Appendix 2

Reservoir Operations

Contents

Reservoir Operations

Theme Subcommittee Members

The Flood-MAR Reservoir Operations Subcommittee collected ideas on research, data, and tools needed to explore and support how to modify reservoir operations as part of implementation of Flood-Managed-Aquifer-Recharge (Flood-MAR) projects. The Reservoir Operations subcommittee consists of two co-chairs, seven subcommittee members, and the California Department of Water Resources' (DWR's) Research and Data Development (R&DD) team; subcommittee members are listed by name below.

Position	Name	Affiliation
Co-Chair	Boone Lek	California Department of Water Resources (DWR)
Co-Chair	Jay Lund	University of California, Davis (UCD)
Subcommittee Member	Jon Herman	UCD
Subcommittee Member	Lee Bergfeld	MBK
Subcommittee Member	Wes Monier	TID
Subcommittee Member	David Ford	HDR
Subcommittee Member	Nathan Pingel	HDR
Subcommittee Member	Joseph Forbis	U.S. Army Corps of Engineers
Subcommittee Member	Joe Countryman	Central Valley Flood Protection Agency
R&DD Team	Sean Sou	DWR
R&DD Team	Alex Vdovichenko	DWR

Subcommittee members communicated mostly through Skype meetings and emails and shared information through emails and Google drive. Subcommittee members identified a list of research, data, and tool gaps; this information was collected and organized using the research, data, and tools template. During a Skype meeting to discuss an original draft list, subcommittee members identified additional items. The updated List of Gaps in the Research, Data, and Tools Related to Flood-MAR, for Reservoir Operations is shown below.

Gaps in Research, Data, and Tools Related to Flood-MAR

Table 1 Forecast-Informed Reservoir Operations (FIRO) Data Products

Other Themes that will Benefit: 1. Hydrology Observation and Prediction 8. Recharge and Extraction Methods and Measures 13. Tool and Application Development
Public Benefits Informed By: Flood risk reduction, drought preparedness, ecosystem enhancement, climate change adaptation.
Description, including Connection to Flood-MAR: Develop data products (observations and forecasts) to be used to inform reservoir operations. This information could be a combination of precipitation, streamflow forecasts, observed snowpack, observed groundwater levels. Choosing the input information is a balance between accuracy and lead time. Approaching the problem in a general way may pose an information selection problem.
Website: Contact: Email:

Table 2 Reservoir Operating Rule

Other Themes that will Benefit:
Public Benefits Informed By: Flood risk reduction, drought preparedness, climate change adaptation.
Description, including Connection to Flood-MAR: Modify the structure of the reservoir operating rule to include the forecast variables described in the FIRO data products research need listed in Table 1 above. Current flood control operations are based on the flood pool idea, where the rule is a function of the time of year, and some antecedent hydrologic variables. How can or should this structure be modified to include the forecast variables, and how should the uncertainty in those forecast variables be incorporated?
Website: Contact: Email:

Table 3 Reservoir Policies Validation

Other Themes that will Benefit:

1. Hydrology Observation and Prediction

Public Benefits Informed By: Flood risk reduction, drought preparedness, climate change adaptation.

Description, including Connection to Flood-MAR:

Validate reservoir policies against out-of-sample data. Reservoir policies (e.g., flood pools) are often designed over a certain period of historical record. But how well do they perform in other time periods? That answer has much relevance to climate change, where future flood events and snowmelt timing are likely to change significantly. Even a FIRO implementation designed to perform using an historical hydrologic data set, may not continue to perform well in the future with, for example, climate changed hydrology.

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Table 4 Identify Changes to Policy (if any) Necessary to Permit Crediting Flood Risk Reduction Attributable to Storage not in Reservoir Flood Pool

Other Themes that will Benefit:

6. Land Use Planning and Management

11. Economic Analysis

12. Local, State, Federal Policies and other Legal Constraints

Public Benefits Informed By: Flood risk reduction.

Description, including Connection to Flood-MAR:

If Flood-MAR will store water “out of a reservoir” to reduce downstream flood risk, is policy sufficiently flexible to permit crediting the benefit associated with that reduction? For example, will the federal feasibility assessment that focuses on national economic development benefit allow evaluating the cost avoided by spreading flood water over the land, including that benefit in the analysis of project accomplishments? If not, what changes are needed to policy and how can those be achieved? Research is needed to provide an answer to this.

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Table 5 Identify Specific Quantitative or Semi-Quantitative Metrics for Evaluating Flood Risk Reduction Benefits Attributable to Storage Not in Reservoir

Other Themes that will Benefit:

11. Economic Analysis

Public Benefits Informed By: Flood risk reduction.

