy rainfall events estimated to increase, the potential for flash flooding is expected to increase as well. Undoubtedly, these events will increase the vulnerability of water management including flood control, water supply and wastewater treatment and disposal. Not to mention, these changes will challenge the current water related operations and will affect the organization for new projects.

Ultimately, extreme weather events result in major impacts on water resources, human activities, agricultural activities and ecosystems. Specially, floods are the costliest types of natural disaster in economic and human terms. California is especially vulnerable and historically has suffered many severe floods. Most importantly, highly populated areas downstream of major rivers and developed infrastructure in low lying areas are another area where the state is vulnerable to floods. Understanding the connection between climate change and extreme weather events, and understanding temperature and precipitation variations in the paleo context as well as research of decade-to century-scale variations in climate, although limited, cannot be ignored in planning for management of water resources in the west and must be a top priority for the scientific community.

The Role of Atmospheric Rivers

17 <http://www.ppic.org/main/publication_show.asp?i=1108 >
20 Ibid., p. 32
22 Ibid., p.2074.
23 < http://www.waterplan.water.ca.gov/docs/climate_change/CCScience_DWROperations.pdf >
24 Ibid., p.36.
Recent breakthroughs in weather and water forecasting is largely due to a deeper understanding of the causes of major precipitation events. These precipitation episodes occur due to atmospheric phenomena known as atmospheric rivers (ARs), which supply up to 50% of California’s water supply in addition to causing roughly 90% of major floods in the region. Thus understanding ARs, given their role as producers of extreme storms and floods while the major source of contributing to California’s water supply, is as important for water management and effective reservoir operations, specifically in the areas susceptible to extreme weather events, such as the Russian River watershed region, as understanding the hydrologic processes and watershed conditions defining soil storage capacity and the relationship between the runoff and recharge.

According to the National Oceanic and Atmospheric Administration (NOAA), atmospheric rivers are relatively narrow regions in the atmosphere that are responsible for most of the horizontal transport of water vapor outside of the tropics. A moderate-sized atmospheric river carries as much water as the Mississippi River dumps into the Gulf of Mexico in an average week. Approximately six ARs per year that make landfall in California have contributed an average of one half of all California’s precipitation, with a single typical AR storm yielding roughly 10% of the annual average runoff of the entire Sacramento River basin.

An extensive research study begun in 1990 has documented the importance of ARs to the global water cycle. A well respected expert in ARs, Marty Ralph, points out the following main characteristic of this atmospheric phenomenon:

- condensed water vapor approximately two centimeters thick;
- wind speeds of greater than 12.5 meters per second in the lowest 2 kilometers;
- narrow, 400–500 kilometers wide that extend for thousands of kilometers, sometimes across entire ocean basins.

Their presence and unique features are at the root of the most extreme precipitation and flooding in Northern California. At the same time, ARs make important contributions to how much snow and water will be available in these regions. For example, the study which is based on NASA satellite and ground-based data from 1998 through 2014, is the first to establish a climatological connection between atmospheric river storms and rain-on-snow events. Understanding the behavior of these ‘rivers in the sky’ may be the key to determining how changing climate patterns influence floods. Furthermore, recognizing ARs is paramount for forecasting extreme precipitation and flooding in the Pacific coast states. Learning more about these phenomena will undoubtedly open the door to a new set of challenges for water cycle, water supply, and flood prediction science.

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28 Ralph, F.M., Storms p.267
29 Ibid. p. 265
30 A study by NASA and other partners has found that in California's Sierra Nevada, atmospheric river storms are two-and-a-half times more likely than other types of winter storms to result in destructive “rain-on-snow” events, where rain falls on existing snowpack, causing it to melt. Those events increase flood risks in winter and reduce water availability the following summer. Additional information on “rain-on-snow” events may be found from http://www.jpl.nasa.gov/news/news.php?release=2016-058>
31 Ralph F.M., Storms, p.267
Over the past fifteen years several studies on ARs have been conducted by the National Oceanic and Atmospheric Administration (NOAA). Through “intense field campaigns and the use of new meteorological and hydro meteorological sensors including radar and sounding assets, research aircraft, and other remote sensing tools as well as numerical models” 32 many facts regarding ARs have become increasingly obvious. Furthermore, as interest in ARs has grown, scientific efforts have expanded to include other agencies and institutions such as the U.S. Army Corps of Engineers (US ACE), the U.S. Geological Survey (USGS), California’s Department of Water Resources (CDWR), NASA, the California Energy Commission, Scripps Institution of Oceanography at UC San Diego and various local agencies around northern and southern California.

