October 4, 2017

Response to 2016 Independent Peer Review of the Sacramento Water Allocation Model (SacWAM)

Background

The Sacramento Water Allocation Model (SacWAM) is a hydrologic and system operations model developed by the Stockholm Environment Institute (SEI) and State Water Resources Control Board (State Water Board) to assess the potential effects of revisions to instream flow and other requirements in the Bay-Delta watershed, including potential changes to the 2006 Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (2006 Bay-Delta Plan) resulting from the Phase II update of the Bay-Delta Plan.[1] The Phase II updated to the Bay-Delta Plan addresses requirements for flows and cold water habitat in the Sacramento River, its tributaries and tributaries to the Delta (the Mokelumne, Cosumnes and Calaveras rivers); Delta outflows; and water project operations in the interior Delta. A Fact Sheet regarding the Phase II update is available on the State Water Board's website here.

SacWAM may be used to estimate streamflows, reservoir storage levels, available water supplies, and related parameters to inform various types of analyses as part of the State Water Board's assessment of potential alternative regulatory requirements. Specifically, in updating the Bay-Delta Plan, the State Water Board must analyze the environmental, economic and related effects of potential changes to the Bay-Delta Plan and must ensure the reasonable protection of beneficial uses, which requires balancing competing beneficial uses of water. SacWAM and other models that utilize SacWAM modeling results will assist in these analyses and will inform the State Water Board in their decision-making on potential changes to the Bay-Delta Plan.

In the fall of 2016, the State Water Board released an early version of SacWAM for public review and review by an independent panel convened by the Delta Stewardship Council's Delta Science Program (DSP) to confirm the appropriateness of the model to inform the update of the Bay-Delta Plan. On October 7, 2016, State Water Board staff and the model development team introduced the SacWAM model (version 0.20) to the panel members. Presentations covered the development of the model, calibration, and validation of modeled flows, and operations. On October 19, 2016, a public meeting was held in which the peer review panel presented initial

[1] Phase I is addressing the protection of beneficial uses in the San Joaquin River watershed and southern Delta in a separate proceeding.

findings, asked additional questions, and engaged in a dialogue with the model development team and State Water Board staff and interested persons.

In late December 2016, the panel released its report (Report). The report states that "SacWAM is a complex model developed with a proven software tool (WEAP) that allows the creation of new scenarios for answering 'what-if' type questions and comparison of results to a base case. The Panel finds the SacWAM model to contain many advantages over CalSIM II for use as a water planning and management tool. The advantages of the SacWAM model include added non-project tributaries and operations, and finer spatial representation, which therefore allows for simulation of flow at locations not included in CalSIM II while maintaining fidelity to existing data representations and specific nodes of interest to the water management community." (Report, p. 10.)

While the panel found the approach taken with SacWAM generally appropriate, it raised issues regarding: the calibration and validation of the model, especially for low flow periods; needs for sensitivity studies and uncertainty analyses; needs for additional model enhancements and documentation; limitations of the model's representation of stream-aquifer interactions; and the temporal and spatial scales of the model. The Report included recommendations that the panel felt should be completed before the model is used for the Bay-Delta Plan update and those that could be delayed.

The State Water Board appreciates the time and insightful comments provided by the panel. In response to their comments several refinements have been made to SacWAM and its documentation, including extension of the model simulation period, recalibration of rainfall runoff processes, addition of upper watershed operations, inclusion of allocation logic for smaller projects, and additional sensitivity analyses and model validation. This response describes these changes and explains why other changes to the model and its documentation raised by the panel were not made. A detailed description of model updates is included in the SacWAM documentation in Appendix C.[2] In April of 2017, an updated version of SacWAM and its documentation that include the changes were completed (version 1.05) for use in the State Water Board's Scientific Basis Report in support of the Phase II update of the Bay-Delta Plan. This version of the model and its documentation are posted on the State Water Board's website. The Science Report that explains how the model was used is also posted on the State Water Board's website.

Responses to Panel Comments and Recommendations

1. Additional Calibration and Validation of the Model

The panel found that the model performs adequately when comparing long-term averages, but suggested that certain results may be biased by water year type. According to the panel, SacWAM estimates of net Delta outflow are high in drier years and low in wetter years, affecting the ability of the model to evaluate potential flows in extremely dry years when the environmental and economic impacts of potential Bay-Delta Plan flow requirements are likely to

[2] SacWAM documentation is posted at http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/sacwam/sacwam_documentation.shtml.

be most significant. The panel recommended including the most recent historical data through 2016 in the model to reflect how the system has been operated under existing regulations for a range of water year types, including a significant drought. In addition, the panel recommended an examination of wet and dry years separately to help determine the cause of the bias and adjust model parameters accordingly.