Description, including Connection to Flood-MAR:

To permit unbiased comparison of proposals for and performance of Flood-MAR activities, firm guidance is required (guidance perhaps similar to or an expansion of DWR's handbook for assessing value of State flood management investments). Research and development is needed to complete this guidance.

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Table 6 Identify Liability Issues from Reliance on Out-of-Reservoir Flood Storage over which Dam Owners Have No Control

Other Themes that will Benefit:

6. Land Use Planning and Management

12. Local, State, Federal Policies and other Legal Constraints

Public Benefits Informed By: Flood risk reduction.

Description, including Connection to Flood-MAR:

A dam owner can control the availability of flood storage space in a reservoir (subject to uncontrollable inflows) and can take actions to maintain that space. For example, the dam owner can take action to maintain the stability of the land adjacent to the pool to avoid landslides, thereby increasing reliability of the storage. But, if a Flood-MAR project depends on spreading water over land outside the direct control of the dam owner, what legal responsibility and authority does the dam owner have to maintain the land? For example, if land use changes because of increased impervious areas, consequently reducing the efficiency of the out-of-reservoir storage, who is responsible and liable for that change? Research needs to be done to determine this issue, with guidance provided.

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Table 7 System Understanding

Other Themes that will Benefit:

1. Hydrology Observation and Prediction
3. Infrastructure Conveyance and Hydraulics
10. People and Water
13. Tool and Application Development

Public Benefits Informed By: Most, if not all.

Description, including Connection to Flood-MAR:

The key to reservoir operations analyses of Flood-MAR is a better understanding of the system. While there are some common elements in Flood-MAR evaluations, each watershed/reservoir is unique. A credible analysis must start with an understanding of the reservoir (purpose, regulations, operations) and how the reservoir fits into the California water system as a whole. This is certainly true for any Central Valley reservoir and potentially true for others. Additionally, Flood-MAR presents a unique challenge because there needs to be understanding of operations for multiple purposes: flood control, water supply, environmental protection, hydropower, among others.

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Table 8 Integration of Multiple Operational Strategies

Other Themes that will Benefit:

1. Hydrology Observation and Prediction
3. Infrastructure Conveyance and Hydraulics
13. Tool and Application Development

Public Benefits Informed By: Flood risk reduction, drought preparedness, aquifer replenishment.

Description, including Connection to Flood-MAR:

With understanding of the system, it becomes possible to integrate multiple operational strategies to recognize synergies between certain strategies. For example, improved prediction of reservoir inflow can improve reservoir operations through relaxation or expansion of flood space requirements. Forecast-based operations create changes in reservoir operations that may integrate with Flood-MAR concepts and strategies to bank water that is released for flood control purposes. Analysis of integrated strategies will likely depend on specialized tools or models designed specifically for these purposes as most existing tools were designed for specific, individual purposes.

Website:

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Table 9 Tools for Multiple Purposes and Strategies

Other Themes that will Benefit:

3. Infrastructure Conveyance and Hydraulics
13. Tool and Application Development

Public Benefits Informed By: Flood risk reduction, drought preparedness, aquifer replenishment.

Description, including Connection to Flood-MAR:

Existing models and tools for many reservoirs were designed for a specific purpose such as flood control, water supply planning, temperature management. These different purposes often require different logic, time-steps, and simulation periods, to name a few. Adequate tools that address multiple purposes are needed for analyzing Flood-MAR. In some cases, this may require using multiple or existing tools, or new tools with expanded capabilities.

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Table 10 Improve Watershed Attributes Data, Real-Time

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: There is a need for better forecast and monitored information related to headwater hydrologic parameters. This includes forecast and monitoring of atmospheric rivers, snow pack, snow water content, vegetative cover, soil moisture. The improved resolution of information will result in the ability to retain more water in reservoirs. In general, reservoir operators know how much more water is needed; success relies on timing and knowing what is coming ahead for slower release.
Website: Contact: Email:

Table 11 Joint Operations Among Multiple Stakeholders

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Develop a coordination scheme between the weather forecaster, reservoir operators, water supplier, flood risk manager, and groundwater manager, to better pre-deliver water ahead of a flood or drought event. This study might consist of a series of practical collaborative exercises built around actual real-time operations, with assessments of the value of such exercises and how they might be improved to make joint operations more effective and routine.
Website: Contact: Email:

Table 12 Characterize Forecast Uncertainty

Other Themes that will Benefit:

1. Hydrology Observation and Prediction

Public Benefits Informed By:

Flood risk reduction, drought preparedness, ecosystem enhancement, climate change adaptation.