One example of the scope of atmospheric rivers research stems from a February 5, 2015 33 study conducted as part of a $10-million CalWater 2015 multidisciplinary field campaign at Scripps Institution of Oceanography at UC San Diego. In this study, scientists in cooperation with a number of other national agencies including NASA, the Department of Energy, the National Science Foundation and NOAA conducted research using airborne vessels and research aircraft flying at different altitudes over the Pacific Ocean near the northern California coast. Back on land, several dozen ground stations with trained experts and scientists were collecting, processing and studying the data pertaining to AR characteristics. The size of this particular research mission made it the most intensive study of extreme weather events in history.34

Today, the detection of atmospheric rivers is possible due to advances in the interpretation of satellite images. AR detection algorithms, established by M. Ralph (2004), are largely based on image reconstruction techniques.35 The analysis of these satellite images representing only water vapor, was confirmed using NOAA research aircraft data over the eastern Pacific Ocean and wind profiles along the coast. 36 The advent of these images have revolutionized the understanding of ARs and their global significance. 37

With regards to atmospheric river forecasting, improvements in weather prediction are striking. Radar technology, satellite images and computer models running on powerful supercomputers all contribute to the advances in extreme weather predictions. Advances in computer technologies and supercomputer performance are crucial for complex forecasting models which are based on physical laws governing atmospheric movements, chemical reactions and other relationships. 38 With the help of computer models, the analysis of millions of datasets representing weather and environmental conditions is now possible at an unprecedented scale. Supercomputers with an

32 Ralph, F.M., Storms, p. 267
33 <https://scripps.ucsd.edu/news/research-highlight-most-studied-atmospheric-river-history >
34 Ibid.
37 <http://www.esrl.noaa.gov/psd/atrivers/questions/>
extremely high-level computational capacity allow weather predicting models to run at very small to very large scales. With all these improvements, meteorologists such as scientists in the University of California, San Diego Scripps Center for Western and Water Extremes (SW3E) are able to predict when an atmospheric river will hit. According to NOAA, national weather forecasters are able to identify the AR in current numerical forecasting models. This helps to give a warning of a potential storm 5 to 7 days in advance. In addition, the monitoring of the polar orbiter microwave satellite imagery also helps AR prediction. However, more research is needed to pinpoint where exactly the AR will landfall. Current inability to precisely understand and predict extremes in precipitation highlight the urgency to implement advanced quantitative methods for broader understanding of atmospheric rivers. This is a major challenge which can only be tackled with all the weapons in hand such as long-term monitoring using satellite data, land-based atmospheric river observations, improvements in numerical modelling and, of course, scientific progress.

According to the California Department of Water Resources, Western States Water Council (WSWC), and the Western Governors’ Association (WGA), recent progress in weather forecasting such as NOAA’s Hydro meteorological test bed program on west coast atmospheric rivers, reveal the potential for improving extreme precipitation prediction at operational time scales. In addition, California Senate Bill 758, establishing “The Atmospheric Rivers and Research and Mitigation Program” was signed into law by California Gov. Jerry Brown on October 9, 2015. This legislation will undoubtedly facilitate advancements towards recognizing the various cause and effect relationships of ARs while improving the state’s response time to extreme weather events. Ideally, public warnings and first responders will have greater lead time, thus mitigating the economic and social costs associated with these events.

**Forecast-Informed Reservoir Operations (FIRO)**

According to Scientific American, FIRO “is a proposed management strategy that uses data from watershed monitoring and modern weather and water forecasting to help water managers selectively retain or release water from reservoirs in a manner that reflects current and forecasted conditions.” Given ongoing progress regarding prediction and monitoring technology for use in the study of atmospheric rivers, which are responsible for most extreme precipitation events in California, FIRO aims to assist reservoir operators in determining the best response to prevent flooding while maintaining adequate water supply during normal weather. These efforts have the added benefit of improving official knowledge of watershed and hydrologic conditions.

