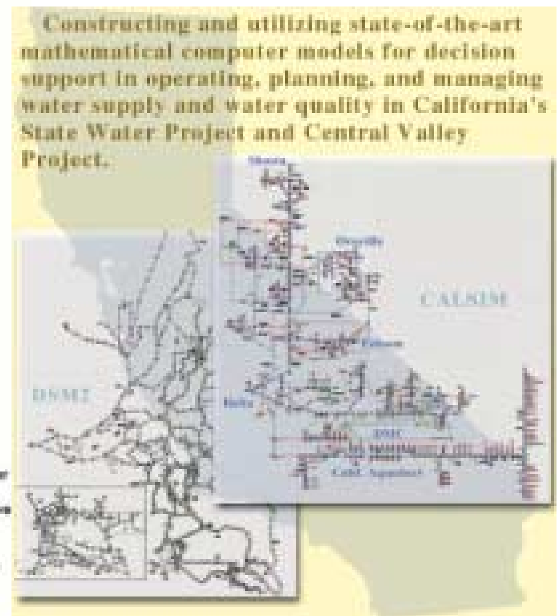
G. CALSIM II PEER REVIEW REPORT AND THE DEPARTMENT'S RESPONSE

A Strategic Review of CALSIM II and its Use for Water Planning, Management, and Operations in Central California



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by

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Executive Summary

1. Summary

The central all-encompassing question put to the panel is whether the CALFED program has adopted an appropriate approach to modeling the CVP-SWP-Central Valley system. Is the general CALSIM modeling approach appropriate for predicting the performance of the general facilities and for use in allocation planning, assessing water supply reliabilities and for carrying out operational studies? We believe the use of an optimization engine for simulating the hydrology and for making allocation decisions is an appropriate approach and is in fact the approach many serious efforts of this kind are using. It is a substantial improvement of the previous modeling approaches and provides a basis for consensus among federal and state interests. The modeling approach addresses many of the complexities of the CVP-SWP system and its water management decisions.

There exists a common tension between those who wish for greater detail and those who want less detail from the model. This argues for a more comprehensive, modular and flexible approach than is now available. In this report we suggest some ways this might be accomplished in the future. We also propose some management procedures that could be considered to improve model and model application quality control and documentation. The openness and availability of the model is admirable and very important given the numerous stakeholders who have interests in the management and allocation of water in the state. To increase the public's confidence in the many components and features of CALSIM II, we suggest that these components of CALSIM be subjected to careful technical peer review by appropriate experts and stakeholders.

2. Background

The California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (USBR) have developed a computer model called CALSIM II that simulates much of the water resources infrastructure in the Central Valley of California and the Delta region. This infrastructure is referred to as the CVP-SWP system. In particular CALSIM II provides quantitative hydrologic-based information to those responsible for planning, managing and operating the State Water Project (SWP) and the federal Central Valley Project (CVP). As the official model of those projects, CALSIM II is the default system model for any inter-regional or statewide analysis of water in the Central Valley of California.

CALSIM II has a central role in the analysis of many CVP-SWP and related issues, some of which require capabilities beyond those included in the model. California needs a large-scale relatively versatile inter-regional operations planning model and CALSIM II currently serves that purpose reasonably well. As the primary State and Federal-sponsored model available for water operations and planning, CALSIM II is critical to the study of many technical and policy issues related to water supply reliability, environmental management and performance, water demands, economics, hydrology and climate, and regulatory compliance.

CALSIM II is a particular application of the California Water Resources Simulation Model called CALSIM. It uses a mixed integer linear programming model solver to route water through a network over time. Currently it uses monthly time steps. Policies and priorities are implemented through the use of user-defined weights applied to the flows in the system (represented by arcs of the network). Simulation cycles at different temporal scales allow for successive implementation of constraints. The model can simulate the operation of relatively complex environmental water accounts and state and federal environmental regulations. In our judgment CALSIM II represents a very impressive modeling effort on the part of all those involved with its development and application.

The CALFED Science Program commissioned this external review panel (Appendix D) to 1) provide an independent analysis and evaluation of the strengths and weaknesses of CALSIM and CALSIM II, and 2) to offer suggestions on the appropriate uses of these modeling tools, on ways their use might complement or be complemented by other models, and on further development, quality assurance, and use in major water systems operations and planning in California.

The panel received background documents (Appendix B), including a survey by the University of California at Davis of stakeholder responses to questions about CALSIM II. We subsequently met for one and a half days in Sacramento for discussions and presentations (Appendix A) by CALFED, DWR and USBR staff. The discussions concluded with a summary presentation by the panel outlining our tentative conclusions.

The information we received and the shortness of our meetings with modeling staff precluded a thorough technical analysis of CALSIM II. We believe such a technical review should be carried out. Only then will users of CALSIM II have some assurance as to the appropriateness of its assumptions and to the quality (accuracy) of its results. By necessity our review is more strategic. It offers some suggestions for establishing a more complete technical peer review, for managing the CALSIM II applications and for ensuring greater quality control over the model and its input data, and for increasing the quality of the model, the precision of its results, and their documentation.

In this review we were asked to address the following questions:

1. Is CALSIM a reasonable modeling approach for current and proposed applications and problems?
2. Do other modeling approaches show similar or greater promise and flexibility for such problems? If so, how?
3. What are the major comparative strengths and weaknesses of the current CALSIM approach and alternative approaches?
4. What are major scientific, technical, and institutional limitations, uncertainties, and impediments for current and proposed applications of CALSIM?
5. What model, software, and data developments, special studies or tests would be beneficial to improve CALSIM for current and proposed uses?
6. How might CALSIM development and applications be managed and overseen to improve the quality assurance of model results for current and proposed applications?

7. What are your suggestions for long-term use, development, or replacement of the current suite of models and data available for the current and proposed uses of CALSIM?

The following sections of this summary present our responses to these questions. The main parts of this report and its appendices provide additional detail.

3. CALSIM Modeling Approach

CALSIM II is a simulation model developed as a joint venture between the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (USBR) to (i) provide a significant modernization and upgrading of the DWRSIM and PROSIM models developed and used by these organizations, (ii) develop a comprehensive modeling system that simultaneously addresses the current and future needs of both the SWP and CVP systems; and (iii) develop a generalized modeling system that could be applied in any river basin system, in contrast with the previous models that were less generalized and more specifically designed for the existing SWP and CVP systems. In this respect, CALSIM II represents a state-of-the-art modeling system that is similar in general concept, while differing in specific details, to other data-driven river basin modeling systems such as ARSP, MODSIM, OASIS, REALM, RiverWare and WEAP.

CALSIM uses linear programming to solve sets of equations that simulate water movement through the CVP-SWP system in accordance with various objectives and constraints. This is a modeling approach which has been used successful in California (Johnson et al., 1991). In a complex system such as that being modeled, it is essential to have some mathematical representation of system flows that reflects all of the interconnections and constraints. Use of an optimization algorithm allows good decisions to be identified from among all possible and feasible decisions. To the extent this simulates what actually occurs, it is a good modeling approach. To the extent it optimizes when in reality no such optimization is implemented, it has the potential to produce inaccurate and overly optimistic outputs.

Most successful applications of optimization that attempt to simulate the behavior of a system have calibrated their objective functions (i.e., set the weights that prioritize flows over time and space) so that the model results correspond to what actually happens or would happen under a particular hydrologic and demand scenario. In these cases the model's decisions correspond to those the operators would make, as often prescribed by rules that have been worked out in a legal/political process. It does not appear that such a calibration of the objective function weights in CALSIM has yet been completed.

4. Other Modeling Approaches

There are two aspects of modeling, the model structure and algorithms used, and the model software. The use of linear optimization algorithms to solve simultaneous equations for simulating hydrology is a common way of avoiding a typically long list of procedural rules for simulating regional water systems. Such sets of procedures can be difficult to generate for complex systems, and very different and new rule sets may be needed if structural or significant policy changes are to be investigated. In addition the performance of the system when simulated will be less than that which can be achieved in practice if a good set of rules is not provided. Optimization models are generally easier to reformulate when system changes are to be investigated. However unless the optimization is calibrated in such a way as to actually resemble what takes place in practice it can produce an optimistic description of system performance. This is particularly true if the optimization model is allowed to have perfect foresight of future events that in practice would not be available to system operators.

Large simulation models using optimization and procedural rules both need to have internal checks to ensure to the extent possible that errors in mass balances, for example, do not occur due to errors made when the model is being defined or created. Such internal checking is not apparent to us in our admittedly brief review of CALSIM II. Nor were calibration procedures well defined.

One obvious limitation of using linear optimization procedures is its inability to model accurately and efficiently some of the non-linear hydrologic and decision processes that occur in systems as complex as the CVP-SWP. One approach to addressing this issue of model accuracy, and possibly for decreasing the computational time as well, is to link linear optimization models to non-linear simulation models in a way that permits the simulation to represent the hydrology in any spatial and temporal detail desired. The optimization is used to determine what the decisions should be at every site where a water allocation, reservoir release, or other management decisions must be made. The time steps for simulation could be daily, or weekly or longer, depending on the needs of the user, but would likely be of shorter durations than the optimization time steps. After a predetermined number of simulation time steps, the optimization model would be run. The initial state of the optimization should be set at the beginning of each optimization time step. The optimization component should include multiple future time periods, with imperfect hydrologic and demand forecasts, but once solved only the current period's solutions are implemented – i.e., these decision variable values are sent to the simulation component. The decisions indicated for future periods are ignored. When appropriate, the initial state of the multi-period optimization model is updated and the model is again solved. And so on. Such a modeling approach may prove to be both more realistic, more accurate, and require less time, once developed. We believe such an approach might be worth considering for future development.

CALSIM II currently consists of a combination of software modules developed in several languages, including FORTRAN, Java and C. Several of the modules require proprietary software packages in order to run CALSIM II (Lahey FORTRAN and XA Solver). DWR and USBR staff have said that these components are being replaced by public domain software that can be obtained free of charge. We agree with this decision. Very good public domain software packages of optimization, visualization, file management, and data base support are currently available, and new ones will continually be produced. Periodic updates should be anticipated as part of the business of maintaining the modeling system.

Significant thought should be given to the sustainability of the CALSIM II software. How will future programmers be able to maintain this software? How will future software developments be incorporated into the system? Will the solver currently being developed by LBNL be adequate in terms of accuracy and computation speed? Will other solvers need to be tested? Can the system accommodate these future developments without major modifications? What reasonable modifications could be made now in anticipate of future developments?

5. Comparative Strengths and Weaknesses

Many of the stakeholder perceived strengths and weaknesses of CALSIM and CALSIM II are very well identified in the survey report from the University of California at Davis (Ferreira, et al. 2003). Our background materials and briefings covered various strengths and weaknesses, but without first hand experience, all we can do here is to summarize those that we have heard expressed by others.

Here we provide a brief summary list.

5.1 Some Prominent Strengths

The strengths of CALSIM II are many. Most are expressed in comparison to previous DWRSIM and PROSIM models DWR and USBR were using. Some of these strengths include:

- Consensus model. CALSIM II is the official joint modeling environment of the State DWR and USBR. This includes a common schematic, hydrologic representation of the system, common set of facility capacities, and common representation of system operating policies. This helps all parties improve representations, rather than compete over representations.

- Common effort. The joint development of CALSIM II by USBR and DWR has provided more focused and effective use of resources and expertise than previous development of agency-specific models. CALSIM II development has also involved other agencies and consulting expertise more than pervious models of this system.

- Data-driven model. CALSIM II is a rather data-driven simulation model with an optimization engine. This modeling approach provides:
    a. greater flexibility than its predecessors and traditional water resources simulation approaches.
    b. a promising framework for improving transparency, data, and model documentation, compared to other approaches.

- Public domain. The model and data are substantially in the public domain, facilitating transparency and adaptability for California's decentralized water system.

- Steady improvements. Data improvements have been steadily pursued following the adoption of CALSIM II, although deficiencies remain.

- Improved Delta water quality representation. Although problems appear to remain, the model developers have made substantial gains in representing Delta water quality operating criteria and performance.

- Better groundwater representation. Efforts to better include groundwater and non-CVP-SWP project operations merit continuation and expansion.

- Benchmark Studies. The development of documented benchmark studies have resulted in significant model improvements and aided in the development of comparative model applications. Such exercises should be continued and improved.

- Long-term vision. The vision of a more transparent and publicly available model that can be employed by those outside the major agencies is excellent. This is a major change in direction, and achieving this vision will require adjustments over time. Often, these adjustments will be externally driven. Externally-driven improvements are a price of success and evidence of success for an open, public, modeling policy.

- Important CALSIM II features:
    a. CALSIM II is able to simulate the operation of the complete CVP-SWP system in all areas that contribute flow to the Delta in monthly time-steps.
    b. CALSIM II is being applied to examine a diverse range of options including flood control, water conservation and supply, power generation, recreation, water transfers, groundwater banking, recycling, desalination, conjunctive use, the purchase of options and streamflow and water quality protection.
    c. CALSIM II has successfully been applied by both DWR and USBR to examine both structural and non-structural changes to the CVP-SWP system as well as to ascertain the risks involved with different potential operating scenarios and to quantify the impacts of proposed actions.
    d. CALSIM II can dynamically model operation of environmental water accounts.
    e. Demands may vary according to various levels of development (e.g. 2001, 2020) and to hydrologic conditions.
    f. The regulatory environment under which the projects must operate can be simulated.
    g. CALSIM II can link to external modules as needed, e.g., to estimate the salinity at water quality stations within the Delta.

5.2 Some prominent weaknesses

As its strengths are many, so are its weaknesses. It seems worth saying, however, that no model can perfectly (meaning efficiently and effectively) serve all interests in a system as complex as the CVP-SWP. Tradeoffs need to be made. This can result in what some would call weaknesses. Such weaknesses are often accepted to gain strengths in another ways.

We heard that the CALSIM II model was too complex. We also heard that it did not handle particular components of the system with sufficient detail. And such is the dilemma of any complex model, such as CALSIM II. The model is clearly too complex, and not complex enough. The root of this difficulty is that when such a model is constructed, it is not clear what level of detail is needed, so the model must be made sufficiently complex to ensure it is complex enough. And the complexity needed to address some issues will remain in the model when it is used to address other less complex issues, or the same issues at less complex locations. One approach to addressing this issue is to develop different linkable modules of CALSIM II having different complexities. In this way the level of detail can be varied to be consistent the application or study at hand, and level of sophistication and resources available to the user.

Other weaknesses model users would like addressed include:

- The model provides limited and inadequate coverage of non CVP or SWP water and of the California water system south of the Delta.
- The model assumes that facilities, land-use, water supply contracts and regulatory requirements are constant over this period, representing a fixed level of development rather than one that varies in response to hydrologic conditions or changes over time.
- Groundwater has only limited representation in CALSIM II.
- Groundwater resources are assumed infinite, i.e., there is no upper limit to groundwater pumping.
- The linear programming model considers only the current month, and hence CALSIM II operating rules are required to determine annual water allocations, to establish reservoir carryover storage targets, and to trigger transfers from north of Delta to south of Delta storage.
- Better quality control is needed both for the model and its current version and the input data. Procedures for model calibration and verification are also needed. Currently many users are not sure of the accuracy of the results. A sensitivity and uncertainty prediction capability and analysis is needed.
- Need improved ways of altering the model's geographic scope and resolution and its temporal resolution to better meet the needs of various analyses and studies.
- Need to improve the model's comparative as well as absolute (or predictive) capabilities.
- CALSIM II needs better capabilities for analyzing economic, water quality, and groundwater issues.
- Need improved documentation explaining how the model works, its assumptions, its limitations, and its applicability to various planning and management issues.
- DWR and USBR have not provided a centralized source of support for CALSIM II. More training for CALSIM II is needed. There is a need for more people who can run CALSIM II. There is a need for a well-publicized user group. A more extensive users' guide is needed.
- Improved capabilities are needed for real-time operations especially during droughts, gaming involving stakeholders during a simulation run, handling of evapotranspiration and agriculture demand changes over time, water transfers, Delta storage, carryover contract rights, refuge water demands and more up to date representation of Feather River, Stanislaus River, Upper American River, San Joaquin River and Yuba River operations.

- Need an improved graphical user interface to facilitate input of model data, setting of model constraints and weights, operating the model, and displaying and post analysis of model results.
- Need to be able to change the model time period durations for improved accuracy of model results.

6. Limitations, Uncertainties, and Impediments

6.1 Absolute Values or Comparative Results

Modelers sometimes make a distinction between the use of a model for *absolute* versus *comparative* analyses. In an absolute analysis one runs the model once to predict an outcome. In a comparative analysis, one runs the model twice, once as a baseline and the other with some specific change, in order to assess change in outcome due to the given change in model input configuration. The suggestion is that, while the model might not generate a highly reliable absolute prediction because of errors in model specification and/or estimation, nevertheless it might produce a reasonably reliable estimate of the relative change in outcome. The panel is somewhat skeptical of this notion because it relies on the assumption that the model errors which render an absolute forecast unreliable are sufficiently independent of, or orthogonal to, the change being modeled that they do not similarly affect the forecast of change in outcome; they mostly cancel out. This feature of the model is something that would need to be documented rather than merely assumed.

In our opinion CALSIM II has not yet been calibrated or validated for making absolute predictions values. Yet it is apparent that there has been a distinct need by model users for absolute predictions. In the absence of alternatives, users are adopting CALSIM II results as the best absolute prediction available and they are likely to continue to do so. We recommend that model developers recognize the requirement for CALSIM II to provide absolute predictions. To satisfy this new purpose, additional calibration of the model will be required to ensure that the output it produces is fit for this purpose. Regardless of how possible it is to match the model closely with observed behavior, statistics on the accuracy of the calibration run should be supplied to users to enable them to gauge the likely errors involved with using the model output.

6.2 Sensitivity and Uncertainty Analyses

Sensitivity analyses would be useful to identify which parameters and input data have major impacts on decisions and system performance criteria of concern. Uncertainty analyses would help users of the model understand better the risks of various decisions and the confidence they can have in various predictions.

6.3 Graphical User Interface

Having a graphical user interface would substantially aid those who use the model in managing both input and output data, and in controlling or managing model operations. This model will not likely become as available to and as well understood by the public, to the extent desired by the model developers, until an effective menu-driven GUI has been created that can help create and draw from a database of system parameters and characteristics, and simulation results.
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6.4 Documentation and Training

When if ever is adequate documentation and training available? Rarely, but we believe there is a serious need to improve the documentation as well as the training available for all those interested in using CALSIM II.

7. Options for Improving CALSIM

7.1 CALSIM Model Software

We encourage the developers of CALSIM to convert their present software to that which is publicly available and to develop a useful graphic based user interface that can facilitate the input, editing, and display of all the data that are input to and output from CALSIM II. There are many options, some of which we have discussed with the model developers.

The CALSIM package should be made more modular and capable of linking to other more complex models of components of the CVP-SWP system. If the changes in code and modeling approach result in a quicker running model, it might be possible to link, when desired, modules that facilitate position analyses and other types of uncertainty analyses. A modular system would allow alternative representations of different components of the system. Thus different levels of spatial detail, or representations of the fundamental processes, would be allowed within the overall system representation and record of California hydrology. This will allow the use of more general and streamlined models for use of preliminary investigation and general planning, as well as a more detailed representation of the system for final analyses and more detailed studies. This would be very useful.

7.2 Sensitivity and uncertainty analyses

Both sensitivity analyses need to be performed, and procedures need to be developed to enable the estimation of measures of uncertainty associated with model output. Perhaps workshops focused on just these needs should be scheduled to better determine how best to meet these needs. There are numerous procedures available that could be applied. Appendix H contains some approaches for performing sensitivity and uncertainty analyses.

7.3 Model calibration

There is a need to develop the model so that it is able to provide absolute estimates of key model outputs rather than limiting the use of the model to comparative studies. One way to do this is to subject the model to a comprehensive calibration process where it is fine-tuned until it is able to reproduce the historical behavior of the system with sufficient accuracy to provide absolute results. The calibration of the model should aim to test all the key outputs of model including water quality in the San Joaquin River and in the Delta. It is necessary to test the monthly values of outputs for those outputs for which the monthly pattern is important.

7.4 Other extensions and improvements

- The opportunity of improving the collection of data on the use of water (preferably broken down by irrigation district and water source) should be investigated. The use of groundwater should be included in this investigation.
- It would be useful to expand the geographic extent of the model so that it includes all the components of the linked water supply system, including both the San Joaquin and Tulare Lake Basins of the Central Valley. The model should also account in some manner for imported supplies of water to users in southern California from the Colorado River.
- The linkage between surface water and groundwater would appear to be of critical importance and output that would enable the impact of surface water use on groundwater extractions would appear to be useful.
- Examination of the report *'CALSIM II Simulation of Historical SWP/CVP Operations',* DWR (2003) indicates that the current formulation of CALSIM II:
    - Overestimates water deliveries to SWP and CVP contractors,
    - Determines carryover storage target values that differ from those the operators have determined in the past, and
    - Operates the San Luis Reservoir at lower levels and fills it later in the season than operators have in the past.

8. Managing CALSIM Development and Applications

The predicted impacts and other information derived from CALSIM II applied to the CVP and SWP can influence major investment decisions. It is thus self evident that those who use the model results need to have some confidence as to their precision. Is the science behind the information derived from CALSIM II been reviewed and judged correct? Is the model software free from errors? Are the assumptions made when performing the modeling the correct ones? Are the model results accurately and fully reported? In other words, just how much credence should decision makers place in the model output? Users of the model results should be assured that they are credible and unbiased. One way to help ensure this is to have the models, their associated software, and their applications under the control of some interagency organization that can oversee and provide quality control over model development, application and documentation. They can also plan and implement needed peer reviews.

One possible means of facilitating the peer review processes and for maintaining control on the particular versions of CALSIM II and accompanying models used for CVP-SWP planning and management decisions is to create an interagency modeling consortium (IMC) consisting of DWR, USBR, and other stakeholder organization (including university) personnel if they are interested and want to participate. This center would be responsible for maintaining a toolbox of 'acceptable' models for use by the agencies and contractors. The models placed in the toolbox should be peer reviewed with respect to their applicability and suitability for use in particular applications. Those that are not peer reviewed should be considered for peer review. New models proposed for use in California should be peer reviewed with respect to their suitability, and for their strengths and limitations, before being placed in the toolbox. The review should be of the theory underlying the model, the model's software, the documentation of the model as well as of its software, the model's functions and capabilities including those pertaining to model data input and output, the input data themselves, model calibration and verification, capabilities for sensitivity and uncertainty analyses, user control of all model operations including pre and post analyses (GUIs), spatial and temporal resolutions, and its limiting assumptions.

9. Future Use, Development, or Replacement of CALSIM

9.1 A coupled optimization simulation approach

Given a system as complex as the SWP/CVP system, it seems to us it might make sense to consider the development of a more detailed simulation 'engine' and couple it to an optimization or management 'engine'. The simulation component can more accurately model hydrologic processes. For example it can include the deterministic non-linear routing of flows and their quality constituents through the system on a smaller time step (e.g., daily) and hence much more realistically or accurately, than can linear optimization using longer time steps, even with all the known tricks for linearizing separable (single variable) non-linear functions and 'if-then-else' statements. The simulation engine itself may require a simultaneous equation solver, especially for the Delta. But the simulation engine needs to know what to do, i.e., what decisions to make. Periodic use of the optimization, say once a week or even less frequently if conditions are relatively constant, for determining the decisions to be simulated, e.g., the water allocation and reservoir release decisions, eliminates much of the maze of rules that otherwise would be required and which developers of CALSIM II are avoiding through the use of optimization. Each time the optimization or management 'engine' is run it is first updated with the current state of the system as determined from the more precise simulation 'engine'. The optimization component would include multiple time periods only to the extent that the current period's solution is not affected by the time horizon in the optimization. The other time period solutions are ignored. This coupled optimization-simulation approach has the potential to be both more accurate as well as quicker to execute. In our opinion it is worth considering for future development.

9.2 Models as hypotheses

CALSIM II is really about the future, not the past. Benchmarking studies can help establish the credibility of the model and provide estimates of its accuracy by comparing its performance to actual historical operations. A concern is how well the model reproduces historical operations, not whether it is valid or invalid on some absolute scale of perfection. But the real issue is how well CALSIM can predict what might happen in the future with sets of hydrological and meteorological conditions that have not yet been experienced, and may be significantly different from the past if climate variability and climate change are considered. In these cases the ability of the model to forecast what will happen depends both upon its ability to describe what would happen should a particular system operating policy, priorities and water demands be adopted. In this sense CALSIM II modeling studies should be thought of as the exploration of a hypothesis that particular policies and priorities have been adopted. Our ability to predict the future has generally been poor, but it is the obligation of agencies such as DWR and USBR to attempt to ensure that should water demands, water supplies, and water policies evolve as one would expect, society is prepared for the consequences. And that would seem to be what CALSIM II is about.

9.3 Future Model Development and Use

From the list of perceived weaknesses above, there are clearly many opportunities for further refinement of CALSIM II. Rather than attempt to meet all needs using only one model, namely CALSIM II, it seems preferable to improve its adaptability to various levels of detail through its ability to link to other models when additional detail in a particular region or for a particular feature is desired. For example, the monthly time step used by CALSIM II is sufficient for many studies. Yet some seasonal (multi-month) decision making is needed in CALSIM II to reflect decisions made by the SWP and CVP as to what Table A and other allocations to honor in full. On the other hand, it is clear that many water quality and ecosystem management decisions would profit from more detailed weekly or daily time steps. However, such shorted time-step models will need the guidance of a longer time-step model. As discussed earlier, models with shorter time scales can require increased spatial resolution, both of which lead to increased model complexity and a strong argument for model modularity.

Additional potential applications of CALSIM II include operational planning using gaming, or the involvement of potential decision makers during the simulation runs via a well developed graphical user interface, and to improve the capability of modeling water quality, energy production, conjunctive groundwater and surface water interactions and use, to mention a few.

There will always be a need to perform alternative ‘what if’ policy analyses where a relatively fast model that also provides some capability for uncertainty analyses is required. Perhaps CALSIM II will never be able to serve this need, and if so another more simplified modeling approach could be developed to fill that need. This simpler screening tool would be calibrated to produce results comparable to those of CALSIM II or observed data. Is this possible? We can not be certain but feel the idea should be seriously considered.

Acknowledgments

We want to acknowledge and thank all those who were involved in preparing the materials we received, in presenting additional information to us, and in arranging our activities and taking care of us during our brief review visit. Our special thanks to Kim Taylor for leading this effort, and to all those who did their best to educate us on the finer points of CALSIM II. All those involved in the development and implementation of CALSIM II are to be congratulated for extending the state-of-the-art in water systems modeling and for making it a critical part of the planning, development and management of California's water resource infrastructure.

Caveat

Just as all models are approximations of reality, so may all advice be an approximation of what it should be. We hope what we have written in this report is correct and useful, but encourage CALSIM model managers and California's water community to take our assessments and suggestions for what they are, arrived at based on our own experiences and some limited exposure to those who know much more about CALSIM and CALSIM II than we do.

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1. CALSIM Compared to Other Modeling Approaches

Management of complex systems such as coordination of the California State Water Project (SWP) and the Federal Central Valley Project (CVP) requires effective decision support tools for simulating and analyzing system components in a fully integrated manner. The classic definition of a decision support system (DSS) provided by Sprague and Carlson (1982) is *"an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems."*

A DSS integrates the following interactive subsystems: (i) dialog generation and management subsystem (DGMS) for managing the interface between the user and the system; (ii) data base management subsystem (DBMS); and (iii) model base management subsystem (MBMS).

CALSIM II is a DSS developed as a joint venture between the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Bureau) to (i) provide a significant modernization and upgrading of the previous models DWRSIM and PROSIM employed by these organizations, (ii) develop a comprehensive modeling system that simultaneously addresses the current and future needs of both the SWP and CVP; and (iii) develop a generalized modeling system that could be applied in any river basin system, in contrast with the previous models that were less generalized and more specifically designed for the SWP and CVP. In this respect, CALSIM II represents a state-of-the-art modeling system that is similar in general concept, while differing in specific details, to other river basin modeling systems such as AQUATOOL (Valencia Polytechnic University, Spain), ARSP (Acres Reservoir Simulation Program) (Boss International, 2003), IRAS (Interactive River-Aquifer Simulation) (Loucks, et al. 1996), MIKE BASIN (Danish Hydrologic Institute, 2002), MODSIM (Labadie and Larson, 2000), OASIS (Randall, et al., 1997), RAISON (Young, et al. 2000), ResSim (U.S. Army Corps of Engineers, Hydrologic Engineering Center), Ribasim (River BAsin SIMulation Model) (Delft Hydraulics, Netherlands), REALM (REsource ALlocation Model) (James, 2003), RiverWare (Zagona, et al. 1998), WaterWare (Jamieson and Fedra, 1996), and WEAP (Water Evaluation and Planning System, 2003) (Hansen, 1994). All of these can be categorized as decision support systems since all three subsystems of a DSS are embodied within them.

A distinguishing feature of several of these modeling systems is the use of optimization on a period by period basis (not fully dynamic) to “simulate” the allocation of water under various prioritization schemes, such as water rights, without the presumption of perfect foreknowledge of future hydrology and other uncertain information. This is a valid approach since use of optimization overcomes the disadvantage of employing numerous, unwieldy prescriptive rules governing water allocation. Systems employing optimization in this manner include: ARSP, MODSIM, OASIS, REALM, RiverWare, and WEAP and are therefore more akin to CALSIM II. ARSP, MODSIM, REALM and Ribasim are further distinguished by use of specialized minimum cost network flow optimization algorithms, although of these only MODSIM includes iterative structures using an imbedded scripting language for including non-network “side constraints” in the optimization. The other modeling systems are essentially limited to a pure network structure that does not allow inclusion of all the complex, non-network type constraints necessary to model the complex CVP-SWP system.

It may be useful to compare this use of optimization with some other uses that have appeared in the modeling literature. One use of optimization is purely for computational convenience; in this case optimization is employed as a numerical method for obtaining the solution of a series of simultaneous (often linear) equations. This approach, which was used in the first generation of computational economic models about forty years ago, exploited the fact that some existing computational algorithms for solving optimization problems were faster than those for solving large systems of simultaneous equations. A second use of optimization applies when the solution of the system of equations characterizing a water balance has multiple possible solutions; this is essentially the case described above, where optimization is being used primarily to identify a unique solution for a system of equations. Both of these uses of optimization are primarily descriptive rather than prescriptive (also referred to as positive vs. normative) in intent: the goal is to model how a system, characterized by a set of equations, operates. To the extent that the real–world managers of the system do optimize some objective function, the aim is to mimic their behavior by setting up and solving a similar optimization. But, the goal is to model what they actually do, not to advise them what they ought to do. The third use of optimization adopts an explicitly prescriptive goal and sets out to ascertain what managers ought to do if they wished to optimize some objective function (e.g. maximize economic efficiency). While this is certainly a legitimate analytical exercise, it should be kept conceptually distinct from the use of optimization in a purely descriptive context.

1.1 Advantages of Optimization-Driven Simulation

For large, complex, integrated systems, simulation models that optimize operation and allocation of water within each time-step by operational priorities have become the major simulation approach. Models of similar approach include ACRES (Acres Engineering), AQUATOOL (Spain), MODSIM (Colorado State U.), OASIS (Hydrologics, Inc.), WASP (Australia), and WEAP (Tellus Institute). Priority-based simulation models with optimization engines have become widespread in part because:

- The models are simpler to develop, comprehend, and modify.
- Their software is easier to upgrade, since the data set describing the system and its operating policies is substantially separate from the software code.
- Data are easier to update and modify, since changes require little or no software changes.
- Priority-based operations are a common basis for water rights and operating policies.
- Priority-based operations are relatively easy to explain.

The major exception to this technological trend in simulation modeling is to use more traditional procedural operating rules in simulation models with a graphical user interface for primarily flood control operations (HEC-RESSIM) or for exploratory study of large systems or detailed management of relatively small systems (Stella-type models).

Similar to several of these systems, CALSIM II allows specification of objectives and constraints in strategic planning and operations without the need for reprogramming of complex models. The CALSIM II authors developed the English-like WRESL (Water Resources Engineering Simulation Language) as an intuitive means of defining the objective function and constraints for a mixed-integer linear programming model, similar to the OCL (Operational Control Language) used in OASIS and the Policy Editor employed in RiverWare. In MODSIM, the optimization model is formulated directly through the graphical user interface with no need for a modeling language, but with supplemental features of the optimization defined through the PERL scripting language. WRESL allows planners and operators to specify targets, objectives, guidelines, constraints, and their associated priorities, in ways familiar to them. WRESL provides simple text file output that is converted to FORTRAN 90 code by a parser-interpreter program, whereas PERL is fully embedded in the network optimization code. Both modeling systems are data centered, meaning that model operation is controlled solely by user specification of input data rather than hidden rules or hard-wired data structures.

CALSIM II, OASIS, RiverWare and MODSIM are similar in that all use a high level language with syntax and logical operators; are written to simple text files which are subsequently parsed and interpreted; use rule-based or IF-THEN-ELSE conditional structures; are designed to be easy for planners and operators to use without the need for reprogramming; allow adaptive and conditional rules which are dependent on current system state variable information; include constructs for assigning targets, guidelines and constraints, along with their associated priorities; and include a goal seeking capability. CALSIM employs a mixed integer linear programming solver for repeated period by period solution that is less efficient computationally than the network solver employed in MODSIM, ARSP, REALM and Ribasim.

Unfortunately, unlike these aforementioned modeling systems, CALSIM lacks a comprehensive graphical user interface for constructing and editing the river basin system topology. CALSIM II would be greatly enhanced if, similar to RiverWare, IRAS, and MODSIM, objects representing features of the basin such as reservoirs, canals, and river reaches, could be created on the palette of a graphical user interface by simply clicking and dragging various icons for the objects to the display. The objects are instances of various classes that share certain common characteristics, and each object contains its own physical process methods and associated data. We believe that complaints concerning the complexity of using CALSIM II would be greatly reduced with development of such an object-oriented graphical user interface.

2. Comparative Strengths and Weaknesses

2.1 Some Prominent Strengths

CALSIM II has important strengths as a general inter-regional operations planning model, particularly compared with available alternatives and its predecessors. The primary strengths include:

- Coordination of Federal and State Interests A unique aspect of CALSIM II is the high degree of cooperation between Federal (i.e., U.S. Bureau of Reclamation) and State (i.e., California Department of Water Resources) interests in its development. This kind of cooperation is rare, and in fact this may be the only such example of such coordination for a system of this scale and complexity. Although it is clear that DWR staff have taken the greatest degree of responsibility in the planning, development, coding, testing and application of CALSIM II, it is also clear that USBR staff have also played an important role. CALSIM II can provide a showcase for other states as to what can be accomplished with Federal and State cooperation for river basin management.

- Consensus model. CALSIM II is the official joint modeling environment of the State and USBR. This includes a common schematic, hydrologic representation of the system, common set of facility capacities, and common representation of system operating policies. This saves a lot of unproductive bickering and helps all parties improve representations, rather than compete over representations.

- Common effort. The joint development of CALSIM II by USBR and DWR has provided more focused and effective use of resources and expertise than previous development of agency-specific models. CALSIM II development has also involved other agencies and consulting expertise more than pervious models of this system.

- Data-driven model. CALSIM II is a rather data-driven simulation model with an optimization engine. This modeling approach provides:

    a. much greater flexibility than its predecessors and traditional water resources simulation approaches.
    b. a promising framework for improving transparency, data, and model documentation, compared to other approaches.

- Public domain. The model and data are substantially in the public domain, facilitating transparency and adaptability for California's decentralized water system. Ongoing software development efforts will improve CALSIM in this regard.

- Steady improvements. Data improvements have been steadily pursued following the adoption of CALSIM II, although deficiencies remain widespread.

- Improved Delta water quality representation. Although problems appear to remain, the model developers have made substantial gains in representing Delta water quality operating criteria and performance.

- Better groundwater representation. Efforts to better include groundwater and non-CVP-SWP project operations are good efforts in the right direction, and merit continuation and expansion.

- Benchmark Studies. The development of documented benchmark studies seems to have resulted in significant model improvements and aided in the development of comparative model applications. Such exercises should be continued and improved.

- Long-term vision. The vision of a more transparent and publicly available model that can be employed by those outside the major agencies is excellent. This is a major change in direction, and achieving this vision will require adjustments over time. Often, these adjustments will be externally driven. Externally-driven improvements are a price of success and evidence of success for modeling policy that is open and public.

Few, if any, modeling organizations in the country have consistently done as good a job on model development and application for such a large, complex, and controversial system as the modeling group which developed CALSIM II. They are to be commended for their work to take California water modeling beyond past "closed shop" practices in favor of the development and dissemination of modeling capabilities that are more relevant to California's current water management problems. Most areas and suggestions for improvement noted below are meant to aid the model developers in moving further and faster in the direction they are already heading.

2.2 Some Prominent Weaknesses

The strengths and weaknesses of CALSIM II are not only technical (software, data, and methods), but also are institutional regarding how this model has been developed and employed. The administrative setting and objectives of model development and application are important, and difficult to manage. Alas, the management/policy problems of a system change frequently, while data and modeling capability change more slowly, and effective administrative structures change very slowly, if at all.

- Inadequate data development and management are principal shortcomings of CALSIM II. There has not been a sufficiently systematic, transparent, and accessible approach to the development and use of hydrologic, water demand, capacity, and operational data for CALSIM II. This problem extends beyond inadequate documentation and has led to controversy, confusion, and inefficiency in application of CALSIM II.
    a. Inadequate data management steepens the unavoidably difficult learning curve inherent for a complex system. Data have mostly been considered a "back room" activity of a few experienced experts. Retirement, promotion, or departure of these experts has left many gaps in knowledge and created difficulties for re-developing data for newer policy and planning problems.
    b. The administration of data development is fragmented, disintegrated, and lacks a coherent technical or administrative framework. Data required by CALSIM II are developed by several administrative units, without systematic technical vision or quality control for modeling purposes. Within DWR, different groups develop hydrologic and water demand data under different Deputy Directors, without effective coordination. This division must be overcome for a coherent data and analytical framework to be developed and implemented.
    c. In many cases it appears that water use and other hydrologic data inputs to CALSIM II are based on data collection and analyses that took place during the 1960s when DWRSIM and PROSIM were being constructed. It is important to ensure that data used for CALSIM II are up-to-date and consistent with the best current information

- The expertise and insights of many in local agencies, system operators, and consulting firms have not been prominent in the development of CALSIM II. For such a system with many hundreds of local experts, this is somewhat unavoidable, especially early in model development. Periodic re-examinations of how each area in CALSIM II is represented, in consultation with local agency and consulting experts, might overcome these technical shortcomings, and create and maintain a broader technical, user, and credibility base for CALSIM II. Active involvement of local agencies in CALSIM II development and applications would be much easier with better data management, and would be rewarded with a broader base of CALSIM II expertise and enhanced model credibility.

- Compared to the current CALSIM II, any central operations planning model for California water management should be:
    a. Expanded in geographic scope to include major non-CVP-SWP areas, especially the Tulare Basin, the Colorado River, and southern California. Operations and demands in these regions seem increasingly important for CVP and SWP operations, and are important for the integrated operations of California's major local and regional water management agencies.
    b. Expanded in management scope to include local management options such as water conservation, reuse, water transfers, groundwater and conjunctive use management, etc. These additional water management options are important for local, regional, and statewide water policy, planning, and management efforts and can have significant effects on CVP and SWP water demands.
    c. Made regionally modular, so smaller regional models can be run independently and tested locally, with boundary conditions consistent with the larger model.
    d. Made modular in terms of hydrologic, water management, and water demand processes, allowing better development, comparison, and updating of hydrologic and water demand process models. Agricultural, urban, environmental, and other water demands should be represented more directly, and explicitly. Groundwater should be represented and operated more explicitly. Land use based local hydrology and water demand approaches might be implemented in such standardized modules.
    e. Subject to a systematic model and data testing regime and continuous quality improvement program. As the problems of California water change, different and greater demands will be placed on analytical capability, requiring an essentially continuous testing, re-testing, and improvement of data and models. This might parallel a continuous review of local representations and data involving local agency and consulting experts.
    f. Financed on a broader base, by more than the CVP and SWP projects. Increasing use of CALSIM II is being made by local, regional, State, and Federal agencies interested in developing bilateral or multi-lateral water transfers or projects, which incidentally involve the CVP and SWP. To develop inter-regional modeling capability needed to integrate these activities at local, regional, and inter-regional scales, more sustained funding and involvement from local and regional agencies is needed. In effect, local and regional agencies have been "free riders" on CALSIM

II's analytical capabilities, and it is not necessarily a good bargain for them. Everyone should benefit from broader technical and financial participation.

g. Capable of analyzing a wide range of scenarios. More capability is needed to examine various long-term scenarios with respect to hydrologic, water demand, and operational uncertainties in the future. There also needs to be a better capacity to accommodate other approaches to representing hydrologic uncertainty and variability besides simply simulating 70-plus years of record.

- Input data and its development. Important aspects of CALSIM II rest upon the representations of other models of Delta hydrodynamics and water quality, water demands, and groundwater. The credibility of CALSIM II also rests on testing these models that send important data/representations to CALSIM II, and documenting them adequately. These models include:
  a. CU Model and SIMETAW: The consumptive use model and the newer SIMETAW model, used to develop hydrologic inputs and estimate return flows, also require testing and more explicit documentation. The underlying data for these models also need more systematic, standardized, and transparent treatment.
  b. DSM2: Representation of the Sacramento-San Joaquin Delta will always be important and prone to controversy, given the prominent importance of Delta flows and water quality for the operation and planning of California's water system. The difficulties of representing the Delta in operations and planning models are compounded by the tidal nature of the Delta, which usually implies a need for shorter time-steps. Representation of Delta water quality constraints currently falls heavily on an ANN method within CALSIM II. This ANN is calibrated (trained) based on a hydrodynamics model, DSM2. Thus, controversies regarding Delta representation in CALSIM II are likely to lead to questions of the adequacy of DSM2. The transparency and testing procedures valuable for establishing the credibility and limitations of a Central Valley operations model would also seem to apply to DSM2, or any other Delta hydrodynamics-water quality model. Tests of methods used to represent small-time step phenomena with larger time-steps (e.g., "partial month standards") should be tested in a forum that would give the approach credibility and where its limits could be developed, discussed, and documented.
  c. CVPM/CALAG/LCPSIM/IWR-MAIN: Representations of water demands in CALSIM II rely heavily on other models, particularly CVPM and eventually CALAG for agricultural water demands and LCPSIM and eventually IWR-MAIN for urban water demands. Thus, these models also will attract attention, and will probably require the same types of testing, transparency, and documentation suggested for DSM2 and CALSIM II. Many water contractors of the CVP and SWP also have internal water sources (groundwater, water conservation, and water reuse) and side contracts with other agencies to supply water that can increase or decrease (at different times) their water demands from the CVP and SWP contracts and from the demands estimated from CALAG and IWR-MAIN types of models.
  d. IGSM /CVGSM: Water users in California rely on groundwater as a water source and as the major source of over-year drought storage. Groundwater is also being increasingly used and looked-towards as a source of storage as part of conjunctive use schemes, and water transfer and market schemes. Thus, representation of

groundwater in the system is important, and probably should be expanded considerably. The representation of groundwater quantities, storage, and recharge and pumping capability will also attract attention from interested and critical parties. Thus, the IGSM/CVGSM modeling efforts of DWR and USBR should include the same types of transparency, documentation, and testing suggested for CALSIM II.

e. Agricultural demands: _Agricultural demands in the model are estimated by an external modeling system (CU model). Staff noted that the estimation methods being used are include out of date information on agricultural cropping patterns and irrigation technology, both of which result in inaccurate estimates of agricultural water demands. This estimation process needs to be revised and updated to include current information on an ongoing basis. The methodology needs to be improved to include economic factors in the estimation of cropping decisions and water demands. In many case, the preferred spatial scale for the economic modeling of agricultural water demand is going to be the individual irrigation district rather than very broad areas containing multiple quite heterogeneous districts.

- CALSIM II is currently awkward to apply for broader State and CVP-SWP policy questions. Practically, the time needed to complete analyses is too long and CALSIM II does not explicitly represent many of the management options which policy makers are interested in investigating, evaluating, and orchestrating.

- More CALSIM II modelers are needed. Many water managers and policy makers across California look to CALSIM II for many purposes, and there is near-universal consensus that the application of CALSIM II is currently limited by a dearth of knowledgeable modelers. Current training by DWR and USBR on CALSIM software is useful, but clearly insufficient. To be a functioning and credible CALSIM II modeler one must understand both CALSIM software and the operational complexities of the system (which probably no one can know in its entirety). Improved model and data documentation is also essential here.

- Stakeholders and policy makers are poorly guided in how to interpret CALSIM II results. Not only must CALSIM II become more responsive to current planning and policy concerns and management options, but current policy makers must receive some education in the benefits and limits of such modeling for their purposes. This is a very difficult problem that will often involve the role assigned to modeling and model results within larger politically-driven policy making processes.

- Non-interpretation of model results is not helpful. Several recent DWR reports based on CALSIM II results have been considerable improvements over past practices in terms of presenting model results, discussion of the model, and examination of model performance in a historical context. However, often the studies have not contained the kind of written discussion and interpretation of results that would demonstrate that the authors have thought about the results and drawn conclusions in a realistic and self-critical manner. This detracts from the perceived credibility of the work and makes the study less informative for readers (most of who surely do not have the modeling background of the authors).

- Some needs exist to improve CALSIM software. These are well-known to the model developers and include:
  a. Elimination of the need for the FORTRAN compiler,
  b. A public-domain mixed integer-linear programming (MIP) solver,
  c. A graphical user interface, including ties to databases and GIS display if possible,
  d. Post-processing tools for users to help new users and broader application and scrutiny of CALSIM II results,
  d. Version control software and system (also a problem for model administration),
  e. Better data and database management software and protocols (this has great data management and administration implications),
  f. An ability to more systematically set objective function weights,
  g. More automated input and output data checking is needed to improve productivity in model application and quality control of modeling output. This would also facilitate use of CALSIM II by a broader range of modelers,
  h. Ability to access and employ sensitivity analysis information coming from the MIP solver to identify possible multiple optima and identify binding constraints and slacks,
  i. A debug version of the code where water can be added or subtracted at any location and time (at a great penalty) to quickly identify locations and times of model infeasibilities. (Prof. J. Lund has had great success with this approach to correcting infeasibilities in the CALVIN model of California for a network flow algorithm.),
  j. Time-step issues should be explored and evaluated comparatively. There are major drawbacks to shortening time-steps system-wide (run-time, data development, interpretability of results, etc.), but short time-step components within the model or other approaches might adequately represent short-period aspects of the system for many purposes.

There will be some who argue that CALSIM II is and should remain a model of only the CVP and SWP system. While this would be simpler administratively and financially, it seems technically and politically untenable. California's water system is being asked to operate in an increasingly integrated manner across local and regional scales, with multiple local water demands, supplies, and aquifers being coordinated with the operations of major aqueduct and storage infrastructure. Any model of the CVP and SWP systems must be responsive to this operational integration, either implicitly through better parameterization of local supplies and demands, or explicitly by widening the geographic and functional scope of the model.

3. Limitations, Uncertainties, and Impediments

3.1 Removal of Unnecessary Ties to DWRSIM and PROSIM

Much of the spatial detail employed in CALSIM II is a carryover from the previous DWRSIM model. This is particularly evident in the coarse delineation of watersheds and sub-areas, which may no longer be relevant for future applications of CALSIM II. It is recommended that all unnecessary ties to the previous DWRSIM and PROSIM models be removed in further development of CALSIM II.

3.2 Relative vs. Absolute Predictions

As noted in the Executive Summary, we are skeptical of the usefulness of the distinction between comparative and absolute predictions. To declare that CALSIM II is intended for comparative predictions and should not be used for absolute predictions is not a helpful or desirable strategy. Rather than embracing this limited view of what CALSIM II can be expected to accomplish, we recommend that model developers recognize the requirement for CALSIM II to provide absolute values. To satisfy this purpose, additional calibration of the model will be required to ensure that it provides a reasonably reliable depiction of how the California water system operates. In addition, data on model accuracy and the outcome of the calibration runs should be made available so that users can gauge the likely errors involved in using the model for their own particular purposes. Some methods for doing this and performing sensitivity and uncertainty analyses are contained in Appendix H.

Model uses should realize that model calibration and validation exercises can illustrate only how well the model can reproduce historical decisions and system behavior. Our ability to predict future policy decisions and the emergency responses to water shortages is clearly limited, thus decreasing the absolute precision of any model's predicted values of various system performance measures. Thus it is useful to distinguish between the ability of the model to reproduce correctly the physical operations of the water systems in California (which should be good), its ability to reproduce and anticipate decisions by the agricultural sector that determine the quantities of water the consume, and its ability to mimic historical and current water operation decisions by the CVP, SWP and other water management agencies.