Description, including Connection to Flood-MAR:

There is a need for longer records of reforecast data (current state-of-the-art forecast models applied to historical weather conditions) so that the accuracy of precipitation forecasts at different locations and different lead times can be assessed. Currently, the best databases are from the European Centre for Medium-Range Weather Forecasts and Scripps Institute of Oceanography. There may also be reforecast databases from the streamflow forecast ensembles generated from the California-Nevada River Forecast Center. This may not be a question of generating new datasets, so much as making sure that the Flood-MAR effort is aware of these datasets and is able to use them to characterize forecast uncertainty.

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Table 13 Forecast Uncertainty and Value of Information

Other Themes that will Benefit:

Public Benefits Informed By:

Description, including Connection to Flood-MAR:

This effort involves estimating the value of additional storm event forecast information in terms of economic value and additional recharge volumes. Reservoir operators must prepare to operate their reservoirs to the brink during droughts and flood. What is the value to improved forecast and/or the resolution of information in the upper watershed? How much more water can we squeeze from this watershed with most update information and by limiting uncertainties? Answers to these questions are needed.

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Table 14 FIRO Limiting Factors

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Under what conditions of storage capacity, inflow characteristics, downstream channel capacities, and forecast horizon reliabilities is FIRO more or less promising? FIRO has shown great promise in locations where the reservoir and downstream channel capacity are sizable, and where the upstream watershed are mostly fed by rainfall runoff (e.g., Lake Mendocino and Folsom Lake). It is unclear if a system with smaller channel capacity and fed mostly by snowmelt will allow similar effective results. Understanding limiting factors to implement FIRO will help prioritize watersheds where this strategy will be the most useful.
Website: Contact: Email:

Table 15 Moving Drought Storage in Reservoir to Groundwater

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Moving more drought storage from surface reservoirs to aquifers should help improve drought water supplies, flood management, and adaptation to a warming climate. This research will consist of evaluating fall release from water storage to MAR. This practice could be a double-edged sword. In the first years, this strategy might increase drought vulnerability; but in the long term, this strategy will support capture of extreme precipitation from atmospheric rivers and climate change, recharge groundwater to prepare for long droughts, and potentially provide baseflow environmental benefits. These positive feedbacks could provide a more flexible/adaptive strategy especially in relation to extreme climate conditions. This strategy could include a series of statewide, regional, and local assessments of promising opportunities, improvements in water supply and flood management under current and warmer climate conditions, and costs (e.g., recreation and hydropower) and impediments to making such shifts.
Website: Contact: Email:

Table 16 Flood Risk Reduction from Lower Surface Water Elevation in Reservoir

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Changing reservoir operation by releasing water in late fall and early winter will potentially create more water availability for aquifer recharge and more flood pool opportunity to capture extreme flood events and reduce flood flows. This change in water release would likely become more valuable with a warmer climate. This study would investigate the cost to implement such operation in comparison to invest in larger infrastructure and its benefits.
Website: Contact: Email:

Table 17 Improved Water Accounting to Credit Additional Recharge (including Water Rights and SGMA)

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: This effort involves developing an improved statewide water accounting to support the kinds of agreements and incentive needed for Flood-MAR, as well as the many Sustainable Groundwater Management Act (SGMA)-related water plans and agreements needed, as well as water markets and enforcement of surface water rights. This is a fundamental need for most serious water management at local, regional, and statewide scales across many agencies and water users. Through SGMA, groundwater sustainability agencies (GSAs) will need to provide in their groundwater sustainability plan water budget. This information will be critical to understand key mechanism in a GSA; nonetheless, important processes will still be missing. Those include water rights (water use and availability) and environmental water budget, among others. This type of information potentially will increase certainty about environmental water allocation and reduce controversy, and will provide the information needed to credit entities that are implementing Flood-MAR.
Website: Contact: Email:

Table 18 Common Database for System Modeling and Integration with Groundwater

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Data is key for any system analysis and the evaluation of project feasibility. Development of a common database set for water system modeling, including reservoir modeling, groundwater modeling, and system modeling. This would include routine, systematic, and transparent procedures and responsibilities for updating these data sets and their documentation. Assembly Bill 1755 will provide some of this information, but there is a need for precise and accurate data related to system analyses, which include network and time series. More data is not necessarily needed and might not result in greater system performance. But, having a better understanding of system interaction between surface water and groundwater (e.g., accretion and depletion) will result in better representation when modeling it.
Website: Contact: Email:

Table 19 Demonstration Projects – Local Cases Showing Different Level of Implementation of Flood-MAR