FIRO is a collaborative effort between NOAA, USACE and USGS, and the FIRO Steering Committee. This group draws on the expertise of hydrologists, meteorologists, biologists, civil

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39 Performance of a supercomputer is measured in floating-point operations per second (FLOPS). As of 2015, there are supercomputers that can perform up to quadrillions of FLOPS (The list, November 2015. Retrieved <http://www.top500.org/lists/2015/11/>).
40 <http://www.esrl.noaa.gov/psd/atmrivers/questions/>
41 Ibid.
42 Ibid.
45 <http://cw3e.ucsd.edu/FIRO/>
engineers, economists and climate scientists from federal, state and local agencies and institutions. Moreover, FIRO has been developed by exploiting current best available science as well as other available weather prediction and monitoring technologies from unrelated but equally vested industries, such as fund management. Incorporation of improved weather forecasts into reservoir operations offer water managers the ability to gain significant lead time during sensitive moments requiring the strategic retention or release of available water from existing reservoirs.

The potential of FIRO has attracted a number of federal and local agencies who rarely cooperate on such a large scale; including the Sonoma County Water Agency, the USACE, the Center for Western Weather and Water Extremes(CW3E), National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS), THE Corps and Bureau of Reclamation (BOR), California Department of Water Resources (DWR), and the Mendocino County Russian Flood Control and Water Conservation Improvement District. Each of these agencies have their own interests in FIRO while realizing their individual objectives are more likely to be reached through interagency cooperation. For example, the Sonoma County Water Agency interest evolves around maximizing available water supply during the dry seasons. In addition, if FIRO viability assessment are proven positive, the SCWA is likely to transfer FIRO strategy to other systems nationwide facing similar challenges, thus giving the overall process greater scientific and political precedent. The USACE is motivated by the possibility of having greater flexibility adjusting water levels below the rule curve in advance of imminent flood events. With the help of better forecasting, according to Michael Dillabough, chief of operations and readiness for the San Francisco District of the U.S. Army Corps of Engineers, this flexibility is not only attainable but can be exponentially increased with the state of technology.

Historically, storms triggered by ARs have also resulted in most floods throughout California. In fact, all storms that resulted in a declared flood condition of some kind on the Russian River from 1998 to 2005 were caused by ARs. Another study from the Journal of Contemporary Water points out that “from 1946 through 2011 there have been 39 Russian River floods, 34 of which were caused by atmospheric rivers”.

The Russian River region has a history of variable weather. As recent events reveal, there is an emerging pattern of more erratic and unpredictable events which exponentially increases the potential downstream economic impact. This exponential spike in possible cost to business and residential areas has greatly increased the economic incentives to improve prediction and management strategies:

- “Valentine’s Day Flood” on the Russian River on February 13, 1986. The six-day deluge that caused more than 1,700 people to be evacuated from Guerneville and neighboring

46 Ibid.
47 The Russian River, a southward-flowing river, drains 1,485 square miles of Sonoma and Mendocino counties in Northern California
48 Ralph, F. M., Storms. p.266
communities, damaged or destroyed a thousand homes, with total losses up to $25 million.\(^{50}\)

- The Christmas Floods of 1995, when the Russian River crested at 47.62 feet in Guerneville.\(^{51}\)
- Flooding and landslides between December 26, 2005 and January 3, 2006. Sonoma County businesses and residential damages reached approximately $104 million. More than 2,100 businesses and residential properties were inundated and 50,000 residents were without power.\(^{52}\)
- 2007-2009 drought, the first in California’s water history for which a statewide proclamation of emergency was issued.
- 2012-2014 period - the most severe drought in CA in the last 1200 years due to anomalously low precipitation and record high temperatures.\(^{53}\)