In general, it appears that the developers of CALSIM II do not have a clear idea of how to define the scope of CALSIM II use and many of the applications are evolving in a reactionary manner. Model developers should identify clearly the desired uses for CALSIM II and then determine acceptable approaches for satisfying those desires. Developers should seek to improve data accuracy and overcome unrealistic assumptions to improve confidence in model results.

3.3 Hydropower

CALSIM II is currently greatly lacking in hydropower computations, which is an important of the federal CVP system. This should include risk-based power capacity evaluation, and possible incorporate the ISM (indexed sequential hydrologic modeling) method that the Bureau has used for many years in hydropower capacity analysis. Also, hydropower should not simply be an after-the-fact calculation, but explicitly included in the system objectives.

3.4 Daily operations

A great challenge awaits the developers as they attempt to adapt CALSIM II to daily operations. These challenges are primarily related to the impacts of routing on distribution of flows and scheduling of reservoir releases. Under the current period-by-period optimization structure over daily time increments, without appropriate consideration of routing there is the danger that the model will allow diversion of upstream flows to lower priority users, resulting in injury to higher priority downstream users in the following days where travel times exceed 1 day. The proper inclusion of routing in the daily operations requires some kind of look-ahead capability in CALSIM II, which is currently lacking. In addition, scheduling of reservoir releases on a daily basis creates difficult timing issues in order to minimize unnecessary downstream spills or shortages caused by routing and attenuation of upstream reservoir releases. Another complexity in moving into daily operations is that reservoir discharges now become head-dependent, whereas this can usually be ignored on a monthly time scale. This means that the maximum reservoir release in any day will be dependent on the head, and should be based on the average head over the day, which introduces the potential for time consuming iterative processes to deal with nonlinear relationships in discharge-head curves for any reservoir.

3.5 Groundwater model

Groundwater has only limited representation in CALSIM II. This resource is modeled as a series of inter-connected lumped-parameter basins. Groundwater pumping, recharge from irrigation, stream-aquifer interaction and inter-basin flow are calculated dynamically by the model.

The purpose of the multi-cell groundwater model is to better represent groundwater levels in the vicinity of the streams to better estimate stream gains and losses to aquifers.

In the Sacramento Valley floor, groundwater is explicitly modeled in CALSIM II using a multiple-cell approach based on DSA boundaries. For the Sacramento Valley, there are a total of 14 groundwater cells.

Currently no multi-cell model has been developed for the San Joaquin Valley. Instead stream-aquifer interaction is estimated from historical stream gage data. These flows are fixed and are not dynamically varied according to stream flows or groundwater elevation.

The approach to modeling groundwater in CALSIM II, a lumped-parameter “tank” model seems to be a reasonable approach. However, few details of this implementation were provided to the review panel, that it is not possible to assess its accuracy or reliability. Details of the calibration and verification activities performed to date should be carried out and reported for the groundwater tank model. The effect of using large size tanks should be assessed and the level of uncertainty in computed results reported. In addition, the effect of these uncertainties on CALSIM II calculations should also be assessed. The San Joaquin valley aquifers are not well represented in the tank model, but it is in the CVGSWM. The San Joaquin valley groundwater should also be modeled in CALSIM II.

Groundwater availability from aquifers is poorly represented in the model. This results from the fact that aquifers in the northern part of the state (Sacramento Valley) have not been investigated regarding storage and recharge characteristics. Thus, in the model, upper bounds on potential pumping from aquifers are undefined. This does not represent reality, since, if CALSIM II is used for statewide planning, it would allow pumping of vast quantities of water for export to southern parts of the state, something which agency staff claim is unrealistic.

Realistic upper bounds to pumping from any of the aquifers represented in the model need to be developed and implemented.

In addition, historical groundwater pumping is used to estimate local groundwater sources in the model. However, the information on the historical pumping is very limited, causing these pumping rates to be very uncertain. Better pumping information is needed and an analysis of the effect of this uncertainty on model results needs to be conducted.

In general, the level of representation of groundwater in CALSIM II is not reasonable from the point of view of the reviewers. This is due to several factors, perhaps the most important being the lack of information presented to the reviewers for their assessment. Another factor is the lack of data collected and analyzed by the State of California to properly account for groundwater resources in the Central Valley. These data are critical to an understanding of the availability of water in the state and the operation of the major water systems that supply water to agriculture and small municipalities in the Central Valley. Assumptions of unlimited groundwater resources in the Sacramento Valley are unfounded and unbelievable. Efforts should be taken to make reasonable estimates of these resources.

There are other approaches that provide reasonably accurate estimates of river-aquifer interactions and groundwater basin response, while not sacrificing computer time. The response function approach is a good example, whereby the CVGSM model is used to develop kernel functions describing this response. A similar approach is described in Fredericks, et al. (1998). These kernels may require readjustment as head conditions change in the basin, but they provide a more accurate prediction tool and are easily incorporated in the MIP model since they apply a linear superposition assumption and retain the linearity of the constraints in the model. A dynamically linked CALSIM-CVGSM configuration is not necessary for reasonably accurate solutions. If computer run time for CALSIM II is considered excessive now, it could only considerably worsen if this type of linkage is incorporated.

Soil moisture is not dealt with in a realistic manner and needs to be improved in applications where the model output might be sensitive to these assumptions.

3.6 Dynamic Variation of Priority Weights

A severe restriction in CALSIM II is the inability to dynamically vary the weights used to prioritize flow allocation in the system. It should not only be possible to dynamically vary these weights, but this variation should be conditional on the current system state, however that state (or states) is defined. In addition to dynamic variation of weights, more explanation is needed of the reservoir operating rules and how these rules are incorporated into CALSIM II. The description of operating rules used in the system is not very clear. For example, what kinds of hedging or shortage rules are used to mitigate the effects of drought?

3.7 Expanding Scope of CALSIM II

CALSIM II is a considerable advance on earlier models in that it fully incorporates both the State Water Project run by the Department of Water Resources and the Central Valley Project operated by the Bureau of Reclamation. However to be able to examine the full range of Californian water issues, it would be desirable that all components of the linked system should be incorporated in the model including the Friant system, the larger Tulare Basin, and southern California and its links to the Colorado River. Also because of the very important linkage between surface water and groundwater use, improvements should be made in this area particularly with regard to how that linkage affects demand for surface water and how access to groundwater reduces the economic impact of surface water restrictions.

When expanding the geographical scope of the model to include non CVP-SWP areas, as well as Southern California, a hierarchical, decomposition approach would allow development of separate models for these areas that can then be linked together through iterative processes. Otherwise, the CALSIM II model can become extremely unwieldy. Again, integration can still be achieved through appropriate iterative interaction between the regional models. In the same vein, it is also unnecessary to explicitly integrate water quality and detailed water demand/consumptive use models into the model structure. Iterative schemes involving successive estimation of water quality and other parameters can produce comparable accuracy at reduced computer run times, while reducing the complexity of the model.

The replacement of DSM2 with a neural network is consistent with reinforcement or machine learning methods which are increasingly being used to replace complex, computationally time consuming models employed in decision support systems. The complex models are only used to provide the data sets used for training the neural network. Current research at Colorado State University and elsewhere is using neural networks for groundwater surface water interaction and return flow computation to replace computationally expensive groundwater models.

3.8 Key Model Outputs

In the past, the primary purpose behind the development of CALSIM II and its predecessors has been the examination of the reliability of water supplied to the State Water and the Central Valley Projects. However it is clear that there is now a demand for a model that will provide a wider range of outputs including:

- Water supply reliability for all water users
- Demand for water by existing users
- Outflows to Delta
- Use of groundwater and the rate of depletion of aquifers
- Water quality in the Delta and in the San Joaquin River
- Indicators of ecological health in particular with regard to key fish species
- The value of hydroelectric generation.

Although the modules in the CALSIM II package currently address many of these areas, the recognition that all these outputs are important may necessitate some further model development and a greater degree of testing and calibration of these parameters.

3.9 Modeling Allocation, Accounting and Operating Rules

CALSIM II uses a system of weights and constraints to define the water allocation process and the operating rules for storage reservoirs. Unfortunately these do not accurately reflect how operators of the state and federal water projects behave in managing their complex systems. Ideally, CALSIM should both reflect how the operators behave and be accepted by them as a useful tool when considering their management alternatives. The failure to achieve this limits the usefulness of CALSIM to investigate the specific operating or accounting rules that are of interest to those operators. For example, CALSIM II was not used to test changes to the accounting and allocation rules that have recently been proposed by the Department of Water Resources and the US Bureau of Reclamation because the rules that were changed do not exist in CALSIM II.

4. Options for Improving CALSIM

4.1 Optimization Model and Run Times

Many of the complaints regarding using of CALSIM II relate to long run times, which is not conducive to sensitivity or uncertainty analyses. Since CALSIM II employs a mixed integer linear programming (MIP) solver, the usual sensitivity information available in linear programming solvers, such as dual variables and right-hand-side ranging, are not available. The problem is that small changes in right-hand-side constants or objective coefficients (i.e., weights on water allocation priorities) can produce large abrupt changes in model solutions. In this case, dual variables do not provide useful information for MIP problems. Sensitivity analysis can only be conducted through trial and error processes involving incremental adjustment of important weights, coefficients, and uncertain data inputs with subsequent repetitive execution of the model. In light of this, it is crucial that the MIP solver employed in CALSIM II is upgraded. Significant advances have been made in MIP solvers, as described by Bixby, et al. (2000), which are not reflected in the current XA solver utilized in CALSIM II. There have been many recent improvements to the branch and bound method which should be incorporated, and the LP solver itself can be improved with better sparse matrix analysis. As planned by the CALSIM II developers, removal of the need for use of the FORTRAN 90 compiler will also improve run times when changes in optimization model structure are required.

4.2 Confidence in the model

The usefulness of a computer model in water resource management is only as good as the confidence that the stakeholders have in the accuracy and reliability of the model and the trust that they have in the modelers. There are several factors that affect that confidence and a number of ways that confidence can be improved.

- **Documentation**

Producing documentation of models requires considerable resources to do properly and ongoing resources to maintain especially when model development is continuing. Typically documentation of any water resource model is poorly done. However, where there are external model users, as is the case with CALSIM II, it is important. The survey conducted by Ferreira et al (2003) indicated that many users of the model thought that documentation of CALSIM II was poor.

- **Seminars**

In the Murray-Darling Basin, seminars with key users and interest groups in which the operation of the model is described and discussed have proved to be useful in increasing confidence in models. The practicality of this approach will depend on the number and location of the prospective participants and the resources available to support the process.

- **Data**

A model can only be as good as the data that is used to develop and calibrate it. The agreement over an acceptable set of hydrologic data that occurred during the development of CALSIM II is a considerable advance. However, there appears to be a need to improve the collection and use of data on water diversions and return flows. Because of the close links between the surface water use and groundwater use there also is a need to have better information on the use of groundwater.

The models used to calculate the Local Water Supplies in the Depletion Study Areas depend on estimates of surface water use, crop evapotranspiration rates and water use efficiencies developed using data from the 1970's. Confidence would be improved if more recent data were available to check these estimates.

- **Calibration**

A very good way to improve confidence in a model is to calibrate it against historical data to ensure that the model output is able to reproduce the observed data. Calibration is the process of using the model to reproduce the historical behavior of the system and then fine-tuning the model so that the match between modeled and observed values improves. The calibration of the model assists in detecting errors in the model and the input data. It also enables a comparison to be made between the way that the operators actually manage the system and the way that the model assumes that the system is managed.

A further consequence of the calibration process is that the statistics of the match between modeled and observed values can be used as a reasonable estimate of the absolute accuracy of the model output.

It is legitimate in a calibration/validation run to incorporate changes to infrastructure, institutional or operational rules as they occurred especially if these changes are specified as input parameters to the model. This was done to a limited extent in the CALSIM II validation run with three regulatory periods modeled related to decisions made by the State Water Resources Control Board. It is also legitimate to incorporate growth in demand especially if that growth is described in a manner that is consistent with the way that demand is specified in the production run. Demand north of the Delta was specified in the validation run by inputting the historical crop areas.

A Calibration/Validation report should be very useful in demonstrating the accuracy of the model. However there are a number of elements in the CALSIM II validation run and the validation report which reduce that confidence including:

- State Water Project (SWP) demands south of the Delta were set at historical deliveries in years with no restriction and at the contractor's request level in restricted years. Neither of these pieces of information is available to a production run which calculates demand based on crop areas. Therefore the validation run does not provide reliable information on how well the model can represent these demands.
- The validation run omitted Article 21 deliveries. Although this omission will not affect the delivery of 'Table A' volumes south of the Delta, it will affect flow in the Delta and Delta water quality. Also, in the example model run presented in the paper by Draper A.J. et al (2003) which was supplied as part of the review, changes to Article 21 deliveries constituted the largest impact resulting from a change to the allowable pumping capacity at Banks between March and December. This suggests that the modeling of these demands is important.
- The DWR (2003) report produces estimates of SWP and Central Valley Project (CVP) deliveries south of the Delta but then adjusts them for changes in storage before presenting comparisons of those results with observed deliveries. This process merely checks that the model is preserving a water balance and does not present a legitimate validation of model deliveries.
- The report provides statistics on long term average deliveries and flows but no statistics on the fit for individual years. Additional analysis of the output would assist stakeholders to assess whether the estimate of water supply reliability and in particular the modeled volumes of water available in the most restricted years are accurate.
- In some instances, such as the examination of water quality in the Delta, the ability to accurately model monthly flows and deliveries will be important. The validation report contains no information that would enable the ability to model monthly flows to be assessed.
- A key model output is the water quality in the Delta. It would assist the validation of the model if a comparison of parameters such as the location of the X2 boundary was provided.

The users of CALSIM should recognize that models are a summary of what one believes to be true and important about a system. Validation is then an exercise to test how good that summary and understanding really is.

Appendix I contains brief descriptions of calibration modeling in the Murray-Darling Basin in Australia and in the State of Texas.

4.3 Assessment of the reliability of "delivered" water

An important recent application of CALSIM II which has drawn widespread attention is the "State Water Project Delivery Reliability Report. While this is an important step forward in the use of CALSIM for policy purposes, it highlights a number of issues, both conceptual and empirical, that need to be resolved in order to provide a more adequate assessment of the reliability of water supply in California.

First, it illustrates the need for sound calibration of CALSIM. The question being asked is not a comparative one – What are the consequences of changing some aspect of the system from X to Y? – but rather an absolute one – How does the system function at present? How often can users expect a shortage in deliveries of Z%?

Second, it highlights the fact any water system model such as CALSIM requires a blend of hydrology and behavioral analysis. To conduct a water balance, the model needs to know what deliveries are required by the customers of the given project, and what are the diversions by other user groups who extract water from the same surface or groundwater sources. These are fundamentally questions of economic and institutional behavior, not matters of hydrology. Therefore they cannot be dealt with by hydrologists alone. Like its predecessors, CALSIM tends to treat these as black boxes. The diversions by water users outside the CVP-SWP are taken as exogenously given, based on an assumed "level of development" and simplistic assumptions about the patterns of water use associated with that level of development. The deliveries required by the water users who are served by CVP-SWP are generally taken as given. For reasons explained below, both of these treatments are simplistic and unsatisfactory.

In CALSIM modeling exercises the level of development plays two different roles depending upon the context. In a simulation context, the level of development is used to represent hydrologic variability and uncertainty; in a calibration/validation context, it is used to reflect the actual historical demand for water withdrawals. These are very different purposes and it is important to keep them distinct. In most applications of CALSIM prior to the recent reliability study, the main focus was simulation and the representation of hydrologic variability. The chief purpose served by using 73 years of adjusted streamflow records was to represent the variability and uncertainty in the streamflow that one can expect to observe in any single year. Therefore, the calendar date of the record has no substantive significance, the (adjusted) streamflows for 1952 or 1982 are not being used to represented what happened historically in 1952 or 1982, but rather as an indication of the variation in streamflow that could be expected to occur next year, or any other year. In this context of simulating hydrologic variability, it makes good sense to apply the *same* level of development (i.e. the same pattern of water use) to every year in the sequence, rather than a series of different levels of development that vary with calendar time, because the streamflows represent alternative hydrologies that can occur in any given year.[1] The situation is different when one is conducting a calibration or validation

[1] This could be modified to allow for the fact that local weather conditions have a significant impact on irrigation (and urban) demands – e.g., farmers plant fewer acres of crops in a drought year. In that case, one could have different levels of water demand and extraction in different year *types;* but, these would all be keyed to the same overall level of economic development (e.g. the California economy in the 1990s). CALSIM II does not presently

exercise. In that case, one wants to represent the historical demands in 1952 or 1982 in order to compare what the model predicts with what actually happened. Therefore, in a calibration or validation exercise one wants the level of development to change each year in order to reflect the demand that occurred historically.

Both simulation and calibration/validation raise some other important technical issues. In the context of simulation, there are several different ways to generate a hydrologic sequence that is calibrated to a fixed level of development. One can use all 73 years for which data are available. One could use a subset of those years chosen either according to some deterministic rule or randomly. The subset could be oriented, for example, towards the extremes of the 73 sequence of annual records. However, the drawback of any approach based on sampling from the observed historical record is that it *understates* the full variability in streamflow that could be experienced in the future. The 73 years of record are drawings from a probability distribution the extremes of which extend beyond the minimum and maximum flows observed in the historical record. Relying on this record, therefore, understates the true minimum and maximum flows that might be encountered. In a reliability assessment exercise, one might want to take some steps to minimize the potential understatement of streamflow uncertainty. This could be accomplished by fitting a (parametric) probability model to the historical streamflow record and then sampling from the tails of the fitted distribution (Stedinger, 1981). The use of statistical models of streamflow variability could be considered in future applications of CALSIM to assess delivery reliability.

The assessment of delivery reliability requires that particular attention be given to the definition and measurement of the water users' demands. In this context, the user's demands play two roles: they affect the definition of "deliveries" and they influence the assessment of "reliability". With respect to deliveries, CALSIM II considers water to be delivered whenever it has the water irrespective of the ability of a contractor to use the water or to store it; The reality is that, if the contractor does not have a demand for the full quantity of water and is not able to store the excess, that amount will not be delivered. Therefore, the calculation of deliveries would be flawed. Furthermore, reliability cannot be assessed without reference to demand. Stating that a water supply system can deliver 100 acre feet in a wet year but only 70 acre feet in a dry year is useful only if one knows what the demands will be in wet and dry years. The implications are quite different if the user needs 105 acre feet per year than if he or she needs 65 acre feet per year. Thus, the users' demands should serve as the norm against which reliability is assessed. Instead, the recent reliability report uses the so-called 'Table A' water amounts as the norm for assessing deliveries to SWP contractors. This does not seem to be a satisfactory approach because there is no presumption that the Table A amounts, negotiated in 1960, measure the actual demands of SWP contractors in any particular year. The actual demands of the individual contractors will be influenced by how much storage they have, what access they have to other surface water or groundwater, and the demands of the farmers they serve to plant crops and apply water. Without accounting for these factors, it is difficult to generate a meaningful assessment of supply reliability.

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consider the impact of annual weather conditions on demands. In order to model water demands accurately in a year, the climate conditions would be linked to the flow conditions to provide an input set for a particular year.

The assessment of reliability should ideally go beyond a comparison with quantities demanded to incorporate the notion of a loss function. If a user has a demand for 100 acre feet and can only receive 90 acre feet in one scenario and 80 acre feet in another, while the shortfall is twice as large in the second scenario the actual *consequences* of the shortfall to the user, in terms of lost profit or higher cost, might be more than twice as large. To assess the economic value of reliability, or the economic cost of a lack of reliability, one needs to be able translate shortages into monetary losses. To accomplish this, the warning time provided and the delivery shortfalls from CALSIM would need to be processed through an economic model of the value of water to different SWP contractors.

Because water users face difference demands and have access to different sources of supply, when assessing reliability it is unhelpful to aggregate all contractors and simply present the results in terms of total annual project deliveries, as was done in the report. Precisely because of the potential non-linearity of the loss function, a given aggregate shortfall can have different consequences when distributed differently among the individual contractors. A similar observation applies to the temporal distribution of delivery shortfalls across the year. It is unhelpful to aggregate supply system deliveries into an annual total, as done in the report. For a user to be able to obtain 100% of his or her demands in the period from March to May but only 60% in the next three-month period from June to August has different consequences than being able to obtain 80% in each of the six months. Furthermore, for both agricultural users and many urban users, major decisions affecting water use have to be made in the spring. They are based on the expectation around March about the amount of water that will subsequently be available for delivery during the summer months. What matters to these users when assessing supply reliability is the amount of water they can expect around March to be delivered over the summer, rather than the ultimate total delivery.

For both reliability assessment and also model calibration/validation, it is important to avoid excessive aggregation when describing shortfalls between demand and supply, or deviations between model predictions and actual outcomes. In regression analysis, it is the convention to measure the goodness of fit of a regression equation not by the average deviation but rather by the sum of the squared deviations. In ordinary least squares regression, by definition the average deviation is always zero (that is to say, the average of the predicted values of the dependent variable always equals the average of the actual values) regardless of how well or badly the regression equation fits the data. The average deviation thus provides *no* information regarding the goodness of fit; by contrast, the sum of squared deviations or the sum of the absolute values of the deviations are sensitive measures of goodness of fit. Although the calibration of CALSIM is not an exercise in least squares regression, the same general principle applies. To judge whether the model is doing a good job, the goodness of fit should be measured by reference to the disaggregate results and not simply by the overall average deviation.

Additional comments on the 2003 CALSIM II Validation Report are contained in Appendix F.

5. Managing CALSIM Development and Applications

The costs of not continuously and substantially improving our analytical capabilities are political (in terms of continued controversy and diminished agency credibility), economic (as inferior system performance for agricultural and urban water users), environmental (in terms of inferior environmental system performance), and financial (lawyers and policy consultants are more expensive than engineers and scientists).

CALSIM II is a substantial improvement over its predecessor models, DWRSIM and PROSIM, with a great deal more flexibility, transparency, and potential than these earlier models. The modeling team for CALSIM has identified an exciting and relevant vision of how modeling should be done for this complex and difficult system in the coming years. However, implementation of this vision in a coherent technical manner that leads to both technical and stakeholder credibility will be a difficult process, requiring financial and institutional support if this kind of capability is to be developed and sustained.

To accomplish these objectives CALSIM II developers need to be in an institutional position where they can see the model more as "outsiders" view it. This would allow them to be more responsive in supporting the credibility of their work and the relevancy of their tools and results to the broad range of current water management problems. As such CALSIM II should no longer be solely responsible to CVP-SWP managers, but should be responsible to a broader range of technical managers from additional interests, reflecting its current and prospective uses.

It would be imprudent to manage a state's finances, a business, or a retirement plan without quantification – quantification in such matters is necessarily imperfect, but necessary nonetheless. While shortcomings have been identified in CALSIM II, it would be similarly irresponsible to manage California's water budget without carefully-interpreted quantification. Progressive and continuous improvement in our quantitative understanding of California's water system provides a common basis for improving its performance for all interests.

One possible means of maintaining control of the quality of particular versions of CALSIM II and accompanying models used for SWP-CVP planning and management decisions is to create an interagency modeling consortium (IMC) consisting of DWR, USBR, and persons from other stakeholder organizations if they are interested and want to participate. This consortium would be responsible for maintaining a toolbox of 'acceptable' models for 'official' use by the agencies and contractors.

IMC responsibilities and authority could include:

- Prioritize, coordinate, and provide consistency, technical guidance and oversight for all modeling applications,
- Approve model selection and insure that each requested application is carried out using the most appropriate model(s) and input data,
- Provide or otherwise insure documentation of the modeling process itself as well as the modeling results,

- Insure that the results are expressed and made available in a way such that others can understand and benefit from that modeling application, as applicable.
- Implement peer reviews of models and their applications as deemed appropriate.

To help meet their responsibilities the IMC will need to establish, publish and implement some procedures for insuring the quality of the entire model development and application process. They will need to identify among all the models that might be used, which are the most appropriate to address each of these separate groups of model applications. They must identify various models, i.e., establish a model toolbox, from which clients can choose the one that best meets their needs (or perhaps argue that another model should be added to the toolbox). The IMC will also need to maintain model documentation and provide for peer reviews of any model, its documentation, and/or its use in a project.

Further suggestions and discussion on the creation and operation of a possible IMC for model development and application, as well as for managing peer reviews of both the models and their applications, are contained in Appendix E.

6. Recommendations for Future Use, Development, and Application of CALSIM II

The most concise recommendation we might make would be to fix the shortcomings beginning with what are considered the most serious, and proceeding to those that are less serious, taking into account the time and other resources needed to address each weakness. However, we believe it is more useful to suggest ideas on how to systematically address both present shortcomings and those likely to emerge as stakeholders' quantitative understanding of California's water system and its problems continue to evolve.

6.1 Model development and support consortium

As discussed in the previous section and in Appendix E, it might be useful to explore creation of a broader interagency modeling consortium for developing operations planning models for California. The joint DWR-USBR development strategy used for CALSIM II has shown some notable successes, and should be expanded to include additional parties and sources of expertise. Such a consortium might include staffs from several agencies (DWR and USBR, as well as potential members from MWD, KCWA, CCWD, and other agencies), NGOs, some consultants, and universities. Such a model development forum would:

a. Bring a wider range of expertise to bear on model development problems.
b. Facilitate having more agencies involved in supporting model development with expertise and financial resources.
c. Better enable model developers to see the model as "outsiders" see it.
d. Potentially improve contracting for model development and testing.

e. Take model development and testing outside of the explicit agency framework; a broader consortium should be more conducive to self-critical and transparent technical practices.
f. Provide a common training ground for agency, NGO, and consulting staffs to become effective modelers, broadening the talent base for technical work in California.
g. Reduce impediments to model development and testing arising from current State budgetary and personnel hiring problems.

Many of the questions, concerns, and problems mentioned in the user community interviews could be addressed well in such a distributed model development, testing, and support framework. It would still be necessary for each stakeholder group and agency to maintain its own modeling staff, but these would be partially shared in an interagency modeling consortium.

The governance and finance of such a consortium would be difficult and would probably require a steering committee or governing board, but any resulting model(s) would have broader credibility and a broader and deeper technical base.

In the immediate term, a users' group should be formed and the formal listing of model development activities should be posted on the web, including short descriptions of each development activity and contact information.

6.2 Quality Control Program

The DWR and USBR modeling team (or a broader model development consortium) need an explicit quality control program. Such a program should include a variety of activities:

a. periodic external reviews on the broad modeling program
b. specialized external reviews of model products and applications
c. a standing (or sitting) external technical advisory body
d. software engineering and maintenance
e. a regime of model testing
f. model and data documentation
g. data development and management
h. user group activities
i. local agency and interest involvement
j. model, data, and documentation accessibility (including web site use).
k.

Such a quality control program would benefit from deep consultation with stakeholders and the broad community of water technical people, perhaps via the California Water and Environment Modeling Forum (www.cwemf.org).

6.3 A Training Program

DWR, USBR, and assorted agencies and consultants should establish a more formal common regimen to train new CALSIM II users in both CALSIM software and the complexities of actual system operation. All these groups currently rely on a relatively small pool of perhaps a dozen knowledgeable CALSIM II users and all proclaim a need for many more capable users. A training regimen consisting of current CALSIM II training classes, supplemented by additional training in software application and system operation and apprenticeships or rotations through operations and model development shops would be useful to all concerned. The entire water community would benefit from having such expertise being widespread. Having widespread CALSIM II modeling expertise also makes explaining CALSIM II and its results easier. This might be an appropriate activity for a model development consortium.

6.4 Extend Improvements in Modeling Practice to Supporting Models

CALSIM II is at the center of a web of additional models used by DWR, USBR, and other agencies to prepare inputs for CALSIM II and post-process outputs from CALSIM II.

Delta controversies and difficulties of representation seem endemic to problems of modeling Central Valley operations. The technical basis for representations of Delta operations and water quality performance requires a similar level of transparency and testing to avoid this becoming a "weak link" in the Valley-wide operations planning model. Since so much is based on the DSM2 Delta model, documentation of fairly strenuous tests of the DSM2 model are highly desirable. This would provide a firm foundation for the use of ANN or other approaches for summarizing DSM2 behavior in an operations model. Similar documentation, testing, and development are desirable for the other models mentioned above which provide data for CALSIM II (CVGSM/IGSM, CVPM/CALAG, IWR-MAIN, LCPSIM, CU model, and SIMETAW).

6.5 Hydrologic Data and Data Development

An effort should be made to step back and perhaps re-define a more systematic and solid basis for developing hydrology for water management models of California's inter-tied water system. Currently, several efforts exist to develop surface or groundwater hydrologies for parts of the Central Valley (sponsored by DWR-USBR, USACE-Sacramento District, USEPA, USGS, CALFED, local agencies, etc.). An effort should be made to broaden the range of hydrologic expertise involved in hydrology data development for management modeling of California's inter-tied water system, and establish a consistent and high, but reasonable, standard of documentation and testing for developed data and any underlying hydrologic models. Establishing such a standard of documentation and testing would make existing hydrologic studies more accessible and useful for future studies and encourage the comparison and further development of existing representations of the system's hydrology.

6.7 Performance-Based Optimization

Performance-based optimization should be added to CALSIM's capabilities; it would not be difficult in terms of software or data, and would add much greater ability to explore and seek improvements in management within a complex system. The multi-period optimization approach being developed (CAM) is an operations-oriented first step in this direction, but could be expanded without great difficulty.

For large-scale water resource systems of great complexity and many options for system management, it is often difficult to find "optimal" operations with simulation modeling. There are simply many myriads of decision options and combinations of options, which theoretically each require a simulation model run – which would be prohibitive in terms of analysis cost and time. In such situations, performance-based optimization models, such as those seeking maximum economic performance, can offer useful insights as to where to look for improving system operations and management. Metropolitan Water District of Southern California (MWD) and San Diego County Water Authority (SDCWA) employ performance-based optimization modeling of parts of California's water system to gain strategic insights for planning and management. An economic-engineering optimization model has been developed for California and, despite significant limitations, shows several insights for California (CALVIN), suitable for identifying promising operational and management strategies worthy of more detailed analysis (Jenkins et al. 2001; Draper et al. 2003; Jenkins et al. 2004). The CALSIM II modeling approach could easily be adapted to provide greater functionality to this type of performance optimization. Having performance-based optimization capability together with a compatible simulation model for more detailed analysis and trade-off evaluation could greatly improve the capability of California's water community to explore and develop promising and creative options for improving operations, facilities, and overall system management.

6.8 Modular and Layered Versions of CALSIM II

Speedier versions of CALSIM II are needed for operations planning and integrated water planning studies. Such versions would be regional modules of CALSIM II (for regional studies) or explicitly aggregated system-wide models from the most detailed CALSIM II schematic for system-wide or statewide studies. Both approaches would simplify the model for particular purposes, yet be tied to a common detailed schematic and detailed hydrologic, operations, and water demand data sets.

Geographically modular or aggregated system-wide versions would allow additional local and regional water management options to be represented for particular operations and policy planning purposes and allow users to more quickly explore and develop operating policies. The final runs from such integrated or exploratory studies could then be evaluated using a more detailed and complete version of CALSIM II.

Modular regional models might represent regions with relatively few inter-ties, such as: Sacramento Valley, Delta and eastside streams, San Joaquin Valley, San Francisco Bay Area, Tulare Basin, and Southern California (DWR's South Coast and Colorado River hydrologic regions). (We have had good success with the CALVIN model of California with 5 modular regional models, which combine to form a system-wide model. These geographic sub-models greatly improved quality control in model development, work flow and data checking, and identification of problems in the model.)

6.9 Model Calibration and Testing

Many approaches exist for model calibration and testing (Modeling Forum 2000). Calibrating a planning model oriented to operations in an uncertain and distant future is always challenging. For a model that serves many uses (including policy-urgent uses unforeseen by developers), use-specific testing will often be impossible within a responsive time frame and budget. Such unavoidable situations call for more thorough, general, and well-documented model calibration and testing than would otherwise be needed.

For the model to have technical credibility, stakeholder credibility, and to serve the kind of training and reference function needed for the water management community, a systematic and coherent means of setting parameter values in the model and documenting these values is needed. Similarly, a systematic self-critical means of testing is needed for a model to establish and retain credibility, and have defined limitations, for a range of applications.

A potentially excellent resource for model testing is comparisons of seasonal operations planning CALSIM II model runs with recent years' seasonal operations, as done by actual operators. Similarly, system operators could scrutinize historical simulations, such as those in the recent November report, for systematic differences from operating practice. Such comparison with operator policies and philosophy could also be performed with SWP or CVP delivery reliability estimates. Such comparative analyses would both help define the likely (and unavoidable) differences between actual and modeled operations and water deliveries and identify potential opportunities to narrow such differences.

Credibility arises, in part, from demonstration that problems and limitations are systematically identified and addressed or considered in model development and in making and interpreting model runs. This can be accomplished by use of documentation, metadata, written guidance, and protocols and logs for identifying model problems and recording model improvements.

Given present and anticipated uses of CALSIM II, the model should be calibrated, tested, and documented for "absolute" or non-comparative uses. This is what many applications require today and will be increasingly desired and required in the future. Maintaining the traditional "comparative-only" use of CALSIM II is undesirable if the model is to be useful for the CVP and SWP systems, the operations of water contractors, or for statewide planning purposes.

6.10 Documentation of Model Improvements

Along with better documentation of model versions, logs of data and model improvements and "bug fixes" should be maintained. Explicit protocols and records for identifying and correcting modeling errors and problems would enhance the credibility of the modeling effort with technical people and policy makers. Such protocols also provide an internal aid to staff and staff development in modeling. I understand that this kind of record-keeping is done, but the precise form of, nature, and extent of this record-keeping is unclear. It would be useful and reassuring to stakeholders and policy makers to know that this kind of record-keeping of the software and data was being done.

6.11 Better Model Integration in Decision-Processes and Stakeholder Education

Greater aid should be given to interested parties and decision-makers who must work with the unavoidable limitations of any model. If possible, a document should be prepared for stakeholders and interested parties outlining the model, summarizing the model's primary limitations, and providing guidelines for interpreting model results. Those developing policy-making forums and processes should thoughtfully incorporate computer models in these processes in ways that do not assume model omniscience, or otherwise place too great or exclusive a reliance on model results.

Models and model results will never be perfect. If models are to be important for planning and policy-making, they be must be presented and used in ways that enlighten policy-makers more than they add confusion and controversy to already difficult situations, if possible.

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A Strategic Review of CALSIM II and its Use for Water Planning, Management, and Operations in Central California

Appendices

Appendix A: CALSIM II Science Review

Dates: Nov 13-14th
Location: Bay-Delta Room, CBDA Offices
650 Capitol Mall, 5th Floor
Sacramento, CA

Day 1: The Management Context, Model and Application Details

9:00 Welcome – Kim Taylor
- Overview of the CALFED Bay Delta Program -
- Introduction of the Panel

9:15 Water issues in California – Francis Chung
- General Hydrology
- SWP/CVP
- Operational challenges
- Sacramento-San Joaquin Delta – Ron Ott (5 min.)

9:35 Panel Q&A

9:45 Planning Models – Andy Draper
- CALSIM software
- CALSIM II application overview
- Interaction with other models

10:10 Panel Q&A

10:20 Break

10:30 Summary of CALSIM Applications
- DPLA/CalFed/US Bureau of Reclamation: Integrated Storage Investigations – Steve Roberts
- Bay Delta Office (DWR): SWP Delivery Reliability Report - Kathy Kelly
- USBR: Multi-layered modeling to simulate CVPIA (b)(2) water and Environmental Water Account Operations – Nancy Parker
- Operations Control Office (DWR): Oroville Relicensing, SWP Allocation decision procedure – Curtis Creel
- Department of Planning and Local Assistance (DWR): California Water Plan Update – Kamyar Guivetchi/Ken Kirby

12:15 Panel Q&A

12:30 Lunch

1:15 Summary of User and Stakeholder Interviews
- 1:15 Interview Summary and Findings – UC Davis
- 1:35 Panel Q&A
- 1:50 Public Comment

2:15 CalSim II Details
- Development philosophy – Francis Chung
- Operation priorities, constraints, common assumptions – Erik Reyes
- Hydrology development – Andy Draper
- Delta water quality constraints – Ryan Wilbur

3:15 CalSim Evaluation
- Historical Operations Study / Sensitivity Analysis – Sushil Arora

3:30 Panel Q&A

3:45 Break

4:00 Future Directions
- Data Structure / Version Control / Multi-Period Prescriptive Optimization – Ryan Wilbur
- Daily Time Step - Dan Easton
- CalSim II – CVGSM Integration – Tariq Kadir
- Water Quality / Upstream Models – Nancy Parker

5:00 Panel organizational meeting (additional information needs, questions of specific staff, discussion plan)

Day 2—Panel Deliberations and Preliminary Report

8:30 Panel Q&A with specific DWR and USBR staff on request

9:30 Panel *in camera* discussions

11:00 Panel presentation of draft main findings—Pete Loucks

12:00 Wrap up and next steps - Kim Taylor i

Appendix B: Briefing Material for CALSIM II Peer Review

California Water
Averting a California Water Crisis (3 pages)
California Water Today, Bulletin 160-0, Chapter 2 (20 pages)
Water Supplies, California Water Plan Update, Bulletin 160-98, Chapter 3 (11pages)
Urban, Agricultural and Environmental Water Use, California Water Plan Update, Bulletin 160-98, Chapter 4 (17 pages)
California's Major Water Projects (map) (1 page)

CVP and SWP
State Water Project Operations (6 pages)
Central Valley Project Operations (16 pages)

CalSim and CalSim II Overview
CalSim: A Generalized Model for Reservoir System Analysis (19 pages)

CalSim Software Details
CalSim water resources simulation model: Users guide (18 pages)
CalSim water resources simulation model: Wresl language reference (11 pages)

CalSim II Details
Network Representation (1 page)
Sacramento-San Joaquin Delta Operations (9 pages)
Coordinated Operating Agreement (3 pages)
Reservoir Rule Curves (2 pages)
CalSim ANN Implementation (8 pages)
*CVPIA (b)(2) Management and Operations (6 pages).*ii
EWA Management and Operations (8 pages)
Multi-Cell Groundwater Model (2 pages)
SWP and CVP Delivery Allocation Logic (3 pages)

Hydrology Development
Surface Water Hydrology Development for CalSim II (8 pages)

Supporting Computer Models
Model Interaction (1 page)
CALAG (2 pages)
CU Model (2 pages)
DSM2 (2 pages)
IGSM2 – CVGSM (4 pages)
LCPSIM (5 pages)

CalSim II Evaluation
Planned Sensitivity Analysis (7 pages)
CalSim II Simulation of Historical SWP-CVP Operations - Extracts (61 pages)

CalSim II Applications
CalSim II Project Applications Summary (not completed)
SWP Delivery Reliability Report – Extracts (25 pages)
North of Delta Offstream Storage Investigations (3 pages)
In-Delta Storage Investigations (3 pages)
California Water Plan Update 2003 (3 pages)
*CalSim II and SWP Operations Control Office (1 page).*iii

Future Model Development

(a) CalSim Software
CalSimMulti-period Prescriptive Optimization (not completed)
CalSim Daily Time Step Model (not completed)
CalSim Water Quality Module (not completed)
Data Structure / Version Control (not completed)
CalSim Graphical User Interface (not completed)

(b) CalSim II Applications
CalSim II – CVGSM Integration (not completed)
CalSim II Geographical Expansion (not completed)
Global Climate Change (not completed)
Refined Spatial Resolution (not completed)
Expansion of Land Use Based Demands (not completed)
CalSim II – CALVIN Integration (not completed)
Revision of Urban Water Demands (not completed)

(c) Supporting Models
Replacement of Consumptive Use Model (not completed)

Appendix C: CALSIM II Review Process and Timeline

Establishing the Peer Review Panel

Dr. Pete Loucks (Cornell University and South Florida Water Management District) has accepted the CALFED Science Program's invitation to chair the panel. Other members are being currently being contacted by the Science Program staff

Organization of Briefing Material

Science Program and key agency staff, in consultation with the review panel chair, are identifying and organizing briefing material for panel members. Target date for completion is Sept 1, 2003. (This was extended to December 8, 2003)

Public Meeting of Review Panel

Target: 2-day session in November, 2003 in Sacramento area

Review workshop structure will include:

- Presentation overviews of California hydrology, water management, current issues, and the development of CALSIM II
- Presentations on the range of different current and potential applications of CALSIM for planning, operations, and supply reliability projects
- A summary of an independent interview project by Dr. Jay Lund of users and stakeholders explaining the major questions people are trying to answer with CALSIM II and other models
- Public comment to the panel
- Detail discussion of the model, including assumptions used in different applications, verification studies, and sensitivity analyses
- Opportunity for panel members to ask follow up questions of CALSIM developers and users
- An in camera session for panelists to discuss and begin compiling review comments
- A public presentation of the panel's draft findings

Panel Chair Provides Final Report to CALFED Lead Scientist

The panelists will be asked to finalize their review comments within 3 weeks of the public meeting and to transmit those directly to the Lead Scientist. The Science Program will transmit the completed review to CBDA and the CALFED community.

Appendix D: Panelists CALSIM II Review, Nov. 13-14, 2003

Name	Affiliation	Position	Address/Phone/E-mail
Andy Close	Murray Darling Basin Commission	Lead Modeler and System Manager	GPO Box 409 Canberra ACT 2601, AUSTRALIA (02)62790102 andy.close@mdbc.gov.au
Michael Haneman	UC Berkeley	"Senior Economist, Professor"	327 Giannini Hall, Berkeley, CA 94720-3310 (510)642-2670 hanemann@are.berkeley.edu
John Labadie	Colorado State University	Professor	B211 Engineering, Fort Collins, CO 80523 (970)491-6898 John.Labadie@colostate.edu
Pete Loucks	Cornell University	Professor	"Civil and Environmental Engineering, 311 Hollister Hall, Ithaca, NY 14853 " (607) 255-4896 DPL3@cornell.edu
Jay Lund	UC Davis	Professor	Civil and Environmental Engineering 3109 Engineering III, Davis, CA 95616" (530)752-5671 jrlund@ucdavis.edu
Daene McKinney	University of Texas at Austin	Professor	Civil and Environmental Engineering Campus Mail Code: C1786, Austin, TX 78712 (512)471-8772 daene_mckinney@mail.utexas.edu
Jery Stedinger	Cornell University	Professor	Civil and Environmental Engineering, Hollister Hall, Ithaca, NY 14853 (607) 255 2351 JRS5@Cornell.edu

Appendix E: Managing Model Development, Application, Documentation and Communication.

One possible means of maintaining control of the quality of particular versions of CALSIM II and accompanying models used for SWP-CVP planning and management decisions is to create an interagency modeling consortium (IMC) consisting of DWR, USBR, and persons from other stakeholder organizations, including NGOs and universities, if they are interested and want to participate. This consortium would be responsible for maintaining a toolbox of 'acceptable' models for 'official' use by the agencies and contractors.

IMC responsibilities and authority could include:

- Prioritize, coordinate, and provide consistency, technical guidance and oversight for all modeling applications,
- Approve model selection and insure that each requested application is carried out using the most appropriate model(s) and input data,
- Provide or otherwise insure documentation of the modeling process itself as well as the modeling results,
- Insure that the results are expressed and made available in a way such that others can understand and benefit from that modeling application, as applicable.
- Implement peer reviews of models and their applications as deemed appropriate.

To help meet their responsibilities the IMC will need to establish, publish and implement some procedures for insuring the quality of the entire model development and application process. They will need to identify among all the models that might be used, which are the most appropriate to address each of these separate groups of model applications. They must identify various models, i.e., establish a model toolbox, from which clients can choose the one that best meets their needs (or perhaps argue that another model should be added to the toolbox). The IMC will also need to maintain model documentation and provide for peer reviews of any model, its documentation, and/or its use in a project.

CMM Level 3 Performance Expectations

Firms that develop professional software are typically required to meet certain software standards. One such standard is defined in a book from Carnegie Mellon University. These so called Capability Maturity Model (CMM 1994) standards have various levels. For example, the South Florida Water Management District, that develops hydrologic models used as inputs to major investment decisions, strives to meet Level 3 standards. To meet such standards in software development and peer review, one needs to show that

- Modeling related problems are anticipated and prevented

- Model development and application groups work together as an integrated product team.
- Model use training is planned and provided as is needed.
- New modeling methodologies are identified and evaluated for possible implementation on a qualitative basis.
- Data are collected and used in all defined processes.
- Data are systematically shared across various projects.
- Both the models and their applications are evaluated and judged satisfactory by independent reviewers.

It seems to this panel that CALFED could without too much difficulty meet such standards if it chose to. Clearly planning for, conducting, and documenting these activities will require additional time and money. The expectation is that in the long run, such documentation and review will save time and money by redirecting misguided initiatives, identifying alternative approaches, or providing valuable technical support for a potentially controversial decision.

Model Toolbox

The IMC in collaboration with all agencies involved in water resources planning could be responsible for creating and maintaining a collection of models that agencies can use to meet their needs. As shown in Figure 1, this collection of models might be called the model toolbox. The criteria to be used as a basis for deciding whether a proposed model should or should not be included in the toolbox will depend in part on an assessment of the attributes of that model compared to alternative models and the suitability of the model to meet the needs of the project. Associated with the model toolbox is a library of completed model application documents and data bases for use by anyone who could benefit from them.

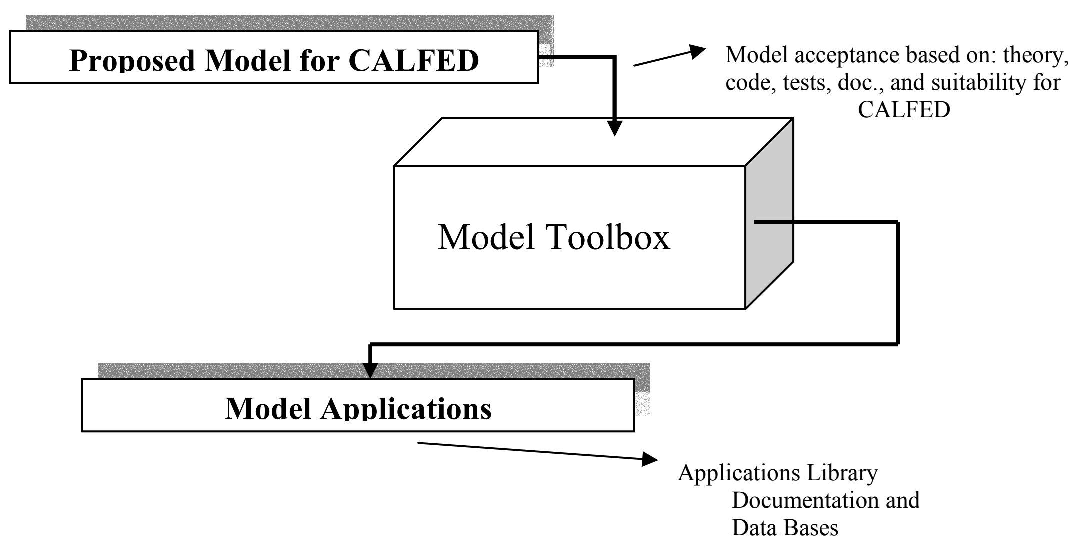

Figure 1. Model Toolbox consisting of approved models for use and Applications Library consisting of documentation and model data bases.

Everyone would agree that all modeling applications should be performed with the 'best' models available. But 'best' does not mean that all models used should be the most detailed, complex, realistic and thus usually the most expensive models available. The decision regarding the 'best' or most appropriate model should be based on the particular issues or questions being addressed, on the quantity and quality of the available input data, and on the time, personnel, and money available to perform the modeling application. The central question to be answered before initiating any modeling application is just what model output information (and precision) is needed to meet the needs of the decision making process. Expressed in other words, just how sensitive will the decision be to the type, amount and precision of the model output?

IMC in consultation with the other agencies could provide guidance on the adequacy of a particular version of CALSIM II or other associated model requested by each client with respect to the theory upon which it is based, its data requirements, its spatial and temporal resolutions, its documentation and status with respect to peer reviews, its capabilities, and its limitations. Similar considerations must be given to the proposed input data. To provide these services to each client requesting services from the IMC would require IMC to be staffed with personnel acquainted with the models in the toolbox, as well as be able to perform or review the simulations requested by various agencies.