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: Flood-MAR has been implemented locally through individual landowners with simple point of diversion. It is not clear how Flood-MAR (which would include reservoir reoperation) would work from multiple stand points, including coordination between stakeholder, quantification of benefits, and level of risk.
Website: Contact: Email:

Table 20 Flood Risk Trading to Support Flood-MAR and Other Purposes

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: By creating flood space in reservoirs ahead of a flood event and diverting water on farmland or a side channel for MAR, there remains a flood risk trade-off between the reservoir operator and the local entity exercising MAR. How would this flood risk trade-off be managed between the two parties involved in Flood-MAR operations? Who will receive credit for its flood risk benefits? Who will be the responsible party for any liability?
Website: Contact: Email:

Table 21 System Analysis of Wet Events vs Seasonal Recharge

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: In general, Flood-MAR can take place during two types of hydrologic conditions: flood events and seasonal period corresponding from normal to wet year. Both conditions could result in different levels of recharge and it is unclear which would result in the most optimal outcome, not only from a public/private benefits perspective, but also from a recharge perspective.
Website: Contact: Email:

Table 22 Potential Value of Longer-Term Atmospheric River Forecasts for Reservoir Operation

Other Themes that will Benefit:
Public Benefits Informed By:
Description, including Connection to Flood-MAR: The potential value of longer-term atmospheric river forecasts for reservoir operation is important to consider. Is there enough skill to overcome the costs of false-positive forecasts? How good do such forecasts need to become to be useful for more reservoirs and the operation of other system components?
Website: Contact: Email:

Prioritization Process

The identified research, data, and tool gaps were prioritized by the subcommittee co-chairs during additional Skype meetings. The two co-chairs identified the top 10 research, data, and tool gaps. From these 10, the top three were converted into actions. Though priority for the top three research gaps was discussed and assigned, the co-chairs did not assign a priority to the seven remaining research gaps so that items 4 through 10 are not necessarily in priority order. The top 10 research gaps including their titles and descriptions are provided below.

Top Ten Research, Data, and Tools Actions

1. Develop an improved statewide water accounting, a common database set for water system modeling, and documentation standards to build an institutional infrastructure to support Flood-MAR and other innovations in California (see the Top Three Research, Data, and Tools Actions section for detailed description and connection to Flood-MAR).
2. Extend forecast-informed reservoir operation (FIRO) to include operations for groundwater recharge, particularly for local and regional agricultural field and basin recharge opportunities (see the Top Three Research, Data, and Tools Actions section for detailed description and connection to Flood-MAR).
3. Analyze reservoir and broader water resources system to assess potential for shifting drought storage from surface water reservoirs to aquifers (see the Top Three Research, Data, and Tools Actions section for detailed description and connection to Flood-MAR).
4. Modify the structure of the reservoir operating rule to include the FIRO forecast variables. Current flood control operations are based on the flood pool idea, where the rule is a function of the time of year, and different antecedent hydrologic variables. How can or should this structure be modified to include the forecast variables, and how should the uncertainty in those forecast variables be incorporated?
5. Identify liability issues from reliance on out-of-reservoir flood storage over which dam owners have no control. A dam owner can control the availability of flood storage space in a reservoir (subject to uncontrollable inflows) and can take actions to maintain that space. For example, the dam owner can take action to maintain the stability of the

land adjacent to the pool to avoid landslides, thereby increasing reliability of the storage. But if a Flood-MAR project depends on spreading water over land outside the direct control of the dam owner, what legal responsibility and authority does the dam owner have to maintain the land? For example, if land use changes because of increased impervious areas, consequently reducing the efficiency of the out-of-reservoir storage, who is responsible and liable for that change? Research needs to be done to determine this issue, with guidance provided.

6. Identify changes to policy (if any) necessary to permit crediting flood risk reduction attributable to storage not in reservoir flood pool. If Flood-MAR will store water "out of a reservoir" to reduce downstream flood risk, is policy sufficiently flexible to permit crediting the benefit associated with that reduction? For example, will the federal feasibility assessment that focuses on national economic development benefit allow evaluating the cost avoided by spreading flood water over the land, including that benefit in the analysis of project accomplishments? If not, what changes are needed to policy and how can those be achieved? Research is needed to provide an answer to this.
7. Study the California water system. While there are some common elements in Flood-MAR evaluations, each watershed/reservoir is unique. A credible analysis must start with an understanding of the reservoir (purpose, regulations, operations) and how the reservoir fits into the California water system as a whole. This is certainly true for any Central Valley reservoir, and potentially true for others. Additionally, Flood-MAR presents a unique challenge because there needs to be understanding of operations for multiple purposes flood control, water supply, environmental protection, hydropower, among others.
8. Develop tools for multiple purposes/strategies. Existing models and tools for many reservoirs were designed for a specific purpose such as flood control, water supply planning, temperature management. These different purposes often require different logic, time-steps, and simulation periods, to name a few. Adequate tools that address multiple purposes are needed for analyzing Flood-MAR. In some cases, this may require using multiple or existing tools, or new tools with expanded capabilities.
9. Validate reservoir policies against out-of-sample data. Reservoir policies (e.g., flood pools) are often designed over a certain period of historical