Given these facts, it is no surprise that forecast-informed reservoir operations (FIRO) which take advantage of the current science of atmospheric rivers and watershed characteristics in addition to the advancements in the weather prediction technology are based on the Lake Mendocino region of the Russian River. In this region of high weather variability, AR storms have been the main reason of ending droughts.\(^{54}\) In particular, according to M. Dettinger research, in the Pacific Northwest, 60%–74% of all drought endings were due to the arrival of AR storms.\(^{55}\) In California, roughly 33%–40% of all drought endings were the result of AR storms.\(^{56}\)

The Russian River drains approximately 1,485 square miles of Sonoma and Mendocino counties in northern California. Two federal projects impound water in the Russian River watershed: the Coyote Valley Dam (CVD) forming Lake Mendocino, and the Warm Springs Dam on Dry Creek (a tributary of the Russian River) in Sonoma County, forming Lake Sonoma.\(^{57}\) Sonoma County Water Agency (SCWA) has the right to control releases from both Lake Mendocino and Lake Sonoma reservoirs. Flood management releases from these reservoirs are controlled by US Army Corps of Engineers (USACE).\(^{58}\) The natural drainage and stream flow of Lake Mendocino and Coyote Valley Dam makes it a perfect model for testing FIRO. Lake natural drainage and stream flow contribute most of the Russian River flow downstream of CVD and above Dry Creek during the rainy season (November through April).\(^{59}\) As for the drier months of May through October, water released from Lake Mendocino accounts for most of the water upstream.

Among the multiple challenges of Lake Mendocino and CVD operations, the most important issue is a frequent inability of the Lake to refill in the spring.

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\(^{50}\) <http://bit.ly/1Sid1PSI>  
\(^{51}\) <http://bit.ly/1RyzisV>  
\(^{55}\) Ibid., p.1721.  
\(^{56}\) Ibid., p.1721.  
\(^{57}\) <http://cw3e.ucsd.edu/FIRO/firo_introduction.html>  
\(^{58}\) Ibid.  
\(^{59}\) Ibid.
Other water supply challenges that might be addressed with FIRO are summarized below:

- A federal biological opinion established by the National Marine Fisheries Services (NMFS) that requires flow changes for the recovery of three species that depend on the Russian River: endangered Coho salmon, Chinook salmon and Steelhead trout. NMFS biologists tell us reduced summertime flows in the Russian River and Dry Creek would be beneficial for the restoration of fishery habitats due to reduced velocity. According to these biologists, less turbidity caused by reduced flow, will result in improved estuary conditions by allowing the formation of a freshwater lagoon.  

- Minimal coordination with downstream water users.

- An out-of-date rule curve for determining flows. The Lake Mendocino Water Control Manual, used by USACE for dam operations, is over 50 years old (revised in 1986) and as a result does not account for changing watershed conditions or hydrologic conditions. For the same reason, the manual doesn’t incorporate the benefits in weather and streamflow predictions due to technological progress.

**Recommendations**

The successful incorporation of FIRO into reservoir operations can be achieved if several potential resources are exploited to achieve the collective goals of those who would benefit most. These resources include decision support tools and models, scientific improvements for continuous data collection and monitoring of watershed and hydrometric conditions, advancements in weather forecasting and last but not least, a more comprehensive understanding of the causes and subsequent effects of ARs. However, even if the Lake Mendocino FIRO Preliminary Viability Assessment Work Plan proves viable due to visible improvements in flood response and water availability during dry seasons, there remains several scientific and technical challenges that must be addressed for lessening flood control risk.

Government support and backing is required for the implementation of any science and technical programs. Additional improvements for Quantitative Precipitation Estimation (QPE) are needed for approximating precipitation in any region during a specified time period. Moreover, improvements are needed in the algorithms used for obtaining quantitative data from radar for the purpose of evaluating precipitation. Presently, the data is corrupted due to high probability error points in the data sets derived from QPE including:

- sensitivity to radar calibration
- presence of hail: the results are not valid when hail is present, leading to the potential for gross over estimation of rain totals.

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60 <http://www.scwa.ca.gov/decision1610/>
61 <http://cw3e.ucsd.edu/FIRO/firo_water_challenges.html>
62 Ibid.
• melting layer challenges. "Since the radar beam intercepts and goes above the melting layer at far ranges, below beam effects in these areas significantly affect precipitation estimations at the ground.”
• partial beam blockage challenges, one of the biggest challenges for any weather radar due to terrain, trees, or man-made obstacles like buildings and towers.