There will likely be requests to use models not yet included in the model toolbox. IMC together with others from the DWR and/or USBR will need to judge the merits of such requests and if deemed beneficial, consider including such models in the toolbox. Undoubtedly the extent and quality of the documentation, testing, and peer review of various models in the toolbox will vary. However, a model's inclusion in the toolbox should signify that the model has been judged to be the best available for meeting the goals for which it was designed and is applicable to conditions in California.

Information Flows and Documentation

The IMC will probably be devoting a substantial amount of time giving guidance to clients and, when applicable, to the public. They will need to be working with the clients who are requesting model applications, and in situations where they are not doing this work, they will need to be reviewing and approving the work of the agencies or contractors who are performing the modeling services. IMC would provide technical assistance as well as oversight and coordination among all CALSIM II modeling activities.

Requests for modeling are easy to make, and time and money are required to carry them out. Requests sent to this proposed IMC should reflect some thought by those requesting such model runs as to just why the model application is desired, and just how the results are to be used. We would propose that requests include such items as:

- Reason for modeling,

- Type of modeling (e.g., event based or continuous),
- Particular model preference if any, and why, and possible alternatives,
- Model output information (data) needed and why and when it is needed,
    - What questions are the model results going to answer?
    - What issues are being studied?
    - What decisions are to be made, or at least to be informed, based on these model results?
    - When are the model results needed?
    - What formats are desired for presenting the model results?
- Location or site being modeled and the spatial and temporal scales desired,
- Particular input data assumptions, boundary conditions and other regional assumptions required,
- Source of input data, and format required or desired for the output data,
- Model calibration and verification needs and preferred procedures if any,
- Money and time available for modeling,
- Extent (duration) of the simulations to be performed,
- Desired performance measures, other than variables being simulated, if any,
- Alternative scenarios to be modeled (i.e., number of simulation runs needed),
- Other analyses or model applications that may or will need the output from this model application,
- Sensitivity and uncertainty analyses needed, and for which decision variables and why,
- Client contact person,
- Requirements for intermediate reviews of results or needs for periodic review of modeling application process logs and documents, and
- Other particular requirements or needs.

The use of a model nearly always takes place within a broader context. The model itself can also be part of a larger whole, such as a network of models in which some are using the outputs of other models. These conditions may impose constraints on the simulation modeling project. All these considerations need to be specified in the modeling application request.

Along with the proposal, there should also be a simple order-of-magnitude estimate of the expected values of all relevant decision variables based on simple mass-balance analytical solution methods that can be used without requiring a computer. These estimated values should be used to validate (check the reasonableness of) selected portions of the model runs. If there are any serious discrepancies, it may signify a major problem in the model output.

Is all this paperwork useful? It is to the extent it leads to a more effective and efficient use of personnel, money and time. Preparing a formal modeling application request requires some serious thought as to just why this is necessary and just what information is needed to further the project or analysis. It involves defining the objectives that are to be accomplished. Writing this down in some detail helps reduce the differences in perception that can exist between those who need information and those who are going to provide that information (IMC or a contractor). The problem as stated is often not the problem as understood, by either the client or the model user. In addition, problem perceptions and modeling objectives can change over the duration of a project. One should ask and answer the question of whether or not modeling in general is the right way to obtain the needed information. What are the alternatives to modeling?

The objective of any modeling project should be clearly understood with respect to the domain and the problem area, the reason for using a particular model, the questions to be answered by the model, the model assumptions and limitations, and the scenarios to be modeled. Throughout the project these objective components should be checked to see if any have changed and if they are being met.

If IMC is to serve as a central point to coordinate CALSIM II-related modeling activities, and to provide modeling services, it needs to have the authority to do so. This authority extends to giving advice on issues related to model and input data selection, and for reviewing, approving and prioritizing requests for services. Should contractors be involved in particular model applications, IMC must be authorized to specify the technical terms to be met and oversee the work done by the contractor. Finally IMC will need the financial and human resources needed to do this in a timely manner.

Modeling Application Documentation

One common problem of model studies once they are underway occurs when one wishes to go back over a series of simulation results to see what was changed or why a particular simulation was made or what was learned. It is also commonly difficult if not impossible for third parties to continue from the point at which any previous modeling project was terminated, especially if some time has passed. These problems are caused by a lack of information on how the study was carried out. What was the pattern of thought that took place? Which actions and activities were carried out? Who carried out what work and why? What choices were made? How reliable are the end results? These questions should be answerable if a model journal is kept. Just like computer programming documentation, modeling project documentation is often neglected under the pressure of time and perhaps because writing it is not as interesting as running the models themselves.

The paper trail of what has happened, what assumptions have been made, how calibration and verification were carried out, what results were obtained, why changes, if any, were made, what sensitivity analysis procedures were used and their results, and so on, could be contained in a modeling application documentation (MAD). Once the model application is completed, a copy of the MAD should be given to the requesting agency, as applicable and a copy should remain in IMC. These reports, or at least a summary of them, should be available for downloading from the web. Should further model applications be requested and approved, the requester as well as the IMC can refer to this previously prepared documentation to better understand what was done previously that pertains to the current request.

Model Calibration

Once a model is tested satisfactorily, it can be calibrated. Calibration of models such as CALSIM II are difficult because there are no historical observations of future scenarios to compare with model results. Historical runs, such as have been made, can provide some basis for calibration. In general the smaller the deviation between the calculated model results and the field observations, the better the model. This is true to a certain extent, as the deviations in a perfect model are only due to measurement errors. In practice, however, a good fit is by no means a guarantee of a good model.

The deviations between the model results and the field observations can be due to a number of factors. These factors include possible software errors, inappropriate modeling assumptions such as the (conscious) simplification of complex structures, neglecting certain processes, errors in the mathematical description or in the numerical method applied, inappropriate parameter values, errors in input data and boundary conditions, and measurement errors in the field observations.

To determine whether or not a calibrated model is a 'good' predictor, it should be validated or verified. Calibrated models should be able to reproduce field observations not used in calibration. Validation can be carried out for calibrated models if an independent data set has been kept aside for this purpose. If all available data are used in the calibration process in order to arrive at the best possible results, validation will not be possible. A decision to leave out validation may be a justifiable one especially when data are limited.

Philosophically it is impossible to know if a simulation model of a complex system is 'correct'. There is no way to prove it. Experimenting with a model, such as by carrying out multiple validation tests, can increase confidence in that model. After a sufficient number of successful tests, one might be willing to state that the model is 'good enough', based on the modeling project requirements. The model can then be regarded as having been validated, at least for the ranges of input data and field observations used in the validation.

If model predictions are to be made for situations or conditions for which the model has been validated, there may be some confidence in the reliability of those predictions. Yet one cannot be certain. Much less confidence can be placed on model predictions for conditions outside the range for which the model was validated.

While a model should not be used for extrapolations as commonly applied in predictions and in scenario analyses, this is often exactly the reason for the modeling project. What is likely to happen given events we have not yet experienced? A model's answer to this question should also include the uncertainties attached to these predictions. Depending on the type of model selected and used, one might end up predicting an incorrect future with great accuracy, or predicting the correct future with great uncertainty'. We don't yet know how to predict the correct future with great accuracy – so we do 'what ifs'. One can then argue about what scenarios – the ifs – are the most reasonable or probable, or about the impacts from improbable scenarios that you want to avoid should such scenarios occur.

Use the model

Once the model has been judged 'good enough,' the model may be used to obtain the information desired. Close communication between the client and the modeler during the modeling application process is essential to avoid any unnecessary misunderstandings about what information is wanted and the assumptions on which that information is to be based.

Before the end of this model-use step one should determine whether all the necessary simulations have been performed and whether they have been performed well. Questions to ask include

- did the model fulfill its purpose?
- are the results valid?
- are the quality requirements met?
- was the discretization of space and time chosen well?
- was the choice of the model restrictions correct?
- was the correct model and/or model program chosen?
- was the numerical approach appropriate?
- was the implementation performed correctly?
- what are the sensitive parameters (and other factors)?
- was an uncertainty analysis performed?

If any of the answers to these questions is no, then the situation should be corrected. If it cannot, the reason(s) for why it cannot be corrected should be documented in the model application document (MAD).

Interpret model results

Interpreting the information resulting from models is a crucial step in the modeling application process, especially in situations in which the client may only be interested in those results and not the way they were obtained. The model results can be compared to those of other similar studies. Are the results consistent? IMC must make that judgment. Any unanticipated results should be discussed and explained. The results should be judged with respect to the modeling project objectives.

The results of any modeling project typically include large files of time-series data. Only the most dedicated of clients will want to read those files. Thus these data must be presented in a more concise form. Statistical summaries should explicitly include any restrictions and uncertainties in the results. They should identify any gaps in the domain knowledge, thus generating new research questions or identifying the need for more field observations and measurements.

Report model results

Once the modeling application is completed, the organization doing the modeling will be responsible for preparing a report. The contents of this report should conform to the agreement made between modeling organization and the client prior to the initiation of the modeling application (see above). Although the results of a model are very rarely used as the sole basis for policy decisions, those requesting model applications may have a responsibility to translate their model results into policy recommendations. Policymakers, managers, and indeed the participating stakeholders typically want simple and clear unambiguous answers to complex questions. Much of the scientifically justified discussion, say regarding the uncertainties associated with some of the data, included in the main body of a report are not included in the executive summary of that report. This executive summary is often the only part read by those responsible for making decisions. Therefore, the conclusions of the model study must not only be scientifically correct, but also concisely formulated, without jargon, and fully understandable by managers and policymakers. When preparing or reviewing contractor model results reports, the IMC should consider this need.

These model application and model results reports should include sufficient detail to allow others to reproduce the model study (including its results) and/or to proceed from the point where this study ended. The report therefore requires a clear indication of the validity, usability and any restrictions of the model results.

Data Management

CALSIM II and its associated or linked models will require data. They will also produce data. Many of these data will have spatial and temporal dimensions. This information must be documented (meta data), preserved, and made accessible to IMC customers, coordination agencies and others. IMC should participate in data management strategic development, storage, documentation and dissemination. It should work with data base managers of various agencies to help them satisfy the IMC's data management requirements.

The availability of quality assured data is a critical dependency that must be met to facilitate timely completion of model development, implementation and application. To mitigate the impact of the availability of data on the timeline for the major model completion deadlines, the following issues should be addressed. :

- Updating land use / land cover data at regular and timely intervals.
- Developing and maintaining a common modeling database. This data base should include infrastructure design and operating policy data as well as water quality, ecological, land use, economic and of course hydrological data. Many of these data sets will have spatial as well as temporal dimensions. Each data set should have an associated metadata file.
- Pre-processed and post-processed datasets from previous model runs should be archived along with its metadata file in a central location for ease of access and availability.
- Measures to insure the consistency and quality of the input data.
- Measures to insure adequate communication among model developers, users and stakeholders. This includes measures to assist in developing documentation appropriate for each type of stakeholder.

Support of IMC activities

Common failures of IMC type organizations are typically due to:

- Insufficient staff to enable cross-training. This may lead to the dependency on one person or a very small group of employees for each sub module or the overall effort.
- Inadequate funding to institute good project management discipline.
- Inadequate funding to contract for technical writers and software engineers.
- Inadequate funding to contract for peer reviews.

Risk assessments

A risk assessment of CALSIM II and its associated models and data should be completed. The timely availability of quality assured data for example, is a risk. Project risk management includes the processes concerned with identifying, analyzing, and responding to uncertainties. Risk management attempts to minimize the results of adverse events. As a guide, the template, such as shown at the end of this Appendix, may be used to facilitate the assessment of risks.

Problem Management

Given the high visibility and criticality of the CALSIM II modeling effort an issue or problem management process should be developed within IMC. Issue/problem management includes the process for identifying, communicating, and resolving issues and problems.

The purpose of this procedure is to ensure that:

- Issues are identified, reported, managed, and resolved in a timely and effective manner. Responsibility is assigned to an owner for reporting, managing and resolving each issue
- All affected stakeholders are aware of the status of the issues
- Escalation of unresolved issues take place according to a defined procedure

In order to ensure that project issues and problems are appropriately managed various issue/problem management steps should be identified and followed to track the actions taken to resolve the issue or problem throughout the life of a modeling project.

B. Managing Peer Reviews

One means of quality control involves peer reviews of the models, their associated software, and their applications. One possible means of facilitating the peer review processes and for maintaining control on the particular versions of CALSIM II and accompanying models used for SWP-CVP planning and management decisions is another reason to create an interagency modeling consortium (IMC) consisting of DWR, USBR, and other stakeholder organization personnel if they are interested and want to participate. As suggested above, this consortium could be responsible for maintaining a toolbox of ‘acceptable’ peer-reviewed models for use by the agencies and contractors. The peer reviews should be of the theory underlying each model, the model's software, the documentation of that software, the model's functions and capabilities including those pertaining to model data input and output, model calibration and verification, sensitivity analyses, uncertainty analyses, user control (GUIs), spatial and temporal resolutions, limiting assumptions, and on the model (as opposed to code) documentation.

Just having evidence of published articles about a particular model in peer reviewed journals is not a substitute for a peer review of the model software and its applicability or suitability for certain types of analyses for SWP-CVP. Peer reviews of all models, their software, and their use should be accomplished by experts both within and outside of the originating agencies. 'Inside' agency (or internal) reviews may uncover some needed changes and identify other issues or problems that external reviewers could be asked to specifically examine and address. Internal reviews can make the external review process more effective, less costly and less time consuming.

Peer reviews are considered a key process area for Level 3 and higher of the Capability Maturity Model guidelines for improving the software process (Carnegie Mellon University, 1994). The purpose of peer review evaluations is to find defects in the model formulation and software and in its use, i.e., model application. Peer reviewers can also identify possible ways of correcting those defects, if any. If there are no defects, or after all known defects have been corrected, both the developers and users of any model and its software can have a stronger basis for believing that their product and its output are reliable.

Peer reviews serve the same function as accountants. Once a firm's financial records have been peer reviewed by accountants (assuming they are qualified, objective and honest) the board of directors as well as the stockholders will have more assurance of the liabilities and net worth of their firm, and just how well it is being managed. In this case it is the assurance of the quality of the models, their software, and on their use in project evaluations, that actual and potential users of the model results depend upon.

The types of problems and issues for which a model, its software, and its documentation are designed to address are called the model's 'application niche'. Peer review of model development should include the evaluation of the intended application niche along with consideration of other aspects of model performance. Users of any model should be aware of the types of analyses for which the model is best suited and those for which the model is not well suited. This, along with the results of a peer review of any model application, should help the potential model user, or the user of the model results, better understand the limitations of the scientific basis of the model and just how much confidence can be placed on the model output.

Peer review triggers

Clearly judgment will have to be exercised as to just when and in what detail a peer review needs to be implemented. However the triggers on when a decision about a peer review needs to be made can be defined.

As shown in Figure 2, decisions regarding peer review are needed when models are proposed for the tool box and when model applications are completed. Should IMC decide a peer review is warranted when either of those events takes place, they will have to decide on the type of review and its level of detail. They will also need to identify the individuals to be asked to carry out that peer review.

Peer reviews are going to take time and cost money. They will also require IMC time to prepare the documentation needed for the peer reviewers and to read and act on reports prepared by the peer reviewers. This will apply if the peer review is internal or external.

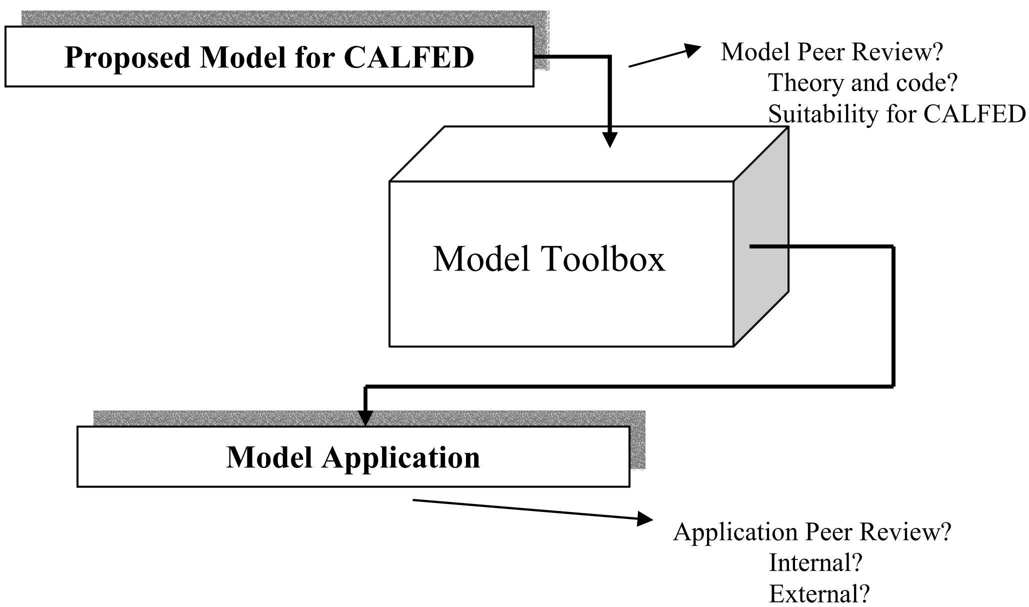

Figure 2. Schematic showing events where a peer review decision can be made.

The particular models and their associated software and documentation to be peer reviewed should be identified by the individuals or departments or agencies. This can include model process descriptions, software source code, documents, test results, and other supporting materials, as needed, for an adequate peer review of the entire model and its software. These products to be reviewed should be identified in writing and a written history of the review of different versions of each item should be maintained.

Events that take place in the progression of model development and use and subsequent modifications that warrant a peer review should be identified and specified in a written document. (This fits in to the model development and use documentation that should be maintained for Level 3 or higher CMM) When these events take place a peer review process should be considered, and if warranted, implemented. Depending on the event, the review can be solely internal, or it can involve an independent external review team as well.

Model application reviews should include an evaluation of the intended model application niche, and its applicability to current needs. Peer review may be appropriate for existing models when new information becomes available that could negate some or all of the conclusions of previous reviews or suggest a change in the currently specified application niche. Peer review of a model's applicability to a particular study should be planned well in advance of when model results are needed. The results of application reviews can influence the decisions made based on the model outputs. Once a peer review has been conducted for a particular model and its input data, peer reviews of subsequent applications of a model with similar inputs might be unnecessary. However, any time the model results may be controversial, or end up in litigation, another peer review may be justified.

Peer Review Process

The extent and process of performing and responding to peer reviews can vary in any organization. The ones discussed in this section attempt to follow the processes recommended by the Capability Maturity Model Level 3 guidelines.

Project peer review process should be specified in writing. A first step in this process should be to identify the particular modeling products and processes that will undergo peer review. This includes the models (i.e. the processes being modeled and the assumptions built into the models for describing these processes), their supporting software, the documentation of the model and its software, as well as all the written guidelines on how the models are to be used.

A second step is to perform an internal peer review prior to a model's use for project evaluation. It should be peer reviewed for accuracy, its suitability for use, and for identifying any possible errors in its logic, its coding, or in its documentation. Following an internal review, an external peer review can be performed.

Following the successful conclusion of internal and external peer reviews of a model and its documentation, the model can be applied to evaluate alternative projects. After the model has been applied to a particular project, the modeling process and its results should be peer reviewed to insure that the model has been applied properly, that the input data were appropriate, and that the conclusions drawn were valid.

Peer review teams should be selected, along with a peer review team leader. The particular personnel on the team will depend on the particular model and its software and documentation being reviewed. CALFED should have a list of qualified peer reviewers representing all applicable disciplines, both internal and external, that it can call upon to perform these reviews. The peer reviews are to be of the models and their use, not of the people who developed or used them. The reviews are to be used to evaluate the quality of modeling products and processes, not of the personnel involved.

Establishing and carrying out ongoing peer review processes costs money. Adequate funding must be made available to

1. identify and recruit a peer review team and team leader
2. prepare and distribute the peer review materials to the peer review team
3. support the time required for the team to review the materials prior to a team meeting
4. support the team meeting and to participate in it as appropriate (e.g., answering questions, conducting model experiments and sensitivity analyses, etc.)
5. reproduce and distribute the team report and to take actions as needed
6. monitor the modifications or changes being made to the model, its software, and its documentation, or redoing the model application, as needed.
7. prepare and distribute to model developers and potential users a report on the results of the peer review and the actions taken.

The particular peer review process may depend on just what is being peer reviewed and the resources and time available to perform the review. In general, however, the steps of a peer review could include the following:

1. DWR or CALFED should identify and establish a pool of possible reviewers representing various disciplines, with sufficient redundancy to allow for scheduling conflicts when ever some subset of those reviewers are needed. This includes both internal as well as external reviewers. What ever administrative work is need to establish this pool should be completed prior to when these reviewers will be needed.

2. At particular milestones in any new model development or in model application an internal peer review process could be initiated, to examine the modeling assumptions, the software that implements those assumptions in the case of model development or the data being used for model inputs in the case of model applications, and the documentation being prepared to describe the processes, to document the software code, and to document the tests that were run to test the code, or to document the results of the model application. If deemed appropriate, an external peer review could also be performed. If an external review is to take place, the particular reviewers need to be selected, notified, sent supporting documents, and be scheduled for one or more meetings, as needed. They should be issued contracts specifying the requirements (the checklist of items to be reviewed) and products expected.

3. Recommendations made by the peer review team need to be addressed and the actions taken along with the rationale for those actions should be documented.

4. The peer review team should review the actions taken and the results obtained from these actions. If not judged acceptable new recommendations should be made and submitted. A final report should be prepared by the peer review team when all recommendations have been successfully implemented or addressed, or if no further actions based on review team's recommendations will be taken by the model developers or users.

The time and effort required for various levels of review should also be assessed and provided to the review team so that they can carry out the level of review requested of them. Otherwise the reviews may be superficial and while appearing to be peer reviewed, a model and its associated products may in fact be inadequately reviewed. Peer review teams have the responsibility to specify in writing the scope and limitations of their reviews.

As was the case for this peer review panel, the materials to be sent to the review team to allow them to prepare for their meeting should include the statement of review objectives and the level of detail desired, the applicable requirements and standards upon which to judge the adequacy of the products being reviewed, and of course the material that is to be reviewed. There should be a list of questions for the reviewers to address. Each review team member should be assigned and given responsibility for answering specific questions and for completing specific aspects of the overall review. All team members should be given specific review standards or requirements, including the expected completion dates. Checklists should be provided the review team that are applicable to the specific type of product being reviewed and the level of detail to be examined. These checklists will contain the criteria for judging the product, such as compliance with any standards and procedures, completeness, correctness, rules of construction, and maintainability.

Peer Review Issues and Questions

Each model development or application review will dictate its own special set of questions to be addressed. Some of these questions could relate to:

- Model Purpose and Objective
  - Use of model related to decisions being considered.
  - Model application niche, and why.
  - Model strengths and weaknesses –is it the best model?
- Model Processes and Limitations
  - Model processes, spatial and temporal scales, grid resolution.
  - Model variables and level of aggregation.
- Model Theoretical Basis
  - Model algorithms, numerical or analytical methods,
  - Model process formulation
  - Modeling approach in comparison with other models
  - Any shortcomings in relation to application niche
- Model Parameter Estimation
  - Methods used
  - Data available for parameter estimation
  - Parameter estimate reliabilities
  - Boundary conditions and appropriateness.
- Model Input Data Quantity/Quality
  - Data used in design of model
  - Data adequacy (quantity, quality, resolution) for model purpose and application
  - Data necessary for application of model
  - Key data gaps in model application
  - Additional data needs and why
- Model Key Assumptions
  - Basis for major assumptions

    - Sensitivity of model outputs to key assumptions
    - Sensitivity of potential decisions to key assumptions
    - Ease in modifying key assumptions
- Model Performance Measures
    - Criteria for assessing model performance
    - Correspondence of model output with measured observed data
    - Any model bias throughout range of model predictions
    - Variability and uncertainty analyses and representations in model results
    - What determines model's variability and uncertainty.
    - Model performance relative to others in application niche
- Model Documentation and User's Guide
    - Clarity of documentation, comprehensiveness of user's guide
    - Model applicability and limitations
    - Input data requirements for calibration, verification, model runs
    - Post modeling analyses, display and interpretation of results
    - Model code documentation
    - Model application documentation examples for prospective users.
- Review Retrospective
    - How well model and its application meet objectives and needs of project
    - Possible changes in the model to improve model performance
    - Robustness of model solutions to small changes in uncertain parameters, etc.
    - Ease of including uncertainty analyses associated with uncertain input data.
    - Key research needs for model improvement.

Peer Review Completion Reports

Procedures need to be established to track and confirm actions based on suggested changes or modifications in the material being reviewed. Once these actions are taken and completed, and documented, the peer review process for that particular product is completed. Peer review completion reports should contain data on what was reviewed and the results of the review. These data should include a description of the products that were reviewed, the level of detail of the review, any review limitations or qualifications, the number and backgrounds of the reviewers, the time spent preparing for and during review team meetings, the defects found and recommendations made, and the actions taken to address these recommendations.

Overall Peer Review Evaluations

The IMC or initiating agency should document the planning for and scheduling of peer reviews. The products to be reviewed and the level of detail to be examined also need to be specified. The procedures to be followed for selecting peer review team members, and the team leader, should also be determined and documented. Procedures for training potential reviewers, if such training is needed, should be identified and implemented, as required.

Periodically the IMC or applicable agency should assess just how well the plan described in the preceding paragraph is being carried out, and just how beneficial these peer reviews are to the overall modeling effort. Measures should be identified and used to determine the status of the peer review activities.   These measures could include the number of completed peer reviews performed compared to the number expected to be performed, the overall effort expended on peer reviews compared to that expected, and the number and extent of peer review recommendations requiring actions.

At a minimum these periodic reviews should verify that

1. The planned peer reviews and/or audits are conducted.
2. The peer review leaders are adequately trained for their roles.
3. The reviewers are properly trained or experienced in their roles.
4. The processes for preparing for and conducting peer reviews, and for following up on reviewer's recommendations are adequate and are being followed.
5. The reporting of peer review results is complete, accurate, timely and is being made available to model users.

Risk Management Template

Risk Definition Name	Enter a short name that uniquely defines the risk
Risk #	Enter a unique number assigned to the risk. Range starts with 1 and continues.
Date Risk Identified	Enter the date the risk was identified
Risk Identification Source	Enter the source of the risk identification. In example, meeting name, group, or person.
Risk Owner	Enter the name of the person who will be responsible for ensuring the risk is approved, managed, periodically assessed, communicated, and tracked through closed or transfer.
Risk Detailed Description	Enter a detailed description of the risk so that a reader clearly understands the risk.
Probable Impact of Risk on Project (H, M, L)	Enter the impact on the project. o High = the risk will most likely occur and the impact could prevent the project from achieving its purpose. o Medium = there is a 50/50 change the risk would occur and the impact is serious but the project could still achieve its purpose if appropriately managed. o Low = there is a low probability that the risk would occur and minimal impact to the project's purpose.
Probable Impact of Risk on Project Costs	Enter the impact on the project in dollars. Determine what the potential cost to the project would be if the risk occurs.
Probable Impact of Risk on Project Schedule	Enter the schedule impact on the project. Determine how the schedule would be potentially impacted if the risk occurs.
Probable Impact of Risk on Project Results	Enter the impact on the project. Determine how the overall project purpose and results will be potentially impacted if the risk occurs.
Detailed Plan to Mitigate or Transfer Risk	Enter the detailed plan to mitigate the risk or a statement that the risk will be accepted. Mitigation could include ways to minimize, avoid, or transfer the risk to another party or group. Risk transfer would include evidence of agreement by the accepting party.
Detailed Project Action Items Required to Mitigate or Transfer Risk	Enter the detailed action items required to mitigate the risk. These items will be summarized and assigned within the project Action Log, along with an action item owner, and target completion date.
Detailed Project Plan Tasks Required to Mitigate Risk	Enter the detailed project plan task required to mitigate the risk. These items will be summarized and contained within the MS Project Schedule along with the effort, duration, schedule, and assigned resources.
Comments	Enter any permanent comments that cannot be included in the above items.
Referenced Documents	Enter any documents that a reader should consider in understanding, analyzing, mitigating, or accepting this risk.
Date Risk Closed	Enter the date this risk was closed. This would include when all action items or project tasks were completed, or the risk was transferred to another party or group.

Appendix F: Analysis of the November 2003 CALSIM II Validation Report

The following comments come from an analysis of the model results presented in the validation report *'CALSIM II Simulation of Historical SWP/CVP Operations'*, DWR (2003). The observations relate to the formulation of the model at November 2003. Changes might be made to that formulation which could resolve these issues.

Overestimation of Project Deliveries

The validation run suggests that the modeled demands included in CALSIM II overestimate the actual demands. CVP demands south of the Delta are assumed to be always equal to the contract entitlement whereas the observed deliveries in unrestricted years are consistently less than this amount. The modeled North of Delta deliveries are also consistently higher than observed. The modeled and observed CVP deliveries from the validation report are listed in Table 1.

Table 1. Comparison of modelled and observed CVP deliveries (1975-1998)

Project	Simulated Delivery (Taf/yr)	Historical Delivery (taf/yr)	Difference (taf/yr)	% Difference
CVP North of Delta	1960	1750	210	12
CVP South of Delta	2650	2490	160	6.4

Because the SWP south of delta demands were set to historical deliveries in many years, comparison with the historical deliveries in the validation report is of limited validity. However the fact that the historical SWP deliveries over the last ten years have averaged only 2385 taf/year while the modeled 'year 2001 development' SWP Delta deliveries reported in the 2002 State Water Project Delivery Reliability Report average 3090 taf/year, suggests that modeled SWP deliveries may also be too high.

Allocations to Project Contractors

Seasonal allocations to SWP and CVP contractors are made on the basis of water in storage, forecast inflows, projected carryover storage requirements and in-Basin and Delta regulatory requirements. The allocation processes used by the operators and those used by CALSIM II, are not identical. An examination of the way that CALSIM II has restricted project deliveries during the dry period of 1987-1992 (Figures 10, 16, 17 and 24 of the validation report) suggests that CALSIM II has allocated less water in the early years of the dry sequence than occurred in practice and consequently had more water available in 1991 and 1992 when the most severe restrictions were experienced. The carryover storage rules adopted can have a significant impact on the expected frequency and severity of water supply restrictions. The model rules need to be examined to ensure that the accurately reflect the way the system will be managed in the future.

San Luis Reservoir Operation

The rules used by the system operators for transferring water from headwater storages to the San Luis Reservoir can have a significant impact on:

- the pattern of flow in the Delta,
- the operation of accounting rules between the SWP and the CVP and
- opportunities for SWP wheeling of CVP water and possibly the availability of Article 21 water to SWP contractors.

A comparison of the modeled and observed storage behavior of the SWP component of San Luis (Figure 15) reveals that the model consistently underestimates the volume in storage. A comparison of the CVP component of the storage (Figure 23) indicates that the actual storage is filled earlier in the season and that the actual storage is also slightly higher than the modeled.

Users of CALSIM II output need to be confident that the rules adopted by the model for determining these transfers reflect the way this component of the system will be operated in the future.

Appendix G: Some Principles for Strategic Water Analysis for the California Water Plan Bulletin 160-03 (from the stakeholder review Draft, Sept. 30, 2003)

Strategy:

1) A frequently amended strategic document will lay out DWR's strategic analysis framework and identify the technical objectives, roles, and responsibilities of major DWR data collection efforts and analytical tools and their interactions and their responsible managers.

Transparency:

2) All data and models should be in the public domain and available on the web.
3) All data and models should have significant documentation.
4) Known limitations should be documented.

Longer-term viability:

5) Modularity: Major analytical tools will be designed and implemented to fit modularly and explicitly within the larger strategic analysis framework.
6) Adaptive data management framework: Major data efforts will fall within a larger data management framework, including protocols for data documentation and updating, and documentation of limitations.
7) A frequently-updated document will outline short-term and long-term efforts, budgets, and responsibilities for continuous improvement of analytical tools and data, with policy for continued user, local agency, and stakeholder involvement.

Coverage:

8) Spatial coverage for the basic data and analytical framework will be statewide.
9) Local and regional water management and resources will be explicitly represented.

Accountability and Quality Control:

10) In developing analytical tools, systematic efforts should be made to involve local agencies and stakeholders.
11) Major analytical products will undergo external review by a) external unaffiliated experts and b) local agencies whose systems are included in the model. User groups will exist for all major analytical products.
12) DWR's strategic analysis framework will undergo periodic internal and external review.

Appendix H: Model Sensitivity and Uncertainty Analysis

(This is a draft of a book chapter by DPL/JRS that may be useful for CALSIM II developers)

The usefulness of any model is in part dependent on the accuracy and reliability of its output data. Yet, because all models are imperfect abstractions of reality, and because precise input data are rarely if ever available, all output values are subject to imprecision. The input data and modeling uncertainties are not independent of each other. They can interact in various ways. The end result is imprecision and uncertainty associated with model output. This chapter focuses on ways of identifying, quantifying, and communicating the uncertainties in model outputs.

1. Introduction

Models are the primary way we have to estimate the multiple affects of alternative water resource system design and operating policies. Models predict the values of various system performance indicators. Model outputs are based on model structure, hydrologic and other time-series inputs and a host of parameters whose values describe the system being simulated. Even if these assumptions and input data reflect, or are at least representative of, conditions believed to be true, we know they will be wrong. Our models are always simplifications of the real systems we are studying. Furthermore, we simply cannot forecast the future with precision. So we know the model outputs of future conditions are uncertain estimates, at best.

Some prediction uncertainties can be reduced by additional research and data collection and analysis. Before undertaking expensive studies to gather and analyze additional data it is reasonable to ask what improvement in estimates of system performance or what reduction in the uncertainty associated with those estimates would result if all data and model uncertainties could be reduced. Such information helps determine how much one would be willing to 'pay' to reduce prediction uncertainty. If prediction uncertainty on average is costing a lot, it may pay to invest in additional data collection, more studies, or in better models all aimed at reducing that prediction uncertainty. If that uncertainty has no, or only a very modest, impact on the likely decision that is to be made, one should find other issues to worry about.

If it appears that reducing prediction uncertainty is worthwhile, then one should consider how best to do it. If doing this involves obtaining additional information, then it is clear that the value of this additional information, however measured, should exceed the cost of obtaining it. The value of such information will be the increase in system performance, or the reduction in its variance, that one can expect from obtaining such information. If additional information is to be obtained, it should be that information which reduces the uncertainties considered important, not the unimportant ones.

This chapter reviews some methods for identifying and communicating model prediction uncertainty. The discussion begins with a review of the causes of risk and uncertainty in model output. It then examines ways of measuring or quantifying uncertainty and model output sensitivity to model input imprecision, concentrating on methods that seem most relevant or practical for large-scale regional simulation modeling. It builds on some of the statistical methods reviewed in Chapter III and the modeling of risk and uncertainty in Chapter VI.

2. Issues, concerns, and terminology

Outcomes or events that cannot be predicted with certainty are often called risky or uncertain. Some individuals draw a special and interesting distinction between risk and uncertainty. In particular, the term risk is often reserved to describe situations for which probabilities are available to describe the likelihood of various events or outcomes. If probabilities of various events or outcomes cannot be quantified, or if the events themselves are unpredictable, some would say the problem is then one of uncertainty, and not of risk. In this chapter what is not certain is considered uncertain, and uncertainty is often described by a probability distribution. When the ranges of possible events are known and their probabilities are measurable, risk is called objective risk. If the probabilities are based solely on human judgment, the risk is called subjective risk.

Such distinctions between objective and subjective risk, and between risk and uncertainty, rarely serve any useful purpose to those developing and using models. Likewise the distinctions are often unimportant to those who should be aware of the risks or uncertainties associated with system performance indicator values.

Uncertainty in information is inherent in future-oriented planning efforts. Uncertainty stems from inadequate information and incorrect assumptions, as well as from the variability of natural processes. Water managers often need to identify both the uncertainty as well as the sensitivity of, or changes in, system performance indicator values due to the any changes in possible input data and parameter values from what were predicted. They need to reduce this level of uncertainty to the extent practicable. Finally, they need to communicate the residual uncertainties clearly so that decisions can be made with this knowledge and understanding.

Sensitivity analysis can be distinguished from uncertainty analysis. Sensitivity analysis procedures explore and quantify the impact of possible errors in input data on predicted model outputs and system performance indices. Simple sensitivity analysis procedures can be used to illustrate either graphically or numerically the consequences of alternative assumptions about the future. Uncertainty analyses employing probabilistic descriptions of model inputs can be used to derive probability distributions of model outputs and system performance indices. Figure 1 illustrates the impact of both input data sensitivity and input data uncertainty on model output uncertainty.

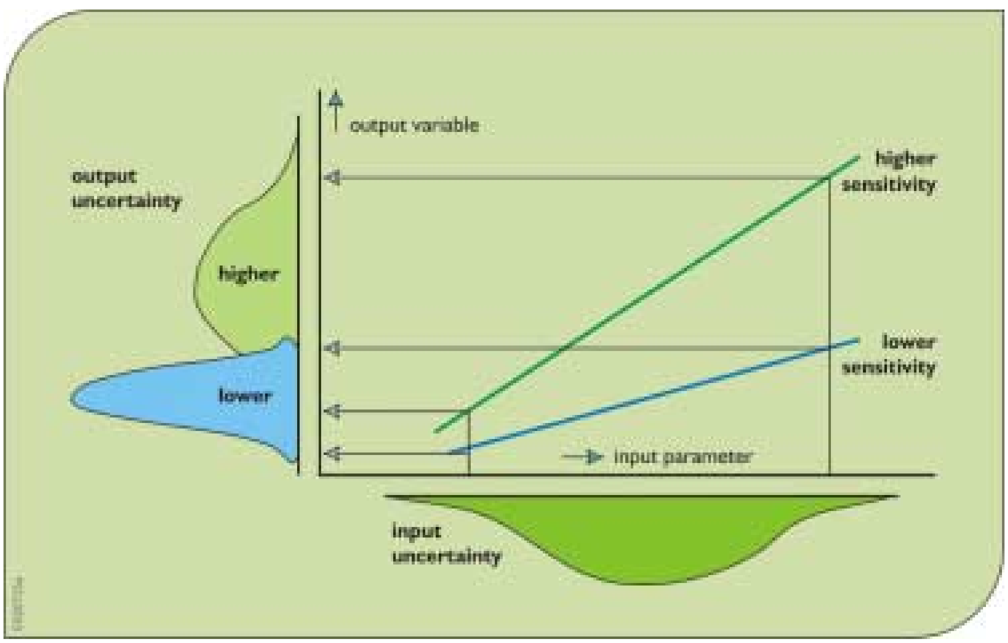

Figure 1. Schematic diagram showing relationship among model input parameter uncertainty and sensitivity to model output variable uncertainty (Lal, 1995).

It is worthwhile to explore the transformation of uncertainties in model inputs and parameters into uncertainty in model outputs when conditions differ from those reflected by the model inputs. Historical records of system characteristics are typically used as a basis for model inputs. Yet conditions in the future may change. There may be changes in the frequency and amounts of precipitation, changes in land cover and topography, and changes in the design and operation of control structures, all resulting in changes of water stages and flows, and their qualities, and consequently changes in the impacted ecosystems.

If asked how the system would operate with inputs similar to those in the historical database, the model should be able to interpolate within the available knowledge base to provide a fairly precise estimate. Still that estimate will not be perfect. This is because our ability to reproduce current and recent operations is not perfect, though it should be fairly good. If asked to predict system performance for situations very different from those in the historical knowledge base, or when the historical data are not considered representative of what might happen in the future, say due to climate change, such predictions become much less precise. There are two reasons why. First, our description of the characteristics of those different situations or conditions may be imprecise. Second, our knowledge base may not be sufficient for calibrating model parameters in ways that would enable us to reliably predict how the system will operate under conditions unlike those that have been experienced historically. The more conditions of interest are unlike those in the historical knowledge base, the less confidence we have that the model is providing a reliable description of systems operation. Figure 2 illustrates this issue.

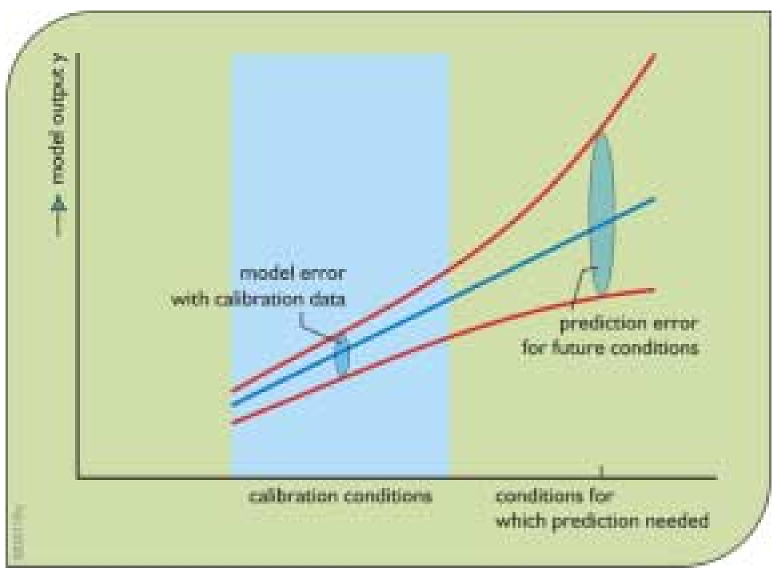

Figure 2. The precision of model predictions is affected by the difference between the conditions or scenarios of interest and the conditions or scenarios for which the model was calibrated.

Clearly a sensitivity analysis needs to consider how well a model can replicate current operations, and how similar the target conditions or scenarios are to those described in the historical record. The greater the required extrapolation from what has been observed, the greater will be the importance of parameter and model uncertainties.

The relative and absolute importance of different parameters will depend on the system performance indicators of interest. Seepage rates may have a very large local effect, but a small global effect. Changes in system-wide evapotranspiration rates will likely impact system-wide flows. The precision of model projections and the relative importance of errors in different parameters will depend upon the:

(1) precision with which the model can reproduce observed conditions,
(2) difference between the conditions predicted and the historical experience included in the knowledge base, and the
(3) system performance characteristics of interest.

Errors and approximations in input data measurement, parameter values, model structure and model solution algorithms, are all sources of uncertainty. While there are reasonable ways of quantifying and reducing these errors and the resulting range of uncertainty of various system performance indicator values they are impossible to eliminate. Decisions will still have to be made in the face of a risky and uncertain future. Decisions can be modified as new data and knowledge are obtained in a process of adaptive management.

There is also uncertainty with respect to human behavior and reaction related to particular outcomes and their likelihoods, i.e., to their risks and uncertainties. As important as risks and uncertainties associated with human reactions are to particular outcomes, they are not usually part of the models themselves. Social uncertainty may often be the most significant component of the total uncertainty associated with just how a water resource system will perform. For this reason we should seek designs and operating policies that are flexible and adaptable.

When uncertainties associated with system operation under a new operating regime are large, one should anticipate the need to make changes and improvements as experience is gained and new information accumulates. When predictions are highly unreliable, responsible managers should favor actions that are robust (e.g., good under a wide range of situations), gain information through research and experimentation, monitor results to provide feedback for the next decision, update assessments and modify policies in the light of new information, and avoid irreversible actions and commitments.

3. Variability and uncertainty in model output

Differences between model output and observed values can result from either natural variability, say caused by unpredictable rainfall, evapotranspiration, water consumption, and the like, and/or by both known and unknown errors in the input data, the model parameters, or the model itself. The later is sometimes called knowledge uncertainty but it isn't always due to a lack of knowledge. Models are always simplifications of reality and hence 'imprecision' can result. Sometimes imprecision occurs because of a lack of knowledge, such as just how a particular species will react to various environmental and other habitat conditions. Other times known errors are introduced simply for practical reasons.

Imperfect representation of processes in a model constitutes model structural uncertainty. Imperfect knowledge of the values of parameters associated with these processes constitutes model parameter uncertainty. Natural variability includes both temporal variability and spatial variability, to which model input values may be subject.

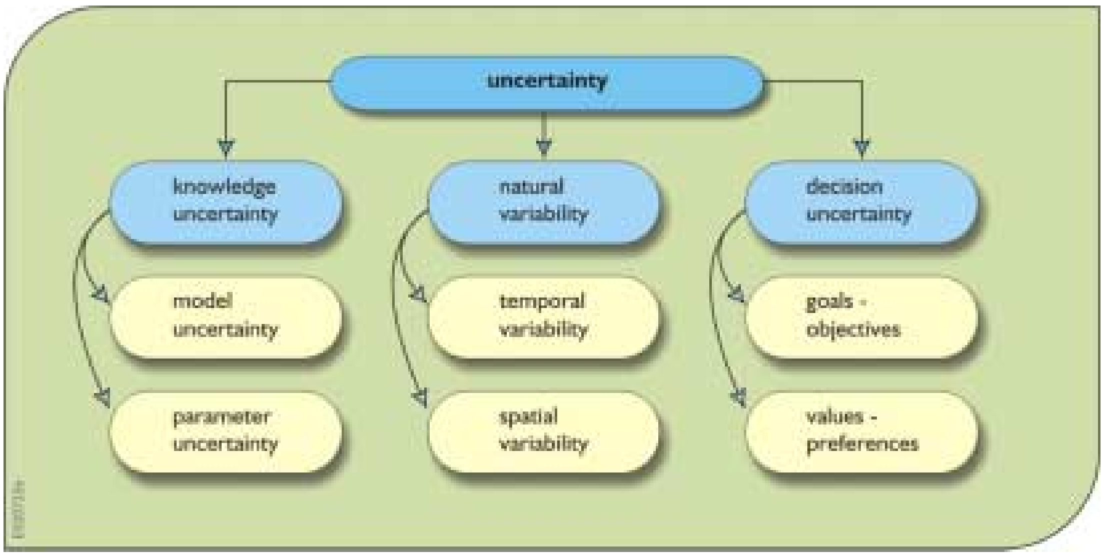

Figure 3. One way of classifying types of uncertainty.

Figure 3 illustrates these different types of uncertainty. For example, the rainfall measured at a weather station within a particular model grid cell may be used as an input value for that cell, but the rainfall may actually vary at different points within that cell and its mean value will vary across the landscape. Knowledge uncertainty can be reduced through further measurement and/or research. Natural variability is a property of the natural system, and is usually not reducible at the scale being used. Decision uncertainty is simply an acknowledgement that we cannot predict ahead of time just what decisions individuals and organizations will make, or even just what particular set of goals or objectives will be considered and the relative importance of each.

Rather than contrasting 'knowledge' uncertainty vs. natural variability vs. decision uncertainty, one can classify uncertainty in another way based on specific sources of uncertainty, such as those listed below, and address ways of identifying and dealing with each source of uncertainty.

Informational Uncertainties:

- imprecision in specifying the boundary and initial conditions that impact the output variable values
- imprecision in measuring observed output variable values

Model Uncertainties:

- uncertain model structure and parameter values
- variability of observed input and output values over a region smaller than the spatial scale of the model
- variability of observed model input and output values within a time smaller than the temporal scale of the model. (e.g., rainfall and depths and flows within a day)
- errors in linking models of different spatial and temporal scales

Numerical Errors:

- errors in the model solution algorithm

3.1 Natural variability

The main source of hydrologic model output value variability is the natural variability in hydrological and meteorological input series. Periods of normal precipitation and temperature can be interrupted by periods of extended drought and intense meteorological events such as hurricanes and tornadoes. There is no reason to think such events will not continue to occur and become even more frequent and extreme. Research has demonstrated that climate has been variable in the past and concerns about anthropogenic activities that may increase that variability increase each year. Sensitivity analysis can help assess the affect of errors in predictions if those predictions are based only on past records of historical time-series data describing precipitation, temperature and other exogenous forces across and on the border of the regions being studied.

Time series input data are often actual, or at least based on, historical data. The time-series values typically describe historical conditions including droughts and wet periods. What is distinctive about natural uncertainty, as opposed to errors and uncertainty due to modeling limitations, is that natural variability in meteorological forces cannot be reduced by improving the model's structure, increasing the resolution of the simulation, or by better calibration of model parameters.

Errors result if meteorological values are not measured or recorded accurately, or if mistakes are made in the generation of computer data files. Furthermore, there is no assurance the statistical properties of historical data will accurately represent the statistical properties of future data. Actual future precipitation and temperature scenarios will be different from those in the past, and this difference in many cases may have a larger affect than the uncertainty due to incorrect parameter values. However, the affects of uncertainties in the parameter values used in stochastic generation models are often much more significant than the affects of using different stochastic generation models (Stedinger and Taylor, 1982).

While variability of model output is a direct result of variability of model input (e.g., hydrologic and meteorological data), the extent of the variability, and the lower and upper limits of that variability, may also be affected by errors in the inputs, the values of parameters, initial boundary conditions, model structure, processes and solution algorithms.