SacWAM v.0.20 simulated water management of the Sacramento Valley and Delta using the historical hydrology from October 1921 through September 2009 to represent the range of possible hydrologic conditions and the relative frequency of wet and dry years. While this period captures a wide range of conditions, including periods of severe drought, following recommendations from the SacWAM peer review panel, the model simulation period was extended. All unimpaired inflows, historical stream gauge data, historical reservoir storage data, and climate inputs were extended through water year 2015. Other model input data files (*.csv files) also were extended as needed. This included extension of water year types, inflow forecasts, and operational triggers. Extension of the simulation period to include water year 2016 was not feasible given time constraints and the lack of unimpaired inflow data at the time the model was updated (California Department of Water Resources (DWR) published data were available for water years 1922-2015).

The extension of the simulation period through 2015 facilitated model validation for the recent dry and critical years, addressing concerns raised by the peer review panel. Based on the Sacramento Valley 40-30-30 index, the extended 2010-2015 period contains two critical years (2014, 2015) following a below normal and dry year. Extension of the SacWAM simulation period also addressed another comment and recommendation of the panel that the model be validated by comparing model output with observed data. Comparisons between historical and simulated data for this period and a discussion of model performance during these years are presented in Appendix B (*Sacramento Valley Floor and Delta Calibration and Validation*).

2. Assumptions for Implementation of Future Regulations

The panel commented that as the State Water Board evaluates new flow and water quality requirements, the model should include logic as to the responsibility for meeting those requirements, including assumptions for contractual obligations, groundwater pumping, and reservoir storage. (Report, p. 13.)

The model includes reasonable assumptions for surface and groundwater use and reservoir management to evaluate the potential range of effects of changes to the Bay-Delta Plan, including changes to inflows, outflows, and cold water habitat requirements. However, it is not yet known precisely how new Bay-Delta Plan requirements will be implemented by water users for several reasons. First, the proposed changes to the Bay-Delta Plan provide flexibility in how the requirements are implemented through the allowance of voluntary agreements and other measures that meet the requirements. Agreements provide for creative problem solving and a variety of flow arrangements, including sharing of shortages in dry years for example. Second, changes to existing contracts will likely be needed but will need to be negotiated and those negotiations may not take place until changes to the Bay-Delta Plan are made. The State Water Board is not involved in contractual matters between water suppliers and their contractors. Lastly, water users have many tools to help them address shortages in supplies and will continue to develop new tools, particularly with new regulations. The modeling and analyses will evaluate a reasonable range of possible effects of the various alternative changes

to the Bay-Delta Plan and will acknowledge that the actual effects will depend on all of the above factors.

To the extent possible, the modeling analyses will generally assume that existing contractual provisions will continue, including provisions of DWR and the U.S. Bureau of Reclamation's (Reclamation) Coordinated Operations Agreement, since it is not known how exactly those agreements may change as the result of changes to the Bay-Delta Plan. In cases where it is not possible to meet the flow and cold water habitat requirements while also meeting the contractual obligations or agreements, the modeling will assume that these provisions may be relaxed in order to meet the Bay-Delta Plan requirements since that is a necessary precondition before making water supply deliveries for water right holders that have such obligations. However, the analysis will acknowledge that the distribution of the water supply effects may vary based on the above considerations.

The panel also suggested incorporating assumptions that account for operations under temporary urgency change petitions (TUCP) of water right requirements that were approved in 2015 (and 2014) in response to drought emergency conditions. The changes approved under the TUCPs during the recent drought are not generally reflective of baseline conditions. Such changes were only made under limited extenuating emergency circumstances and are not approved moving forward or likely to be part of a future regulatory regime and are thus not appropriate baseline assumptions. Instead, changes to the Bay-Delta Plan are proposed to include specific provisions for drought. Those provisions will be appropriately evaluated in the environmental analyses supporting the update to the Bay-Delta Plan.

3. Improvements to Stream-Aquifer Interactions

In SacWAM v.0.20, stream-aquifer interactions were based on annual correlations. The panel found that the "lumped parameter approach" simplified hydrology and had inherent limits for simulating extreme events. The panel recommended that a seasonal consideration be applied to reduce error and uncertainty. In addition, the panel recommended incorporating baseflows into Valley floor simulations to ensure that baseflows are adequately represented. (Report, p. 20.)