For more precise models, high-quality rain gauge networks are needed to provide robust statistical analyses of radar-based precipitation algorithms such as the QPE. Any programs on expanding high quality rain gauge networks must be encouraged. Improvements to QPF algorithms will undoubtedly have a significant impact on reservoir risk management operations, allowing water managers to make prompt decisions relating to flood control. This will allow managers to release water from reservoir with less risk for unanticipated effects. The scientific community should have access to all necessary resources to foster good practices by disseminating new information through seminars, conference presentations, articles in the scientific literature and webinars to ensure a broad impact. Given the complexity of the QPE algorithm, keeping the field apprised of the latest developments regarding QPE is an absolute must. With regard to informational gaps about atmospheric rivers, the knowledge of ARs landfall position, strength, orientation, timing and duration need further improvement as well.

In addition, even the best plan for managing water can be enhanced with community participation and cooperation. An aggressive public outreach and education programs is essential and must be nurtured. Especially given the fact, that the survey of 85 winegrowers in the Sonoma and Mendocino County, that are the major users of the Russian River water, showed that the main users of the water in the “wine country” are mostly not familiar with the agency’s effort to reduce the risk of the catastrophic floods and maintain the adequate water supply during the dry seasons. The survey, conducted in Spring 2016 showed that 65% of the surveyed have never heard the term “atmospheric river”, 75% - have no knowledge about the FIRO project and its potential benefits. What is more, most of the respondents have a very limited knowledge of how the dams are operated and many of the surveyed don’t know the names of the endangered and threatened species that depend on the Russian River (see Appendix B for the survey results). Ultimately, public information and education are important ways to be prepared for emergencies, such as flooding. What is more, public awareness about the SCWA programs as well as scientific research targeting water resources might lead to useful comments and cooperation, such as permission to install rain gauges or other necessary equipment for watershed monitoring in the privately owned territories for a common benefit. Better public education and outreach might even lead to the potential contribution of private funding and support of costly scientific research projects aiming at increasing the water availability and better emergency preparedness with the help of improved extreme precipitation forecast. An information program must educate citizens about the water and scientific challenges and make citizen involvement part of the solution.

65 Ibid., p. 3.
66 Ibid., p. 4.
To sum up, it is highly recommended to support scientific research which will lead to fulfilling the key information gaps to aid decision making related to reservoir operations. There are several information requirements for accomplishing the goal of improved reservoir operations:

- Accurate Quantitative Precipitation Estimates (QPE) in complex terrain.
- Accurate Quantitative Precipitation Forecasts (QPF) for extreme events.
- Accurate collection and monitoring of hydrometeorological data, including soil moisture conditions, snow pack, existing stream flow, base flow, precipitation inputs, temperature, and evapotranspiration.  
- Better understanding of ARs landfall position, strength, orientation, timing and duration.

**References:**


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68 Ibid., p.24.
69 Ibid., p.24.


Web Sources:
<http://www.ppic.org/main/publication_show.asp?i=1108>
<https://scripps.ucsd.edu/news/research-highlight-most-studied-atmospheric-river-history>
<http://cw3e.ucsd.edu/FIRO/firo_introduction.html>
<http://www.scwa.ca.gov/decision1610/>

Appendix A: Temperature and Precipitation at Santa Rosa, CA, from 1890 to 2014 (Data source: National Climatic Data Center, NOAA).
Appendix B: Winegrowers of the Russian River watershed region survey results, March 2016

1. Level of knowledge of how the dams are operated

2. Level of knowledge of endangered and threatened species that depend on the Russian River

3. Level of knowledge of the term "atmospheric river"

4. Level of awareness of the term "forecast-informed reservoir operations"
5. Do you believe that FIRO could represent a type of "common ground" for the many competing needs for water and its associated infrastructure, from agriculture, to environmental and flood control?

- Strongly agree: 93%
- Neither Agree nor Disagree: 5%
- Strongly Disagree: 2%