Figure 4 illustrates the distinction between the variability of a system performance indicator due to input data variability, and the extended range of variability due to the total uncertainty associated with any combination of the causes listed in the previous section. This extended range is what is of interest to water resource planners and managers.

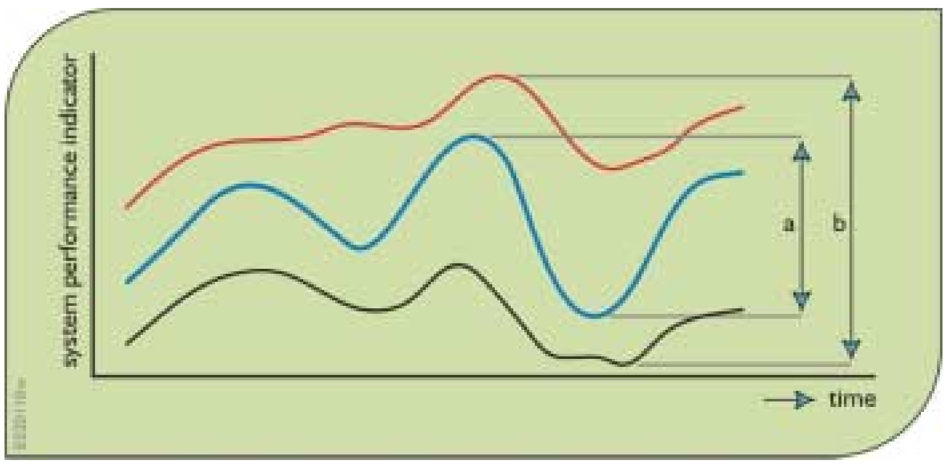

Figure 4. Time-series of model output or system performance showing variability over time. Range "a" results from the natural variability of input data over time. The extended range "b" results from the variability of natural input data as well as from imprecision in input data measurement, parameter value estimation, model structure and errors in model solution algorithms. The extent of this range will depend on the confidence level associated with that range.

What can occur in practice is a time-series of system performance indicator values that can range anywhere within or even outside the extended range, assuming the confidence level of that extended range is less than 100%. The confidence one can have that some future value of a time series will be within a given range is dependent on two factors. The first is the number of measurements used to compute the confidence limits. The second is on the assumption that those measurements are representative of - come from the same statistical or stochastic process yielding - future measurements. Figure 5 illustrates this point. Note that the time series may even contain values outside the range "b" defined in Figure 4 if the confidence level of that range is less than 100%. Confidence intervals associated with less than 100% certainty will not include every possible value that might occur.

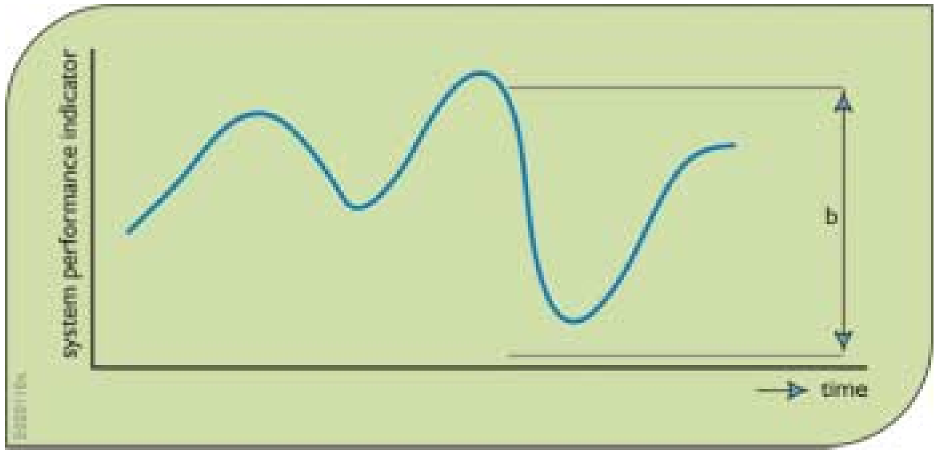

Figure 5. Typical time series of model output or system performance indicator values that are the result of input data variability and possible imprecision in input data measurement, parameter value estimation, model structure and errors in model solution algorithms.

3.2 Knowledge uncertainty

Referring to Figure 3, knowledge uncertainty includes model structure and parameter value uncertainties. First we consider parameter value uncertainty including boundary condition uncertainty, and then model and solution algorithm uncertainty.

3.2.1 Parameter value uncertainty

A possible source of uncertainty in model output results from uncertain estimates of various model parameter values. If the model calibration procedure were repeated using different data sets, different parameter values would result. Those values would yield different simulated system behavior, and thus different predictions. We can call this parameter uncertainty in the predictions because it is caused by imprecise parameter values. If such parameter value imprecision were eliminated, then the prediction would always be the same and so the parameter value uncertainty in the predictions would be zero. But this does not mean that predictions would be perfectly accurate.

In addition to parameter value imprecision, uncertainty in model output can result from imprecise specification of boundary conditions. These boundary conditions can be either fixed or variable. However, because they are not being computed based on the state of the system, their values can be uncertain. These uncertainties can affect the model output, especially in the vicinity of the boundary, in each time step of the simulation.

3.2.2 Model structural and computational errors

Uncertainty in model output can also result from errors in the model structure compared to the real system, and approximations made by numerical methods employed in the simulation. No matter how good our parameter value estimates, our models are not perfect and there is a residual model error. Increasing model complexity to more closely represent the complexity of the real system may not only add to the cost of data collection, but also introduce even more parameters, and thus even more potential sources of error in model output. It is not an easy task to judge the appropriate level of model complexity, and to estimate the resulting levels of uncertainty associated with various assumptions regarding model structure and solution methods. Kuczera (1988) provides an example of a conceptual hydrologic modeling exercise with daily time steps where model uncertainty dominated parameter value uncertainty.

3.3 Decision uncertainty

Uncertainty in model predictions can result from unanticipated changes in what is being modeled. These can include changes in nature, human goals, interests, activities, demands, and impacts. An example of this is the deviation from standard or published operating policies by operators of infrastructure such as canal gates, pumps, and reservoirs in the field, as compared to what is specified in documents and incorporated into the water systems models. Comparing field data with model data for model calibration may yield incorrect calibrations if operating policies actually implemented in the field differ significantly from those built into the models. What do operators do in times of stress? And can anyone identify a place where deviations from published policies do not occur?

What humans will want to achieve in the future may not be the same as what they want today. Predictions of what people will want in the future are clearly sources of uncertainty. A perfect example of this is in the very flat Greater Everglades region of south Florida in the US. Fifty years ago folks wanted the swampy region protected from floods and drained for agricultural and urban development. Today many want just the opposite at least where there are no human settlements. They want to return to a more natural hydrologic system with more wetlands and unobstructed flows, but now for ecological restoration objectives that were not a major concern or much appreciated some half a century ago. Once the mosquitoes return and if the sea level continues to rise, future populations who live there may want more flood control and drainage again. Who knows? Complex changing social and economic processes influence human activities and their demands for water resources and environmental amenities over time. Some of these processes reflect changes in local concerns, interests and activities, but population migration and many economic activities and social attitudes can also reflect changing national and international trends.

Sensitivity scenarios that include human activities can help define the affects of those activities within an area. It is important that careful attention go into the development of these alternative scenarios so that they realistically capture the forces or stresses that the system may face. The history of systems studies are full of examples where the issues studied were rapidly overwhelmed by much larger social forces resulting from, for example, the relocation of major economic activities, an oil embargo, changes in national demand for natural resources, economic recession, sea-level rise, an act of terrorism, or even war. One thing is sure; the future will be different than the past, and no one is certain just how.

3.3.1 Surprises

Water resource managers may also want to consider how vulnerable a system is to undesirable environmental surprises. What havoc might an introduced species like the zebra mussel invading the Great Lakes of North America have in a particular watershed? Might some introduced disease suddenly threaten key plant or animal species? Might management plans have to be restructured to address the survival of some species such as salmon in the Rhine River in Europe or in the Columbia River in North America? Such uncertainties are hard to anticipate when by their nature they are truly surprises. But surprises should be expected. Hence system flexibility and adaptability should be sought to deal with changing management demands, objectives, and constraints.

4. Sensitivity and uncertainty analyses

An uncertainty analysis is not the same as a sensitivity analysis. An uncertainty analysis attempts to describe the entire set of possible outcomes, together with their associated probabilities of occurrence. A sensitivity analysis attempts to determine the relative change in model output values given modest changes in model input values. A sensitivity analysis thus measures the change in the model output in a localized region of the space of inputs. However, one can often use the same set of model runs for both uncertainty analyses and sensitivity analyses. It is possible to carry out a sensitivity analysis of the model around a current solution and then use it as part of a first order uncertainty analysis.

This discussion begins by focusing on some methods of uncertainty analysis. Then various ways of performing and displaying sensitivity analyses are reviewed.

4.1 Uncertainty Analyses

Recall that uncertainty involves the notion of randomness. If a value of a performance indicator or performance measure, or in fact any variable, like the phosphorus concentration or the depth of water at a particular location varies and this variation over space and time cannot be predicted with certainty, it is called a random variable. One cannot say with certainty what the value of a random variable will be but only the likelihood or probability that it will be within some specified range of values. The probabilities of observing particular ranges of values of a random variable are described or defined by a probability distribution. There are many types of distributions and each can be expressed in several ways as presented in Chapter III.

Suppose the random variable is *X*. If the observed values of this random variable can be only discrete values, the probability distribution of *X* can be expressed as a histogram, as shown in Figure 6a. The sum of the probabilities for all possible outcomes must equal 1. If the random variable is a continuous variable that can assume any real value over a range of values, the probability distribution of *X* can be expressed as a continuous distribution as shown in Figure 6b. The shaded area under the density function for the continuous distribution is 1. The area between two values of the continuous random variable, such as between u and v in Figure 6c, represents the probability that the observed value *x* of the random variable value *X* will be within that range of values.

The probability distribution, $P_X(x)$ shown in Figure 6 (a) is called a probability mass function. The probability distributions shown in Figure 6 (b and c) are called a probability density functions (pdf) and are denoted by $f_X(x)$. The subscript *X* of P_X and f_X represents the random variable, and the variable *x* is some value of that random variable *X*.

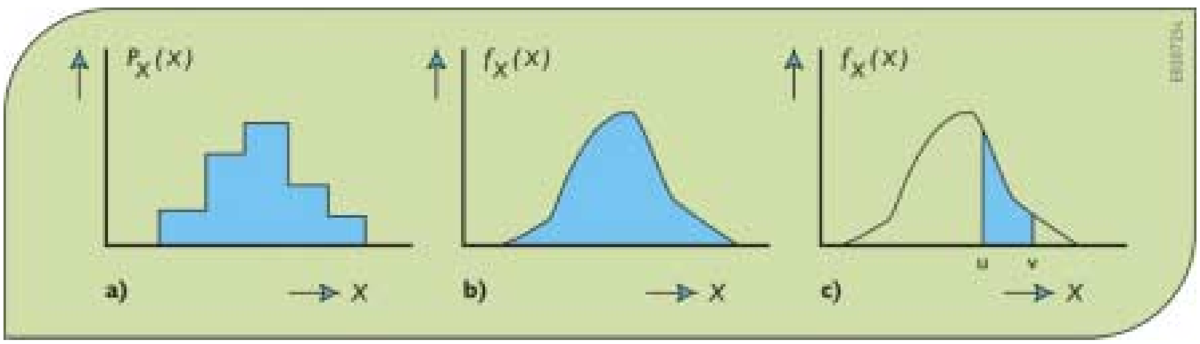

Figure 6. Probability distributions for a discrete or continuous random variable *X*. The area under the distributions (shaded areas in a and b) is 1, and the shaded area in c is the probability that the observed value x of the random variable *X* will be between u and v.

Uncertainty analyses involve identifying characteristics of various probability distributions of model input and output variables, and subsequently functions of those random output variables that are performance indicators or measures. Often targets associated with these indicators or measures are themselves uncertain.

A complete uncertainty analysis would involve a comprehensive identification of all sources of uncertainty that contribute to the joint probability distributions of each input or output variable. Assume such analyses were performed for two alternative project plans, *A* and *B*, and that the resulting probability density distributions for a specified performance measure were as shown in Figure 7. Figure 7 also identifies the costs of these two projects. The introduction of two performance criteria, cost and probability of exceeding a performance measure target (e.g., a pollutant concentration standard) introduces a conflict where a tradeoff must be made.

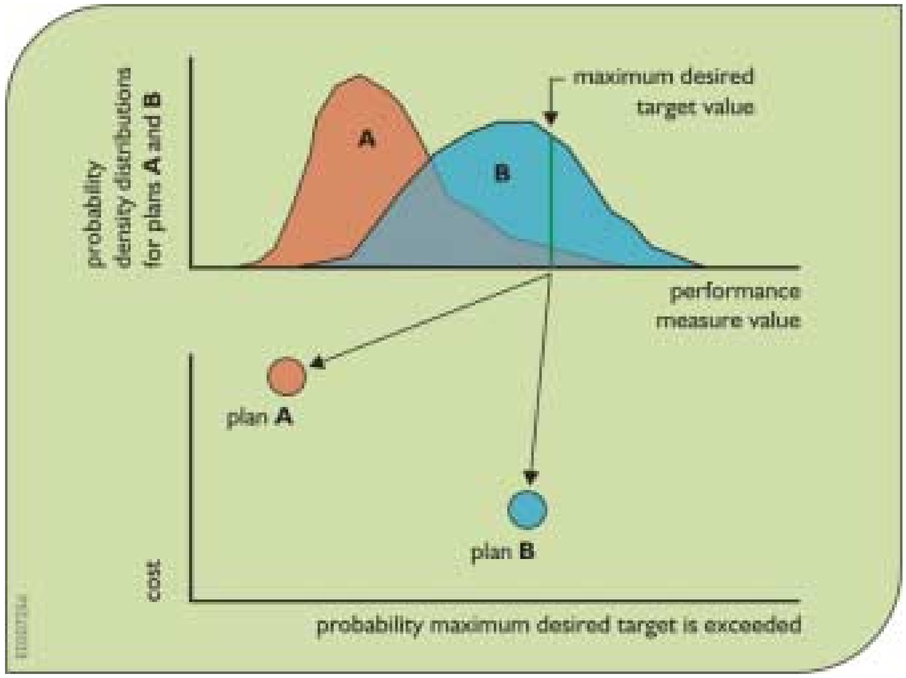

Figure 7. Tradeoffs involving cost and the probability that a maximum desired target value will be exceeded. In this illustration we want the lowest cost (*B* is best) and the lowest probability of exceedance (*A* is best).

4.1.1 Model and model parameter uncertainties

Consider a situation as shown in Figure 8, in which for a specific set of model inputs, the model outputs differ from the observed values, and for those model inputs, the observed values are always the same. Here nothing randomly occurs. The model parameter values or model structure needs to be changed. This is typically done in a model calibration process.

Given specific inputs, the outputs of deterministic models are always going to be the same each time those inputs are simulated. If for specified inputs to any simulation model the predicted output does not agree with the observed value, as shown in Figure 8, this could result from imprecision in the measurement of observed data. It could also result from imprecision in the model parameter values, the model structure, or the algorithm used to solve the model.

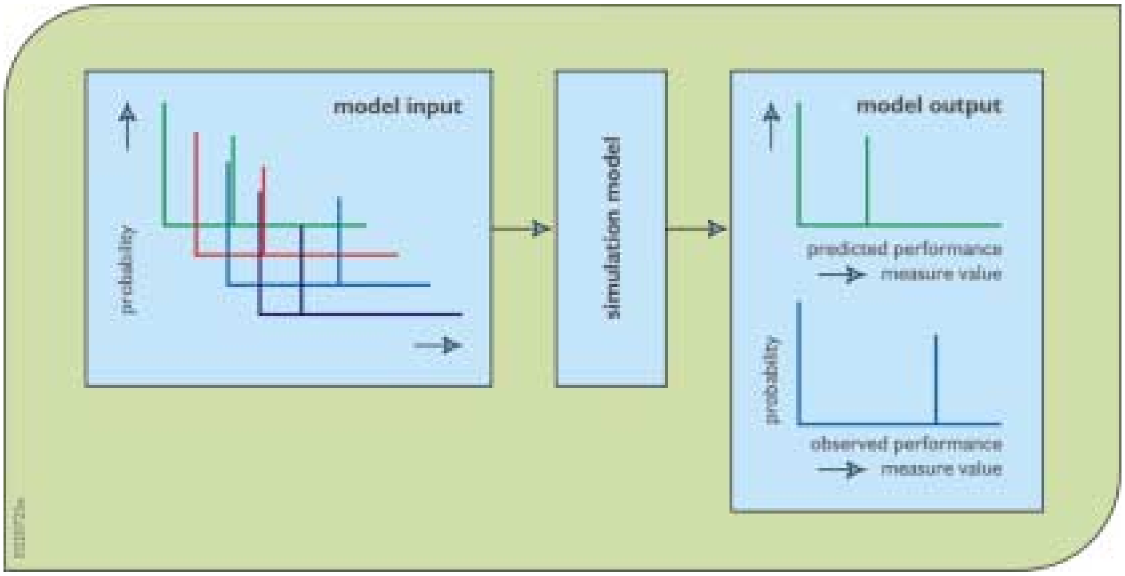

Figure 8. A deterministic system and a simulation model of that system needing calibration or modification in its structure. There is no randomness, only parameter value or model structure errors to be identified and corrected.

Next consider the same deterministic simulation model but now assume at least some of the inputs are random, i.e., not predictable, as may be case when random outputs of one model are used as inputs into another model. Random inputs will yield random outputs. The model input and output values can be described by probability distributions. If the uncertainty in the output is due only to the uncertainty in the input, the situation is similar to that shown in Figure 8. If the distribution of performance measure output values does not fit or is not identical to the distribution of observed performance measure values, then calibration of model parameter values or modification of model structure may be needed.

If a model calibration or 'identification' exercise finds the 'best' values of the parameters to be outside reasonable ranges of values based on scientific knowledge, then the model structure or algorithm might be in error. Assuming the algorithms used to solve the models are correct and observed measurements of system performance vary for the same model inputs, as shown in Figure 9, it can be assumed that the model structure does not capture all the processes that are taking place that impact the value of the performance measures. This is often the case when relatively simple and low-resolution models are used to estimate the hydrological and ecological impacts of water and land management policies. However, even large and complex models can fail to include or adequately describe important phenomena.

In the presence of informational uncertainties there may be considerable uncertainty about the values of the "best" parameters during calibration. This problem becomes even more pronounced with increases in model complexity.

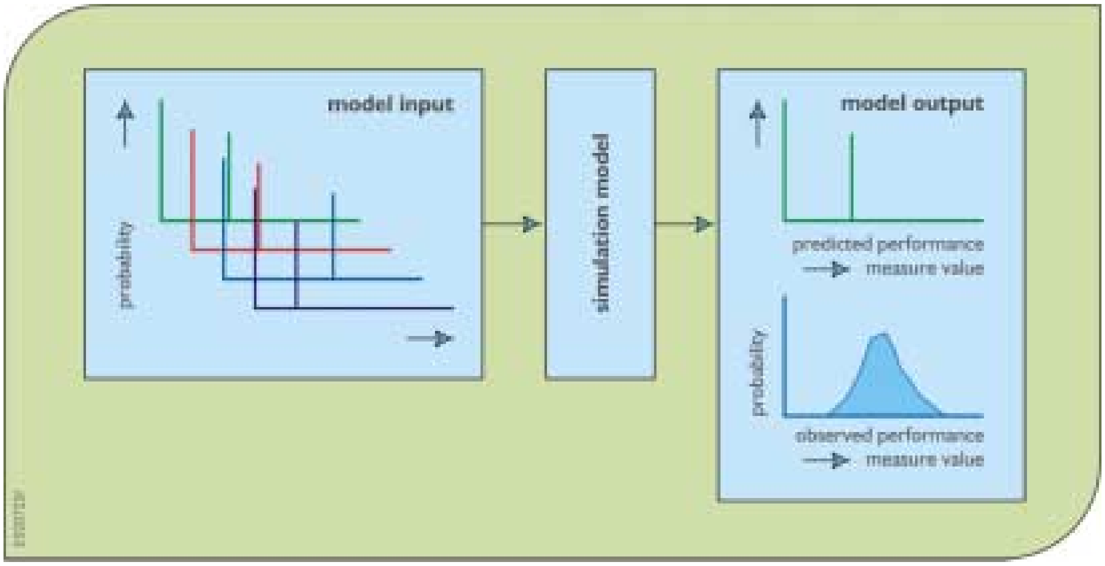

Figure A deterministic simulation model of a 'random or stochastic' system. To produce the variability in the model output that is observed in the real system, even given the same input values, the model's parameter values may need to vary over distributions of values and/or the model structure may need modification along with additional model inputs.

An example: Consider the prediction of a pollutant concentration at some site downstream of a pollutant discharge site. Given a streamflow *Q* (in units of 1000 m^3/day), the distance between the discharge site and the monitoring site, *X* (m), the pollutant decay rate constant *k* (day^{-1}), and the pollutant discharge W (Kg/day), we can use the following simplified model to predict the concentration of the pollutant *C* (g/m^3 = mg/l) at the downstream monitoring site:

$$C = (W/Q)\ \exp\{-k(X/U)\}$$

In the above equation assume the velocity *U* (m/day) is a known function of the streamflow *Q*.

In this case the observed value of the pollutant concentration *C* may differ from the computed value of *C* even for the same inputs of *W, Q, k, X*, and *U*. Furthermore, this difference varies in different time periods. This apparent variability, as illustrated in Figure 9, can be simulated using the same model but by assuming a distribution of values for the decay rate constant *k*. Alternatively the model structure can be modified to include the impact of streamflow temperature *T* on the prediction of *C*.

$$C = (W/Q)\ \exp\{-k\theta^{T-2}(X/U)\}$$

Now there are two model parameters, the decay rate constant *k* and the dimensionless temperature correction factor θ and an additional model input, the streamflow temperature, *T*. It could be that the variation in streamflow temperature was the sole cause of the first equation's 'uncertainty' and that the assumed parameter distribution of k was simply the result of the distribution of streamflow temperatures on the term $k\theta^{T-20}$.

If the output were still random given constant values of all the inputs, then another source of uncertainty exists. This uncertainty might be due to additional random loadings of the pollutant, possibly from non-point sources. Once again the model could be modified to include these additional loadings if they are knowable. Assuming these additional loadings are not known, a new random parameter could be added to the input variable W or to the right hand side of the equations above that would attempt to capture the impact on C of these additional loadings. A potential problem, however, might be the likely correlation between those additional loadings and the streamflow Q.

While adding model detail removed some 'uncertainty' in the above example, increasing model complexity will not always eliminate or reduce uncertainty in model output. Adding complexity is generally not a good idea when the increased complexity is based on processes whose parameters are difficult to measure, the right equations are not known at the scale of application, or the amount of data for calibration is small compared to the number of parameters.

Even if more detailed models requiring more input data and more parameter values were to be developed, the likelihood of capturing all the processes occurring in a complex system is small. Hence those involved will have to make decisions taking this uncertainty into account. Imprecision will always exist due to less than a complete understanding of the system and the hydrologic processes being modeled. A number of studies have addressed model simplification, but only in some simple cases have statisticians been able to identify just how one might minimize modeling related errors in model output values.

The problem of determining the "optimal" level of modeling detail is particularly important when simulating the hydrologic events at many sites over large areas. Perhaps the best approach for these simulations is to establish confidence levels for alternative sets of models and then statistically compare simulation results. But even this is not a trivial or costless task. Increases in the temporal or spatial resolution typically require considerable data collection and/or processing, model recalibrations, and possibly the solution of stability problems resulting from the numerical methods used in the models. Obtaining and implementing alternative hydrologic simulation models will typically involve considerable investments of money and time for data preparation and model calibration.

What is needed is a way to predict the variability evident in the system shown in Figure 9. Instead of a fixed output vector for each fixed input vector, a distribution of outputs are needed for each performance measure based on fixed inputs (Figure 9) or a distribution of inputs (Figure 10.). Furthermore the model output distribution for each performance measure should 'match' as well as possible the observed distribution of that performance measure.

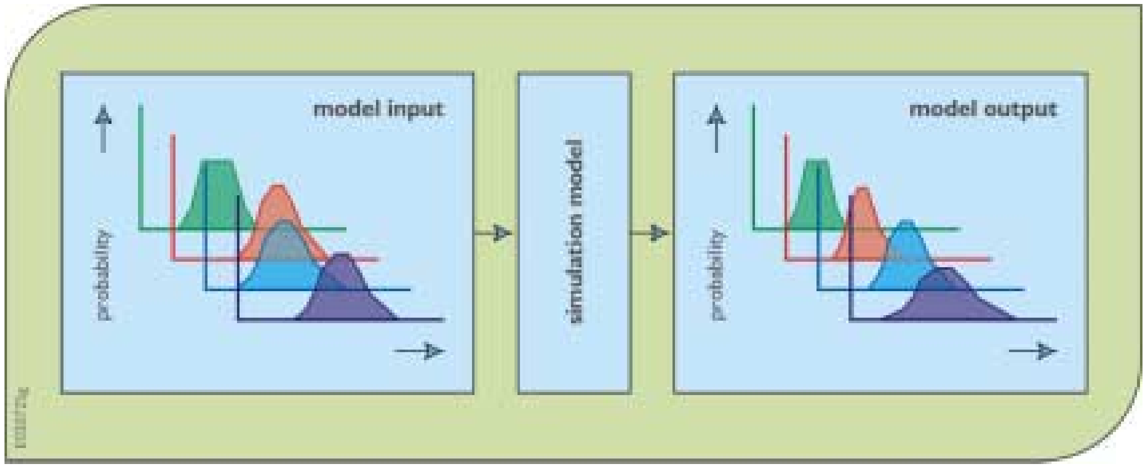

Figure 10. Simulating variable inputs to obtain probability distributions of predicted performance indices that match the probability distributions of observed performance values.

4.1.2 What uncertainty analysis can provide

An uncertainty analysis takes a set of randomly chosen input values (that can include parameter values), passes them through a model (or transfer function) to obtain the distributions (or statistical measures of the distributions) of the resulting outputs. As illustrated in Figure 11, the output distributions can be used to

- Describe the range of potential outputs of the system at some probability level.
- Estimate the probability that the output will exceed a specific threshold or performance measure target value.

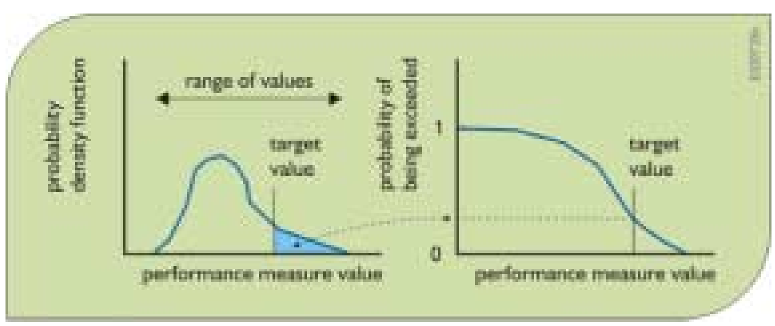

Figure 11. The distribution of performance measures defines range of potential values and the likelihood that a specified target value will be exceeded. The shaded area under the density function on the left represents the probability that the target value will be exceeded. This probability is shown in the probability of exceedance plot on the right.

Common uses for uncertainty analyses are to make general inferences, such as the following:

- Estimating the mean and standard deviation of the outputs.
- Estimating the probability the performance measure will exceed a specific threshold.
- Putting a reliability level on a function of the outputs, e.g., the range of function values that is likely to occur with some probability.
- Describing the likelihood of different potential outputs of the system.

Implicit in any uncertainty analysis are the assumptions that statistical distributions for the input values are correct and that the model is a sufficiently realistic description of the processes taking place in the system. Neither of these assumptions is likely to be entirely correct.

4.2 Sensitivity analyses

"Sensitivity analysis" is aimed at describing how much model output values are affected by changes in model input values. It is the investigation of the importance of imprecision or uncertainty in model inputs in a decision making or modeling process. The exact character of sensitivity analysis depends upon the particular context and the questions of concern. Sensitivity studies can provide a general assessment of model precision when used to assess system performance for alternative scenarios, as well as detailed information addressing the relative significance of errors in various parameters. As a result, sensitivity results should be of interest to the general public, federal and state management agencies, local watershed planners and managers, model users, and model developers.

Clearly, upper level management and the public may be interested in more general statements of model precision, and should be provided such information along with model predictions. On the other hand, detailed studies addressing the significance and interactions among individual parameters would likely be meaningful to model developers and some model users. They can use such data to interpret model results and to identify where efforts to improve models and their input values should be directed.

Initial sensitivity analysis studies could focus on two products:

(1) detailed results to guide research and assist model development efforts, and
(2) calculation of general descriptions of uncertainty associated with model predictions so that policy decisions can reflect both the modeling efforts best prediction of system performance and the precision of such predictions.

In the first case, knowing the relative uncertainty in model projections due to possible errors in different sets of parameters and input data should assist in efforts to improve the precision of model projections. This knowledge should also contribute to a better understanding of the relationships between model assumptions, parameters, data and model predictions.

For the second case, knowing the relative precision associated with model predictions should have a significant effect on policy development. For example, the analysis may show that, given data inadequacies, there are very large error bands associated with some model variables. When such large uncertainties exist, predictions should be used with appropriate skepticism.

Incremental strategies should be explored along with monitoring so that greater experience can accumulate to resolve some of those uncertainties.

Sensitivity analysis features are available in many linear and nonlinear programming (optimization) packages. They identify the changes in the values of the objective function and unknown decision variables given a change in the model input values, and a change in levels set for various constraints (Chapter V). Thus sensitivity analysis addresses the change in “optimal” system performance associated with changes in various parameter values, and also how “optimal” decisions would change with changes in resource constraint levels, or target output requirements. This kind of sensitivity analysis provides estimates of how much another unit of resource would be worth, or what “cost” a proposed change in a constraint places on the optimal solution. This information is of value to those making design decisions.

Various techniques have been developed to determine how sensitive model outputs are to changes in model inputs. Most approaches examine the affects of changes in a single parameter value or input variable assuming no changes in all the other inputs. Sensitivity analyses can be extended to examine the combined effects of multiple sources of error, as well.

Changes in particular model input values can affect model output values in different ways. It is generally true that only a relatively few input variables dominate or substantially influence the values of a particular output variable or performance indicator at a particular location and time. If the range of uncertainty of only some of the output data is of interest, then undoubtedly only those input data that significantly impact on the values of those output data need be included in the sensitivity analysis.

If input data estimates are based on repeated measurements, a frequency distribution can be estimated that characterizes natural variability. The shorter the record of measurements, the greater will be the uncertainty regarding the long-term statistical characteristics of that variability. If obtaining a sufficient number of replicate measurements is not possible, subjective estimates of input data ranges and probability distributions are often made. Using a mixture of subjective estimates and actual measurements does not affect the application of various sensitivity analysis methods that can use these sets or distributions of input values, but it may affect the conclusions that can be drawn from the results of these analyses.

It would be nice to have available accurate and easy-to-use analytical methods for relating errors in input data to errors in model outputs, and to errors in system performance indicator values that are derived from model output. Such analytical methods do not exist for complex simulation models. However methods based on simplifying assumptions and approximations can be used to yield useful sensitivity information. Some of these are reviewed in the remainder of this chapter.

4.2.1 Sensitivity coefficients

One measure of sensitivity is the sensitivity coefficient. This is the derivative of a model output variable with respect to an input variable or parameter. A number of sensitivity analysis methods use these coefficients. First-order and approximate first-order sensitivity analyses are two such methods that will be discussed later. The difficulty of

1. obtaining the derivatives for many models,
2. needing to assume mathematical (usually linear) relationships when obtaining estimates of derivatives by making small changes of input data values near their nominal or most likely values, and
3. having large variances associated with most hydrologic process models have motivated the replacement of analytical methods by numerical and statistical approaches to sensitivity analysis.

Implicit in any sensitivity analysis are the assumptions that statistical distributions for the input values are correct and that the model is a sufficiently realistic description of the processes taking place in the system. Neither of these assumptions is likely to be entirely correct.

The importance of the assumption that the statistical distributions for the input values are correct is easy to check by using different distributions for the input parameters. If the outputs vary significantly, then the output is sensitive to the specification of the input distributions and hence they should be defined with care. A relatively simple deterministic sensitivity analysis can be of value here (Benaman, 2002). A sensitivity coefficient can be used to measure the magnitude of change in an output variable Q per unit change in the magnitude of an input parameter value P from its base value P_o. Let SI_{PQ} be the sensitivity index for an output variable Q with respect to a change ΔP in the value of the input variable P from its base value P_o. Noting that the value of the output $Q(P)$ is a function of P, the sensitivity index could be defined as

$$SI_{PQ} = [\, Q(P_o + \Delta P) - Q(P_o - \Delta P)\,] / 2\,\Delta P \qquad (1)$$

Other sensitivity indices could be defined (McCuen 1973). Letting the index i represent a decrease and j represent an increase in the parameter value from its base value P_o, the sensitivity index SI_{PQ} for parameter P and output variable Q is could be defined as

$$SI_{PQ} = \{\, |(Q_o - Q_i) / (P_o - P_i)| + |(Q_o - Q_j) / (P_o - P_j)|\,\} / 2 \qquad (2)$$

or

$$SI_{PQ} = \max\{\, |(Q_o - Q_i) / (P_o - P_i)|,\ |(Q_o - Q_j) / (P_o - P_j)|\,\} \qquad (3)$$

A dimensionless expression of sensitivity is the elasticity index, EI_{PQ}, that measures the relative change in output Q for a relative change in input P could be defined as

$$EI_{PQ} = [P_o / Q(P_o)]\, SI_{PQ} \qquad (4)$$

4.2.2 A simple deterministic sensitivity analysis procedure

This deterministic sensitivity analysis approach is very similar those most often employed in the engineering economics literature. It is based on the idea of varying one uncertain parameter value, or set of parameter values, at a time. The ideas are applied to a water quality example to illustrate their use.

The output variable of interest can be any performance measure or indicator. Thus one does not know if more or less of a given variable is better or worse. Perhaps too much and/or too little is undesirable. The key idea is that, whether employing physical measures or economic metrics of performance, various parameters (or sets of associated parameters) are assigned high and low values. Such ranges may reflect either the differences between the minimum and maximum values for each parameter, the 5 and 95 percentiles of a parameters distribution, or points corresponding to some other criteria. The system model is then run with the various alternatives, one at a time, to evaluate the impact of those errors in various sets of parameter values on the output variable.

Table 1 illustrates the character of the results that one would obtain. Here Y_0 is the nominal value of the model output when all parameters assume the estimated best values, and $Y_{i,L}$ and $Y_{i,H}$ are the values obtained by increasing or decreasing the values of the ith set of parameters.

Table 1. Sensitivity of model output Y to possible errors in four parameter sets containing a single parameter or a group of parameters that vary together.

parameter set	low value	nominal	high value
1	$Y_{1,L}$	Y_0	$Y_{1,H}$
2	$Y_{2,L}$	Y_0	$Y_{2,H}$
3	$Y_{3,L}$	Y_0	$Y_{3,H}$
4	$Y_{4,L}$	Y_0	$Y_{4,H}$

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A simple water quality example is employed to illustrate this deterministic approach to sensitivity analysis. The analysis techniques illustrated here are just as applicable to complex models. The primary difference is that more work would be required to evaluate the various alternatives with a more complex model, and the model responses might be more complicated.

The simple water quality model is provided by Vollenweider's empirical relationship for the average phosphorus concentration in lakes (Vollenweider, 1976). He found that the phosphorus concentration, P (mg/m^3), is a function of the annual phosphorus loading rate, L (mg/m^2•a), the annual hydraulic loading, q (m/a or more exactly m^3/m^2•a), and the mean water depth, z (m).

$$P = (L/q) / [\ 1 + (z/q)^{0.5}\ ] \qquad (5)$$

L/q and P have the same units; the denominator is an empirical factor that compensates for nutrient recycling and elimination within the aquatic lake environment.

Data for Lake Ontario in North America would suggest that reasonable values of the parameters are $L = 680$ mg/m^3; $q = 10.6$ m/a; and $z = 84$ m, yielding $P = 16.8$ mg/m^3. Values of phosphorus concentrations less than 10 mg/m^3 are considered oligotrophic, whereas values greater than 20 mg/m^3 generally correspond to eutrophic conditions. Reasonable ranges reflecting possible errors in the three parameters yield the values in Table 2.

Table 2. Sensitivity of estimates of phosphorus concentration (mg/m^3) to model parameter values. The two right most values in each row correspond to the Low and High values of the parameter, respectively

	parameter value low	parameter value high	phosphorus concentration P_{low}	phosphorus concentration P_{high}
L – P loading (mg/m^3. a)	500	900	12.4	22.3
q – hydraulic loading (m/a)	8	13.5	20.0	14.4
z – mean depth (m)	81	87	17.0	16.6

One may want to display these results so they can be readily visualized and understood. A tornado diagram (Eschenbach, 1992) would show the lower and upper values of P obtained from variation of each parameter, with the parameter with the widest limits displayed on top, and the parameter having smallest limits on the bottom. Tornado diagrams (Figure 12) are easy to construct and can include a large number of parameters without becoming crowded.

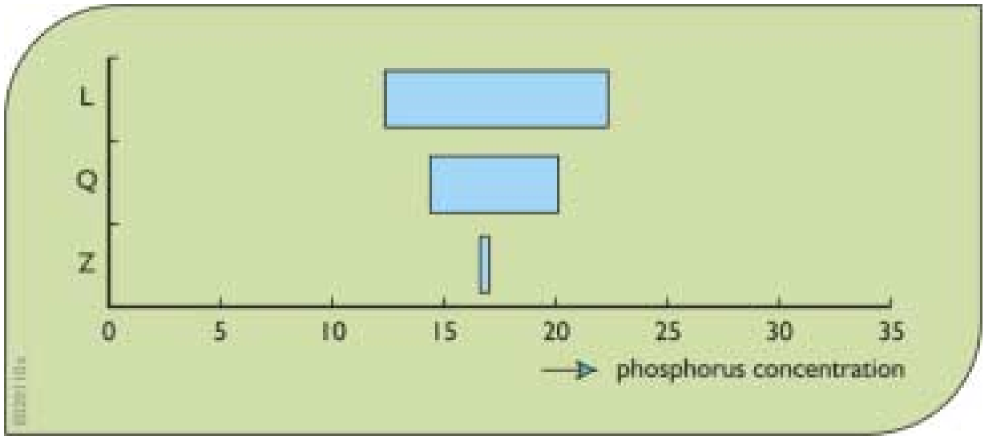

Figure 12. A Tornado diagram showing the range of the output variable representing phosphorus concentrations for high and low values of each of the parameter sets. Parameters are sorted so that the largest range is on top, and the smallest on the bottom.

An alternative to tornado diagrams is a Pareto chart showing the width of the uncertainty range associated with each variable, ordered from largest to smallest. A Pareto chart is illustrated in Figure 13.

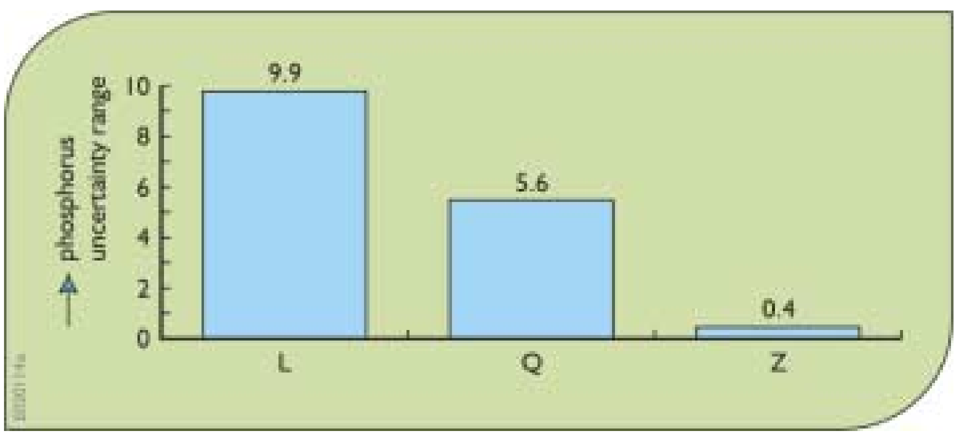

Figure 13. A Pareto Chart showing the range of the output variable representing phosphorus concentrations resulting from high and low values of each parameter set considered.

Another visual presentation is a spider plot showing the impact of uncertainty in each parameter on the variable in question, all on the same graph (Eschenback, 1992; DeGarmo, 1993, p. 401). A spider plot, Figure 14, shows the particular functional response of the output to each parameter on a common scale, so one needs a common metric to represent changes in all of the parameters. Here we use percentage change from the nominal or best values.

Spider plots are a little harder to construct than tornado diagrams, and can generally include only 4 - 5 variables without becoming crowded. However, they provide a more complete view of the relationships between each parameter and the performance measure. In particular, a spider plot reveals nonlinear relationships and the relative sensitivity of the performance measure to (percentage) changes in each variable.

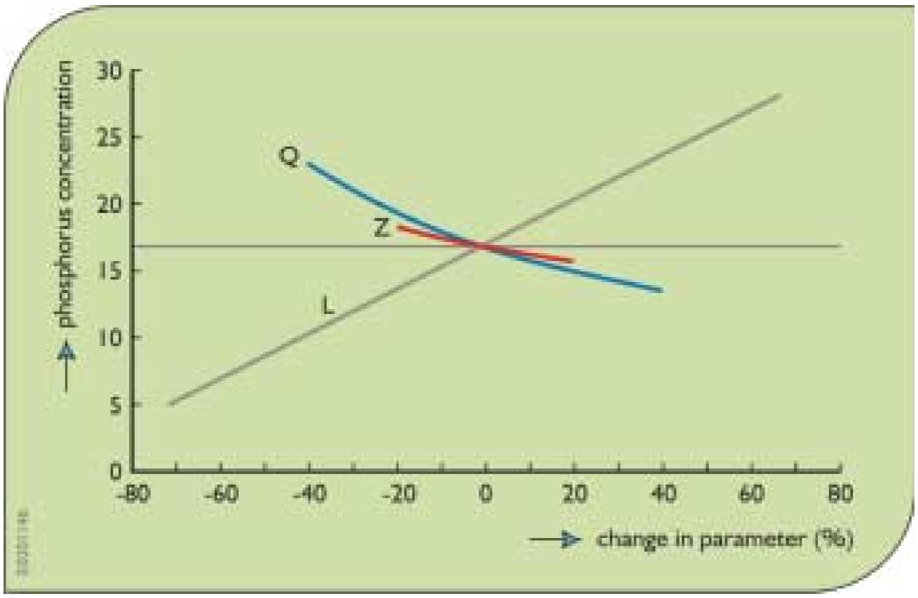

Figure 14. Spider Plot illustrates the relationships between model output describing phosphorus concentrations and variations in each of the parameter sets, expressed as a percentage deviation from their nominal values.

In the spider plot, the linear relationship between *P* and *L* and the gentle nonlinear relationship between *P* and *q* is illustrated. The range for *z* has been kept small given the limited uncertainty associated with that parameter.

4.2.3 Multiple errors and interactions

An important issue that should not be ignored is the impact of simultaneous errors in more than one parameter. Probabilistic methods directly address the occurrence of simultaneous errors, but the correct joint distribution needs to be employed. With simple sensitivity analysis procedures, errors in parameters are generally investigated one at a time, or in groups. The idea of considering pairs or sets of parameters is discussed here.

Groups of factors. It is often the case that reasonable error scenarios would have several parameters changing together. For this reason, the alternatives have been called parameter sets. For example, possible errors in water depth would be accompanied with corresponding variations in aquatic vegetation and chemical parameters. Likewise, alternatives related to changes in model structure might be accompanied with variations in several parameters. In other cases, there may be no causal relationship among possible errors (such as model structure versus inflows at the boundary of the modeled region), but they might still interact to effect the precision of model predictions.

Combinations. If one or more non-grouped parameters interact in significant ways, then combinations of one or more errors should be investigated. However, one immediately runs into a combinatorial problem. If each of m parameters can have 3 values (high, nominal, and low) there are 3^m combinations, as opposed to 2m + 1 if each parameter is varied separately. [For m = 5, the differences are $3^5 = 243$ versus 2(5)+1 = 11.] These numbers can be reduced by considering instead only combinations of extremes so that only $2^m + 1$ cases need be considered [$2^5 + 1 = 33$], which is a more manageable number. However, all of the parameters would be at one extreme or the other, and such situations would be very unusual.

Two factors at a time. A compromise is to consider all pairs of two parameters at a time. There are m(m-1)/2 possible pairs of m parameters. Each parameter has a high and low value. Since there are 4 combinations of high and low values for each pair, there are a total of 2m(m-1) combinations. [For m = 5 there are 40 combinations of two parameters each having two values.]

The presentation of these results could be simplified by displaying for each case only the maximum error, which would result in m(m-1)/2 cases that might be displayed in a Pareto diagram. This would allow identification of those combinations of two parameters that might yield the largest errors and thus are of most concern.

For the water quality example, if one plots the absolute value of the error for all four combinations of high (+) and low (-) values for each pair of parameters, they obtain Figure 15.

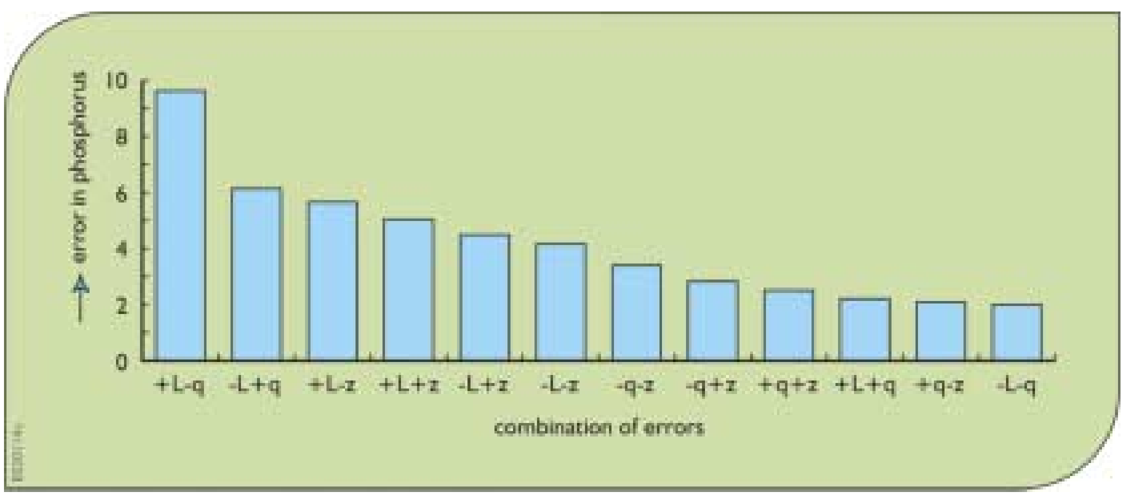

Figure 15. Pareto diagram showing errors in phosphorus concentrations for all combinations of pairs of input parameters errors. A + indicates a high value, and a - indicates a low value for indicated parameter. *L* is the phosphorus loading rate, *q* is the hydraulic loading, and *z* is the mean lake depth.

Considering only the worst error for each pair of variables yields Figure 16.

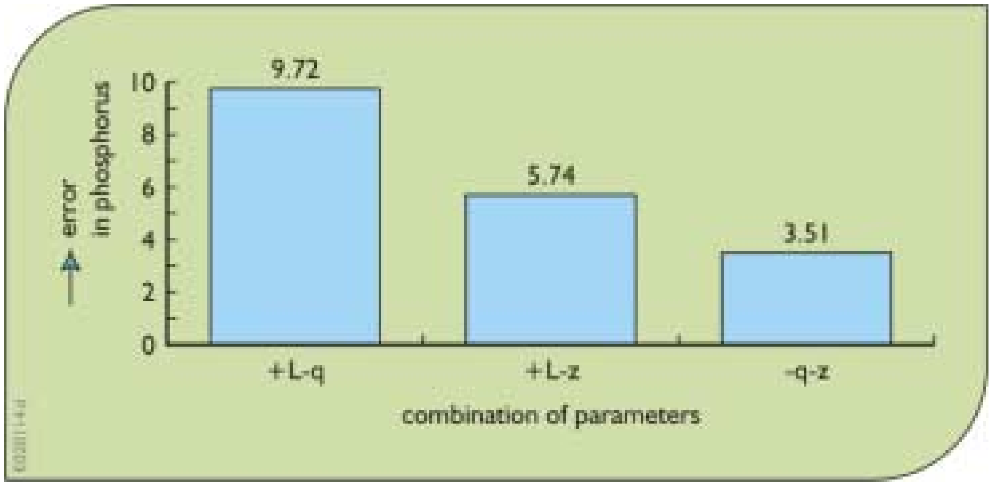

Figure 16. Pareto diagram showing worst error combinations for each pair of input parameters. A '+' indicates a high value, and a '–' indicates a low value for indicated parameter.