Following recommendations from the SacWAM peer review panel, groundwater inflow and outflow parameters were refined to capture the seasonal nature of the stream-aquifer interaction. Using the C2VSim simulated relationships, separate parameters were developed for October-December, January-March, April-June, and July-September periods. To better represent inter-annual variation of baseflows, groundwater inflow parameters are varied by Sacramento Valley water year type. These changes are discussed in greater detail in Appendix B, and in Section 6.3.1.3 of the SacWAM documentation.

Baseflows sustain surface water flows in streams and creeks during the summer and fall, particularly during dry and critical years. A representation of baseflows was already present in SacWAM version 0.20, which the peer review panel reviewed; however, this may not have been adequately explained to the panel. Minor changes were made to the parameters that govern baseflows based on the updated seasonal regressions from C2VSIM as suggested by the panel.

4. Additional Valley Floor Calibration and Validation

SacWAM represents water demands and water use on the Sacramento Valley floor using WEAP's catchment and demand site objects that are divided by land use type into agricultural, urban, and refuge areas. Valley watersheds are aggregated into Water Budget Areas (WBA) that generally represent the spatial resolution of DWR's land use and water use survey data.[3] This simplifies the generation of model input data and model validation through comparison with annual water budgets prepared by DWR for use in the California Water Plan. WBAs are subdivided into demand units (DU) that are computational units represented by WEAP catchment or demand site objects in SacWAM, and represent groups of water users who have similar land uses, climatic conditions, water delivery systems, and water use efficiencies. There are 78 agricultural catchment objects in SacWAM, defining most land use on the Valley floor.

a. Crop Demand Parameters

The panel commented on how Valley floor water diversions were corroborated with a focus on one rice parameter, and recommended including other demands to assist in defining uncertainty. The panel specifically recommended that crops and demands with large seasonal and inter-annual demands should be examined.

In response to the panel's comments, Appendix B was updated to include a comparison of simulated to observed surface water deliveries that account for 80 percent of the total simulated surface water diversions in SacWAM, which include deliveries to a variety of crops. These comparisons include: Anderson-Cottonwood Irrigation District, which is predominantly irrigated pasture; the Tehama-Colusa Canal service area, which includes a diverse mix of annual and perennial crops; and Yolo County Flood Control and Water Conservation District, in which alfalfa, grain, and tomatoes are the dominant crops. Additionally, many of the rice-growing irrigation districts also include significant areas of other crops. For example, Glenn-Colusa Irrigation District's service area includes approximately 20 percent of "other" crops and Yuba County Water Agency's service area includes 34 percent of other crops.

b. Evapotranspiration

The SacWAM water demand estimation component is based on the methodology for estimating water requirements presented in the publication from FAO 56. (Allen et al. 1998.) The panel noted that "the water demand estimations of FAO 56 are scientifically sound and adequate for the planning purposes of SacWAM…." (Report, p. 18.) The panel cited additional and updated work related to Valley floor evapotranspiration (ET) for the State Water Board's consideration. The panel also commented that Valley floor ET was compared to the DWR CUP (consumptive use program) work, but only a single example was provided in the documentation. The panel noted that a more thorough evaluation should be shown in the documentation and a comparison with more recent measurements and analysis of ET in the Valley would better define the uncertainty.

In response, the discussion of ET in Appendix B has been updated to include comparisons of SacWAM ET with estimates from other sources. This includes comparisons with DWR county-

[3] DWR conducts regular land and water use surveys for use in statewide water planning efforts through its Land and Water Use Program (http://www.water.ca.gov/landwateruse/index.cfm).

level data developed by DWR's regional land and water use specialists and crop ET values used in the C2VSim model. Additionally, SacWAM simulated reference ET (ET_o) is compared to reference crop ET determined using observed data at CIMIS agro-meteorological stations. Section B.2.2 of the SacWAM documentation includes a discussion of this issue.

5. Improvements to Upper Watershed Functionality

SacWAM has two possible modes to simulate upper watershed input hydrology. SacWAM can calculate the input hydrology based on climate inputs, or users can select preprocessed hydrology developed by DWR. In both modes, upper watershed reservoirs, interbasin transfers, and other operations are dynamically simulated.

The panel indicated that additional corroboration and calibration should be performed prior to the use of the SacWAM upper watershed functionality. We understand the term "upper watershed functionality" to refer to SacWAM's ability to simulate upper watershed hydrology as a function of climate data. For Phase II, State Water Board staff plans to use preprocessed unimpaired upper watershed hydrologic inflows developed by DWR. Accordingly, no additional work was needed to address this comment at this time.