record. But how well do they perform in other time periods? That answer has much relevance to climate change, where future flood events and snowmelt timing are likely to change significantly. Even a FIRO implementation designed to perform using an historical hydrologic data set, may not continue to perform well in the future with, for example, climate changed hydrology.

10. Improve real-time watershed attributes data. There is a need for better forecast and monitored information related to headwater hydrologic parameters. This includes forecast and monitoring of atmospheric rivers, snow pack, snow water content, vegetative cover, soil moisture. The improved resolution of information will result in the ability to retain more water in reservoirs. In general, reservoir operators know how much more water is needed; success relies on timing and knowing what is coming ahead for slower release.

Top Three Research, Data, and Tools Actions

The top three research, data, and tools actions, presented below, include a one sentence description, detailed description and connection to Flood-MAR, and implementation strategy, including a rough cost estimate.

Table 23 Action 1

Action 1 Description:
Develop an improved statewide water accounting, a common database set for water system modeling, and documentation standards to build an institutional infrastructure to support Flood-MAR and other innovations in California.
Description and Connection to Flood-MAR:
Develop an improved statewide water accounting to support the kinds of agreements and incentives needed for Flood-MAR, SGMA-related water plans, water markets, and enforcement of surface water rights. Build a common database set for water system modeling, including reservoir operations modeling, groundwater modeling, etc. This would include routine, systematic, and transparent procedures and responsibilities for updating these data sets and their documentation. Develop documentation standards for reservoir, groundwater, and water system models for use in Flood-MAR, SGMA, water rights, and water marketing agreements and plans.
Draft Strategy for Implementation:
Provide strategic funding to support both local incremental water accounting as well as a larger systematic statewide accounting system. The funding can range from $50,000 to $250,000 for smaller local studies and may reach up to $10 million for larger statewide studies. The effort should begin with assembling and prioritizing the existing studies and identifying the gaps where further research is needed. The water accounting system should work across all subjects of water management in California, including Flood-MAR, SGMA, and water rights. The system should give credit to farmers and reservoir operators engaged in Flood-MAR and other related activities.

Table 24 Action 2

Action 2 Description:
Extend forecast-informed reservoir operation (FIRO) to include operations for groundwater recharge, particularly for local and regional agricultural field and basin recharge opportunities.
Description and Connection to Flood-MAR:
Conduct regional or local FIRO studies having more reservoir operation and conjunctive use content in addition to hydrology forecasting to show benefits for both FIRO and non-FIRO operation strategies. Conduct research to estimate statewide and regional implications and impacts of local and regional FIRO operations. Determine value, costs, and barriers, as well as policy implications and opportunities. Estimate the value of additional storm event forecast information in terms of economic value and additional recharge volumes.
Draft Strategy for Implementation:
FIRO is being developed and tested as a collaborative effort by experts from several federal, state and local agencies, universities and others. Additional funding to include operations for groundwater recharge is needed, which may range from $5 million to $10 million. The FIRO Steering Committee will need to be expended to include expertise in land use, crops, soils, and groundwater subjects. The effort may take from two to five years.

Table 25 Action 3

Action 3 Description:
Analyze reservoir and broader water resources system to assess potential for shifting drought storage from surface water reservoirs to aquifers.
Description and Connection to Flood-MAR:
Conduct research to evaluate flood risk reduction benefits from lower drought storage levels in major reservoirs including an assessment of the relative likely flood and water supply benefits from systemic shift of drought storage to aquifers and storm capture from storm events. Assess statewide, regional, and local opportunities for improvements and costs (e.g., recreation and hydropower) to water supply and flood management for current and warmer climate conditions. Identify impediments to making such shifts. Estimate potential value of longer-term atmospheric river forecasts for reservoir operation to overcome the costs of false-positive forecasts.
Draft Strategy for Implementation:
Moving much of the drought water storage maintained in surface water reservoirs to currently empty space in aquifers would have many advantages, as well as some costs. The research may include a series of statewide, regional, and local assessments where the funding can range from $500,000 to $1 million for smaller local and regional studies and may reach up to $10 million for larger statewide studies. The effort may take from two to five years.