Here we see, as is no surprise, that the worst error results from the most unfavorable combination of *L* and *q* values. If both parameters have their most unfavorable values, the predicted phosphorus concentration would be 27 mg/m^3.

Looking for non-linearities. One might also display in a Pareto diagram the maximum error for each pair as a percentage of the sum of the absolute values of the maximum error from each parameter separately. The ratio of the joint error to the individual errors would illustrate potentially important nonlinear interactions. If the model of the system and the physical measure or economic metric were strictly linear, then the individual ratios should add to one.

4.2.4 First-order sensitivity analysis

The above deterministic analysis has trouble representing reasonable combinations of errors in several parameter sets. If the errors are independent, it is highly unlikely that any two sets would actually be at their extreme ranges at the same time. By defining probability distributions of the values of the various parameter sets, and specifying their joint distributions, a probabilistic error analysis can be conducted. In particular, for a given performance indicator, one can use multivariate linear analyses to evaluate the approximate impact on the performance indices of uncertainty in various parameters. As shown below, the impact depends upon the square of the sensitivity coefficients (partial derivatives) and the variances and covariances of the parameter sets.

For a performance indicator $I = F(Y)$, which is a function $F(\bullet)$ of model outputs Y, that are in turn a function $g(P)$ of input parameters P, one can use a multivariate Taylor series approximation of F to obtain the expected value and variance of the indicator:

$$E[I] = F(\text{ based on mean values of input parameters}) + (1/2) \{\Sigma_i \Sigma_j [\partial F^2/\partial P_i \partial P_j] \text{ Cov } [P_i, P_j] \} \quad (6)$$

and

$$\text{Var}[I] = \Sigma_i \Sigma_j (\partial F/ \partial P_i)(\partial F/ \partial P_j) \text{ Cov } [P_i, P_j] \quad (7)$$

where $(\partial F/\partial P_i)$ are the partial derivative of the function F with respect to P_i evaluated at the mean value of the input parameters P_i, and $\partial F^2/\partial P_i \partial P_j$ are the second partial derivatives. The covariance of two random input parameters P_i and P_j is the expected value of the product of differences between the values and their means.

$$\text{Cov}[P_i, P_j] = E[(P_i - E[P_i])(P_j - E[P_j])] \quad (8)$$

If all the parameters are independent of each other, and the second-order terms in the expression for the mean E[I] are neglected, one obtains

$$E[I] = F(\text{ based on mean values of input parameters}) \quad (9)$$

and

$$\text{Var } [I] = \Sigma_i [\partial F/ \partial P_i]^2 \text{ Var } [P_i] \quad (10)$$

(Benjamin and Cornell, 1970). Equation 6 for E[I] shows that in the presence of substantial uncertainty, the mean of the output from nonlinear systems is not simply the system output corresponding to the mean of the parameters (Gaven and Burges, 1981, p. 1523). This is true for any nonlinear function.

Of interest in the analysis of uncertainty is the approximation for the variance Var[I] of indicator I. In Equation 10 the contribution of P_i to the variance of I equals Var[P_i] times $[\partial F/ \partial P_i]^2$, which are the squares of the sensitivity coefficients for indicator I with respect to each input parameter value P_i.

4.2.4.1 An example of first-order sensitivity analysis

It may appear that first-order analysis is difficult because the partial derivatives of the performance indicator I are needed with respect to the various parameters. However, reasonable approximations of these sensitivity coefficients can be obtained from the simple sensitivity analysis described in Table 3, as shown below. In that table, three different parameter sets, P_i, are defined in which one parameter of the set is at its high value, P_{iH}, and one is at its low value, P_{iL}, to produce corresponding values (called high, I_{iH}, and low, I_{iL}) of a system performance indicator I.

Table 3. Approximate parameter sensitivity coefficients.

parameter set	value low	value high	sensitivity coefficient
1	I_{1L}	I_{1H}	$[I_{1H}–I_{1L}]/[P_{1H}–P_{1L}]$
2	I_{2L}	I_{2H}	$[I_{2H}–I_{2L}]/[P_{2H}–P_{2L}]$
3	I_{3L}	I_{3H}	$[I_{3H}–I_{3L}]/[P_{3H}–P_{3L}]$

It is then necessary to estimate some representation of the variances of the various parameters with some consistent procedure. For a normal distribution, the distance between the 5 and 95 percentiles is 1.645 standard deviations on each side of the mean, or 2(1.645) = 3.3 standard deviations. Thus, if the high/low range is thought of as approximately a 5-95 percentile range for a normally distributed variate, a reasonable approximation of the variance might be

$$\mathrm{Var}[P_i] = \{ [P_{iH}–P_{iL}]/3.3 \}^2. \qquad (11)$$

This is all that is needed. Use of these average sensitivity coefficients is very reasonable for modeling the behavior of the system performance indicator *I* over the indicated ranges.

As an illustration of the method of first-order uncertainty analysis, consider the lake quality problem described above. The "system performance indicator" in this case is the model output, the phosphorus concentration *P*, and the input parameters, now denoted as $X = L$, q, and z. The standard deviation of each parameter is assumed to be the specified range divided by 3.3. Average sensitivity coefficients $\partial P/\partial X$ were calculated. The results are reported in the table below.

Table 4. Calculation of approximate parameter sensitivity coefficients.

variable X	units	$\delta P/\delta X$	St Dev[X]	$(\delta P/\delta X)^2$ Var[X]	%
L	$mg/m^2 \cdot a$	0.025	121.21	9.18	75.7
q	m/a	-1.024	1.67	2.92	24.1
z	m	-0.074	1.82	0.02	0.2

Assuming the parameter errors are independent:

$$\text{Var}[P] = 9.18 + 2.92 + 0.02 = 12.12 \qquad (12)$$

The square root of 12.12 is the standard deviation and equals 3.48. This agrees well with a Monte Carlo analysis reported below.

Note that 100*(9.18/12.12), or about 76% of the total parameter error variance in the phosphorus concentration *P* is associated in the phosphorus loading rate *L* and the remaining 24% is associated with the hydrologic loading *q*. Eliminating the uncertainty in *z* would have a negligible impact on the overall model error. Likewise, reducing the error in *q* would at best have a modest impact on the total error.

Due to these uncertainties, the estimated phosphorus concentration has a standard deviation of 3.48. Assuming the errors are normally distributed, and recalling that ± 1.645 standard deviations around the mean define a 5-95 percentile interval, the 5-95 percentile interval would be about

$$16.8 \pm 1.645\ (3.48)\ \text{mg/m}^3 = 16.8 \pm 5.7\ \text{mg/m}^3 = 11.1 \text{ to } 22.5\ \text{mg/m}^3. \qquad (13)$$

These error bars indicate there is substantial uncertainty associated with the phosphorus concentration *P*, primarily due to uncertainty in the loading rate *L*.

The upper bound of 22.6 mg/m^3 is considerably less than the 27 mg/m^3 that would be obtained if both *L* and *q* had their most unfavorable values. In a probabilistic analysis with independent errors, such a combination is highly unlikely.

4.2.4.2 Warning on accuracy.

First-order uncertainty analysis is indeed an approximate method based upon a linearization of the response function represented by the full simulation model. It may provide inaccurate estimates of the variance of the response variable for nonlinear systems with large uncertainty in the parameters. In such cases Monte Carlo simulation (discussed below and in Chapter VII) or the use of higher-order approximation may be required. Beck (1987, p. 1426) cites studies that found that Monte Carlo and first-order variances were not appreciably different, and a few studies that found specific differences. Differences are likely to arise when the distributions used for the parameters are bimodal (or otherwise unusual), or some rejection algorithm is used in the Monte Carlo analysis to exclude some parameter combinations. Such errors can result in a distortion in the ranking of predominant sources of uncertainty. However, in most cases very similar results were obtained.

4.2.5 Fractional factorial design method

An extension of first-order sensitivity analysis would be a more complete exploration of the response surface using a careful statistical design. First consider a complete factorial design. Input data are divided into discrete "levels'. The simplest case is two levels. These two levels can be defined as a nominal value, and a high (low) value. Simulation runs are made for all combinations of parameter levels. For n different inputs, this would require 2^n simulation runs. Hence for a three-input variable or parameter problem, 8 runs would be required. If 4 discrete levels of each input variable or parameter were allowed to provide a more reasonable description of a continuous variable, the three-input data problem would require 4^3 or 64 simulation runs. Clearly this is not a useful tool for large regional water resources simulation models.

A fractional factorial design involves simulating only a fraction of what is required from a full factorial design method. The loss of information prevents a complete analysis of the impacts of each input variable or parameter on the output.

To illustrate the fractional factorial design method, consider the two-level with three-input variable or parameter problem. Table 5 below shows the 8 simulations required for a full factorial design method. The '+' and the '–' show the upper and lower levels of each input variable or parameter P_i where $i = 1, 2, 3$. If all 8 simulations were performed, seven possible effects could be estimated. These are the individual effects of the three inputs P_1, P_2, and P_3, the three two-input variable or parameter interactions, $(P_1)(P_2)$, $(P_1)(P_3)$, and $(P_2)(P_3)$, and the one three-input variable or parameter interaction $(P_1)(P_2)(P_3)$.

Table 5. A three-input factorial design.

simulation run	value of input P_1	value of input P_2	value of input P_3	value of output - variable Y
1	-	-	-	Y_1
2	+	-	-	Y_2
3	-	+	-	Y_3
4	+	+	-	Y_4
5	-	-	+	Y_5
6	+	-	+	Y_6
7	-	+	+	Y_7
8	+	+	+	Y_8

Consider an output variable Y, where Y_j is the value of Y in the jth simulation run. Then an estimate of the effect, denoted $\delta(Y|P_i)$, that input variable or parameter P_i has on the output variable Y, is the average of the four separate effects of varying P_i:

For i = 1:

$$\delta(Y \mid P_1) = 0.25 \, [\, (Y_2 - Y_1) + (Y_4 - Y_3) + (Y_6 - Y_5) + (Y_8 - Y_7) \,] \qquad (14)$$

Each difference in parentheses is the difference between a run in which P_1 is at its upper level and a run in which P_1 is at its lower level, but the other two parameter values, P_2 and P_3, are unchanged. If the effect is equal to 0, then, in this case, P_1 has no impact on the output variable Y.

Similarly the effects of P_2 and P_3, on variable Y can be estimated as:

$$\delta(Y \mid P_2) = 0.25 \, \{ \, (Y_3 - Y_1) + (Y_4 - Y_2) + (Y_7 - Y_5) + (Y_8 - Y_6) \, \} \qquad (15)$$

and

$$\delta(Y \mid P_3) = 0.25 \, \{ \, (Y_5 - Y_1) + (Y_6 - Y_2) + (Y_7 - Y_3) + (Y_8 - Y_4) \, \} \qquad (16)$$

Consider next the interaction effects between P_1 and P_2. This is estimated as the average of the difference between the average P_1 effect at the upper level of P_2, and the average P_1 effect at the lower level of P_2. This is the same as the difference between the average P_2 effect at the upper level of P_1 and the average P_2 effect at the lower level of P_1:

$$\delta(Y \mid P_1, P_2) = (1/2) \, \{ \, [\, (Y_8 - Y_7) + (Y_4 - Y_3)]/2 - [\, (Y_2 - Y_1) + (Y_6 - Y_5)]/2 \, \}$$

$$= (1/4) \, \{ \, [\, (Y_8 - Y_6) + (Y_4 - Y_2)] - [\, (Y_3 - Y_1) + (Y_7 - Y_5)] \, \} \qquad (17)$$

Similar equations can be derived for looking at the interaction effects between P_1 and P_3, and between P_2 and P_3 and the interaction effects among all three inputs P_1, P_2, and P_3.

Now assume only half of the simulation runs were performed, perhaps runs 2, 3, 5 and 8 in this example. If only outputs Y_2, Y_3, Y_5, and Y_8 are available, for our example:

$$\delta(Y \mid P_3) = \delta(Y \mid P_1, P_2) = 0.5 \, \{ \, (Y_8 - Y_3) - (Y_2 - Y_5) \, \} \qquad (18)$$

The separate effects of P_3 and of P_1P_2 are not available from the output. This is the loss in information resulting from fractional instead of complete factorial design.

4.2.6 Monte Carlo sampling methods

The Monte Carlo method of performing sensitivity analyses, illustrated in Figure 16, first selects a random set of input data values drawn from their individual probability distributions. These values are then used in the simulation model to obtain some model output variable values. This process is repeated many times, each time making sure the model calibration is valid for the input data values chosen. The end result is a probability distribution of model output variables and system performance indices that results from variations and possible errors in all of the input values.

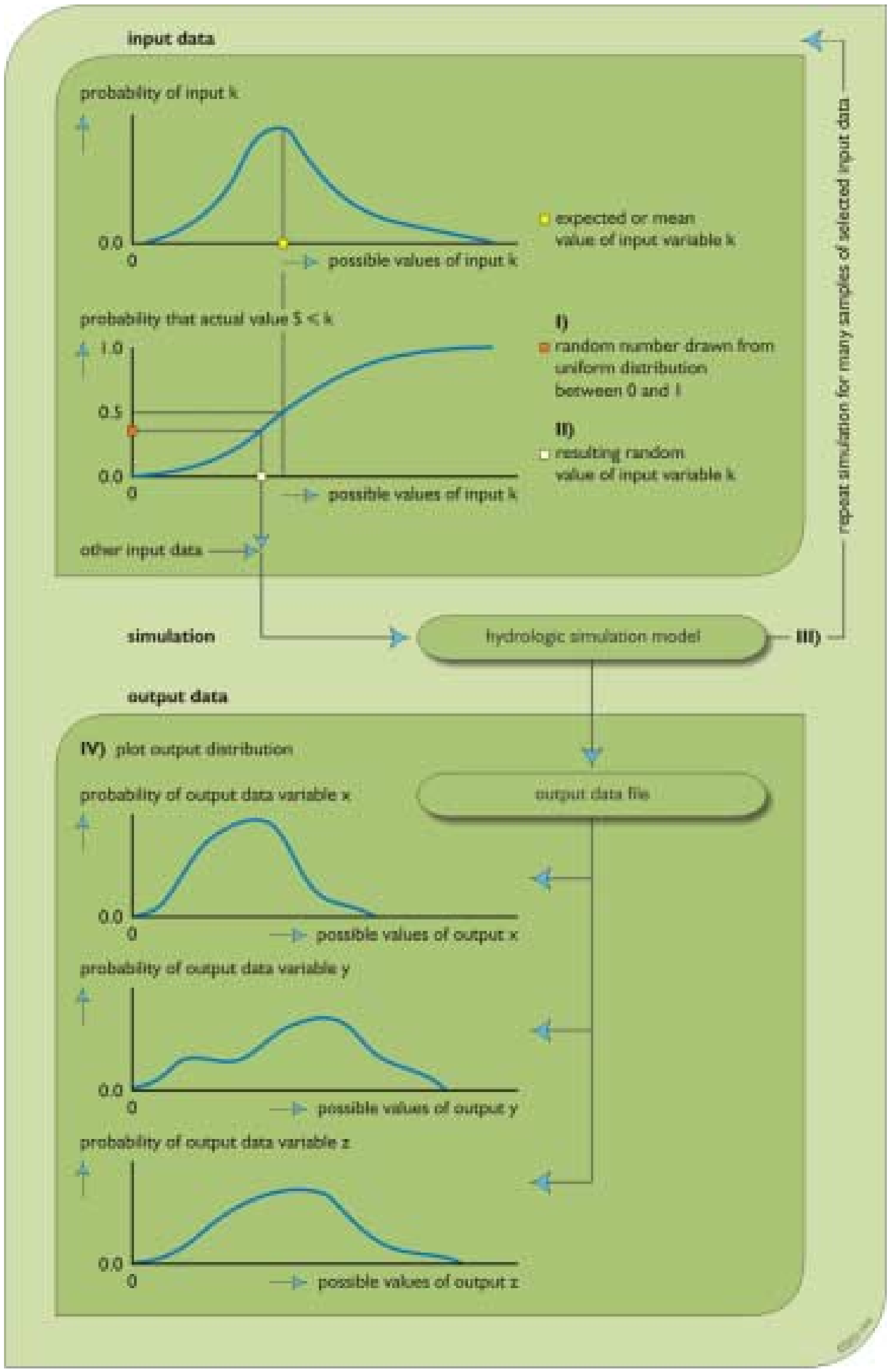

Figure 16. Monte Carlo sampling and simulation procedure for finding distributions of output variable values based on distributions, for specified reliability levels, of input data values. This technique can be applied to one or more uncertain input variables at a time. The output distributions will reflect the combined effects of this input uncertainty over the specified ranges.

Using a simple Monte Carlo analysis, values of all of the parameter sets are selected randomly from distributions describing the individual and joint uncertainty in each, and then the modeled system is simulated to obtain estimates of the selected performance indices. This must be done many times (often well over 100) to obtain a statistical description of system performance variability. The number of replications needed is generally not dependent on the number of parameters whose errors are to be analyzed. One can include in the simulation the uncertainty in parameters as well as natural variability. This method can evaluate the impact of single or multiple uncertain parameters.

A significant problem that arises in such simulations is that some combinations of parameter values result in unreasonable models. For example, model performance with calibration data sets might be inconsistent with available data sets. The calibration process places interesting constraints on different sets of parameter values. Thus, such Monte Carlo experiments often contain checks that exclude combinations of parameter values that are unreasonable. In these cases the generated results are conditioned on this validity check.

Whenever sampling methods are used, one must consider possible correlations among input data values. Sampling methods can handle spatial and temporal correlations that may exist among input data values, but the existence of correlation requires defining appropriate conditional distributions.

One major limitation of applying Monte Carlo methods to estimate ranges of risk and uncertainty for model output variable values, and system performance indicator values based on these output variable values, is the computing time required. To reduce the computing times needed to perform sensitivity analyses using sampling methods, some tricks and as well as stratified sampling methods are available. The discussion below illustrates the idea of a simple modification (or trick) using a "standardized" Monte Carlo analysis. The more general Latin Hypercube Sampling procedure is also discussed.

4.2.6.1 Simple Monte Carlo sampling

To illustrate the use of Monte Carlo sampling methods consider again Vollenweider's empirical relationship, Equation 5, for the average phosphorus concentration in lakes (Vollenweider, 1976). Two hundred values of each parameter were generated independently from normal distributions with the means and variances as shown in Table 6.

The table contains the specified means and variances for the generated values of L, q and z, and also the actual values of the means and variances of the 200 generated values of L, q, z and also of the 200 corresponding generated output phosphorus concentrations, P. Figure 17 displays the distribution of the generated values of P.

Table 6. Monte Carlo analysis of lake phosphorus levels.

parameter	*L*	*q*	*z*	*P*
specified means and standard deviations				
mean standard deviations	680.00 121.21	10.60 1.67	84.00 1.82	— ---
generated means and standard deviations				
mean standard deviations	674.18 130.25	10.41 1.73	84.06 1.82	17.07 3.61

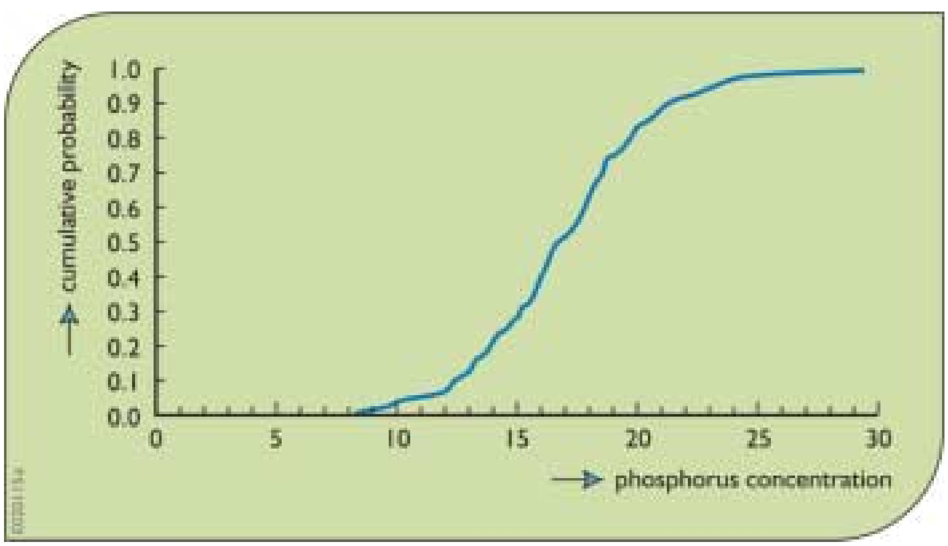

Figure 17. Distribution of lake phosphorus concentrations from Monte Carlo analysis

One can see that given the estimated levels of uncertainty, phosphorus levels could reasonably range from below 10 to above 25. The probability of generating a value greater than 20 mg/m^3 was 12.5%. The 5% to 95 percentile range was 11.1 to 23.4 mg/m^3. In the figure, the cumulative probability curve is rough because only 200 values of the phosphorus concentration were generated, but these are clearly enough to give a good impression of the overall impact of the errors.

4.2.6.2 Sampling uncertainty.

In this example, the mean of the 200 generated values of the phosphorus concentration, *P*, was 17.07. However a different set of random values would have generated a different set of *P* values as well. Thus it is appropriate to estimate the standard error, SE, of this average. The standard error equals the standard deviation σ of the *P* values divided by the square root of the sample size *n*:

$$SE = \sigma/(n)^{0.5} = 3.61/(200)^{0.5} = 0.25. \quad (19)$$

From the central limit theorem of mathematical statistics, the average of a large number of independent values should have very nearly a normal distribution. Thus, 95% of the time, the true mean of *P* should be in the interval 17.1 ± 1.96 (0.25), or 16.6 to 17.6 mg/m^3 . This level of uncertainty reflects the observed variability of *P* and the fact that only 200 values were generated.

4.2.6.3 Making sense of the results.

A significant challenge with complex models is to determine from the Monte Carlo simulation which parameter errors are important. Calculating the correlation between each generated input parameter value and the output variable value is one way of doing this. As Table 7 below shows, based upon the magnitudes of the correlation coefficients, errors in *L* were most important, and those in *q* second in importance.

Table 7. Correlation analysis of Monte Carlo results.

variable	L	q	z	P
L	1			
q	0.079	1		
z	0.1297	-0.139	1	
P	0.851	-0.434	0.144	1

One can also use regression to develop a linear model defining variations in the output based on errors in the various parameters. The results are shown in the Table 8. The fit is very good, and R^2 = 98%. If the model for *P* had been linear, a R^2 value of 100% should have resulted. All of the coefficients are significantly different from zero.

Note that the correlation between *P* and *z* was positive in Table 7, but the regression coefficient for *z* is negative. This occurred because there is a modest negative correlation between the generated *z* and *q* values. Use of partial correlation coefficients can also correct for such spurious correlations among input parameters.

Table 8. Results of Regression Analysis on Monte Carlo Results

	coefficient	standardized error	ratio t
intercept	18.605	1.790	10.39
L	0.025	0.000	85.36
q	-1.068	0.022	-48.54
z	-0.085	0.021	- 4.08

Finally we display a plot, Figure 18, based on this regression model illustrating the reduction in the variance of *P* that is due to dropping each variable individually. Clearly *L* has the biggest impact on the uncertainty in *P,* and *z* the least.

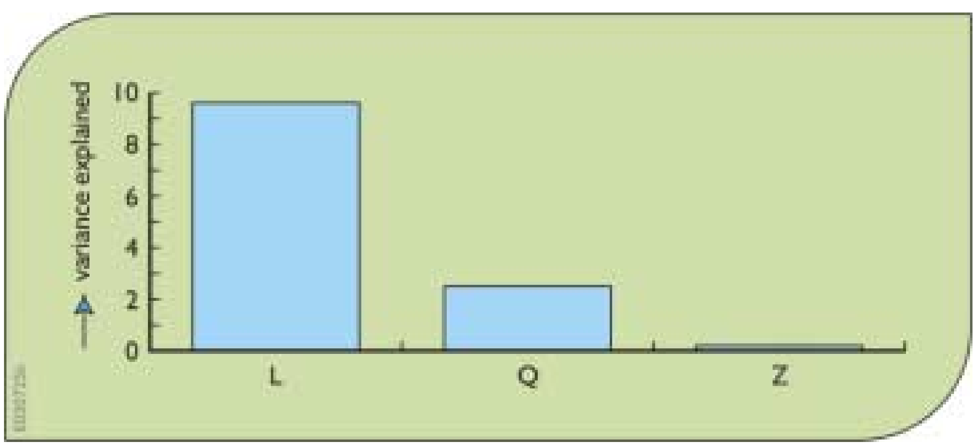

Figure 18. Reduction in the variance of P that is due to dropping from the regression model each variable individually. Clearly L has the biggest impact on the uncertainty in P, and z the least.

4.2.6.4 Standardized Monte Carlo analysis

Using a "standardized" Monte Carlo analysis, one could adjust the generated values of L, q and z above so that the generated samples actually have the desired mean and variance. While making that correction, one can also shuffle their values so that the correlations among the generated values for the different parameters are near zero, as is desired. This was done for the 200 generated values to obtain the statistics shown in Table 9.

Table 9. Standardized Monte Carlo analysis of lake phosphorus levels

parameter	L	q	z	P
	specified means and standard deviations			
Mean	680.00	10.60	84.00	—
Standard deviations	121.21	1.67	1.82	---
	generated means and standard deviations			
Mean	680.00	10.60	84.00	17.03
Standard deviations	121.21	1.67	1.82	3.44

Repeating the correlation analysis from before (shown in Table 10) now yields much clearer results that are in agreement with the regression analysis. The correlation between P and both q and z are now negative as they should be. Because the generated values of the three parameters have been adjusted to be uncorrelated, the signal from one is not confused with the signal from another.

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Table 10. Correlation analysis of standardized Monte Carlo results

variable	L	q	z	P
L	1.00			
q	0.01	1.00		
z	0.02	0.00	1.00	
P	0.85	-0.50	-0.02	1.00

The mean phosphorus concentration changed very little. It is now 17.0 instead of 17.1 mg/m^3.

Using control variates with a linear predictive model in conjunction with the standardized Monte Carlo variates, the standard deviation of the errors associated with the 200 observations is only 0.45. Thus the standard error for this estimate of the mean of P is $0.45/(200)^{0.5}$ or just 0.03. Thus this is a highly accurate result. The regressions were also repeated and yielded very similar results. The only real difference was that the parameter estimates had small standard errors and were more significant because of the elimination of correlation between the generated parameters.

4.2.6.5 Generalized likelihood estimation

Beven (1993) and Binley and Beven (1991) suggest a Generalized Likelihood Uncertainty Estimation (GLUE) technique for assessment of parameter error uncertainty using Monte Carlo simulation. It is described as a "formal methodology for some of the subjective elements of model calibration" (Beven, 1989, p. 47). The basic idea is to begin by assigning reasonable ranges for the various parameters and then to draw parameter sets from those ranges using a uniform or some similar (and flat) distribution. These generated parameter sets are then used on a calibration data set so that unreasonable combinations can be rejected, while reasonable values are assigned a posterior probability based upon a likelihood measure which may reflect several dimensions and characteristics of model performance.

Let $L(P_i) > 0$ be the value of the likelihood measure assigned to the i^{th} parameter set's calibration sequence. Then the model predictions generated with parameter set/combination P_i are assigned posterior probability, $p(P_i)$.

$$p(P_i) = L(P_i)/\Sigma_j L(P_j) \quad (20)$$

These probabilities reflect the form of Bayes theorem, which is well supported by probability theory (Devore, 1991). This procedure should capture reasonably well the dependence or correlation among parameters, because *reasonable* sequences will all be assigned larger probabilities, whereas sequences that are unable to reproduce the system response over the calibration period will be rejected or assigned small probabilities.

However, in a rigorous probabilistic framework, the L would be the likelihood function for the calibration series for particular error distributions. (This could be checked with available goodness-of-fit procedures; for example, Kuczera, 1988.) When relatively ad hoc measures are adopted for the likelihood measure with little statistical validity, the $p(P_i)$ probabilities are best described as pseudo probabilities or "likelihood" weights.

Another concern with this method is the potential efficiency. If the parameter ranges are too wide, a large number of unreasonable or very unlikely parameter combinations will be generated. These will either be rejected or else will have small probabilities and thus little effect on the analysis. In this case the associated processing would be a waste of effort. A compromise is to use some data to calibrate the model and to generate a prior or initial distribution for the parameters that is at least centered in the best range (Beven 1993, p. 48). Then use of a different calibration period to generate the $p(P_i)$ allows an updating of those initial probabilities to reflect the information provided by the additional calibration period with the adopted likelihood measures.

After the accepted sequences are used to generate sets of predictions, the likelihood weights would be used in the calculation of means, variances and quantiles, rather than the customary procedure of giving all the generated realizations equal weight. The resulting conditional distribution of system output reflects the initial probability distributions assigned to parameters, the rejection criteria, and the likelihood measure adopted to assign "likelihood" weights.

4.2.7 Latin hypercube sampling

For the simple Monte Carlo simulations described above, with independent errors, a probability distribution is assumed for each input parameter or variable. In each simulation run, values of all input data are obtained from sampling those individual and independent distributions. The value generated for an input parameter or variable is usually independent of what that value was in any previous run, or what other input parameter or variable values are in the same run. This simple sampling approach can result in a clustering of parameter values and hence both redundancy of information from repeated sampling in the same regions of a distribution and lack of information from no sampling in other regions of the distributions.

A stratified sampling approach ensures more even coverage of the range of input parameter or variable values with the same number of simulation runs. This can be accomplished by dividing the input parameter or variable space into sections and sampling from each section with the appropriate probability.

One such approach, Latin hypercube sampling (LHS), divides each input distribution into sections of equal probability for the specified the probability distribution, and draws one observation randomly from each range. Hence the ranges of input values within each section actually occur with equal frequency in the experiment. These values from each interval for each distribution are randomly assigned to those from other intervals to construct sets of input values for the simulation analysis. Figure 19 shows the steps in constructing a LHS for six simulations involving three inputs P_j (P_1, P_2, and P_3) and six intervals of their respective normal, uniform and triangular probability distributions.

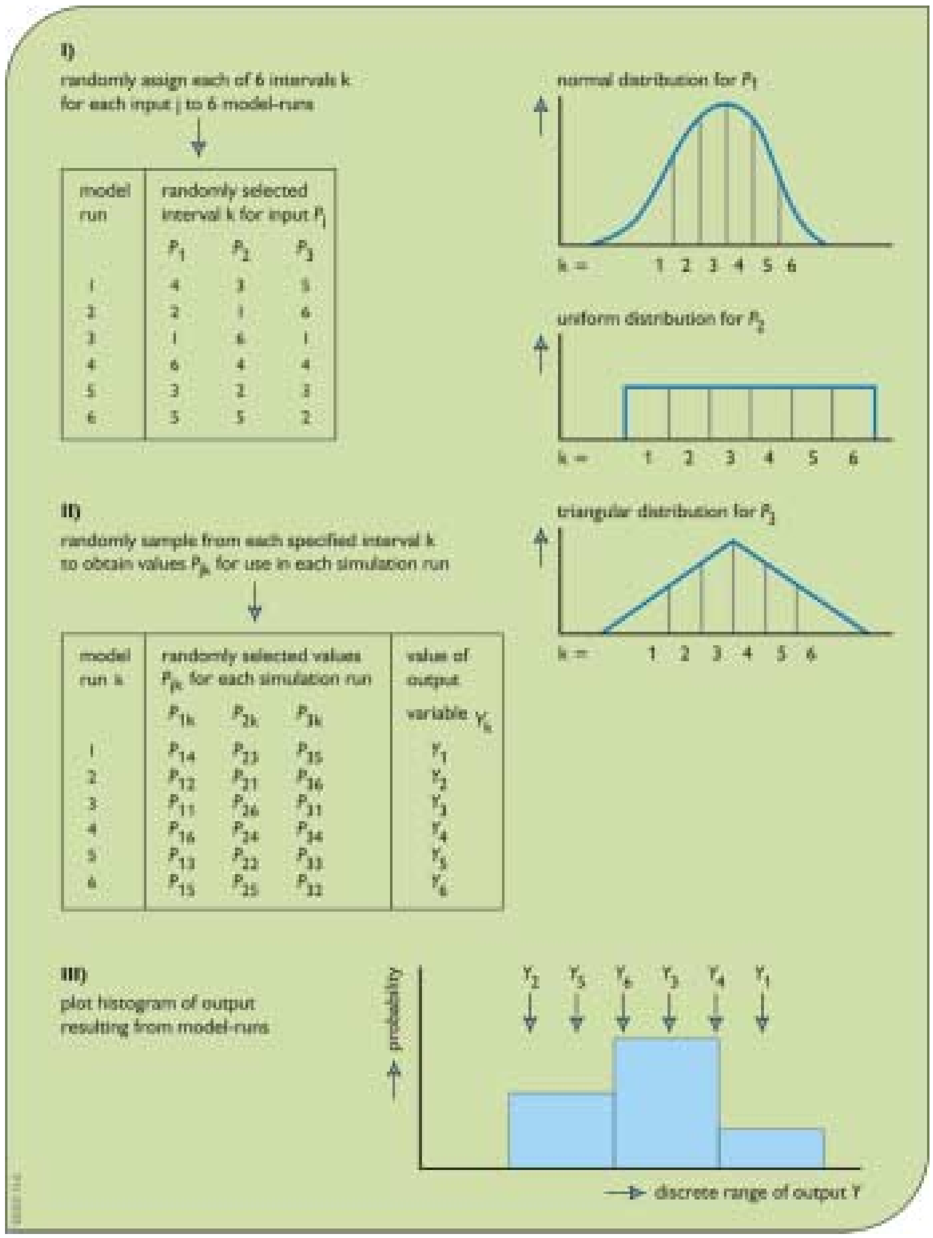

Figure 19. Schematic representation of a Latin hypercube sampling procedure for six simulation runs.

5. Performance indicator uncertainties

5.1 Performance measure target uncertainty

Another possible source of uncertainty is the selection of performance measure target values. For example, consider a target value for a pollutant concentration based on the effect of exceeding it in an ecosystem. Which target value is best or correct? When this is not clear, there are various ways of expressing the uncertainty associated with any target value. One such method is the use of fuzzy sets (Chapter VI). Use of 'grey' numbers or intervals instead of 'white' or fixed target values is another. When some uncertainty or disagreement exists over the selection of the best target value for a particular performance measure it seems to us the most direct and transparent way to do this is to subjectively assume a distribution over a range of possible target values. Then this subjective probability distribution can be factored into the tradeoff analysis, as outlined in Figure 20.

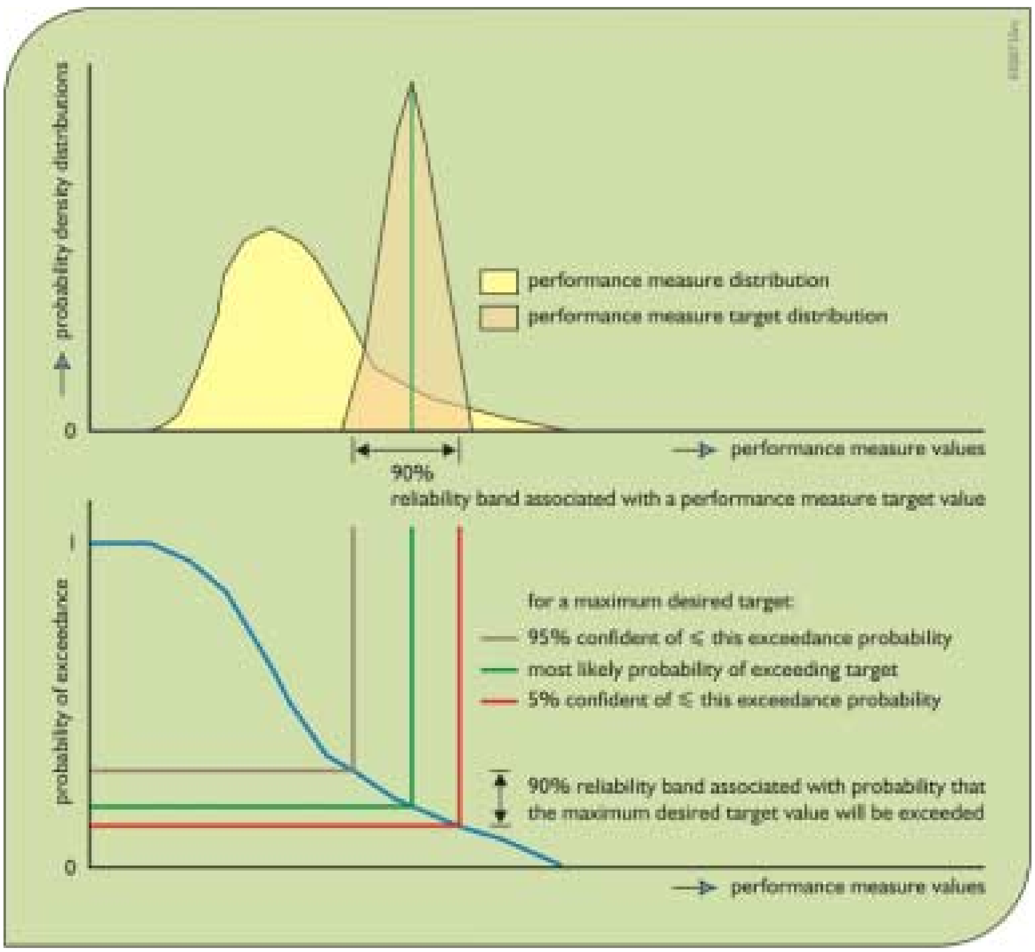

Figure 20. Combining the probability distribution of performance measure values with the probability distribution of performance measure target values to estimate the confidence one has in the probability of exceeding a maximum desired target value.

One of the challenges associated with defining and including in an analysis the uncertainty associated with a target or threshold value for a performance measure is that of communicating just what the result of such an analysis means. Referring to Figure 20, suppose the target value represents some maximum limit of a pollutant, say phosphorus, concentration in the flow during a given period of time at a given site or region, and it is not certain just what that maximum limit should be. Subjectively defining the distribution of that maximum limit, and considering that uncertainty along with the uncertainty (probability of exceedance function) of pollutant concentrations – the performance measure – one can attach a confidence to any probability of exceeding the maximum desired concentration value.

The 95% probability of exceedance shown on Figure 20, say $P_{0.95}$, should be interpreted as "we can be 95% confident that the probability of the maximum desired pollutant concentration being exceeded will be no greater than $P_{0.95}$." We can be only 5% confident that the probability of exceeding the desired maximum concentration will be no greater than the lower $P_{0.05}$ value. Depending on whether the middle line through the subjective distribution of target values in Figure 20 represents the most likely or median target value, the associated probability of exceedance is either the most likely, as indicated in Figure 20, or that for which we are only 50% confident.

Figure 21 attempts to show how to interpret the reliabilities when the uncertain performance targets are

- minimum acceptable levels that are to be maximized,
- maximum acceptable levels that are to be minimized or
- optimum levels.

An example of a minimum acceptable target level might be the population of wading birds in an area. An example of a maximum acceptable target level might be, again, the phosphorus concentration of the flow in a specific wetland or lake. An example of an optimum target level might be the depth of water most suitable for selected species of aquatic vegetation during a particular period of the year.

For performance measure targets that are not expressed as minimum or maximum limits but that are the 'best' values, referring to Figure 21, one can state that one is 90% confident that the probability of achieving the desired target is no more than B. The 90% confidence level probability of not achieving the desired target is at least A+C. The probability of the performance measure being too low is at least A and the probability of the performance measure being too high is at least C, again at the 90% confidence levels. As the confidence level decreases the bandwidth decreases, and the probability of not meeting the target increases.

Now, clearly there is uncertainty associated with each of these uncertainty estimations, and this raises the question of how valuable is the quantification of the uncertainty of each additional component of the plan in an evaluation process. Will plan evaluators and decision makers benefit from this additional information, and just how much additional uncertainty information is useful?

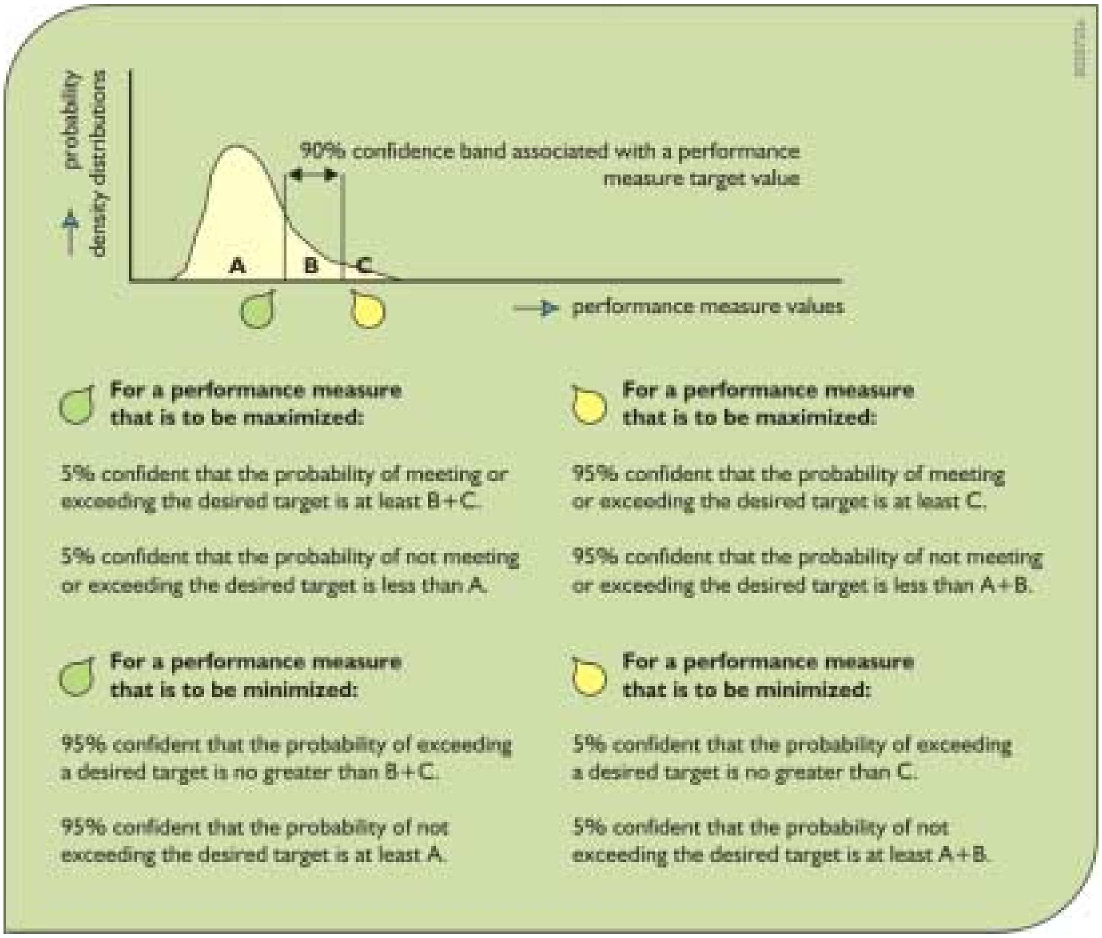

Figure 21. Interpreting the results of combining performance measure probabilities with performance measure target probabilities depends on the type of performance measure. The letters A, B, and C represent proportions of the probability density function of performance measure values. (Hence probabilities A + B + C = 1.)

Now consider again the tradeoffs that need to be made as illustrated in Figure 7. Instead of considering a single target value as shown on Figure 7, assume there is a 90% confidence range associated with that single performance measure target value. Also assume that the target is a maximum desired upper limit (e.g., of some pollutant concentration).

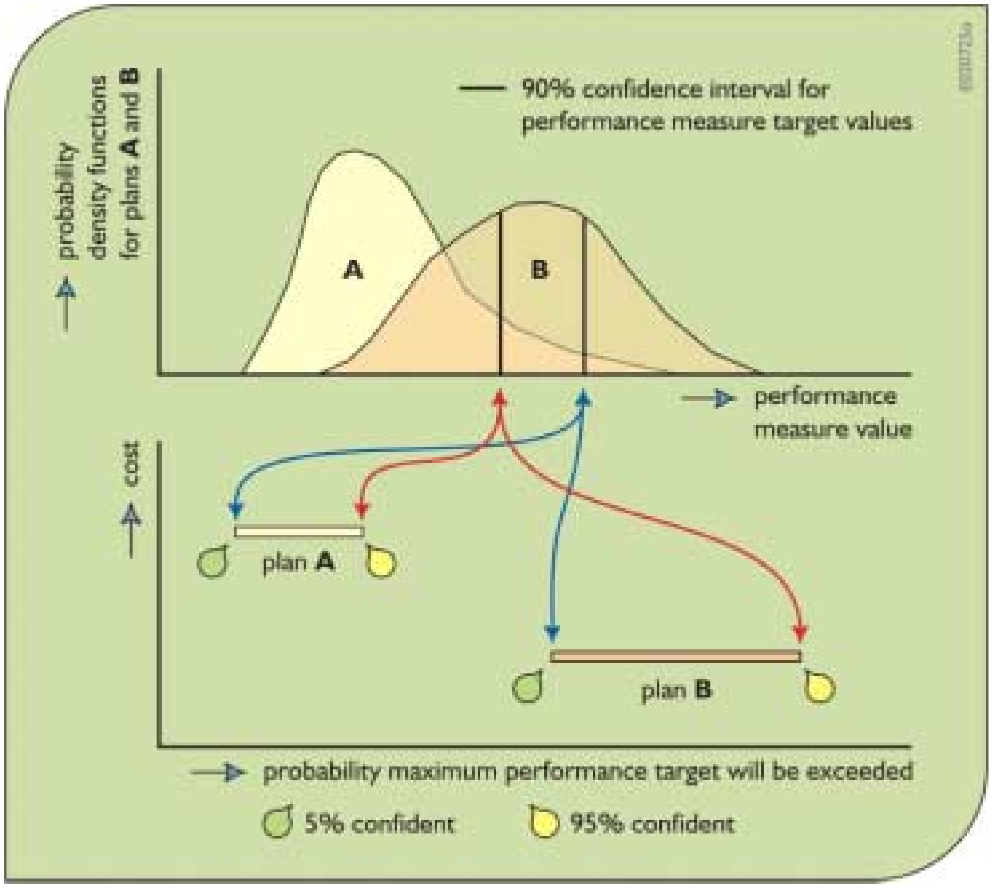

Figure 22. Two plans showing ranges of probabilities, depending on one's confidence, that an uncertain desired maximum (upper limit) performance target value will be exceeded. The 95% confidence levels are associated with the higher probabilities of exceeding the desired maximum target. The 5% confident levels are associated with the more desirable lower probabilities of exceeding the desired maximum target. Plan A with reduced probabilities of exceeding the upper limit costs more than Plan B.

In the case shown in Figure 22, the tradeoff is clearly between cost and reliability. In this example, no matter what confidence one chooses, Plan A is preferred to Plan B with respect to reliability, but Plan B is preferred to Plan A with respect to cost. The tradeoff is only between these two performance indicators or measures.

Consider however a third plan, as shown in Figure 23. This situation adds to the complexity of making appropriate tradeoffs. Now there are three criteria: cost, probability of exceedance (reliability) and the confidence in those reliabilities or probabilities. Add to this the fact that there will be multiple performance measure targets, each expressed in terms of their maximum probabilities of exceedance and the confidence in those probabilities.