6. Sensitivity Analyses

The panel commented that sensitivity analyses should be conducted on variables "where mostly default values have been applied." In particular, they noted that since SacWAM does not include feedback from the San Joaquin River system, sensitivity to changes in the San Joaquin boundary condition should be better understood. Additionally, the panel recommended sensitivity analyses on parameters that may be manipulated in Phase II modeling scenarios, suggesting in particular that "various WSI-DI [water supply index-delivery index] curves should be included in the sensitivity analysis." (Report, p. 21.)

In response to these comments, model sensitivity analyses were conducted and are presented in Section B.10 of Appendix B. As recommended by the panel, the sensitivity of model flows and storage to assumed flows on the San Joaquin River at Vernalis was tested. In addition to that test, a comparison of crop ET rates from different data sources was presented, as discussed above.

In SacWAM, a water supply index (WSI) is a conservative estimate of the water available to the Central Valley Project (CVP) or State Water Project (SWP) (collectively Projects) to be shared among different uses, including deliveries, flow requirements, and carryover storage. WSI-DI curves relate this estimate of total water availability to a demand index (DI), which provides an estimate of the water available for deliveries and carryover storage after other obligations have been met. Annual allocations are then determined using logic in the model that balances deliveries with carryover storage. In CalSIM modeling studies, WSI-DI curves are generated using an optimization procedure intended to minimize the differences between the annual quantities of water allocated and actually delivered within the model over the full period of simulation (see Sections 7.2.1.4 and 7.2.1.9 of the SacWAM documentation for further discussion of WSI-DI curves and Project allocations).

SacWAM will be used in a comparative manner to assess a broad range of alternatives under which deliveries may change substantially due to additional demands on the system, including new or revised instream flow requirements and additional carryover storage requirements. Use

of WSI-DI curves and delivery-carryover relationships developed for existing conditions would not reflect the additional demands on the system and are therefore unlikely to be appropriate for simulating Phase II alternatives. Therefore it will be necessary to develop new methods to assess the water available to the Projects and the balancing of deliveries and carryover storage. This issue will be further evaluated in the environmental review process for Phase II. That review may include sensitivity analyses to evaluate this issue further.

7. Operational Verification

The panel noted that the SacWAM approach to validating operations is a "good first step" but advised the State Water Board to consult with experts in order to determine if the model is performing in a realistic manner. (Report, p. 19.)

The representations of local water supply infrastructure and operations have been improved following comments by the panel and discussions with local water supply operators. The schematic in the upper watersheds was modified to include some additional storage reservoirs and operations of the upper watershed reservoirs were also modified to be more realistic. A complete description of these changes is provided in Section C.6 in Appendix C.

Appendix A of the panel's Report identified an error in the modeling, largely caused by the settings in the model. For the model run used to generate results for the peer review panel, certain constraints and logic in the model were inactivated. This error has been corrected and the operations of Contra Costa Water District's Los Vaqueros Reservoir are now much more realistic. A full report on the changes made to this portion of the model is contained in Section C.6.15 of Appendix C.

Additionally, since the peer review process was initiated, the model development team has met with experts in the operations of several local water supply projects to better understand and reflect those operations in the updated model. A full report on the changes to specific projects within the model is contained in Section C.6 of Appendix C.

8. Monthly Time Step

The panel noted that the monthly time step used in the model is "as good as what has been available to date" but may not be useful for modeling functional flow concepts being articulate in the proposed Bay-Delta Plan amendments. (Report, p. 19.) The monthly SacWAM simulated flows can be post-processed for other analyses as appropriate. However, a monthly time step is appropriate for most, if not all, of the needed analyses to support the Phase II update of the Bay-Delta Plan. This issue will be further addressed in the environmental and other documentation is support of Phase II. Although the revisions to the Bay-Delta Plan may include adaptive management of flows in a manner that is protective of fish and wildlife, SacWAM is not currently intended to be used to assist with adaptive management or the development of functional ecological flows.

9. Ease of Use

The model development team and State Water Board staff appreciates the panel's concerns regarding the usability of the model for casual users. The panel noted that the ease of modifying scenarios is a "great strength" of SacWAM; however, raised concerns that the model requires extensive post processing, expertise in the model may be required since the model is

not necessarily intuitive, and the model is "occasionally buggy." (Report, p. 21.) The panel also expressed concerns about the required use of a commercial numerical solver. (Report, p. 12.) The panel found that "WEAP provides a better scenario comparison tool than CalSIM II; however, the SacWAM application is highly detailed and consequently the tool often takes considerable computer resources and time to generate comparisons, and differences between scenarios can be difficult to track." (Report, p. 14.)

The model development team agrees that SacWAM is a complex model, as it must be to represent the complex physical and regulatory reality that is water management in the Bay-Delta watershed. However, in developing the model, every effort was taken to make the model transparent and usable. Parameters that most users are likely to wish to modify are located in the model Key Assumptions, and are well documented in the SacWAM documentation. All logic related to operations of the CVP, SWP, and local water supply projects is easily found in the data tree. All aspects of the model have been documented in a way that facilitates searching for information. Chapters 4 through 9 of the model documentation are structured so that the table of contents displayed in the navigation pane of the document is aligned with the data tree of the model. This greatly facilitates navigation through the document.

A fully-functioning version of WEAP software for use with SacWAM is now freely available to the public. Additionally, the development team is working to use a free, open-source solver in SacWAM. However, because of the large computational requirements of SacWAM, commercial solvers currently remain the only feasible option to solve the complex series of equations. WEAP model results may easily be exported to Microsoft Excel or CSV files for further analysis, either manually or using automated scripts. Additionally, recent modifications to WEAP include the ability to export selected model results to HEC-DSS.

The WEAP scenario analysis is based on the concept of inheritance in which a scenario inherits all of the properties of a 'base' model run. Model users subsequently modify particular input data, model priorities, properties, or constraints to define an alternative scenario. The difference between a base run and a scenario may be rapidly determined by exporting the model data tree to Excel. Only differences between the scenario and its base are listed.

10. CalSIM II

The panel included a discussion about CalSIM II, how it relates to SacWAM, and the importance of maintaining synchronization as the two models continue to evolve. (Report, p. 14.) The panel notes "[a]gencies involved with project operations are more likely to maintain their use of CalSIM II and any future versions, i.e. CalSIM III[4]…[and] could obviate SacWAM utilization or run counter to SacWAM results."

Both SacWAM and CalSim II/III use mixed integer linear programming to simulate water management operations. In many cases, this allows CalSim code to be easily reproduced in SacWAM using WEAP's User-Defined Constraints. However, differences in the solution algorithm prevent CalSim's system of weights, penalties, and objective function to be implemented directly in SacWAM. Additionally, SacWAM's ability to short demands and define

[4] CalSIM III is an update to the CalSim II model in development by DWR.

an explicit set of demand priorities makes some operational scenarios difficult to reproduce in CalSim. With a clear understanding of the operational objective and some ingenuity, similar circumstances can be reproduced with both models.

Advances and refinement of CalSim can be readily identified using third party tools to highlight changes in text-based input files. Similarly, changes to SacWAM are tracked automatically by the WEAP software and written to WEAP's "changes.txt" file. Good model documentation would facilitate tracking of model refinements. Unfortunately, this has been absent in past CalSim model development.

Since merging DWRSIM and PROSIM into a single model (CalSim II), DWR and Reclamation have often stated that benefits of a single model include greater efficiency and elimination of duplicative efforts by the two agencies. However, different models of California's water resources allow a particular model to be selected for a particular objective. CalSim II has been developed for performing planning studies relating to CVP and SWP operations. SacWAM has been developed for a broader objective of analyzing potential impacts of new regulatory requirements on all water users in the Sacramento Valley and Bay-Delta watershed. Having more than one system model allows greater scrutiny of model performance and results, facilitates model review, and is likely to lead to improvements in both models.

Conclusion

Understanding the adequacy and limitations of the model is important. As the panel explained in its initial findings and recommendations, "all models are wrong but some are useful." (SacWAM Independent Science Review Panel, Initial Findings and Recommendations, October 19, 2016 [citing George E.P. Box].) Computer-based modelling should be used to enhance, but not fully replace mental models and real decision-making. (Id.) For the purpose of the Bay-Delta Plan Update, SacWAM results are believed to be more reliable in a comparative study than an absolute study. Model errors, introduced through necessary simplification of the real world and which render absolute analysis unreliable, are assumed to be independent of the scenario being considered, so that these errors will largely cancel out in a comparative analysis. In addition to the many refinements made to date to SacWAM and the model documentation, State Water Board staff will continue to make improvements to the model in light of the panel's observations.

References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Rome. http://www.fao.org/docrep/x0490e/x0490e00.htm. Accessed July 2016.