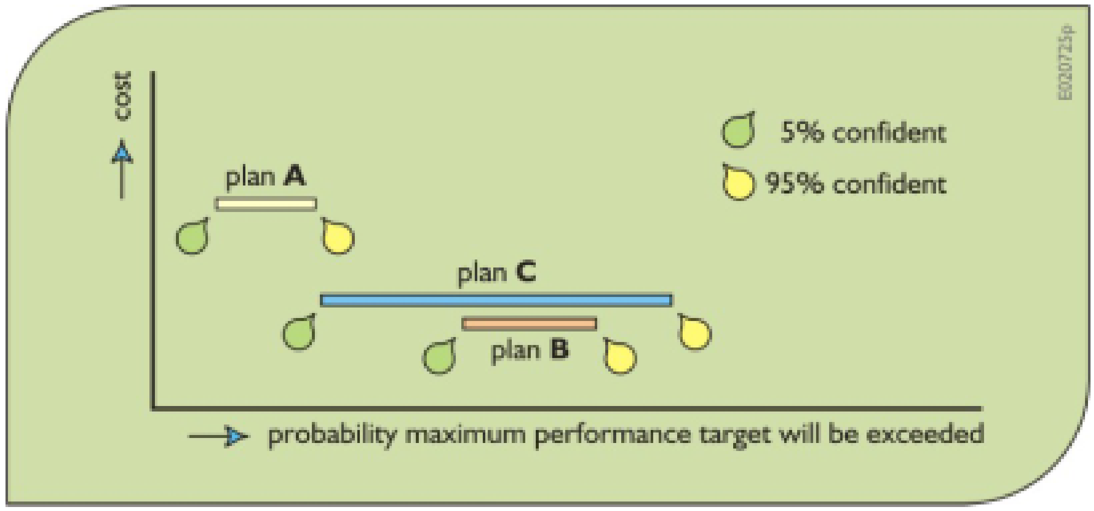

Figure 23. Tradeoffs among cost, reliabilities, and the confidence level of those reliabilities. The relative ranking of plans with respect to the probability of exceeding the desired (maximum limit) target may depend on the confidence given to that probability.

In Figure 23, in terms of cost the plans are ranked, from best to worst, B, C, and A. In terms of reliability at the 90 percent confidence level, they are ranked A, B, and C but at the 50 percent confidence level the ranking is A, C and B.

If the plan evaluation process has difficulty handling all this it may indicate the need to focus the uncertainty analysis effort on just what is deemed important, achievable, and beneficial. Then when the number of alternatives has been narrowed down to only a few that appear to be the better ones, a more complete uncertainty analysis can be performed. There is no need nor benefit in performing sensitivity and uncertainty analyses on all possible management alternatives. Rather one can focus on those alternatives that look the most promising, and then carry out additional uncertainty and sensitivity analyses only when important uncertain performance indicator values demands more scrutiny. Otherwise the work is not likely to affect the decision anyway.

5.2 Distinguishing differences between performance indicator distributions

Simulations of alternative water management infrastructure designs and operating policies require a comparison of the simulation outputs – the performance measures or indicators – associated with each alternative. A reasonable question to ask is are the observed differences statistically significant. Can one really tell if one alternative is better than another or are the observed differences explainable by random variations attributable to variations in the inputs and how the system responds?

This is a common statistical issue that is addressed by standard hypothesis tests (Devore, 1991; Benjamin and Cornell, 1970). Selection of an appropriate test requires that one first resolve what type of change one expects in the variables. To illustrate, consider the comparison of two different operating policies. Let Y_1 denote the set of output performance variable values with the first policy, and Y_2 the set of output performance variable values of the second policy. In many cases, one would expect one policy to be better than the other. One measure might be the difference in the mean of the variables; for example is $E[Y_1] < E[Y_2]$?. Alternatively one could check the difference in the median (50 percentile) of the two distributions.

In addition, one could look for a change in the variability or variance, or a shift in both the mean and the variance. Changes described by a difference in the mean or median often make the most sense and many statistical tests are available that are sensitive to such changes. For such investigations parametric and non-parametric tests for paired and unpaired data can be employed.

Consider the differences between "paired" and "unpaired" data. Suppose that the meteorological data for 1941-1990 is used to drive a simulation model generating data as described in Table 11:

Table 11. Possible flow data from a 50-year simulation

1941	Y_1 (1)	Y_2 (1)
1942	Y_1 (2)	Y_2 (2)
1943	Y_1 (3)	Y_2 (3)
1944	Y_1 (4)	Y_2 (4)
1989	Y_1 (49)	Y_2 (49)
1990	Y_1 (50)	Y_2 (50)

Here there is one sample, $Y_1(1)$ through $Y_1(50)$, for policy 1, and another sample, $Y_2(1)$ through $Y_2(50)$, for policy 2. However, the two sets of observations are not independent. For example, if 1943 was a very dry year, then we would expect both $Y_1(3)$ for policy 1 in that year and $Y_2(3)$ for policy 2 to be unusually small. With such paired data, one can use a paired hypothesis test to check for differences. Paired tests are usually easier than the corresponding unpaired tests that are appropriate in other cases. (For example, if one were checking for a difference in average rainfall depth between 1941-1960, and 1961-1990, they would have two sets of independent measurements for the two periods. With such data, one should use a two-sample unpaired test.)

Paired tests are generally based on the differences between the two sets of output, $Y_1(i) – Y_2(i)$. These are viewed as a single independent sample. The question is then are the differences positive (say Y_1 tends to be larger then Y_2), or negative (Y_1 tends to be smaller), or are positive and negative differences are equally likely (there is no difference between Y_1 and Y_2).

Both parametric and non-parametric families of statistical tests are available for paired data. The common parametric test for paired data (a one-sample t test) assumes that the mean of the differences

$$X(i) = Y_1(i) - Y_2(i) \tag{21}$$

are normally distributed. Then the hypothesis of no difference is rejected if the t statistic is sufficiently large, given the sample size n.

Alternatively, one can employ a nonparametric test and avoid the assumption that the differences X(i) are normally distributed. In such a case, one can use the Wilcoxon Signed Rank test. This nonparametric test ranks the absolute values $|X(i)|$ of the differences. If the sum S of the ranks of the positive differences deviates sufficiently from its expected value, $n(n+1)/4$ (were there no difference between the two distributions), one can conclude that there is a statistically significant difference between the $Y_1(i)$ and $Y_2(i)$ series. Standard statistical texts have tables of the distribution of the sum S as a function of the sample size n, and provide a good analytical approximation for $n > 20$ (for example, Devore, 1991). Both the parametric t test and the nonparametric Wilcoxon Signed Rank test require that the differences between the simulated values for each year be computed.

6. Communicating model output uncertainty

Spending money on reducing uncertainty would seem preferable to spending it on ways of calculating and describing it better. Yet attention to uncertainty communication is critically important if uncertainty analyses and characterizations are to be of value in a decision making process. In spite considerable efforts by those involved in risk assessment and management, we know very little about how to ensure effective risk communication to gain the confidence of stakeholders, incorporate their views and knowledge, and influence favorably the acceptability of risk assessments and risk-management decisions.

The best way to communicate concepts of uncertainty may well depend on what the audiences already know about risk and the various types of probability distributions (e.g., density, cumulative, exceedance) based on objective and subjective data, and the distinction between mean or average values and the most likely values. Undoubtedly graphical representations of these ways of describing uncertainty considerably facilitate communication.

The National Research Council (NRC 1994) addressed the extensive uncertainty and variability associated with estimating risk and concluded that risk characterizations should not be reduced to a single number or even to a range of numbers intended to portray uncertainty. Instead, the report recommended managers and the interested public should be given risk characterizations that are both qualitative and quantitative and both verbal and mathematical.

In some cases communicating qualitative information about uncertainty to stakeholders and the public in general may be more effective than quantitative information. There are, of course, situations in which quantitative uncertainty analyses are likely to provide information that is useful in a decision-making process. How else can tradeoffs such as illustrated in Figures 10 and 27 be identified? Quantitative uncertainty analysis often can be used as the basis of qualitative information about uncertainty, even if the quantitative information is not what is communicated to the public.

One should acknowledge to the public the widespread confusion regarding the differences between variability and uncertainty. Variability does not change through further measurement or study, although better sampling can improve our knowledge about variability. Uncertainty reflects gaps in information about scientifically observable phenomena.

While it is important to communicate uncertainties and confidence in predictions, it is equally important to clarify who or what is at risk, possible consequences, and the severity and irreversibility of an adverse effect should a target value, for example, not be met. This qualitative information is often critical to informed decision-making. Risk and uncertainty communication is always complicated by the reliability and amounts of available relevant information as well as how that information is presented. Effective communication between people receiving information about who or what is at risk, or what might happen and just how severe and irreversible an adverse effect might be should a target value not be met, is just as important as the level of uncertainty and the confidence associated with such predictions. A two-way dialog between those receiving such information and those giving it can help identify just what seems best for a particular audience.

Risk and uncertainty communication is a two-way street, It involves learning and teaching. Communicators dealing with uncertainty should learn about the concerns and values of their audience, their relevant knowledge, and their experience with uncertainty issues. Stakeholders' knowledge of the sources and reasons for uncertainty needs to be incorporated into assessment and management and communication decisions. By listening, communicators can craft risk messages that better reflect the perspectives, technical knowledge, and concerns of the audience.

Effective communication should begin before important decisions have been made. It can be facilitated in communities by citizen advisory panels. Citizen advisory panels can give planners and decision makers a better understanding of the questions and concerns of the community and an opportunity to test its effectiveness in communicating concepts and specific issues regarding uncertainty.

One approach to make uncertainty more meaningful is to make risk comparisons. For example, a ten parts per billion target for a particular pollutant concentration is equivalent to 10 seconds in over 31 years. If this is an average daily concentration target that is to be satisfied "99 percent," of the time, this is equivalent to an expected violation of less than one day every three months.

Many perceive the reduction of risk by an order of magnitude as though it were a linear reduction. A better way to illustrate orders of magnitude of risk reduction is shown in Figure 24, in which a bar graph depicts better than words that a reduction in risk from one in a 1,000 (10^{-3}) to one in 10,000 (10^{-4}) is a reduction of 90% and that a further reduction to one in 100,000 (10^{-5}) is a reduction 10-fold less than the first reduction of 90%. The percent of the risk that is reduced by whatever measures is a much easier concept to communicate than reductions expressed in terms of estimated absolute risk levels, such as 10^{-5}.

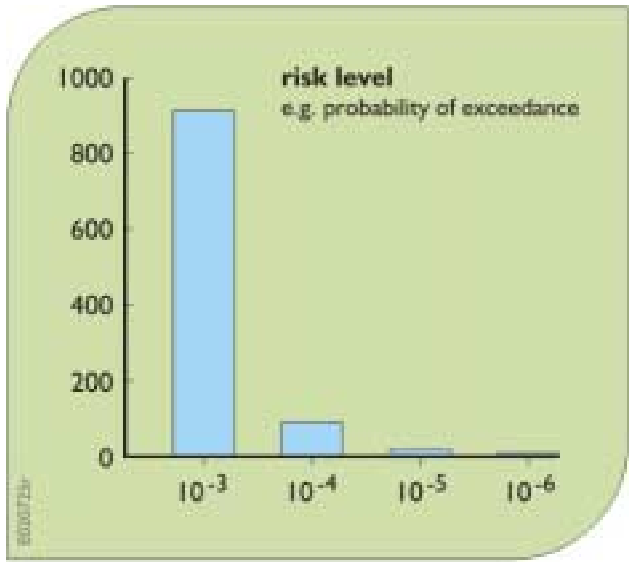

Figure 24. Reducing risk by orders of magnitude is not equivalent to linear reductions.

Risk comparisons can be helpful, but they should be used cautiously and tested if possible. There are dangers in comparing risks of diverse character, especially when the intent of the comparison is seen as minimizing a risk (NRC 1989). One difficulty in using risk comparisons is that it is not always easy to find risks that are sufficiently similar to make a comparison meaningful. How is someone able to compare two alternatives having two different costs and two different risk levels, for example, as is shown in Figure 7? One way is to perform an indifference analysis (Chapter X), but that can lead to different results depending who performs it. Another way is to develop utility functions using weights, where, for example reduced phosphorus load by half is equivalent to a 25 percent shorter hydroperiod in that area, but again each person's utility or tradeoff may differ.

At a minimum, graphical displays of uncertainty can be helpful. Consider the common system performance indicators that include:

- Time-series plots for continuous time-dependent indicators (Figure 25 upper left)
- Probability exceedance distributions for continuous indicators (Figure 25 upper right),
- Histograms for discrete event indicators (Figure 25 lower left), and
- Overlays on maps for space-dependent discrete events (Figure 25 lower right).

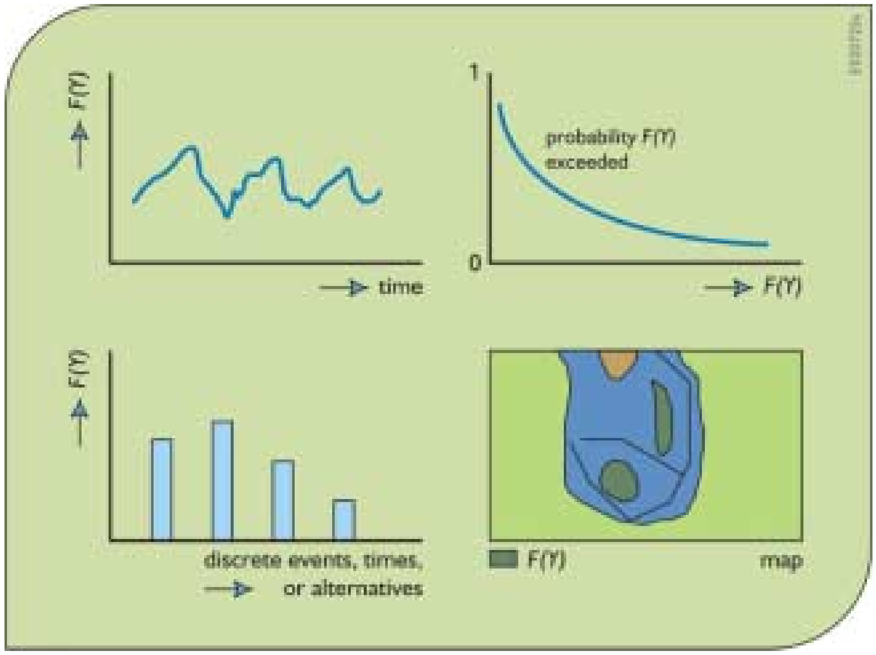

Figure 25. Different types of displays used to show model output *Y* or system performance indicator values *F*(*Y*).

The first three graphs in Figure 25 could show, in addition to the single curve or bar that represents the most likely output, a range of outcomes associated with a given confidence interval. For overlays of information on maps, different colors could represent the spatial extents of events associated with different ranges of risk or uncertainty. Figure 26, corresponding to Figure 25, illustrates these approaches for displaying these ranges.

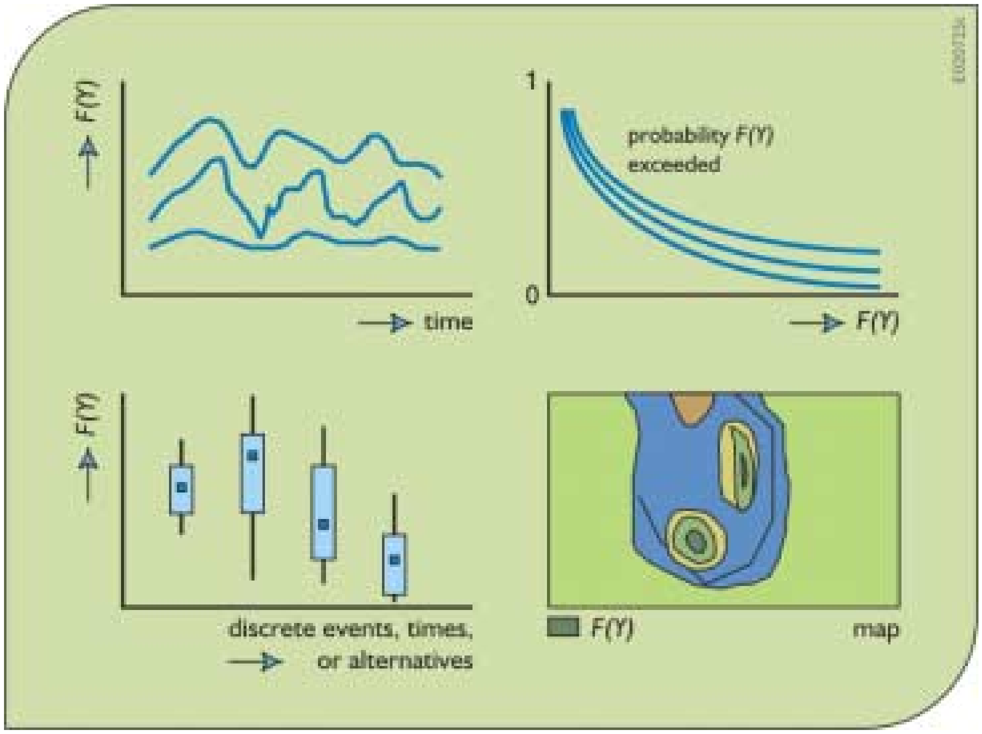

Figure 26. Plots of ranges of possible model output *Y* or system indicator values *F*(*Y*) for different types of displays.

7. Conclusions

This chapter provides an overview of uncertainty and sensitivity analyses in the context of hydrologic or water resources systems simulation modeling. A broad range of tools are available to explore, display, and quantify the sensitivity and uncertainty in predictions of key output variables and system performance indices with respect to imprecise and random model inputs and to assumptions concerning model structure. They range from relatively simple deterministic sensitivity analysis methods to more involved first-order analyses and Monte Carlo sampling methods.

Because of the complexity of many watersheds or river basins, Monte Carlo methods for uncertainty analyses may be a very major and unattractive undertaking. Therefore it is often prudent begin with the relatively simple deterministic procedures. This coupled with a probabilistically based first-order uncertainty analysis method can help quantify the uncertainty in key output variables and system performance indices, and the relative contributions of uncertainty in different input variables to the uncertainty in different output variables and system performance indices. These relative contributions may differ depending upon which output variables and indices are of interest.

A sensitivity analysis can provide a systematic assessment of the impact of parameter value imprecision on output variable values and performance indices, and of the relative contribution of errors in different parameter values to that output uncertainty. Once the key variables are identified, it should be possible to determine the extent to which parameter value uncertainty can be reduced through field investigations, development of better models, and other efforts.

Model calibration procedures can be applied to individual catchments and subsystems, as well as to composite systems. Automated calibration procedures have several advantages including the explicit use of an appropriate statistical objective function, identification of those parameters that best reproduce the calibration data set with the given objective function, and the estimations of the statistical precision of the estimated parameters.

All of these tasks together can represent a formidable effort. However, knowledge of the uncertainty associated with model predictions can be as important to management decision and policy formulation as are the predictions themselves.

No matter how much attention is given to quantifying and reducing uncertainties in model outputs, uncertainties will remain. Professionals who analyze risk, managers and decision makers who must manage risk, and the public who must live with risk and uncertainty, have different information needs and attitudes regarding risk and uncertainty. It is clear that information needs differ among those who model or use models, those who make substantial investment or social decisions, and those who are likely to be impacted by those decisions. Meeting those needs should result in more informed decision making. But it comes at a cost that should be considered along with the benefits of having this sensitivity and uncertainty information.

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Appendix I: Model Calibration Examples

- *Calibration of models in the Murray-Darling Basin*

In the Murray-Darling Basin, in order to preserve water quality, water reliability and the environment, a decision was made in 1995 to restrict water use to the 1993/94 level of development. Computer models of the major tributary streams are now used at the end of each year to determine the annual use target for the previous season based on that level of development. Rules are in place to ensure that long term usage is maintained at the agreed level. Because the models now define the overall water rights of each valley, there are legal requirements to calibrate models and each model is independently audited and certified as being unbiased before being approved as fit for purpose. The key model output of interest is water use but emphasis is also placed on the modeling of downstream flow which impacts the rights of downstream regions. Each model must be calibrated over at least ten years and this often means that changes in infrastructure, operating rules and growth in demand have to be incorporated into the calibration run. Calibration reports contain plots of modeled and observed water use, storage behavior and flow and statistics such as mean error, correlation coefficients and standard errors. The aim of calibration is to ensure that the model is unbiased and to give confidence to stakeholders.

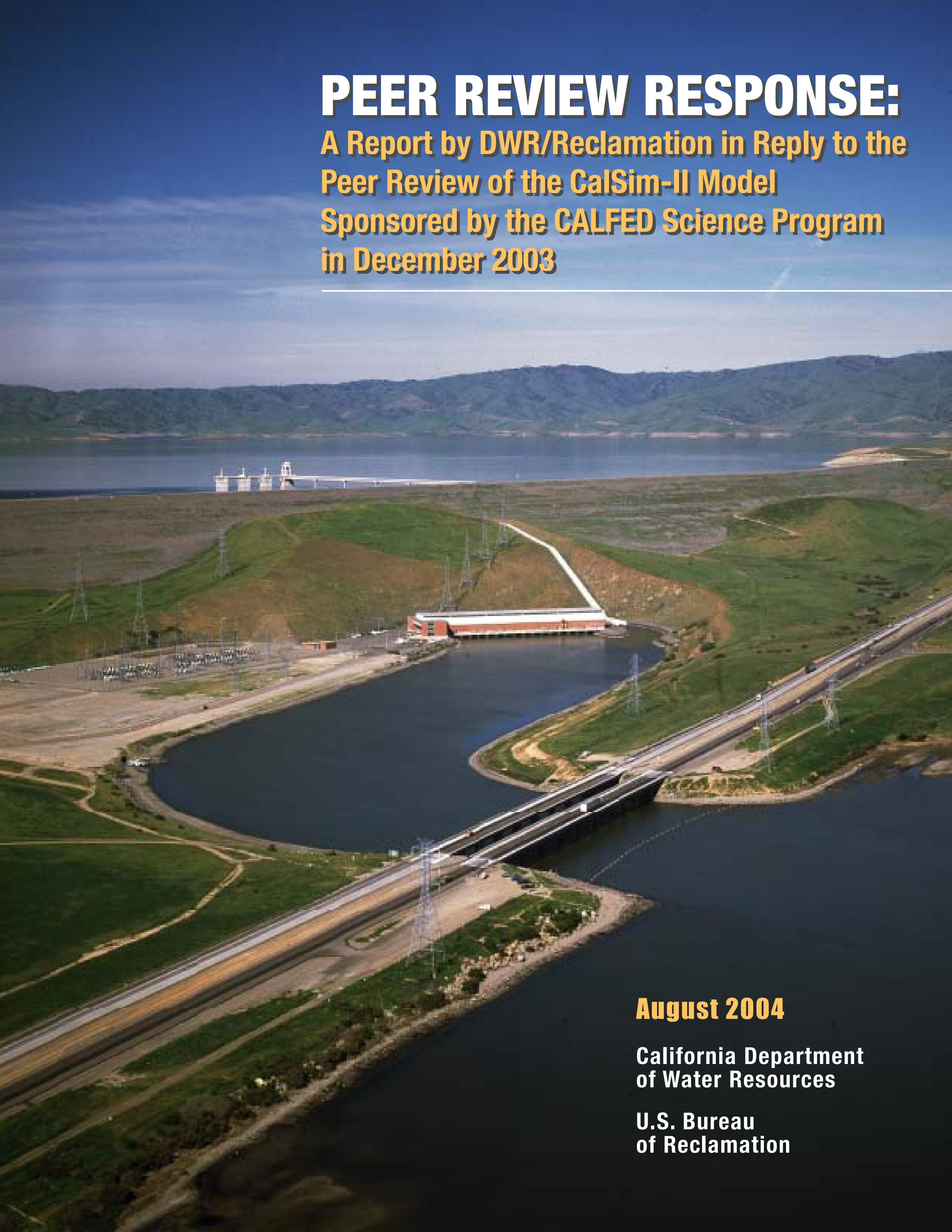
An issue that is sometimes raised with model development is the role of calibration, where the model is fine-tuned to match the observed data, and validation where the model is tested against data that was not used in the calibration process to get an independent assessment of the model's accuracy. For the Murray River, because of the variability of our climate, we like to calibrate our model against a long period of data including the most recent years when the current operating rules were being used and the historical data is generally the most reliable. Validation is considered to be less important and is typically carried out using the two or three years of data available following the completion of model calibration.

- *Use of models for Allocating Water in Texas*

Recent legislation in Texas revised the State Water Planning process and mandated the development of water allocation models for every river basin in the state (http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/permits.html). Similar to the Murray – Darling situation, these models are used to provide estimates of reliability for all permitted water diversions in the state as well as analysis of the effects of all permit applications. Naturalized, or predevelopment, time series of flows were constructed for the basins, and then the effects of developments were added in to achieve models of the current situation. The process of developing the basin models was an iterative, peer reviewed calibration process subject to stakeholder comment at several critical junctures. The naturalized flows and subsequent development of the basins now form an accepted and legal basis for future water allocations. Currently, similar activities are ongoing to provide calibrated and verified models of the state's groundwater aquifers and usage.

PEER REVIEW RESPONSE:

A Report by DWR/Reclamation in Reply to the Peer Review of the CalSim-II Model Sponsored by the CALFED Science Program in December 2003



August 2004

California Department of Water Resources

U.S. Bureau of Reclamation

Peer Review Response:

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This report was prepared jointly

By the

Department of Water Resources

And

U.S. Bureau of Reclamation

August, 2004

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Peer Review Response: ***A Report by DWR/Reclamation in Reply to the Peer Review of the CalSim-II Model Sponsored by the CALFED Science Program in December 2003***

Table of Contents

1. Introduction

The California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) have jointly developed a computer model called CalSim-II that simulates much of the water resources infrastructure in the Central Valley of California and Delta region. CalSim-II provides quantitative hydrologic-based information to those responsible for the planning, managing and operating the State Water Project (SWP) and federal Central Valley Project (CVP).

CalSim-II is a particular application of software developed primarily by DWR called CalSim. CalSim is a generalized water resources tool that can be applied to most reservoir-river basin systems. CalSim was recently renamed by DWR and Reclamation to WRIMS (Water Resources Integrated Modeling System). For consistency, however, the name CalSim rather than WRIMS will be used throughout this report.

In 2003, the CALFED Science Program commissioned an external review panel to provide an independent analysis and evaluation of the strengths and weaknesses of CalSim and CalSim-II. Specifically the review panel was asked (Strategic Review, p3) to answer the following questions below: (note: The Strategic Review report used the upper case "CALSIM" for the engine and the upper case "CALSIM II" for the application. In the seven questions below, as extracted from that report, the word "CALSIM" appears to imply both the engine CALSIM and, more importantly, the application CALSIM II. For consistency in this report, the words CalSim will be used for the engine and CalSim-II for the application)

1. Is CALSIM a reasonable modeling approach for current and proposed applications and problems?
2. Do other modeling approaches show similar or greater promise and flexibility for such problems?
3. What are the major comparative strengths and weaknesses of the current CALSIM approach and alternate approaches?
4. What are the major scientific, technical, and institutional limitations, uncertainties, and impediments for current and proposed applications of CALSIM?
5. What model, software, and data developments, special studies or tests would be beneficial to improve CALSIM for current and proposed uses?
6. How might CALSIM development and applications be managed and overseen to improve the quality assurance of the model results for current and proposed applications?
7. What are the panel suggestions for long-term use, development, or replacement of the current suite of models and data available for the current and proposed uses of CALSIM?

The Peer Review was held November 13-14, 2003. The panel's responses to the above questions were published in "*A strategic review of CALSIM II and its uses for water planning, management, and operations in central California*" (Strategic Review, December 4, 2003), herein referred to as the Strategic Review. This report is a response from DWR and Reclamation to the Strategic Review. The following information clarifies issues raised by the Peer Review, outlines the priority of development, and addresses current and future development work.

2. Goals of CalSim-II Development

The Department of Water Resources (DWR) and U.S. Bureau of Reclamation (Reclamation) strive to develop, maintain, and apply CalSim-II as the simulation model of the State Water Project and Central Valley Project best representing the two projects for planning and management studies. It is intended to serve organizations with an interest in the CVP/SWP management with the goals of developing and maintaining the best available technical tools for planning and management studies.

3. Summary of Response Goals and Priorities

DWR and Reclamation share the view that our response priorities need to be steered by a philosophy for carrying out the goals of CalSim-II development. This philosophy begins with the overarching goal of maintaining trust and credibility of CalSim-II among the user community. A complimentary goal of equal priority is assuring quality of CalSim-II data, assumptions and results. With credibility maintained and quality assured, we adopt secondary goals of implementing obvious and feasible enhancements of CalSim-II and providing service to the evolving needs of the user community with advancements that go beyond the present application of CalSim-II.

Given this philosophy of meeting the goals of CalSim-II development, DWR and Reclamation suggest the following prioritization of response projects. Many of these projects have already been initiated (independent of this prioritization, see Table 2). Each response item is discussed in more detail in section 4 and the Appendices. Items are listed in order of priority:

1. Establish Credibility and Trust
    a. Uncertainty and Sensitivity Analysis (*section 4.4.2, 4.4.3)*
    b. Documentation (*section 4.2.13, 4.3.4.1, Appendix D*)
    c. Establish formal schedule of Training Classes and User Group meetings (*section 4.3.5.6)*

2. Hydrology Enhancement (priority order beginning after 1., implemented over a longer term)
    a. Sacramento Valley (*section 4.2.1, 4.2.2, 4.2.11, Appendix E, F*)
    b. West Side San Joaquin (*Appendix F)*

3. Software Development Needs – Part 1 (priority order after 2., although many of these projects have been initiated (Table 2)).
    a. Version Control (*section 4.3.4.14)*
    b. (Meta) Data Control (*section 4.3.2, 4.3.3)*
    c. Error Checking (*section 4.3.4.2)*
    d. Solver Reliability/Infeasibility Handling (*section 4.3.1, 4.3.4.5*)
    e. Graphical Network Builder (*section 4.3.4.4)*

4. CalSim-II Module Enhancements (priority order after 3., although many of these projects have been initiated (Table 2))
    a. CalSim Allocation Module (CAM) (*section 4.2.8, 4.3.1, 4.3.4.8, Appendix B)*
    b. Water Quality Modules for the MWD-related facilities and the San Joaquin Valley (*section 4.2.7, 4.3.4.15, Appendix B)*

5. Software Development Needs – Part 2 (priority order after 4, although many of these projects have been initiated (Table 2)).
    a. Modularity (*section 4.3.4.7)*
    b. Runtime (*section 4.3.4.11)*
    c. Ability to Link Linear Optimization and Non-Linear Extensions (*section 4.3.4.12)*

6. Application/Software Extensions (priority listed in order after 5, although many of these projects have been initiated (Table 2)).
    a. Modular Application of CalSim (*section 4.2.6)*
    b. Demand Management and Supply Augmentation Schemes (Conjunctive Use) (*section 4.2.9).*

    DWR and Reclamation plan to explore partnerships with stakeholder groups and outside resources to support implementation of some of these priority items in a comprehensive manner.

4. DWR/Reclamation Response to Specific Issues

4.1. Summary of Comments and Responses

Table 1 is a matrix of the various comments raised in the Strategic Review. The comments have been grouped into categories. The column on the far right-hand side of Table 1 refers to DWR and Reclamation's response to each individual comment as summarized below:

1 DWR and Reclamation do not agree with the comment stated.

2 DWR and Reclamation agree with the comment stated.

2a DWR and Reclamation agree with the comment stated and staff is currently working on it as part of our immediate needs for CalSim-II. A work plan is being developed by both DWR and Reclamation and will be shared with the public in the very near future.

2b DWR and Reclamation agree with the comment stated and consider it important to address in the short term with a target date of January 2007.

2c DWR and Reclamation agree with the comment stated but considers it should be addressed on a longer term with a target date of January 2011.

Where there is agreement (i.e., 2) then DWR and Reclamation attempt to fit the response within their projected timelines. Sometimes there is agreement and disagreement on an issue (e.g., 1, 2) indicating disagreement with portions of the comment but agreements on other parts.

4.2. Conceptual Level

The scope of a model should be defined in relation to its intended purpose. CalSim-II was originally conceived as a model of the CVP-SWP system to be used for planning purposes and comparative analysis of ***project*** alternatives. CalSim-II is now being advocated for analysis of more general water management issues. The Strategic Review (p2) states that:

"*As the official model of those projects, CalSim-II is the default system model for any inter-regional or statewide analysis of water in the Central Valley of California.*"

"California needs a large-scale relatively versatile inter-regional operations planning model and CalSim-II currently serves that purpose reasonably well."

Clearly, CalSim-II has evolved from being a CVP-SWP specific model. Yet, its wider role and purpose has not been clearly stated. The Strategic Review contains many recommendations relating to the wider (non CVP-SWP) role of the model. DWR/Reclamation agrees in principal to most of these recommendations. Any planner would wish for additional capabilities. However, implementation of these recommendations is constrained by the limited resources available to DWR and Reclamation.

It is necessary to examine the applicability of CalSim-II to a wider range of water related questions and to plan how further model development can support future planning activities associated with California water. The following is a set of modeling policy statements that DWR/Reclamation support and advocate to help direct future model development.

- Model users and decision-makers need to have confidence in CalSim-II for both absolute and comparative analysis (Strategic Review, p9)

- CalSim-II should evolve toward a more consistent representation of the rules that govern annual and real-time operations planning (Strategic Review, p8)
- CalSim-II needs to evolve from a model of the CVP-SWP system to a model of California's inter-connected water system (Strategic Review, p24)
- CalSim-II needs to explicitly represent a wide range of water management options, that include water conservation, reuse, water transfers, and groundwater conjunctive use management (Strategic Review, p21)
- Groundwater needs to be more fully represented in CalSim-II (Strategic Review, p19)

The Strategic Review (p2) agrees that CalSim is an appropriate approach for the modeling of the CVP-SWP-Central Valley system. The following sub-sections discuss particular issues raised in the Strategic Review that would broaden the model's applicability.

4.2.1. Geographical Scope

Development of CalSim-II beyond the needs of the SWP/CVP systems and the Sacramento-San Joaquin drainage area may go further than the current purpose of the model. Widening the geographic scope encompassing the Tulare Basin and Southern California would require considerable additional resources and greater support and involvement of local agencies. DWR, however, is currently working on the calibration of CVGSM2 (an application of IGSM2 to the Central Valley which includes Tulare Basin). DWR and Reclamation expect to use CVGSM2 or an alternative tool as the principal tool for developing the hydrology, modeling surface water – ground water interaction, and modeling ground water flow.

DWR and Reclamation support the development of CalSim models of the upstream watersheds, and the integration of these models with CalSim-II. An example of this cooperation is the development of the CalSim Yuba model that is supported by Yuba County Water Agency, and development of a daily time-step model of Upper American River operations (above Folsom Lake), commissioned by Reclamation. DWR and Reclamation support the vision of CalSim providing a common platform for water resources analysis in California.

4.2.2. Groundwater

Modeling groundwater in CalSim has evolved from the simpler Depletion Analysis approach to the current multiple-cell approach used in the Sacramento Valley. As part of its short-term goals, DWR is working on enhancing the modeling of groundwater flow and the surface water – groundwater interaction through the use of CVGSM2 (Central Valley Groundwater – Surface water Model) or its variants. CVGSM2 is the application to the Central Valley of the IGSM2 (Integrated Groundwater – Surface water Model) model. IGSM2 is currently developed and supported by DWR. A brief description of IGSM2 is given in Appendix F. One clarification: Page 8 of the Strategic Review lists a series of weaknesses model users would like addressed. These concerns were identified in a survey of stakeholders conducted by the University of California at Davis, prior to the Peer Review during the summer 2003. One of the concerns is stated as:

> *"Groundwater resources are assumed infinite, i.e., there is no upper limit to groundwater pumping"*

This is a mischaracterization of the model. Groundwater pumping *is* constrained in CalSim-II, and is also only available to meet local agricultural or urban demands. A full description of how groundwater pumping is modeled is given in Appendix A.

4.2.3. Hydropower

Reclamation has incorporated project hydropower generation and use directly into a version of CalSim-II, but hydropower is not included as an objective. Reclamation and DWR are currently using post-processing spreadsheets to analyze hydropower operations in CalSim-II. The Reclamation post-processing spreadsheet was originally designed for and approved by the Western Area Power Authority (WAPA). The WAPA spreadsheet currently represents all the CVP facilities. DWR uses a spreadsheet that was originally designed for DWRSIM (predecessor to CalSim-II) and applies to all SWP facilities. In the near future, the SWP plans to adopt a methodology for approximating hydropower that is similar to the WAPA spreadsheet.

DWR may consider integrating hydropower as a decision variable or objective in SWP operations as part of its long-term planning for CalSim-II. This will also be dependent on the availability and/or development of trade-off curves between hydropower generation and surface water deliveries.

4.2.4. Local Projects

Similar to the geographical extension of CalSim-II, DWR and Reclamation welcome and support, as far as possible, the use of CalSim by local agencies to develop planning models of their local facilities. These detailed models should be ‘collapsible’ so that they can be included in CalSim-II in an aggregate form, and so that CalSim-II can provide the local boundary conditions for more detailed local planning. This approach is consistent with the modular approach advocated by the Strategic Review.

4.2.5. Analyzing Future Scenarios

The Strategic Review (p22) recommends that capability to analyze a greater range of future scenarios be enhanced. Long-term planning for California may be best served by considering the notion other than that of a certain future, and implementing plans that best position the State to respond to a range of possible futures. This approach has been adopted by the California Water Plan Update, and DWR is evaluating the use of CalSim-II for future quantitative analysis. DWR and Reclamation agree that this is a desirable approach. However, the current hydrology development process is too unwieldy to efficiently produce a suite of possible land use, water supply and demand scenarios. DWR and Reclamation agree that, as part of the near term future model development the agencies examine ways to streamline the development of alternate futures, and restructuring of code to allow users to quickly change key input assumptions.

4.2.6. Modular Approach

The Strategic Review (p2) identifies a *‘common tension between those who wish for greater detail and those who want less detail from the model.’* The successful implementation of an expanded role for CalSim-II depends on the adoption of a modular approach to modeling. This should allow the quick construction of different CalSim-II versions, ranging from a very simple system representation for preliminary screening analysis or educational purposes, to a detailed and complex model that includes many local project operations. Modularity can be addressed at three levels: hierarchical, spatial, and temporal. An example of hierarchical level is a screening version of CalSim (as compared to a detailed representation of the system). DWR and Reclamation are also considering that the CalSim-II code be restructured to implement the modular approach before more detail is added to the model to represent local project operations in the Sacramento and San Joaquin Valleys.

4.2.7. Operational Objectives

Operational objectives in CalSim-II are either flow or storage related (minimum instream flows, storage targets, deliveries). Although water quality in the Delta is a constraint on project operations, it is not an objective. The Strategic Review (p8) suggests the capability of CalSim-II to analyze economic, water quality and groundwater issues be improved. Reclamation has developed a San Joaquin River Westside Drainage module for CalSim-II that disaggregates electrical conductivity (EC) source components that contribute to simulated Vernalis EC, which is an integral first step of future San Joaquin water quality investigations involving the main stem of SJR, Westside irrigation activities, and Upper/Eastside San Joaquin tributary operations. DWR is currently working with the Metropolitan Water District of Southern California (MWD) to add water quality functionality to the CalSim software. Using economic drivers for initial screening analysis has been discussed. Reclamation has worked with UC Davis on the development of the CALVIN model, which uses prescriptive optimization techniques and economic drivers to manage California’s water system. Both agencies remain interested in adding CALVIN-type capabilities to CalSim-II. This work would probably best be implemented by the University of California, supported by DWR and Reclamation as part of the long-term strategy.

4.2.8. Real-Time Operations

Both DWR and Reclamation share the modeling vision to narrow the gap between their respective operations models and CalSim-II. One key area where operations and planning tools overlap is that the former is used to set allocation targets and the latter must represent the *process* of setting allocation targets. In actual operations, the DWR and Reclamation spreadsheet operations models are applied by operators to establish annual allocation levels; these levels evolve through the snowmelt season. In planning application within CalSim-II (i.e. during a multi-year simulation), the *process* of setting annual allocations is currently emulated in a very simplified manner that considers stored-water inventory and forecast hydrology at the time of allocation setting.

This simplified representation stands to be improved greatly through the application of the CalSim Allocation Module (CAM), which is being developed by DWR in collaboration with Reclamation. CAM was developed to mimic the procedure used by operations staff. This includes using forecasted hydrology for a 12 month time horizon and a simplified representation of the system (as compared to CalSim-II). Operating guidelines are being developed in consultation with SWP/CVP operators to reflect the procedures used in real-time operations. Use of multi-period optimization simplifies the required simulation rules by relying on the MIP solver to optimize the monthly reservoir release/export decisions subject to the system constraints and operating guidelines of the project reservoirs. Linking CAM with CalSim-II takes advantage of both model approaches and improves the ability of the planning tool to mimic real-time operations.

4.2.9. Water Management Options

The Strategic Review (p21 & 23) states that CalSim-II should more explicitly model many demand management and supply augmentation options. The demand management options require that CalSim-II represent demands in greater detail and more explicitly. DWR and Reclamation will consider if modeling of these options may best be achieved through better linkages of CalSim-II to its agricultural (CALAG) and urban (IWR-MAIN, LCPSIM) demand counterparts. This will include how data inputs and outputs can be more easily communicated between these models. Also for consideration is revising urban demands in CalSim-II so as to represent them in their entirety rather than limiting representation to outdoor (consumptive) urban demand.

4.2.10. Objective Function

The Strategic Review (p4) raises an important issue regarding the characterization of reservoir operators' behavior.

"*Most successful applications of optimization that attempt to simulate the behavior of a system have calibrated their objective function so that the model results correspond to what actually happens or would happen under a particular hydrologic and demand scenario*."

A good example of this approach is the positive mathematical programming technique used in DWR's agricultural production models CVPM and CALAG. The lack of calibration is one reason why the *CalSim-II Simulation of Historical SWP/CVP Operations* study was unable to mimic historical project carryover storage during drought conditions.

In the past, DWRSIM and CalSim-II had a prescriptive rather than a descriptive approach in defining reservoir operation rules. For example, carryover storage targets were developed that maintained minimum storage levels during a prolonged drought while trying to minimize shortages in any particular year. While this is a valid approach, it may lead to over-optimistic model results due to discrepancies between model and actual operators' decisions.

DWR and Reclamation are engaged with their respective project operators to reduce these discrepancies. The difficulty in calibrating CalSim-II to past behavior is that the behavior is dynamic. Reservoir operations continually evolve due to changing regulatory conditions, changing systems demands, and requests from project contractors. The agencies modeling staff, reservoir operators and contractors are working together to develop a CalSim-II module (CAM) that can be used to determine present month decision variables (e.g., allocation levels, expectations on future carryover or fill targets) based on foreseen operations determined through multi-period optimization and hydrologic foresight. If successful, this approach will be extended to other model rule curves, such as balancing north and south of Delta storage.

4.2.11. Land Use

Projected-level land-use in CalSim-II is assumed constant. It is an exogenous input derived from the Central Valley Production Model (CVPM). Land use projections result from assumptions regarding farmer's long-run response to long-term average annual surface water and groundwater availability and associated cost. Evidently, farmer's planting decisions will vary in the short-run due to annual variation in supply. This short-term response is not modeled in CalSim-II, although it can be modeled using CVPM (or its successor CALAG). DWR has developed an internal memorandum on how such a response could be represented in CalSim-II. However, modeling land-use variation is considered secondary to a more general revision and update of the CalSim-II hydrology development (Appendix E).

4.2.12. Hydrologic Uncertainty

The Strategic Review states that there needs to be *'a better capacity to accommodate other approaches to representing hydrologic uncertainty and variability besides simply simulating 70-plus years of record.'* DWR and Reclamation believe that the use of explicitly stochastic techniques or the use of synthetic hydrologic data would not be a useful contribution at this time. Assembling a reasonable representation of auto- and cross-correlation of inflows for a large-part of California is a daunting task. Preservation of the persistence of drought phenomena is very difficult. Even harder would be gaining public acceptance of such an approach. Nonetheless, DWR and Reclamation do believe that there are alternatives to the reliance on a single hydrology. Underlying the use of historical flows is the belief that the past is a good indicator of the future. DWR and Reclamation are currently working with the Scripps Research Institute to develop alternate hydrologies that may be more likely to occur due to global climate change. DWR and Reclamation are also considering the use of rainfall-runoff models as part of the hydrology development, which offer a more flexible approach to modeling extreme events beyond the recent historical record.

4.2.13. Documentation

Over the last two years DWR and Reclamation have worked together to document the model system representation and logic. As part of the September 30, 2002 Benchmark release, the agencies issued a 156 page model description and a document summarizing the simulation output. Since the release, DWR and Reclamation have dedicated time and resources to the following documentation activities:

- Creation of the CalSim-II Review and Documentation Team
- Development of WRESL code commenting protocol
- Implementation of commenting protocol for the September 30, 2002 Benchmark (review and revision of existing comments)
- Development of CalSim reference manual outline
- Development of CalSim documentation management system strategy

Despite the coordinated effort, documentation activities have often been given second priority to the production of model studies. Both DWR and Reclamation acknowledge the need to prioritize and supplement the Review and Documentation Team effort with additional resources to complete the documentation task. A brief description of the proposed CalSim-II documentation management system is given in Appendix D.

4.3. Implementation Level

4.3.1. Numerical Approach

CalSim uses mixed integer linear programming (MIP) to route water through a network of nodes and links in accordance to a user-defined set of priorities and constraints. The Strategic Review states (p4) that this approach is similar to other state-of-the art modeling tools such as ARSP, MODSIM, OASIS, REALM, Riverware and WEAP. However, the peer review does warn that optimization "*has the potential to produce inaccurate and overly optimistic results.*"

The Strategic Review recommends (p5) that the current strategy of single-step optimization should be supplemented by:

- Multi-period optimization to guide decisions with impacts that stretch beyond the current time-step,
- Detailed simulation of some system elements, allowing modeling of non-linearities, and potential reduction in run time.

DWR and Reclamation are currently implementing these recommendations in various ways. These fall under categories for enhancing and streamlining the numerical procedure. Enhancements to the numerical procedure of CalSim will allow expanded functionality, including

- Iterative solution of a cycle. A cycle will repeatedly be solved until the user-specified convergence criteria are met (or maximum number of iterations). This will increase the ability to model nonlinear aspects of the system.
- Automation of writing decision variables and constraints for multi-period optimization. The CAM model (briefly described in Appendix B) uses a time-consuming manual process for defining the MIP for multi-period optimization. This may be automated by introducing arrays for decision variables and constraints.
- Dynamic computation of decision variable weights. This will allow increased flexibility of the MIP.

Streamlining of the numerical procedure of CalSim will reduce run-times and simplify software maintenance. Items include the following:

- Streamlining of cycling MIP solutions. Cycles will be streamlined to eliminate the need for separate "Single Study Runner" and "Multi-Study Runner". This will allow a single GUI to be used for all CalSim simulations.
- Expanded use of DSS pathnames. A single DSS output file may be used for all "multi-step" studies. Transfer files may be eliminated, reducing time-consuming reading/writing to hard drive.
- Allowing State Variables to be written to DSS. Currently only Decision Variables are written to the DSS output file. Allowing State Variables to be directly written to the DSS file will eliminate the current practice of sending these parameters through the MIP solver and unnecessarily increasing the overhead on the solver.

4.3.2. Data

Concern of the quality of data in CalSim-II, is one of the most recurrent themes of the Strategic Review. For example (p20): "*There has not been sufficiently systematic, transparent, and accessible approach to the development and use of hydrologic, water demand, capacity and operational data. The administration of data development is fragmented, disintegrated, and lacks a coherent technical or administrative framework*."

The validity of data inputs impacts both model results and model credibility. The greatest concern is the validity of the hydrologic inputs and parameters. Concern is compounded by the current lack of complete documentation. Over the last two years DWR and Reclamation have attempted to document model inputs. Reclamation is currently documenting the current CalSim-II hydrology procedures. This effort needs to be extended and updated.

It is worth noting that the restructuring of the CalSim software as part of release 2.0 allows metadata describing the source of model inputs to be stored with the actual data. A brief description of the proposed CalSim-II data and documentation management system is given in Appendix D.

4.3.3. Data Management

The Strategic Review (p.58) identified data management as a critical aspect for CalSim. A web-based version control software (Perforce) is used by DWR modelers for managing the text-file input files of the current version of CalSim (v1.2). Adoption of a public domain relational database management system is under development for the next version of CalSim (v2.0). This database will provide a central repository that will contain documentation in addition to the model input/output data (time series data may continue to be stored in HEC-DSS). This will provide a full-featured client/server database including version control, integrity of data, documentation (including metadata), and ease of dissemination.

4.3.4. Software

In general, DWR agrees with the recommendations of the Strategic Review regarding the CalSim software. Many of these recommendations have been adopted and are being implemented for the next version of CalSim (v2.0). Given the growing use of CalSim outside of the two agencies, DWR accepts the need for extensive discussion and input from the wider modeling community and extensive beta-testing before the release of the next version of CalSim (v2.0). New software developments must take into account the considerable familiarity represented by the body of existing software users. It is important that major changes to the structure and look of the CalSim software benefit from feedback from this user-pool.

The following sections answer specific points raised in the Strategic Review. A brief general description of the next version of CalSim (v2.0) is given in Appendix B. In general, DWR's goal is to cease development work on the current release of CalSim (v1.2), and to implement improvements discussed below for the next version of CalSim (v2.0).

4.3.4.1. <u>Documentation</u>

Three documents are currently available to the CalSim user: the CalSim User's Guide, the CalSim Manual, and the WRESL Language Reference. These documents offer the minimum required help to the CalSim novice. DWR accepts that these documents need to be updated and expanded. Initially DWR supported a web-based software bug reporting and archiving system. This system needs to be reactivated. DWR and Reclamation intend to publish a list of frequently asked questions (FAQ). This will eliminate many wasted hours of model user's time due to minor software bugs and idiosyncrasies. DWR accepts the need to provide centralized support. Given the agencies current workload and resource constraints it seems that it may be best to contract this to a third party.

4.3.4.2. Error Checking

The Strategic Review identified automated error (p5) and input/output (p24) checking for increased productivity. Staff from DWR, Reclamation, and other agencies or consultants has developed several spreadsheets for such purposes. A short-term goal of DWR is to collect, refine, and develop such spreadsheets into a series of standard pre and post processors that become a standardized set of tools. In addition, development of the next version of CalSim (v2.0) software may include expanding the solvers capability to track potential errors in setting up input data.

4.3.4.3. Gaming

Stakeholder participation will be sought to develop a gaming interface for the next version of CalSim (v2.0).

4.3.4.4. GUI

A CalSim-II geo-referenced network schematic is under development by Reclamation. The primary purpose of this project is to provide a communication tool between CalSim-II users, agency management, project managers, and the public. Geo-referencing the network provides quality control and a spatial connection between the system and the topography. The general CalSim GIS toolbox can be applied in any geographic location and features drag and drop icons with connector linkages for easy modifications. CalSim-II network schematic developments also anticipate future integration options. GIS is capable of generating CalSim code based on the network representation to run an application, storing pertinent meta data and coverage information, and has online integrated mapping system capabilities. In addition, the CalSim GIS toolbox has been applied to the SWP and CVP system and is now under review. Alternative options (public domain) for schematic generation are also in discussion.

4.3.4.5. Infeasibilities

DWR recognizes that the solver report of an infeasible solution is a periodic, but potentially very time-consuming problem. Tools do exist currently in CalSim to identify the causal constraints, but they are not well documented. The current LP solver in CalSim is XA (by Sunsoft, Inc). Users may use the XA reporting options in CalSim to help identify the problem. In many cases XA will report which constraints it has not been able to satisfy, and by how much it would need to relax the constraint to find a solution. However, in some cases XA fails to identify the problematic constraints. The Strategic Review (p24) recommends overcoming the infeasibility problem, which adds slack and surplus auxiliary variables to each constraint. High penalty values assigned to the auxiliary variables would assure that they would be non-basic (i.e. have a value of zero) unless the solution would otherwise be infeasible. The auxiliary variables would only be added to the MIP problem if an infeasible solution were obtained, so as not to increase run-time There is merit to this approach ,which is currently used in CalSim to assure that the continuity constraint for storage nodes can always be met.

DWR is working with Lawrence Berkeley Laboratories on an alternate approach to develop analysis tools for infeasible and non-unique solutions (Section 4.3.4.10).

4.3.4.6. LP Output

CalSim currently provides limited output from the MIP solver. For successful solutions, only final decision variable values are reported. These include Lagrange multipliers (a.k.a. dual variables, shadow prices, trade offs) which indicate the sensitivity of the objective function to each decision variable, slack variables which indicate the sensitivity of decision variable bounds on the solution, and basic and non-basic variables which are used internally by the solver. These output parameters may help users understand the complex nature of the multiple constraints on the system and how they interact with the MIP.

4.3.4.7. Modularity

The Strategic Review (p21) indicated modularity of data components will help to alleviate the conflicts of different users requiring both a less complicated and more details system representation (p21). Included in the next version of CalSim (v2.0) is the ability to store data in modules. This functionality may be used in several ways, which the CalSim user community should establish protocols for their use. Possibilities include various levels of geographic resolution (ranging from simple to complex), modularizing regulations into distinct packages and/or representing hydrologic processes in different levels of complexity. These various components may be linked together in a simulation to form various distinct models suitable to the user and purpose of simulation.

4.3.4.8. Multi-Period Optimization

CalSim-II uses the MIP to route water through the system on a single time step. Simulation rules are used to bind the optimization solver for monthly decisions. The Strategic Review suggested use of multi-period optimization may provide a useful platform to represent the system and interact with the simulation model (p5, 8, 38). The CalSim Allocation Module (CAM, Appendix B) uses this methodology for a remainder-of-Calendar-Year optimization window (e.g., twelve months if initiated in January). During the multi-month optimization window the solver is allowed to determine the optimal pattern of reservoir releases, channel flows, and exports relative to storage and release constraints that represent operator sensibilities during allocation planning, rather than specifying simulation rules. CAM was developed within the existing CalSim software by writing the system constraints manually. DWR will automate implementation of multi-period optimization by allowing the next version of CalSim (v2.0) GUI to essentially write and interpret arrays. This functionality will facilitate the exploration of multi-period optimization within the CalSim environment.

4.3.4.9. Post-Processing

The CalSim software has some limited functionality to analyze and interpret model results. This is primarily the viewing and comparison of base and alternate time series data using charts and tables. While DWR and Reclamation acknowledge the need for better post-processing tools, it is the belief of both agencies that this functionality is best provided by third-party tools such as Excel. There are currently many different post-processing tools used by CalSim users to import HEC-DSS data into Excel and subsequently to manipulate the data for interpretation.

DWR and Reclamation recommend that resources be invested into pooling the availability of these tools with further investment in their development. In addition to automated generation of charts and tables within Excel, it has been shown that for developed gaming models MS-Excel can be a good visualization tool.

4.3.4.10. Public Domain

DWR is following a policy of adopting public domain software for CalSim. This includes:

- Elimination of the FORTRAN compiler,
- Replacement of the XA proprietary MIP solver, and
- Search for a public domain GUI for the construction and editing of the river basin topology.

DWR is currently testing the public domain solver GLPK for use in CalSim. At this time, individual CalSim cycles have been solved by GLPK, and, so far, it reproduces the proprietary XA solver solutions. The next version of CalSim (v2.0) is being modified to use GLPK for further testing. Based on initial tests, GLPK is not as efficient in solving CalSim type problems as the XA solver. Solve time is approximately three times greater with GLPK. Lawrence Berkeley Laboratory (LBL) is working on improving the efficiency of GLPK. LBL has also been asked to add other utilities to GLPK such as analysis tools for infeasible and non-unique solutions.

4.3.4.11. Run Time

Advances in computer processing speeds are steadily reducing model run times. However long run time remains a problem, precluding for example sensitivity analysis on model inputs. Much of the problem relates to inefficient coding of the MIP problem in which large parts of the system are unnecessarily simulated multiple times in each time step. To reduce run times DWR and Reclamation are adopting the following strategy:

- Eliminate unnecessary variables from the LP problem (e.g. use of alias statements),
- Restructure the WRESL code to eliminate repetitive calculations,
- Optimize the reading and writing of data to HEC-DSS.

4.3.4.12. Simulation

The Strategic Review (p5) suggests that linking of linear multi-period optimization procedures to non-linear simulation models might both increase the accuracy of the model, and possibly decrease run time. The optimization module would be run each time some type of 'optimal' decision needs to be made e.g. annual allocations, reservoir releases or other management decisions. More detailed simulation at a shorter time step would subsequently implement these decisions, and define the consequences, routing water through the network according to a set of rules.

The peer review panel was not unanimous in this view. Most of the panel agreed that single time-step optimization is needed to reduce the dependence on operating rules. The use of multi-period optimization is discussed in Section 4.3.4.8. DWR, however, does agree that greater use of simulation might reduce run-time. The CalSim software should be modified to permit simulation both at the end and beginning of each time-step. Subsequently the CalSim-II code should be reviewed so as to eliminate variables from the MIP problem that could be defined through simple arithmetic calculations.

4.3.4.13. Time-Step

CalSim-II is a monthly planning model of a geographically extensive system. Aggregation in time and space, by necessity, simplifies or omits many operational details. Of particular concern has been the error that a monthly time-step may introduce in representing the Delta.

- Project export capability may be over-estimated due to monthly averaging of Delta inflow,
- A monthly time-step may poorly represent regulatory requirements, such as X2, which may be met on the basis of 14-day running average EC, or 3-day running average Net Delta Outflow Index.

DWR has developed a daily time-step version of CalSim-II for the Sacramento Valley and Delta (Appendix B).

DWR and Reclamation heed the warnings of the Strategic Review (p24) that shortened time steps pose problems of run-time, data development and model interpretability, amongst others. DWR proposes to conduct a study to evaluate the errors introduced by using a monthly time-step. The study will compare project exports from CalSim-II to the daily Delta CalSim model. In the first part of the study the daily model will be run with the daily Delta inflow set equal to the average monthly inflow as determined by the monthly CalSim-II model, i.e. with no day-to-day flow variation. In the second part of the study the daily model will be re-run, but imposing a daily fluctuating flow pattern on the Delta inflow. This two-stage approach will distinguish between the impacts of modeling Delta regulations at a daily time scale to the impacts due to the varying daily flow pattern. A technical report of this evaluation will be published.

At this time DWR does not anticipate further extension of the daily-time step model or the introduction of routing into CalSim-II.

4.3.4.14. Version Control

Good quality control is essential given the complexity of CalSim-II, the enormous data requirements and the number of model developers. Good quality control is a key component to model credibility. Without it the accuracy or reliability of CalSim-II could quickly degenerate. The Strategic Review (p37 & 58) makes detailed recommendations relating to quality control. It cannot be achieved solely through software innovations. Protocols for data management and model development need to be written, published and adhered to.

Quality control needs to start with the central storing and sharing of data and the implementation of a version control system. This version control system should at a minimum:

- Keep track of model changes
- Facilitate the storage of metadata regarding those changes
- Allow any previous version of the model to be recovered

- Allow multiple developers to work simultaneously
- Alert model users to model changes

DWR and Reclamation have implemented a version control system for CalSim-II's text-based input files. The system allows model users web-based access to a central database. Model studies can be downloaded from the database, changes made locally to the model, and the revised data input stored back in the central location. The system has not been fully adopted, due in part to the lack of in-place model development/model management protocols. The current text-based version control system will be replaced by an analogous version-control feature with the release of the nexe version of CalSim (v2.0) that is centered on a relational database. DWR and Reclamation agree that it is a high priority to develop enterprise database capabilities for the next version of CalSim (v2.0), so that central data management and version control can be implemented.

4.3.4.15. Water Quality

DWR is currently working with MWD to develop a water quality module for CalSim. The first-phase of the project would permit the user to specify inflow concentrations, and concentrations for agricultural and urban return flows for various conservative constituents. CalSim would calculate the resulting water quality throughout the network using constituent mass balance. Water quality calculations would be post-processed at the end of each time-step. A second phase of development would allow the model user to specify water quality targets as drivers in the optimization procedure.

4.3.4.16. Weights

The objective function weights establish the priority for releasing water from storage and making deliveries to different parts of the network. DWR and Reclamation accept that the process of weight setting is as much an art as a science. Currently the creation of a successful set of weights requires a sophisticated model user or a very patient one that is willing to submit to a time consuming trial and error process. A systematic and standardized approach is needed to generate weights, once the user has defined relative priorities (Strategic Review, p24). The acceptability of CalSim-II results and ease of model use are subject to some debate and concern, partly due to the current difficulties in weight setting.

DWR and Reclamation support the idea of research into a method of automatically assigning values to individual weights to represent the underlying water right-based allocation rules, contractual and institutional requirements, regulatory policy layers and operating rules simulated in CalSim-II.

4.3.5. Administrative Issues

4.3.5.1. Resources

DWR and Reclamation will explore and work with other public agencies; at local, regional, state or federal level, to seek needed resources to continue the development work proposed in this response plan.

4.3.5.2. Model Management

DWR and Reclamation will also seek new opportunities and avenues, both private and public, to broaden the management base for the existing and future model developments. Currently there is an interagency team coordinating this effort.

4.3.5.3. Peer Review

DWR and Reclamation believe that peer review enhances the acceptability of the modeling tool. The agencies may suggest peer reviews of modeling components it deems necessary.

4.3.5.4. Public Involvement

DWR and Reclamation will work with all interested parties, both public and private, to seek technical input in developing and enhancing the current and future modeling components.

4.3.5.5. Sustainability

The proposed Model Management Team (DWR, Reclamation and others) will work to develop a strategy in this important area.

4.3.5.6. Training and Education

The agencies modelers will continue to support, to the extent resources permit, to broaden the model users' base for appropriate use of models. The Proposed Model Management Team may also be charged with this responsibility.

4.4. Model Testing

4.4.1. Calibration and Validation

Model calibration is the process of fine-tuning the value of various model parameters, so that model results match the observed data. Validation is the subsequent testing of the model against data that has not been used in the calibration to obtain an independent assessment of the model's accuracy.

The need for testing, calibration and validation of CalSim-II is one of the most controversial issues raised in the Strategic Review. Some of the peer review panel recommended that further validation of the model is required through the comparison of model results to recent historical data. However some in the modeling community express their doubts on the usefulness of such a comparison (CalSim-II in California's Water Community – Musing on a Model, p158). The Strategic Review (p129) notes that for the Murray-Darling Basin model, validation is considered to be less important. The Murray-Darling Basin model is calibrated using a long period of data. In contrast validation is carried out using only two to three years of data.

In discussing the merits of calibration it is important to distinguish between physical parameters that remain essentially constant (e.g. stream-bed conductance), and behavioral parameters that may change and adapt (e.g. reservoir operating policy). Water use parameters such as irrigation efficiency may fall somewhere in between these two extremes. Where possible the value of parameters should be determined from direct observation. This may not be possible for some parameters such as regional scale reuse of water.

DWR and Reclamation believe that model calibration to determine the value of physical parameters, and parameters such as irrigation efficiency, is a valuable exercise, and benefits model accuracy and model credibility. However, DWR and Reclamation suggest that a more reasonable approach to defining behavioral parameters is through discussions with system operators to define *current* operational policy or rules. California's water system, especially with regard to the Delta, has undergone many changes in the 1990s (Delta Water Quality Control Plan, CalFed, ESA actions, CVPIA (b)(2), Environmental Water Account) so that calibration to historical practice has limited value. It would appear more reasonable to define operating rules in conversations with operators and subsequently use a recent wet, normal and dry year in a validation exercise.

The debate on calibration stems partly from a misunderstanding of the hydrology development. The CalSim-II hydrology is tied to historical stream gage data. The following points explain what calibration has been undertaken for the Sacramento Valley:

- The accretions and depletions between the project reservoirs and the Delta ***are*** calibration terms. They have been determined so that at a historical level CalSim-II will exactly match historical gage data if reservoir releases are fixed at their historical level and groundwater pumping and stream-aquifer interaction are fixed at their assumed historical values.
- Calibration of groundwater use has not been carried-out due to the lack of historical data.
- The stream-aquifer model in CalSim-II is calibrated to the more sophisticated Central Valley Groundwater Surface Water Model (CVGSM).
- The CalSim-II hydrology is calibrated to net consumptive use rather than stream diversions and return flows. CalSim-II may therefore not simulate well diversions to particular irrigation districts.
- The hydrology adjustment to account for the impact of land-use change on rainfall-runoff has not been calibrated or validated.
- Calibration or validation of district-scale diversions in CalSim-II cannot be undertaken without increasing the resolution of the model.

DWR and Reclamation recommend the following approach to CalSim-II calibration and validation:

- DWR and Reclamation modeling staff continue to work with project operators to define operating rules that correctly capture current (rather than historical) operational policies.
- Following re-calibration of CVGSM[1], the CalSim-II groundwater model is refined and re-calibrated.
- DWR and Reclamation develop methods to validate assumptions regarding land use change impacts on rainfall-runoff.

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[1] Major revisions to the underlying IGSM software and the input data sets to CVGSM have been made by DWR since the development and calibration of the CalSim-II groundwater module.

- DWR and Reclamation work with local irrigation districts and their consultants to refine the spatial scale of CalSim-II and calibrate/validate local projects operations through comparison of model output with historical data,
- Modeling groundwater pumping is modified to a land-use based approach. DWR has identified through land use surveys areas that are dependent on groundwater, areas that rely on surface water and areas that use groundwater as a contingent supply. The spatial resolution of CalSim-II should be refined to distinguish between these three land types.

After the completion of the above, CalSim-II should undergo a limited validation exercise using different recent year types.

Validation of local project operations has been shown to work well with the recent model enhancements to the San Joaquin Valley. Working with local districts has resulted in successfully calibrated hydrologic parameters so that CalSim-II has matched recent historical storage and flow data.

4.4.2. Sensitivity Analysis

The primary goal of CalSim-II sensitivity analysis is three-fold: (1) to verify if the key model input parameters are working properly within their reasonable range of variations; (2) to determine the impact of each parameter on selected model results; and (3) to set up priorities for potential refinements of model input parameters. Some of the parameters being evaluated are: SWP demands, target carryover storages, reservoir inflows, agricultural and urban water use, water use efficiencies, Delta water quality requirements etc. This sensitivity analysis had been undertaken by DWR and will be coordinated with Reclamation.

4.4.3. Uncertainty Analysis

Uncertainty analysis uses probabilistic descriptions of model inputs to derive probability distributions of model outputs and system performance indices (Strategic Review, p73). CalSim-II users need not only stand alone for absolute model results but also the degree of confidence they can place them. For example, what is the 95% confidence limit on the exceedence curve of project exports from the Delta? Hydrologic uncertainty is expressed through the use of a 73-year time series. There is currently no measure of data input uncertainty. Appendix H of the Strategic Review focuses on ways to identify and quantify uncertainty.

DWR and Reclamation agree that a method of implementing uncertainty analysis for CalSim-II needs to be defined. One approach is to simulate historical operations and use the statistics of goodness of fit to identify the uncertainty. An alternate approach is to identify plausible ranges of input parameters and to repeat model runs using high and low values of complimentary parameters (e.g. low efficiency in conjunction with high demands). This approach is more akin to the multiple future scenarios adopted by the California Water Plan Update.

4.4.4. CalSim-II Historical Operations Study

The primary purpose of the *CalSim-II Simulation of Historical SWP/CVP Operations Study* (DWR, 2003) was to evaluate the ability of CalSim-II to represent CVP and SWP operations, in general, and the delivery capability of the projects, in particular, when compared with a recent historical 24-year period. The following paragraphs discuss issues regarding this study raised in the Strategic Review.

4.4.4.1. <u>Overestimation of Project Deliveries (Strategic Review, p68)</u>

Comments in the Appendix E of the Strategic Report suggest that CalSim-II Historical Operations Study overestimates Project deliveries. The reviewers observe that CVP deliveries in the validation study are higher than historic; and the SWP deliveries taken from a model study conducted at 2001 level of development, are higher than the average of the last ten years. We do not believe this will be the case when compared with appropriate studies.

The Historical Operations Study was designed to simulate historical deliveries to evaluate how well other components of the system (such as reservoir storage, river flows, Delta outflow) compare with historical values. In this study, a simplistic demand assumption was made for the CVP. For each year of the simulation, CVP demands were fixed at the contractual amounts for north and south-of-delta contractors. It appears this assumption is the main reason for the overestimation of CVP deliveries. The historical data show that for most years during the study period of 1975-1998, especially during 1980s and early 1990s, CVP contractors received 100 percent of what was requested. If the CVP demand assumption could be refined for each year of the historical simulation, then, of course, the CVP overestimation is significantly reduced.

The reviewers observe the SWP deliveries also appear overestimated. This observation is not based upon the Historical Operations Study because the SWP demands in that study are artificially set at the values for historical deliveries during non-dry years when contractors received 100 percent of what was requested. The comment is based on comparing actual average annual deliveries for the last 10 years (2385 taf/yr) with the modeled 73-year average annual deliveries (3090 taf/yr) from a study conducted at 2001 Level of Development, based on current entitlement request. Note that this study was conducted for a different purpose for use in the *SWP Delivery Reliability Report, 2003*. DWR does not believe 2001 level study overestimates SWP deliveries. For dry periods, the results are very close to historical because the deliveries are limited by supply. The modeled average annual south-of-delta deliveries for the recent drought of 1987-1992 compare well with the actual values. The average annual values for SWP deliveries during this period are 1,930 taf/yr for the 2001 level study and 2,030 taf/yr historical. Similarly, the average south-of-Delta CVP deliveries are 2,340 taf/yr for 2001 level study and 2,320 taf/yr historical. In the wetter years, the demand (2001 level) is higher than the historical demand, so estimated deliveries are higher than the historical amounts.

When long term deliveries are compared among appropriate studies, the average annual values for SWP during the 23 year period are 1810 taf/yr for the Historical Operations Study and 1790 taf/yr actual historical deliveries for the same period. Similarly, the average south-of-Delta CVP deliveries are 2650 taf/yr for Historical Operations Study and 2490 taf/yr actual historical.

4.4.4.2. Allocation to Project Contractors (Strategic Review, p68)

Real-time allocation rules are moving targets that are year-specific and are based on entitlement requests, hydrology forecasts, initial storage conditions (both north and south of the Delta), and many other operational considerations. As such, allocation rules are very closely tied to each historical year's operation, and are not easily amenable to general mathematical formulations under a wide range of hydrologic conditions for use in the CalSim-II modeling studies. Knowing this, DWR does agree in general with the reviewers' observation that current allocation rules in the model tend to deliver water more uniformly over the dry period. Current allocation rules in CalSim-II have been designed to operate the system at a fixed level of development, present or future, which tend to maximize long-term deliveries while protecting the average annual deliveries during the historical dry periods of 1987-1992 and 1928-1934. This rule reduces the potential variability of deliveries from year to year. During the dry period of 1987-1992, more water was delivered by the SWP and the CVP during the first years of the drought and less during the latter part when compared to the delivery values of the Historical Operations Study. Although CalSim-II does not capture the potential variability of deliveries during dry periods, the simulations are useful for quantifying the total amount of deliveries over dry periods and providing information for more detailed analyses designed to address this variability. At this time, DWR will continue with the method currently used in CalSim-II for allocating water.

4.4.4.3. San Luis Reservoir Operations (Strategic Review, p69)

DWR acknowledges the reviewer's statement that San Luis Reservoir storage in the Historical Operations Study is consistently underestimated during the 1987 1992 drought when compared to the historically observed storage and that this can significantly effect the results for the pattern of flow in the Delta, opportunities for wheeling and pumping under Article 21, and accounting under the Coordinated Operations Agreement. It is also acknowledged that users of CalSim-II output need to be confident that the rules adopted by the model for determining how water is moved from north of the Delta to south of the Delta reflect the way San Luis Reservoir will be operated in the future.

DWR and Reclamation agree this component of the model merits additional review and plan to review CalSim-II's operation criteria for San Luis Reservoir with project operators and stakeholders.

4.4.5. Comparative vs. Absolute Predictions

CalSim-II and its predecessor models can be used in two ways. The first is in the comparative mode and the other is in the absolute mode. The comparative mode consists of comparing two model runs: one that contains a proposed action and one that does not. Differences in certain factors, such as deliveries or reservoir storage levels, are analyzed to determine the effect of the proposed action. In the absolute mode, the results of one model run, such as the amount of delivery or reservoir levels, are analyzed directly.

Traditionally both DWR and Reclamation have assumed that model assumptions are less significant in a comparative study than an absolute study. All of the assumptions are the same for both the "with-action" and "without-action" model runs, except the action itself, and the focus of the analysis is the differences in the results. The Strategic Review (p9), however, suggests that the assumed relative accuracy of a comparative analysis may be incorrect as:

"…*it relies on the assumption that the model errors which render an absolute forecast unreliable are sufficiently independent of, or orthogonal to, the change being modeled that they do not similarly affect the forecast of change in outcome; they mostly cancel out*."

CalSim-II and its predecessors DWRSIM, PROSIM, and SANJASM were originally conceived for comparative analysis. However, for endangered species consultation, biological assessments, facility re-licensing efforts under FERC, or local planning efforts by project contractors and local agencies, absolute values of delivery reliability or other performance measures are required. DWR and Reclamation recognize the requirement of CalSim-II to provide absolute predictions, and consequently the need for further work in refining model inputs and quantifying the likely range of model error. Relying on analysis of long periods (anywhere from a few years to the period of record) through calculation of statistical parameters and development of exceedence data may be useful for absolute predictions. Reliance on individual monthly values or yearly averages is not recommended.

The relative accuracy of a comparative analysis can be demonstrated through sensitivity analysis. Sensitivity to model inputs can be compared between a stand-alone study and a comparative analysis. In the comparative sensitivity analysis, a unit change of input to both the “with” and “without” project model, results in a change in the difference in the model outputs.

CalSim-II is constantly improving. DWR and Reclamation will consider, through discussions with stakeholders, the relative priorities of (1) refining the current model to improve its accuracy, and (2) quantifying the level of accuracy of the current CalSim-II model.

5. Development Priorities

Table 2 summarizes current CalSim/CalSim-II development projects and recommends priorities for future development. These are categorized according to immediate needs, short-term priorities, and long-term priorities. The time frame for the short and long-term priorities is January 2007 and January 2011, respectively. Comments and references in Table 1 can be matched (in general) with those in Table 2.

6. Summary and Conclusions

6.1. Summary

6.1.1. Model Scope

The Strategic Review identified many areas in which the scope of CalSim-II could be extended to support a wider range of planning activities. In its current form it is predominantly a model of the CVP-SWP system. The coarse spatial resolution of the model and the limited integration of groundwater limit its usefulness in other planning forums. Nonetheless DWR and Reclamation believe that CalSim-II is an adequate model for planning studies for new storage and conveyance facilities in the CVP & SWP systems.

DWR and Reclamation support further development of CalSim-II to broaden its applicability to California water planning issues other than those relating to the CVP-SWP. DWR and Reclamation intend to work with stakeholders to produce a model strategy for future model development. In the near-term, DWR and Reclamation believe that the geographical and conceptual extension of CalSim-II to non-project areas and issues should be secondary to a technical audit/peer review of the existing model data input and logic, and completion of application documentation.

Future model extension should be modular. A more complete groundwater model for the Sacramento and San Joaquin valleys is an essential component. Other important modules that should be added include:

1) Water transfers
2) Groundwater banking, and conjunctive use
3) Water conservation options
4) Water quality
5) Economic drivers

Consideration should also be given to extending land use based demands to the west side of the San Joaquin Valley and to areas in the Tulare Basin served by the two projects.

DWR is evaluating the use of CalSim-II to analyze a broad range of future scenarios for the California Water Plan Update. DWR will examine ways to streamline the development of alternate water supply and demand input data. DWR and Reclamation will also examine ways to better integrate CalSim-II with the Department's other planning models (CVGSM, CALAG, LCPSIM) that would benefit both agencies.

6.1.2. Data and Documentation

Model credibility is viewed as the most immediate concern. Unless the credibility of CalSim-II stays above a certain threshold, the continued development and use of the model will be threatened. The issue of credibility stems partly from the complex representation of California's water system, exasperated by incomplete documentation. It also stems from the limited efforts to demonstrate that CalSim-II's water accounting is unbiased and reasonably accurate. Many of the data concerns relate to the input hydrology. Priorities for the two agencies are:

1) Documentation of the CalSim-II's conceptual model and associated data inputs
2) Overhaul of the CalSim-II hydrology, with the development of updated hydrologic inputs supported by calibration and or validation
3) Integration of CalSim-II and CVGSM2 (or alternative) system representation and data set
4) Extension of hydrologic data to 2002 or beyond
5) Validation of CalSim-II using different year types
6) Uncertainty analysis

6.1.3. Software

Improvements to the CalSim software should focus on the release of the next version of CalSim (v2.0). This represents a major restructuring of the model, with the replacement of text input files with a relational database. This will provide the functionality to implement many of the Strategic Review recommendations: modularity, version control, and documentation (metadata). The database will allow users to quickly query constraint sets and decision variables, and more easily follow model coding logic. Elimination of the FORTRAN compiler and the use of a public domain solver will make the software more accessible. Other important software development goals are:

1) Development of a GUI for construction of reservoir river-basin topology and the input and output of data
2) Creation of a common post-processing utility (using third-party tools such as Micosoft Excel) that streamlines the comparison of model results across model runs
3) Update and expand the CalSim user's manual and provide centralized support to CalSim/CalSim-II users
4) Reduce model run times by implementing better data transfer efficiency, increased modularity, and a more efficient solver
5) Develop a stripped-down CalSim-II for training of new users
6) Develop and automated procedure for weight setting
7) Develop multi-period optimization capabilities

6.1.4. Long-term Development

Models take time to develop. Substantial thought should be given to the problems and type of analysis that CalSim will have to address in the next five to ten years, and the likely available resources within DWR and Reclamation. DWR and Reclamation will seek involvement from local agencies in model development. With modeling needs clearly defined, a strategy should then be devised for how to go from the current state of the model to the desired state of the model within the given timeframe.

6.2. Conclusions

The following remarks are extracted from the CalSim-II peer review panel

"A unique aspect of CALSIM II is the high degree of cooperation between federal (i.e. U.S. Bureau of Reclamation) and State (i.e. California Department of Water Resources) interests in its development. This kind of cooperation is rare, and in fact this may be the only such example of such coordination for a system of this scale and complexity…..CALSIM II can provide a showcase for other states as to what can be accomplished with Federal and state cooperation for river basin management." (Strategic Review, p18):

"We believe the use of an optimization engine for simulating the hydrology and for making allocation decisions is an appropriate approach and is in fact the approach many serious efforts of this kind are using." (Strategic Review, p2)

"…CALSIM II represents a state-of-the-art modeling system that is similar in general concept, while differing in specific details, to other data-driven river basin modeling systems such as ARSP, MODSIM, OASIS, REALM, RiverWare, and WEAP." (Strategic Review, p4)

DWR and Reclamation believe that CalSim-II is an adequate model for planning studies for new storage and conveyance facilities in the CVP & SWP systems. For certain applications of CalSim-II as described in section 4.4.5, absolute values of CalSim-II results are required as projected estimates of future system performance. For such applications of CalSim-II, full discussion of all pertinent assumptions and careful examination of input data must accompany presentation of CalSim-II results. Many enhancements described in this Response Plan, when properly implemented, will greatly improve the performance of CalSim-II, thereby expanding the applicable scope of the model and enhancing the level of public acceptance. Sustained effort will be required to accomplish the planned enhancements. Periodic review and updates of the planned enhancements will also be part of this sustained effort.

APPENDIXES

Appendix A. Representation of Groundwater Pumping

Modeling of Groundwater Resources

In CalSim-II, groundwater in the Sacramento Valley is used to meet both agricultural and urban demand. The volume of groundwater pumping varies according to the availability of surface water, and spring precipitation. In modeling groundwater, the developers of CalSim-II had a choice: (1) to restrict the volume of groundwater pumping in drier years to, for example, an estimate of the installed pumping capacity for a particular sub-basin; or (2) to assume groundwater pumping continues until demand is fully met. In either case, the impact of groundwater extraction can be measured by the impact on groundwater storage of each sub-basin, which is explicitly modeled in CalSim-II. Average annual groundwater pumping over and above the natural and artificial recharge will result in depletion of the basin. Once a groundwater basin is fully depleted, CalSim-II will no longer run. Model developers selected option (2) above, which gave rise to the concern of unlimited groundwater pumping voiced by the peer review. It is important to note, however, that CalSim-II does not include local ground water inventories. Currently the multiple-cell approach mimics the CVGSM model, which in itself is an "approximation" of built-in inventories (based on the historical calibration).

CalSim-II attempts to mimic farmers pumping decisions over the recent historical period. Groundwater extraction in CalSim-II is limited in several ways:

- The total of stream diversions and groundwater pumping must be less than the land use based demand. This demand is calculated from an assumed cropping pattern and monthly crop evapotranspiration, and takes into account the monthly and annually varying precipitation.
- The assumed cropping pattern used for CalSim-II is based on an agricultural economic production model that is calibrated to recent observed water use and cropped acreage. As such, CalSim-II implicitly accounts for the cost of groundwater pumping, which limits farmer's willingness to pump water.
- For areas that have access to both surface water and groundwater, groundwater is the secondary or contingent resource. Groundwater pumping occurs only after the model has tried to maximize service water deliveries given the various operational constraints (minimum instream flows, Delta water quality requirements, minimum reservoir levels and reservoir carryover storage targets).
- Groundwater pumping may only be used to satisfy the demands of overlying landowners. No groundwater is exported from the overlying watershed (except in the form of surface water return flow or tailwater that results from irrigation using groundwater).

The above bulleted items are discussed in more detail in the following sections.

Land Use Based Demands

Demands in the Sacramento River Basin (including the Feather and American River basins) and Delta are determined based on land use and vary by month and year according to hydrologic conditions. Land use-based demands are calculated using DWR's Consumptive Use

(CU) model. The CU model simulates soil moisture conditions for 13 different crop types over the historical period. Irrigation demand is triggered when soil moisture falls below a specified minimum. The CU model calculates the crop consumptive use of applied water. The consumptive use is subsequently multiplied by water use efficiency factors to obtain a regional water requirement to be met from stream diversions or groundwater pumping. Agricultural demands in the Delta are represented more simply as an overall mass balance between precipitation and crop evapotranspiration.

Central Valley Production Model

The Central Valley Production Model (CVPM) predicts cropping patterns, land use, and water use within the Central Valley by considering land availability, water availability and cost, irrigation technology, market conditions, and production costs. CVPM was used in the California Water Plan Update (Bulletin 160-98) to forecast future agricultural acreage. CVPM has recently been updated and extended into a statewide model, known as CALAG.

CVPM is a regional model of irrigated agricultural production and economics that simulates the decisions of agricultural producers (farmers) in the Central Valley. The model assumes that farmers maximize profit subject to resource, technical, and market constraints. Farmers sell and buy in competitive markets, and no one farmer can affect or control the price of any commodity. To obtain a market solution, the model's objective function maximizes the sum of producers' surplus (net income) and consumers' surplus (net value of the agricultural products to consumers).

The model is calibrated using recent historical irrigated acreage, applied surface water and groundwater pumping for 21 sub-regions in the Central Valley. The model includes information on pumping depth and pumping costs.

Matching of Demands and Supply

Within the Sacramento Valley CalSim-II always meets the land use based demand.

Groundwater Pumping Logic

In the Sacramento Valley demand is met by a mix of surface water and ground water. Farmers and urban municipalities may have access to either one or both of these supplies. In CalSim-II a minimum groundwater pumping is specified to represent those demands that only have access to groundwater. The CalSim-II code is written so that demands are first met by groundwater pumping, up to the minimum specified volume. It is subsequently met by surface water diversions up to the contract amount for project demands and up to its availability for riparian demands. Any difference between demand and supply is finally met by additional pumping. No shortages occur. Minimum groundwater pumping volumes are based on water years 1981-1993 of the historical CVGSM run.

Groundwater Export

There are a total of seven basins that represent the Sacramento Valley floor north of the Delta. There is no export of groundwater from the sub-basin. Groundwater is pumped only to meet the demands within each sub-basin. The CalSim-II logic allows a certain percentage of pumped groundwater applied as irrigation to flow to the stream network as return flow.

Results from CalSim-II Historical Operations Study

DWR recently released a report describing the results of a CalSim-II Historical Operations Study. The purpose of the Historical Operations Study was to evaluate the ability of

CalSim-II to represent CVP and SWP operations, in general, and the delivery capability of the projects, in particular, through the simulation of recent historical conditions (water years 1975-1998). The following is an extract from that report.

> *Does CalSim-II overestimate the availability of surface water in the Delta by meeting Sacramento Valley in-basin use through excessive groundwater pumping?*
>
> *The mix of surface water and groundwater used by the model to meet Sacramento Valley consumptive demands depends primarily on project water allocation decisions and levels of minimum groundwater pumping that are specified in the model. Over the 24-year period average annual net groundwater extraction in CalSim-II as compare to estimates based on the Central Valley Groundwater Surface water Model (CVGSM) is lower by 378 taf. The average annual net stream inflow from groundwater in CalSim-II is 190 taf greater than estimated by the CVGSM for the same period. The combined affect of dynamically modeling groundwater operations in CalSim-II (pumping, recharge and stream-aquifer interaction) leads to 188 taf/yr less water being available to the Delta. For the 1987-92 period the combined effect results in 46 taf/yr additional water being available to the Delta.*

Thus the Historical Operations Study concludes that the current representation of groundwater in CalSim-II results, on average, in an underestimate of the water available at the Delta.

Appendix B. Current CalSim / CalSim-II Development Projects

CalSim Software

Version Control

Good quality control is essential given the complexity of CalSim-II, the huge data requirements and the number of model developers. Good quality control is essential to model credibility. Without it, the accuracy or reliability of CalSim-II could quickly degenerate. The Strategic Review (p37 & 58) makes detailed recommendations relating to quality control. It cannot be achieved solely through software innovations. Protocols for data management and model development need to be written, published and adhered to.

Quality control needs to start with the central storing and sharing of data and the implementation of a version control system. This version control system should at a minimum:

- Keep track of model changes
- Facilitate the storage of metadata regarding those changes
- Allow any previous version of the model to be recovered
- Allow multiple developers to work simultaneously
- Alert model users to model changes

DWR and Reclamation have implemented a version control system for CalSim-II's text-based input files. The system allows model users web-based access to a central database. Model studies can be downloaded from the database, changes made locally to the model, and the revised data input stored back in the central location. The system has not been fully adopted, due in part to the lack of in-place model development/model management protocols. The current text-based version control system will no longer work with the release of the next version of CalSim (v2.0) that is centered on a relational database. DWR and Reclamation agree that it is a high priority to develop enterprise database capabilities for the next version of CalSim (v2.0), so that central data management and version control can be implemented.

Geographically Referenced Network Schematic

DWR and Reclamation are working cooperatively to develop a GIS based geo-referenced schematic of CalSim-II which would allow a user to interactively query attributes (e.g., reservoir or channel physical characteristics or all references to a node or link in the WRESL files), and time series data.

Public Domain Solver

DWR is currently working with the LBL to investigate the possibility of replacing the current XA solver in CalSim with a public domain solver.

CalSim-II Applications

Geographical Expansion

Over the last four years DWR and Reclamation have worked to develop CalSim models for the mountain watersheds in the Sacramento Valley. Models for Stony Creek, Yuba River, Bear River, and Upper American River have been successfully developed. These models require a technical peer review before being integrated into CalSim-II. The Yuba River model is currently being reviewed by Yuba County Water Agency's consultants, and is expected to be an integral part of the next CalSim-II benchmark study release.

Global Climate Change

CalSim-II is being used by a joint DWR-Reclamation Climate Change Work Team to investigate impacts of climate change on California's water resources. Currently downscaled projections of future climates are being used to generate reservoir inflow time series for use in CalSim-II to investigate impacts on water allocation and Delta water quality. The work is an extension of previous studies conducted at UC Berkeley. Future work will focus on incorporating probabilistic risk analysis. Initial assessments focus on potential climate change impacts on SWP and CVP yield, carry-over reservoir storage, Delta outflow and compliance with Delta water quality standards.

East-Side San Joaquin Operations/Hydrology

The representation of the east-side of the San Joaquin Valley has been substantially revised. Modifications include:

- Use of land use based demands
- Refine spatial resolution
- Revised reservoir operational logic for local projects
- Revised accretions and depletions

This effort is currently being extended to the Delta east-side streams.

CalSim-II Modules

Daily Time Step Model

DWR has created a daily time-step CalSim Delta Model as part of the evaluation of the proposed In-Delta Storage Project. This model was used in conjunction with the CalSim-II monthly model. The entire system's operation was simulated for a one month period with the CalSim monthly model and then the information on inflows to the Delta and south-of-Delta delivery amounts were passed on to the Daily Delta Model. The Daily Delta Model was used to re-simulate the operations in the Delta and the export facilities.

The monthly CalSim-II model provides monthly flows for various Delta locations. However, the daily model requires daily flow data as its input. Thus, a disaggregating model, which was trained using historical observations, was used to generate the daily flows from the monthly flows. While the daily inflow hydrograph was patterned after the historically recorded inflow, the total volume of the inflow to the Delta provided by the monthly model was preserved. The results of the Daily Delta Model are provided to the monthly model as the initial conditions for the following month's simulation. The operation of the upstream reservoirs is re-simulated, and any gains or losses of water are reflected in Delta outflow and storage at San Luis Reservoir. The next month's simulation is then started with the modified end-of-month storage in San Luis Reservoir and the state of the Delta as simulated by the Daily Delta Model.

Since its use for evaluating the In-Delta storage Project, the daily model has been extended upstream to include the Sacramento Valley downstream of the major project reservoirs.

Water Quality Module

MWD is taking the lead to develop and implement a water quality mass- tracking algorithm in the CalSim-II model. The implementation will track water quality constituent mass through arcs and reservoirs with the assumptions that the constituent is conservative and that perfect and instantaneous mixing occurs over the time step. Linearization of the mass balance relationship, by using source concentrations from beginning of time step, may be necessary for efficient implementation in CalSim-II. Linkage of Delta flow-salinity results to the south-of-Delta water quality mass tracking will be included.

CalSim Allocation Module

The CalSim Allocation Module (CAM) was developed to help integrate the CalSim-II planning model with operational models used by the CVP and SWP. Specifically it was created to help operators:

- Define project reservoir carryover storage targets
- Define what hydrologic probabilities should be used in making projections
- Investigate how late the projects should make adjustments to annual allocations

CAM uses multi-period optimization to make annual allocation decisions based on imperfect hydrologic forecasts. By necessity this requires a much simpler representation of the system compared to CalSim-II. At the beginning of the contract year, CAM is run to define an initial annual allocation decision. The period of optimization is from the current month to the end of the September. The resulting allocation decision, based on maximizing deliveries for a given carryover storage target, is passed to the full CalSim-II model, which simulates in greater detail the response of the system for the current month. Updated forecasts and storage conditions from CalSim-II are subsequently passed back to CAM. CAM model is rerun to obtain an updated allocation. This process is continued until annual allocation decisions become firm, usually in the month of May.

On-going work for CAM includes the refinement of hydrologic forecasts, and developing better Delta required outflow projections.

San Joaquin River West-Side Drainage WQ Module

Reclamation is working with consultants and DWR to complete development of a water quality mass-balance module that maps source loads of electrical conductivity associated with the San Joaquin River irrigation activities to electrical conductivity conditions in the main stem of the San Joaquin River. The purpose of the module is to improve the CalSim-II salinity estimate at Vernalis through: (1) San Joaquin River westside flow disaggregation; (2) salt balance along the San Joaquin River main stem (nodes between Lander Avenue and Vernalis) by assigning EC values to the disaggregated flows.

CalSim Water Transfers Tool (Screening Model)

The Water Transfers Tool (WTT) currently being developed for DWR will be a separate, smaller application from CalSim-II but will incorporate the major hydrologic, SWP/CVP system, and operational features of the larger model. Changes in the land use-based diversion requirements included in the model -by Depletion Study Area (DSA)- will serve as a surrogate for a variety of fallowing, crop change, conservation, and groundwater substitution transfers. Stored water transfers will be simulated through a surrogate reservoir concept at the location of the transfer and limited to upstream storage capacity availability. The WTT will be developed through a layering approach to allow for a large number of transfers at varying priorities for purchase and conveyance.

Appendix C. Software Development Proposed Plan

The original CalSim 1.0 program was initially released to the public in 1999. Since that time, updates have been made to refine the original software and add capabilities as required by users. In that time the manner in which CalSim based modeling has been used has grown in terms of the number of users, the complexity of the regulatory environment needed to be simulated, and an increase in the scope and detail of the system required to be modeled. These and a number of other concerns led to the recognition that in order to achieve a robust and fully acceptable model of the current CalSim (v1.2) program required improvement.

The development of the next version of CalSim (v2.0) is intended to create a more robust modeling environment for the increasing number of users and complexity of system representation. These improvements fall under three categories of data management, a graphical user interface, and the solution controller.

Data Management

Proper data management is an essential component for applications relying on large amounts of data. The text-based structure of the current CalSim application is sufficient for small numbers of users. However, as the complexity of the model and number of users increases, the greater the chances are for mismanagement of data. Integration of a relational database management system for CalSim's data storage formalizes the collection of data into a state-of-the-art management tool. Version control, integrity of data (validity of data is still required on the user side), reduction of duplicated data, and ease of linking with a graphical user interface are all advantages of using a relational database system.

Client/server functionality of the database provides for a central repository of benchmarked and finalized projects. Users may connect as a client to the database server to send and receive updates. The client may keep a local copy of the database on their computer and update with the server as desired.

Incorporation of metadata into the relational database is a significant step forward in automated documentation. As data is entered or manipulated the author and date is automatically recorded. A text area is also available for user comments and documenting the source of the data. Protocols on what users should record in this field have been developed by the CalSim-II Review and Documentation Team.

A tool will be developed that will ease the adoption of the next version of CalSim (v2.0) by automating the transfer of existing text files into the database.

Graphical User Interface

With the incorporation of a relational database management system there needs to be a user interface for entering, manipulating and viewing the information. An integrated graphical user interface (GUI) is being developed for this purpose. All data required for running CalSim simulations is interfaced through this single menu-driven GUI using standard windows features.

A hierarchical visualization of the relation of Projects, Simulations, and Cycles is the main component of the GUI. Properties of these components are viewable/editable through a standard point-and-click window. WRESL and Lookup tables are viewable/editable through similar standard windows. Standard editing features such as searching and copy/paste will also be provided.

The next version of CalSim (v2.0) GUI controls the management of projects which encapsulate any number of simulations. User privileges defined in the database allow for management of projects and simulations by controlling who may modify such data.

Solution Controller

A JAVA based solution controller has replaced the current FORTRAN package. Adoption of object-oriented programming into the controller allows for more robust techniques. This increases not only the longevity of the management of source code but provides a simpler context for probable future modifications to the solution package.

Additional features of the new solution controller include the following:

- Elimination of the FORTRAN compiler. Reduces cost.
- Investigation of alternative MIP solvers. Potential cost reduction.
- Streamlining relationship of ‘projects’, ‘simulations’, and ‘cycles’.
- Embedded ‘cycles’. Replaces the Multi-Study Runner by allowing ‘cycles’ to contain other ‘cycles’.
- Introduction of ‘layers’. Collection of data (WRESL, tabular lookup, etc.) that allows for modularity of data across ‘projects’. Cycles may contain any number of ‘layers’. Layers are overlaid one on top of the other and may overwrite previously defined data. Protocols will be developed for sufficient need of using ‘layers’ (i.e. geographic subsystems, regulatory components, etc.).
- Iteration of a ‘cycle’. A single ‘cycle’ may iterate on its solution until convergence criteria is met.
- Increased use of DSS path names. Using the ‘cycle’ name in one of the DSS path names facilitates the use of embedded cycles and eliminates the need for the costly run-time transfer files.
- Pre/Post-MIP ‘state variables’. Some ‘state variables’ are functions of ‘decision variables’. These are evaluated after the MIP solver but remain on the current time step.
- Direct writing of ‘state variables’ to the results file. Eliminates the need to send unnecessary decision variables and constraints to the solver to get ‘state variables’ in the results file.
- Dynamic calculation of ‘decision variable’ weights. Increases ability to control the MIP for each ‘cycle’ and time step.

- Introduction of ‘watch variables’. Allows results from the simulation to be dynamically viewed while the simulation is running.
- Facilitation for an interactive schematic. Development of GIS or other tools is being investigated.
- Facilitation of multiple-period optimization. GUI-assistance in writing WRESL that will span multiple time periods

Appendix D. Documentation Proposed Plan

The most recent release of CalSim-II application documentation accompanied the September 30, 2002 benchmark. This literature is contained within the Benchmark Assumptions Document and Study Results, a summary of the simulation output. Criticisms to the documentation include a deficiency in: explaining how the model works, the underlying assumptions, limitations, and applicability to planning and management issues (Strategic Review, p 8). In addition, CalSim-II documentation is hampered by three factors: protocol has been mostly absent, maintenance is difficult and the knowledge of the vast SWP and CVP systems resides in many different individuals. Both DWR and Reclamation realize the importance of documenting information. However, more often than not, documentation has been placed at a lower priority or overlooked as an integral task to data and logic development or modification.

Despite the difficulties and challenges both agencies face to complete documentation of the CalSim-II application, a consorted effort has been initiated to remedy the deficiencies identified by both internal and external criticisms. DWR and Reclamation have proposed to develop a CalSim documentation management system. The purpose of the documentation management system is to

- Institute documentation protocol
- Provide a convenient method for documentation updates
- Flexible media products for users

This documentation system will become fully integrated within the next version of CalSim (v2.0) data management system and will be linked to the CalSim logic and data. The data management system will require a standardized set of documentation fields and meta data. Finally, the management system will be capable of generating a variety of media products with graphics, linking, indexing and searching options.

Documentation Management

The current documentation techniques are cumbersome for the CalSim-II modeling community to maintain. A variety of formats such as text documents, comments in the code, spreadsheets, supporting model reports, and PDFs are housed in several different locations. The formats and locations make it almost impossible to update all aspects of a modification with absolute certainty.

Therefore, a documentation management system is proposed that utilizes a database to organize and maintain the information. The system will be used as a “central-file” for all model documentation. The new system will track and maintain a documentation history similar to features in the next version of CalSim (v2.0) data management system. Existing documentation will also be rolled into the new management system.

The key features of the documentation management system include:

- Documentation linked to the code
- Tiered levels of detail
- New topics of documentation not yet covered
- Links to source documents (e.g. PDFs or spreadsheets)
- Documentation of state, initial, and decision variables
- Documentation of lookup tables
- Documentation of logic and system control files
- Data confidence rating
- Distinction between actual practice and implementation
- Flexible report templates
- Advanced query options
- Electronic, hard-copy and Help File applications

It is anticipated that the organized and centralized documentation management system will be the new standard for CalSim documentation procedures. Linkages between the documentation and the code will eliminate undocumented or overlooked topics. New documentation coverage will address deficiencies and multi levels of detail will support both the novice and expert. The document management system is also expected to be an integral and priority component of the CalSim work effort.

Appendix E. Surface Water Hydrology Enhancement Proposed Plan

The term hydrology development is used to describe: (1) the conceptual (node-link) model of the Central Valley, (2) the calculation of water supply and demand inputs and (3), water use parameters (efficiencies, losses, minimum groundwater pumping, etc.). Many of the methods used in the hydrology development were originally formulated in the 1960s and 1970s. This section proposes a major overhaul of the surface water hydrology, particularly for the Sacramento Valley, which provides approximately 80% of the inflow to the Delta.

The redevelopment of the surface water hydrology is to meet the following goals:

- Integrate the hydrology development with other statewide data collection and analysis efforts, in particular the land and water analysis carried-out by DWR's Division of Planning and Local Assistance (DPLA) regional offices
- Allow for spatial and temporal aggregation/disaggregation
- Provide a common approach for other agency planning models (CalSim-II, IGSM, CALAG)
- Easy to understand and implement
- Facilitate the use of CalSim-II to support other CalFed, DWR and Reclamation planning processes: e.g. Water Use Efficiency Program
- Refine estimate of Sacramento Valley 'in-basin use'
- Correct minor conceptual errors in existing methods

Both DWR and Reclamation agree on modifying and enhancing the hydrology development for CalSim-II. At this time, different proposals are being considered; but no agreement has yet been finalized (including the approaches discussed below).

Conceptual Model

Water supplies and demands are currently represented in CalSim-II in a very aggregate form. For example, in the Sacramento Valley floor water supplies (other than inflows from the surrounding foothills) and agricultural and urban demands are lumped into only seven Depletion Study Areas (DSAs). The typical representation for each DSA is shown in Figure 11-1. A single inflow arc typically represents total regional inflow from minor ungaged streams and direct runoff. This flow is an unimpaired inflow. Any irrigation demands associated with these minor streams are met by proxy by diversions from the principal stream running through the DSA (the Sacramento River, the Feather River and the American River). A single land use based demand is calculated for each DSA using DWR's Consumptive Use (CU) model[2]. This demand is subsequently disaggregated into project and non-project demands using a constant fraction or percentage. Project demands may be met from releases of stored water from project reservoirs, but are constrained by the annual project allocation/contract entitlement. Non-project demands

[2] The CU model estimates irrigation demands by simulating monthly soil moisture conditions in the root zone for 13 crop types.

are not constrained by contract, but are constrained by the availability of stream flow, unimpaired by project operations. Both project and non-project diversions are constrained by the land use based demand.

It is assumed that a certain percentage of demand must be met from groundwater pumping to represent areas that have no access to groundwater. Above a specified minimum pumping, demand is met from surface water supplies up to its availability or allocation. Supplemental groundwater pumping meets any unmet demand.

Land use based demands are at the resolution of the DSA. However, contract entitlements represented in CalSim-II are at a more disaggregated scale, typically at the level of the larger irrigation districts. To resolve this discrepancy in resolution, CalSim-II disaggregates demand by assuming it is proportional to the contract entitlement.

The aggregation of demand by DSA leads to assumptions about project and non-project water use that may not be entirely accurate.

- Project and non-project demands have identical efficiencies
- Project and non-project demands have the same monthly pattern of diversion requirements (implicitly the same cropping pattern)
- Project and non-project demands have similar dependency on groundwater (as represented by the assumed minimum groundwater pumping)

Non-project demands are predominantly located on the minor streams tributary to the Sacramento River. These supplies may be more restricted in dry years. The DSAs are currently not consistent with DPLA's proposed new Planning Areas used for land use planning and economic analysis. The boundaries of the DSAs make hydrologic mass balance calculations difficult in some areas (e.g. the Colusa Basin)

Spatial Representation

There is a proposal to replace the existing DSAs with new water management areas so that demand units are associated with their correct water supply sources. Demands would be distinguished according to:

- Source of water,
- Contract type,
- Cropping pattern, and
- Water use efficiency.

The proposed new water demand areas are shown in Figure 11-2. Both project and non-project demands may be present in one planning area. Different project demands in a single planning region may be differentiated according to their water source, type of contract (with the CVP, SWP or local project), type of use (M&I vs. agriculture), cropping pattern, and water use efficiency. However non-project demands within a planning region are represented as a single aggregated unit. This proposed refinement of CalSim-II's spatial resolution could lead to greater engagement of local irrigation districts and water agencies.

Water Use Efficiency

DWR's CU model calculates the irrigation water required to meet crop evapotranspiration while maintaining soil moisture above some minimum threshold. A 'basin efficiency' factor is subsequently used to calculate the water demand at a regional level. The basin efficiency factors are based on field measurements conducted by DWR during 1969-1974. These efficiencies were derived for use in DWRSIM (CalSim-II's predecessor). DWRSIM modeled groundwater as a net extraction from the aquifer, rather than explicitly modeling pumping and subsequent recharge from irrigation activities. The original basin efficiencies therefore had to be modified to account for losses from deep percolation. Use of a lumped efficiency factor, rather than explicitly representing losses at different scales, leads to assumptions and potential inaccuracies:

- Water use efficiencies are independent of the source of water, although most groundwater pumping is at farm/field level, and significant conveyance losses may be associated with stream diversions
- Project contractors and non-project diverters have identical water use efficiencies (conveyance losses, farm efficiencies, reuse, etc.)
- The project non-project demand split does not account for differences in water use efficiency so may be incorrect
- It is difficult to assess the impacts of on-farm and in-district water conservation measures due to the poor representation of efficiencies, losses and return flows
- The representation of demands in CalSim-II, CALAG/CVPM and CVGSM are difficult to reconcile since efficiencies and losses are represented in different ways
- CalSim-II demands are not related to applied water demands at the farm level and demands at the district level, although most of the available data is at these scales rather than at a regional level

It is also proposed to replace the existing representation of agricultural demand with an explicit representation of on-farm applied water demands, reuse (both intra-district and inter-district), conveyance losses, and operational spills. Different conveyance loss factors would be applied to the different contractors and non-project diverters according to their water source. The proposed approach is shown diagrammatically in Figure 11-3.

Rainfall-Runoff Modeling

CalSim-II uses the historical hydrology to represent the possible range of water supply conditions that could occur at a future point in time (level of development). This enables future water supply reliability to be expressed in probabilistic terms. DWR and Reclamation recognize that this approach poses several problems. The historical stream flow record is incomplete. Flow data, where it exists, is impaired by historical diversions and return flows. Lastly historical stream flows are affected by the stream-aquifer interaction, a process that CalSim-II models dynamically. The current hydrology development uses a 'depletion analysis' to estimate the historical and projected level flows. The aggregate stream inflow for each DSA is calculated as the closure term of a hydrologic mass balance. Subsequently, historical flows must be adjusted to account for the impact of land use change on runoff. While this approach has its advantages, there are also disadvantages:

- The need to define historical land use, and historical consumptive use resulting from irrigation
- The need to define historical groundwater pumping and recharge
- The need to define the historical stream-aquifer interaction
- The need to define historical water transfers (imports and exports) across the model boundary
- The absence of a good measure of the associated error (errors are encompassed in the closure term)

With increasing demands for details, the depletion analysis approach (while serving its original intent) is becoming more difficult to use, requiring a detailed knowledge of the basin. It is very time-consuming to develop new hydrologies for different levels of development or to extend the period of simulation. To model historical water use also imposes considerable constraints on modernizing the approach. For example, representing changes in rice irrigation requirements due to changes in planting dates, shorter-growing crop varieties, winter flooding for rice straw decomposition all have to be represented as phased changes over time rather than simply considering today's practices. Lastly, the current depletion analysis does not lend itself to the modular approach advocated by the Strategic Review (p21).

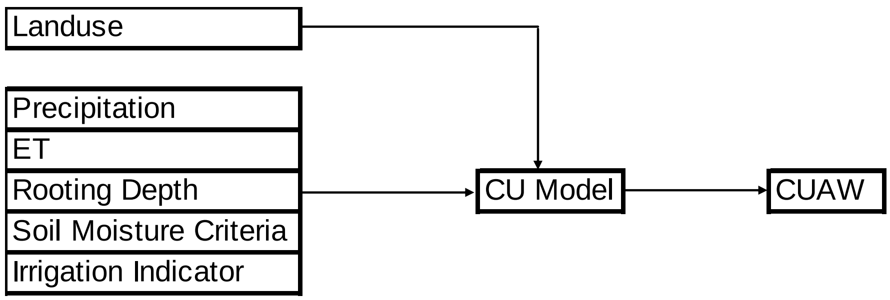
Under consideration is proposed work that a more modern and flexible rainfall-runoff approach to estimating local hydrology and rim inflows for use in CalSim-II would have considerable advantages. The rainfall-runoff approach has been successfully implemented for use in other planning models. The benefits of rainfall-runoff modeling include:

- Easier to field verify
- Easier to update hydrology for changing land use conditions (or climate conditions)
- Easier to document and sustain with personnel changes
- Easier for various model users and hydrologists to understand and use
- Easier for more groups of hydrologists (agencies and consultants) to contribute to model upgrades and refinements
- Easier to apply consistently across basins
- Provides a framework for keeping land use, water demand, surface hydrology, and groundwater hydrology assumptions consistent
- Provides consistency with CVGSM/IGSM (or alternative model) representation of groundwater hydrology
- Easier to change modeling time-step
- Easier to modify spatial coarseness
- Easier for state, regional, and local agencies to employ for a wider range of hydrologic, planning, and management studies (such as local water supply, flooding, and restoration problems)

Consumptive Use Model

The Consumptive Use (CU) model was originally developed by DWR to create input for the water resources planning model DWRSIM. Its role in CalSim-II is essentially unchanged. The CU model simulates monthly soil moisture conditions in the root zone using simple mass balance accounting. For a given land use, the model calculates:

- Monthly agricultural and outdoor urban water use (consumptive use of applied water)
- Monthly precipitation that is used consumptively through evapotranspiration.



The time series of CUAW is aggregated by DSA and multiplied by efficiency factors to obtain the land use based target demands used in CalSim-II. The consumptive use of precipitation on developed areas compared to pre-development is used to calculate the effects of land use change on runoff. These adjustments are required to estimate the local water supplies or accretions in CalSim-II.

A main limitation of the CU model is that it does not integrate soil moisture accounting with rainfall-runoff and deep percolation. The separate estimation of rainfall runoff, evapotranspiration and deep percolation in CalSim-II can lead to errors. One approach under consideration is:

- Replace CU model with a soil moisture accounting model (e.g., Sacramento Watershed Model framework, implemented by CA-NV RFC) that directly estimates runoff and deep percolation
- Structure new model so that it can be directly incorporated into IGSM or alternative model
- Integrate new model's current work on irrigation model development such as DPLA's CUP and SIMETAW

Modularity

The refinement of the CalSim-II spatial resolution should go hand-in-hand with implementation of the modular concept of modeling. For example, agricultural areas in the Sacramento and San Joaquin Valley could be represented as a black box with boundary flows linking the black box to the major stream and groundwater system. The boundary flows are:

- Diversion arc(s) from the stream network with associated monthly demands and monthly weights

- Return flow arc(s) to the stream network, with flow calculated as a piecewise linear function of the flow in the diversion arc
- A groundwater pumping arc, with flow calculated as a piecewise linear function of the flow in the diversion arc
- An inflow arc to the groundwater system representing recharge from deep percolation (given a fixed land use, flow in this arc could be constrained to a fixed time series)

Alternatively, a region may be represented in more detail, broken-down into constituent irrigation districts with arcs showing conveyance losses, reuse, and operational spills. This more detailed representation is required for defining the relationship between surface water deliveries, groundwater pumping and return flows. Once these relationships have been established, the detailed model can be switched to the 'black box' representation to simplify the CalSim-II model and reduce run-times. The more detailed model can be used for analyzing impacts of water conservation measures.

DWR is considering implementing this dual modular approach for a test area, such as the Feather River Basin, that has a very complex internal structure of diversions from different sources and reuse between irrigation districts.

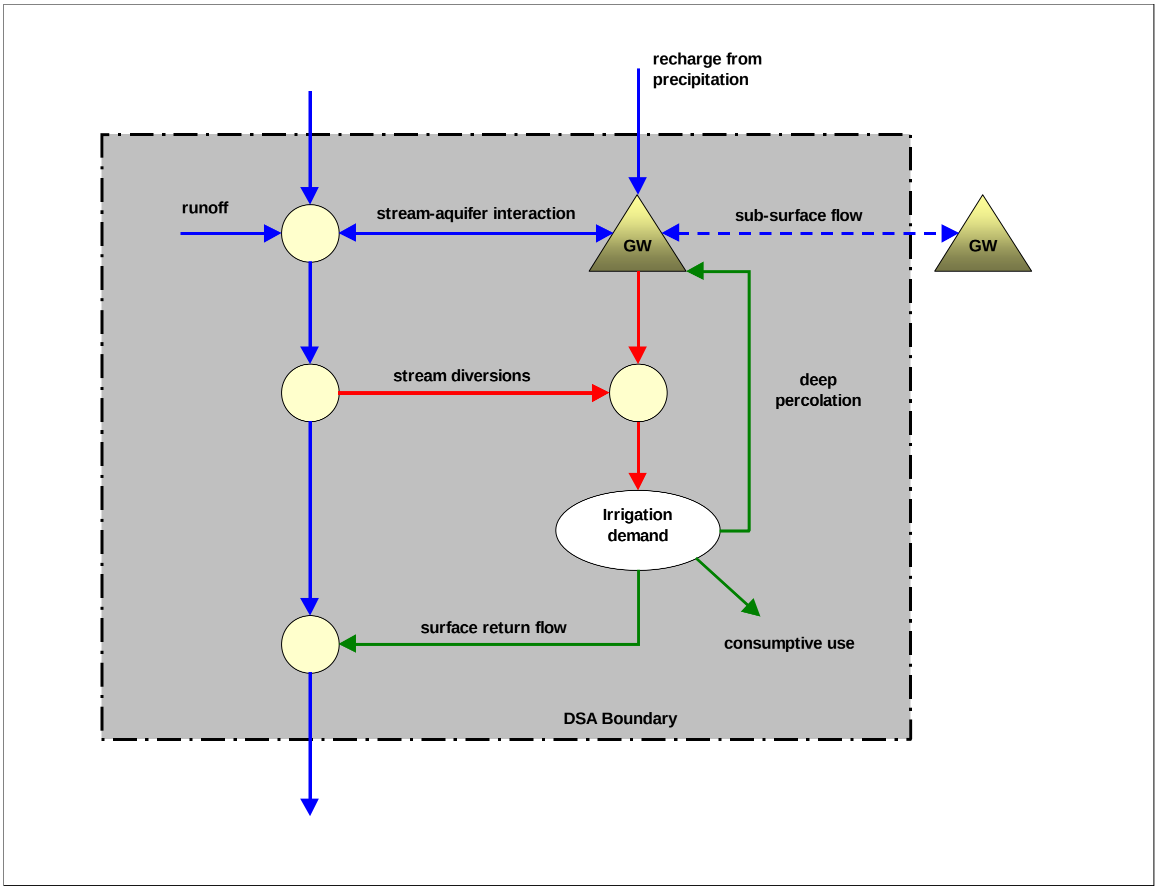


Figure E-1 Existing Conceptual Water Use Diagram

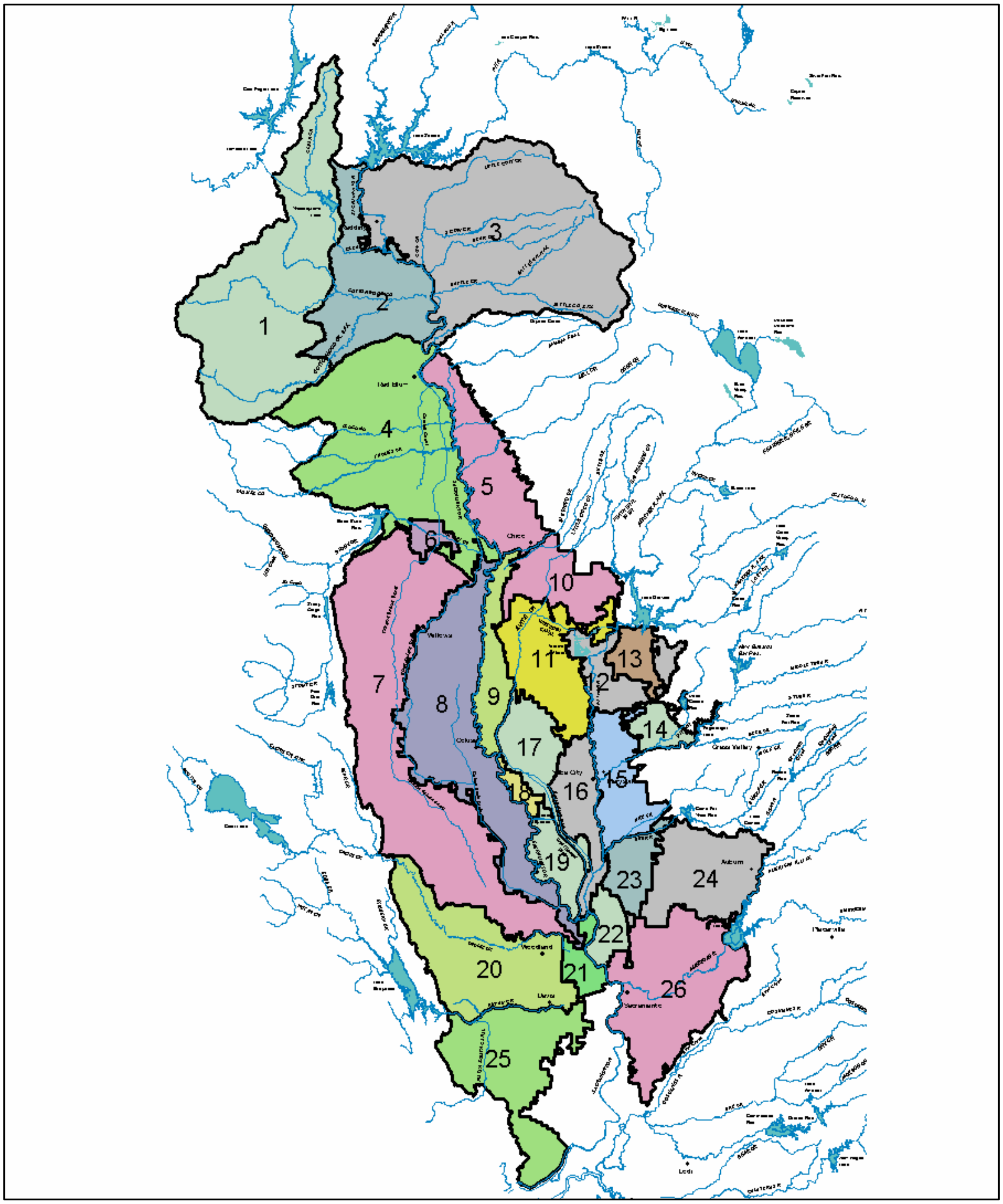


Figure E-2 Proposed New Water Management Areas

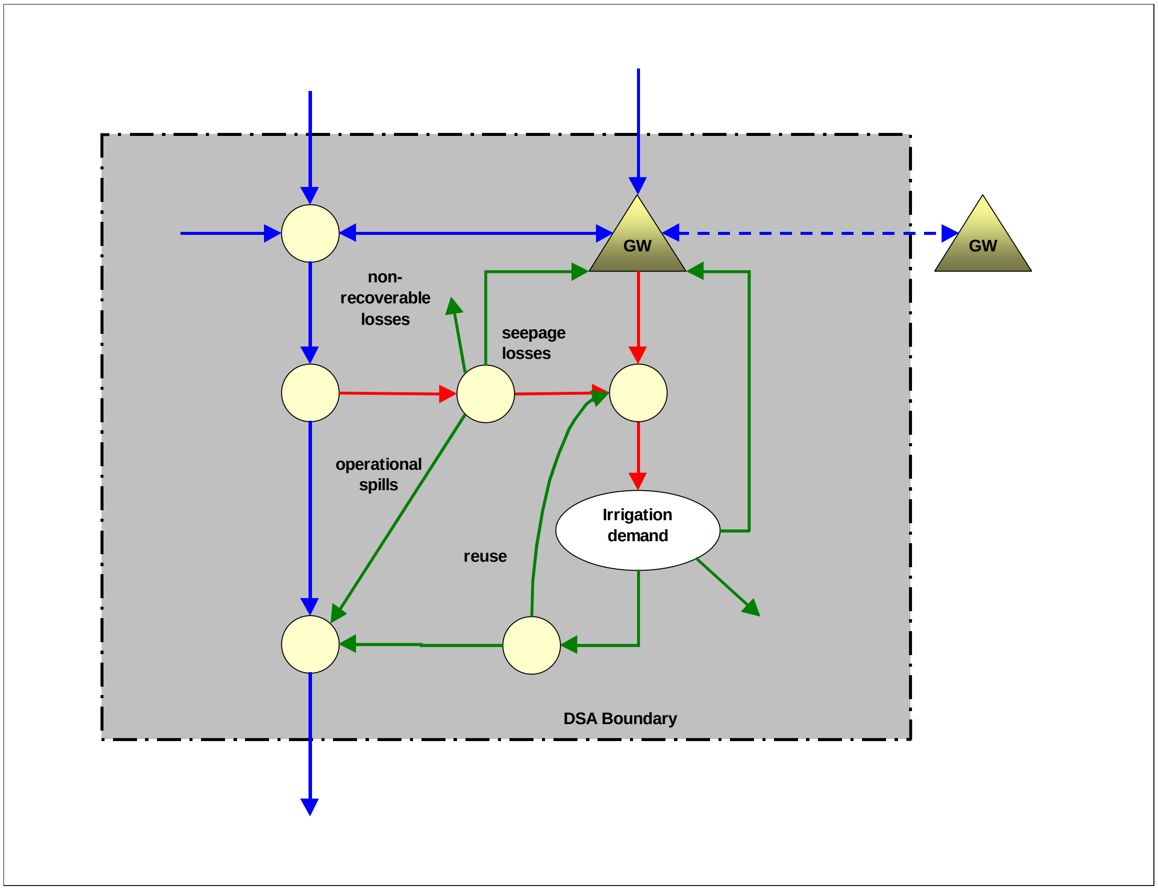


Figure E-3 Proposed Conceptual Water Use Diagram

Appendix F. Groundwater Modeling Proposed Plan

Current representation of groundwater (inventories and impacts) in CalSim-II is approximate and limited. Both DWR and Reclamation recognize the strong need to enhance the modeling of groundwater in CalSim-II and a more realistic impact of recharge and pumping on local ground water resources. One model under consideration is the Integrated Groundwater – Surface water Model IGSM2 (Figure 12-1) the latest version of which was developed and is supported by DWR. The application of IGSM2 to the Central Valley is called the Central Valley Groundwater – Surface water model CVGSM2 (Figure 12-2). However, other models will also be investigated, including how the model is used (e.g, directly, or mimicked through approximate methods such as response functions).

One approach for meeting such an objective is the coupling of CalSim-II and IGSM2/CVGSM2 (or alternative model or mimicked version) for hydrology development, ground water representation and assessment in future versions of CalSim-II. This new approach could be used calculating the hydrology input to CalSim-II, the accounting for surface water – ground water interaction, and the modeling of groundwater flow. The type of "linkage" between CalSim-II and CVGSM2 (or alternative) would depend on what hierarchical level of CalSim-II is being used. For example, at its simplest formulation CalSim-II as a screening model of the SWP/CVP system may use an emulation of CVGSM2 (or alternative) to account for the accretions and surface water – groundwater interaction (e.g, through the use of response functions that would be developed based on CVGSM2 or alternative model runs). At a different level, resolution at a planning area level may be sufficient. At another level, interactions at the finite element level of CVGSM2 may be important. This hierarchical approach of CalSim-II and the associated form of using CVGSM or alternative (direct, indirect, or by emulation) is still being investigated by DWR and Reclamation.

There are many benefits for linking CalSim-II with IGSM2 (or alternative):

- The hydrology at future levels of development would be integrated in the simulation and developed on-the-fly allowing for modifications to land use (especially during dry periods) and/or modifications for meeting demands from surface water and groundwater.
- The spatial resolution would be enhanced, and allow for GIS technologies for use in calculating water demands by element of CVGSM (or alternative), rather than DSA.
- The accretions calculations will be more physically based, and would eliminate the use of the CU model and the Depletion model and their limitations for the valley floor areas. Currently IGSM2 uses the NRCS (SCS) method for calculating rainfall/runoff components.
- There would be a marked theoretical improvement in modeling groundwater flow and the surface water - ground water interaction, and allow for carrying conjunctive use studies.
- The extent of the simulation areas would be extended to include Tulare Basin.

In modeling California's complex water resources, it is important that key elements reflecting hydrologic processes be accounted for either directly or indirectly in the model itself, its assumptions, or input. Key elements to consider in modeling surface hydrologic processes include: rainfall, snowfall, snowmelt, interception, retention, detention, infiltration, evaporation, surface runoff, return flows, artificial recharge, land and water use, water quality, and water rights. Key elements that need to be considered in modeling subsurface hydrologic processes include saturated flow, unsaturated flow in the vadose zone, ground water pumping, evapotranspiration, water quality, and water rights. The interaction between the two processes occurs through streams, rivers, canals, lakes, reservoirs, and land surface. The IGSM2 incorporates most of the processes listed. Other models exist also, but the focus of this section is to use IGSM2 as a surrogate model.

IGSM2 is a regional scale model developed by DWR for the simulation of groundwater elevations, surface flows and surface-subsurface flow interactions. It is a completely revamped version of its predecessor IGSM version 5.0. IGSM was originally developed by consultants for Reclamation, DWR and other agencies. The first major public release of IGSM was in 1991. The first public release of CVGSM was also in 1991. Since its 1991 version, IGSM has undergone various upgrades by different groups based on specific applications to numerous basins in California, Colorado, Wisconsin, and Florida. In January 2001, DWR began the development of IGSM2 that included an extensive review and revamp of the theory, simulation methodologies and the source code used in IGSM. Based on this work, IGSM2 Version 1.0 that utilized enhanced/modified theory and simulation techniques was made available to public in December 2002. IGSM2 Version 2.0 was released in December 2003.

IGSM2 simulates groundwater elevations in a multi-layer aquifer system and the flows among these layers. The depth-integrated conservation equation is solved for horizontal flows in each layer and an approximate method is utilized to compute vertical flows among layers. The Galerkin finite element method is used to solve the non-linear conservation equation for each aquifer layer. A mixture of confined and unconfined aquifer layers that are separated by semi-confining layers can be modeled. The changing aquifer conditions (confined to unconfined and vise versa) as well as subsidence, and effect of tile drains, injection and pumping wells can also be modeled.

Stream flows, lake storages, and their interaction with the aquifer system are also modeled in IGSM2. Stream flow simulation is similar to that used in MODFLOW 2000. Conservation equations for streams, lakes and aquifer system are solved simultaneously to compute the interaction among these components accurately.

The distribution of four land use types (agricultural with specified crops, urban, native and riparian vegetation) dictate the evapotranspiration, surface runoff and infiltration characteristics (calculated using the NRCS method) as well as the demand for agricultural and urban water supply. The infiltrated water is routed vertically through root and vadose zones to compute the recharge to the groundwater. Stream diversions and groundwater pumping can be specified and distributed to meet agricultural and urban water requirements, and also adjusted dynamically to balance supply and demands. DWR staff also provides technical support of IGSM2.

Hydrologic input to the CalSim-II model includes WY1922-1994 time series for reservoir inflows, local accretions, and projected land-use based demands. The land use based demands are using the Consumptive Use CU model, and local accretions and reservoir inflows are calculated using the Depletion Analysis approach. The CU model is a monthly soil moisture accounting model using known precipitation, crop and urban acreages, and crop soil moisture characteristics to calculate monthly demands (Diversion Requirements) by Depletion Study Area DSA. It calculates monthly demands for both historical (time-varying land use) conditions and projected (constant future land use) demands. Inflows into the reservoirs are calculated using the Depletion Analysis approach developed by both DWR and Reclamation. The procedure begins with measured historical outflows at gauged streams of a DSA which are unimpaired for historical conditions by adding back the historical calculated land-use based demands from the CU model, and re-impairing the flows by subtracting out the future level demands from the CU model. Local accretions are calculated using simple budget analysis, and the results are used as input to CalSim-II.

Local water supply computations (accretions) are currently pre-processed for CalSim-II. The CU model is used to calculate land-use based applied water demands at both historical and projected levels of development. A simple water budgeting approach by DSA then allows for calculating local water supplies (accretions).

The accounting of groundwater in CalSim-II (and its predecessor DWRSIM) has undergone an evolutionary process. In the past the Depletion Model was used to calculate the additional groundwater pumping (above historical) required at a future level of development, along with future recharge of the past-pumped water using simple specified rules. This implicitly also fixed the historical surface-ground water interaction at future levels of development. In the current CalSim-II for the Sacramento Valley, a multiple-cell MC approach was used (each DSA represented by one cell), allowing for the interaction between cells and streams. The MC approach used actually emulated CVGSM in a very simple form, but allowed for ground water elevation accounting, and the stream-aquifer interaction.

With IGSM2/CVGSM2 (or alternative) it is possible to enhance the hydrology input and the modeling of groundwater resources in CalSim-II, by eliminating the use of the CU model and the depletion analysis approach. DWR and Reclamation will investigate the different options of how best to achieve this objective.

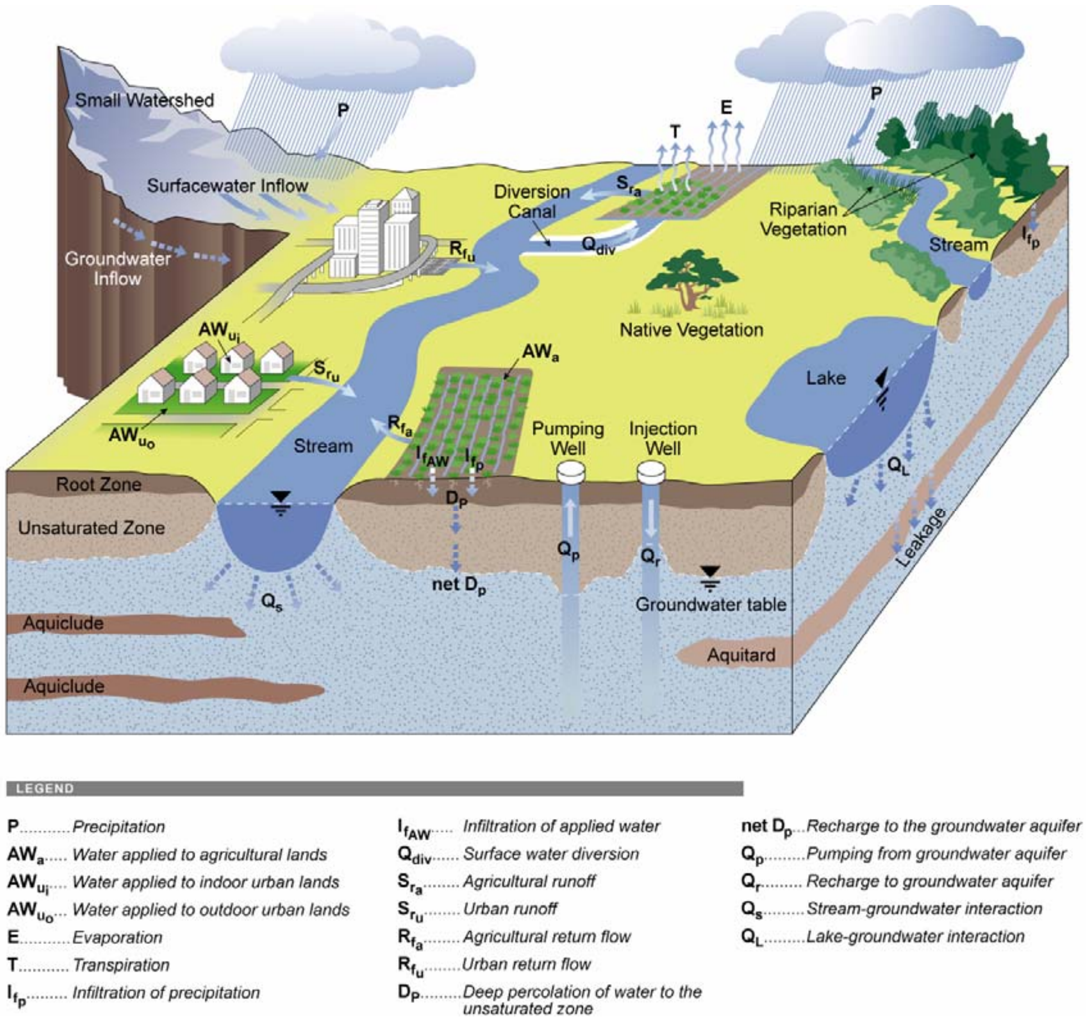


Figure F-1 Hydrologic Processes Modeled in IGSM2

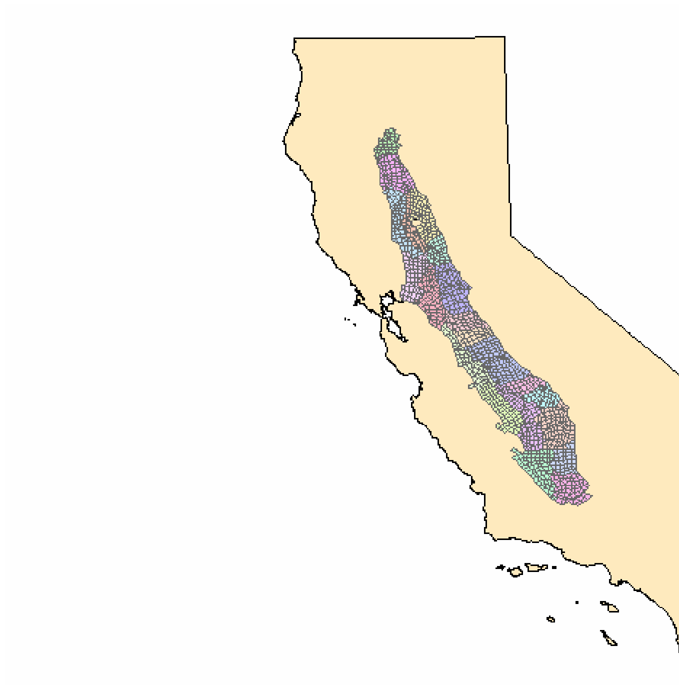


Figure F-2 CVGSM2 Finite Element Grid and Subregions

Table 1. Summary of Peer Review Comments

CONCEPTUAL LEVEL

Type	*Comment*	*Pg*	*Sec*	*Prg*	#	*Resp-onse*
Local Projects	Efforts to model local projects should be continued and expanded	19	2.1	9	1	2b,2c
Geographic Scope	Include Friant System, Tulare basin, Southern California, Colorado River. Hierarchical decomposition approach would allow development of separate models that can be linked through iterative process.	27	3.7	2	2	2b,2c
	CalSim-II should be expanded to include major non-CVP/SWP areas, especially the Tulare Basin, the Colorado River, and Southern California.	21	2.2	4	3	2b,2c
Management Scope	CalSim-II does not explicitly represent many of the management options in which policy makers are interested	23	2.2	6	4	1,2
	CalSim-II should be expanded to include local management options such as water conservation, reuse, water transfers, groundwater and conjunctive use management.	21	2.2	4	5	2a,2b
Modular Approach	Common tension for those who wish for greater detail and those who want less detail from the model. Need for more flexible, modular approach to modeling.	2	1	2	6	2
	Too complex. Not sufficiently detailed. Develop linkable modules of different complexity.	7	5.2	2	7	2
	CalSim-II should be modular.	21	2.2	4	8	2b,2c
Real-time Operations	Improve capabilities for real-time operations, gaming, ag demands, water transfers, Delta storage, carryover contract rights, refuge water demands, updated operations for Feather, Stanislaus, Upper American, San Joaquin, Yuba.	8	5.2	3	9	2a,2b
Model Purpose	For CalSim-II to remain a model of only the CVP and SWP seems technically and politically untenable. California's water system asked to be operated in an increasingly integrated manner. Widen geographical and functional scope of model. Better parameterize local supplies and demands.	24	2.2	10	10	2a,2b,2c
Hydropower	CalSim-II should include risk-based power capacity evaluation and incorporation of indexed sequential hydrologic modeling. Hydropower should not be after-the-fact calculation, but explicitly included in system objectives.	25	3.3	1	11	2b
Groundwater	Efforts to include groundwater should be continued	19	2.1	9	12	2a,2b
Analyzing Future Scenarios	Need to examine greater range of long-term scenarios with respect to hydrology, demands, and operational uncertainty	22	2.2	4	13	2b
Operational Objectives	Better capabilities for analyzing economic, water quality and groundwater issues.	8	5.2	3	14	2a,2b,2c
Documentation	Documentation required that describes applicability of model to different problems.	8	5.2	3	15	2a,2b

Type	*Comment*	*Pg*	*Sec*	*Prg*	#	*Response*
Objective Function	Need to calibrate the CalSim-II objective function so that CalSim-II model decisions correspond to those operators would make. Unless calibrated the model may produce overly optimistic answers.	4	3	1	16	2b
Hydrologic Uncertainty	Need other approaches to representing hydrologic uncertainty and variability besides using historical record.	22	2.2	4	17	2b,2c
Groundwater	Limited representation. Infinite resource.	8	5.2	3	18	1,2
DWRSIM/PROSIM	Remove ties to DWRSIM and PROSIM	24	3.1	1	19	2
Rule Curves	Documentation required.	27	3.6	1	20	2a,2b
	CalSim-II rule curves should reflect operator's behavior.	29	3.9	1	21	2b,2c
Land Use	Consider a land use that changes over time or responds to hydrologic conditions	8	5.2	3	22	2b
Model Improvements	Develop protocols and records for identifying and correcting model errors and making model improvements.	40	6.10	1	23	2b,2c

Note: The keys to the "Response" column is on page F-10

IMPLEMENTATION LEVEL

Numerical Model

Type	Comment	Pg	Sec	Prg	#	Response
Daily Operations	Inclusion of routing requires look-ahead optimization ability. Daily releases are head dependent.	26	3.4	1	24	2a,2b,2c
Groundwater Model	Consider use of response functions. A dynamically linked CalSim-II -CVGSM is not necessary to obtain accurate groundwater predictions. It would also lead to greater run times.	27	3.5	9	25	2b,2c
	Possibility of using ANN for groundwater.	27	3.7	3	26	2b
Soil Moisture	Soil moisture is not dealt with in a realistic manner within the CU model.	27	3.5	10	27	1,2b

Data

Type	Comment	Pg	Sec	Prg	#	Response
Required Accuracy	Model developers should recognize the requirement that CalSim-II provide absolute values. Additional calibration required.	25	3.2	1	28	2a,2b
	Need to improve CalSim-II's comparative as well as absolute capabilities.	8	5.2	3	29	2a,2b,2c
Data Development	There has not been sufficiently systematic, transparent, and accessible approach to the development and use of hydrologic, water demand, capacity and operational data. The administration of data development is fragmented, disintegrated, and lacks a coherent technical or administrative framework. Needs to be greater coordination of data collection and analysis between different administrative units within DWR.	20	2.2	2	30	2a,2b
	Develop protocols for data documentation and development.	70	G	3	31	2a,2b
Groundwater	Details of GW calibration should be available. The San Joaquin system should be added to the multi-cell model. The accuracy of using a coarse representation should be assessed. Better historical groundwater pumping data is needed to confirm whether the use of groundwater in CalSim-II is accurate.	26	3.5	5	32	2a,2b
Hydrologic Data	Needs updating.	20	2.2	2	33	2a,2b
	Develop documentation and testing regime for developed data.	38	6.5	1	34	2a,2b
Agricultural Demands	Update data. Use of economic factors in estimation of water demands. Preferred spatial scale for economic modeling is irrigation district scale.	23	2.2	5	35	2b,2c
Documentation	Documentation required that describe assumptions and limitations.	8	5.2	3	36	2a,2b
Metadata	Provide metadata for data inputs	58	E		37	2a,2b,2c
DWRSIM/PROSIM	Remove ties to DWRSIM and PROSIM	24	3.1	1	38	2

Data Management System

Type	Comment	Pg	Sec	Prg	#	Response
Accountability and Quality Control	Need for quality control and documentation	2	1	2	46	2a,2b
	Need for version control, quality control, calibration, and verification.	8	5.2	3	47	2a,2b
	Develop an explicit quality control program.	37	6.2	1	48	2a,2b
Model runs	Input and output data sets from model runs should be archived in a central location.	58	E		49	2a,2b

Software

Type	Comment	Pg	Sec	Prg	#	Response
Error Checking	Create automated mass balance checking procedure.	5	4	2	50	2a,2b
	Automated input and output checking is needed.	24	2.2	10	51	2a,2b
Non-Linearity	Link linear optimization model with non-linear simulation models.	5	4	3	52	2b
Public Domain	Switch to public domain software for optimization, visualization, file management and data base support.	5	4	4	53	2a,2b,2c
	Eliminate FORTRAN compiler, use public domain MIP solver.	24	2.2	10	54	2a,2b
Multi-period Optimization	Introduce multi-period optimization for decision making based on uncertainty information.	5	4	3	55	2b,2c
	Multi-period optimization could replace rule curves.	8	5.2	3	56	2b,2c
	Performance based optimization should be added to WRIM's capabilities	38	6.7	1	57	2b,2c
Modularity	Ability to change geographic scope, spatial resolution, temporal resolution as required for the analysis.	8	5.2	3	58	2b,2c
Documentation	Improve software documentation.	8	5.2	3	59	2a,2b
GUI	Improved GUI for facilitating model input, setting of constraints and weights, operating the model, displaying and analyzing results.	9	5.2	3	60	2b,2c
	CalSim lacks a comprehensive, graphical user interface for constructing and editing the river basin system topology. The complexity of CalSim would be greatly reduced with development of an object-oriented graphical user interface.	18	1.1	5	61	2b,2c
	Develop GUI tied to databases with GIS display.	24	2.2	10	62	2b,2c
Time-Step	Consider use of shorter time-step for some aspects of the model.	24	2.2	10	63	2b,2c
Post-Processing	Need for better post-processing tools	24	2.2	10	64	2a,2b,2c
Version Control	Need for version control, and database management software and protocols.	24	2.2	10	65	2b
Weights	Need systematic and objective method of setting weights.	24	2.2	10	66	2b
	Need capability to dynamic vary weights, as a function of the state of the system.	27	3.6	1	67	2b
Run Time	Long run times preclude sensitivity analysis. Update solver to gain from efficiency improvements in the Branch and Bound algorithm and better sparse matrix analysis.	29	4.1	1	68	2b,2c
Gaming	Improve capabilities for gaming involving stakeholders.	8	5.2	3	69	2a
Output	Provide access to Lagrange multipliers, identification of binding constraints and value of slack variable	24	2.2	10	70	2a

Type	Comment	Pg	Sec	Prg	#	Response
	Develop output for a wider set of variables other than CVP_SWP e.g. groundwater depletion, water quality, supply reliability for non-project users, hydroelectric generation, indicators of ecological health.	28	3.8	1	71	2a,2b
Infeasibilities	Add capability for automated debugging of infeasibilities.	24	2.2	10	72	2a,2b

Administrative

Type	Comment	Pg	Sec	Prg	#	Response
Model Peer Review	Shortness of 2003 CalSim/CalSim-II Peer Review precluded technical analysis of CalSim-II. Such a technical review should be carried-out.	3	2	6	73	2b,2c
	A peer review is required for each separate element of the model	2	1	2	74	2a,2b,2c
	CalSim-II should be subject to a systematic and frequent review and testing program	21	2.2	4	75	2a,2b,2c
Sustainability	Develop strategy on how to sustain software development.	5	4	5	76	2a,2b
	Produce strategic document that outlines short-term and long-term efforts, budgets, and responsibilities for model and data improvements, with policy for local agency and stakeholder involvement.	70	G	3	77	2a,2b
Public	Local agencies, system operators, and consulting firms should be actively involved in the development and application of CalSim-II.	21	2.2	3	78	2a,2b
Involvement	Broaden the range of hydrologic expertise involved in hydrology data development.	38	6.6	1	79	2a,2b
Financing	The financing for CalSim/CalSim-II development should be wider than CVP/SWP projects. Funding should be forthcoming from local and regional agencies	21	2.2	4	80	2a,2b
Staff	Not enough knowledgeable modelers	23	2.2	7	81	2
Model Interpretation	Stakeholders and policy makers are poorly guided in how to interpret model results.	23	2.2	8	82	1,2
	Studies have not contained the kind of written discussion and interpretation of results that would demonstrate that the authors have thought about the results and drawn conclusions.	23	2.2	9	83	1,2
Model Management	CalSim-II should no longer be solely responsible to CVP-SWP managers but a broader range of technical managers from additional interests.	35	5	3	84	2
	Create a broader interagency modeling consortium for developing operations planning models. Might require steering committee or governing board.	36	6.1	1	85	2
Training & Education	Hold seminars on CalSim-II to increase public confidence in model.	29	4.2	3	86	2a,2b
	Develop a formal common regimen to train CalSim-II users.	37	6.3	1	87	2a,2b
	Provide centralized support.	8	5.2	3	88	2b
	Develop a users group	37	6.1	1	89	2a

MISCELLANEOUS

Type	Comment	Pg	Sec	Prg	#	Response
Supporting Models	Documentation, calibration, testing, peer review should be extended to other models that provide data input for CalSim-II.	38	6.4	2	90	2b,2c

CALIBRATION AND VALIDATION						
Type	***Comment***	***Pg***	***Sec***	***Prg***	***#***	***Response***
Calibration	CalSim-II should be calibrated, tested, and documented for absolute and comparative use.	40	6.9	1	39	1,2a,2b,2c
Validation Report	Evaluation of CalSim-II by comparison with historical operations should be more rigorous.	40	6.9	3	40	2a,2b
	Comparison of simulated and historical deliveries suggests that the model over-estimates project deliveries	68	F	3	41	1
	Model rules on carryover storage during drought should be examined so that they reflect the system will be managed in the future.	68	F	4	42	2a,2b
	Comparison of simulated and historical deliveries suggests that the model underestimates storage in San Luis Reservoir.	69	F	6	43	1,2
Sensitivity Analysis	Need for sensitivity and uncertainty analysis.	8	5.2	3	44	2a,2b,2c
Advisory Board	Create external technical advisory body as part of a quality control program.	37	6.2	1	45	2a

<u>Keys to the "Response" column of Table 1:</u>

1 DWR and Reclamation do not agree with the comment stated.

2 DWR and Reclamation agree with the comment stated.

2a DWR and Reclamation agree with the comment stated and staff is currently working on it as part of our immediate needs for CalSim. A work plan is being developed by both DWR and Reclamation and will be shared with the public in the very near future.

2b DWR and Reclamation agree with the comment stated and consider it important to address in the short term with a target date of January 2007.

2c DWR and Reclamation agree with the comment stated but considers it should be addressed on a longer term with a target date of January 2011.

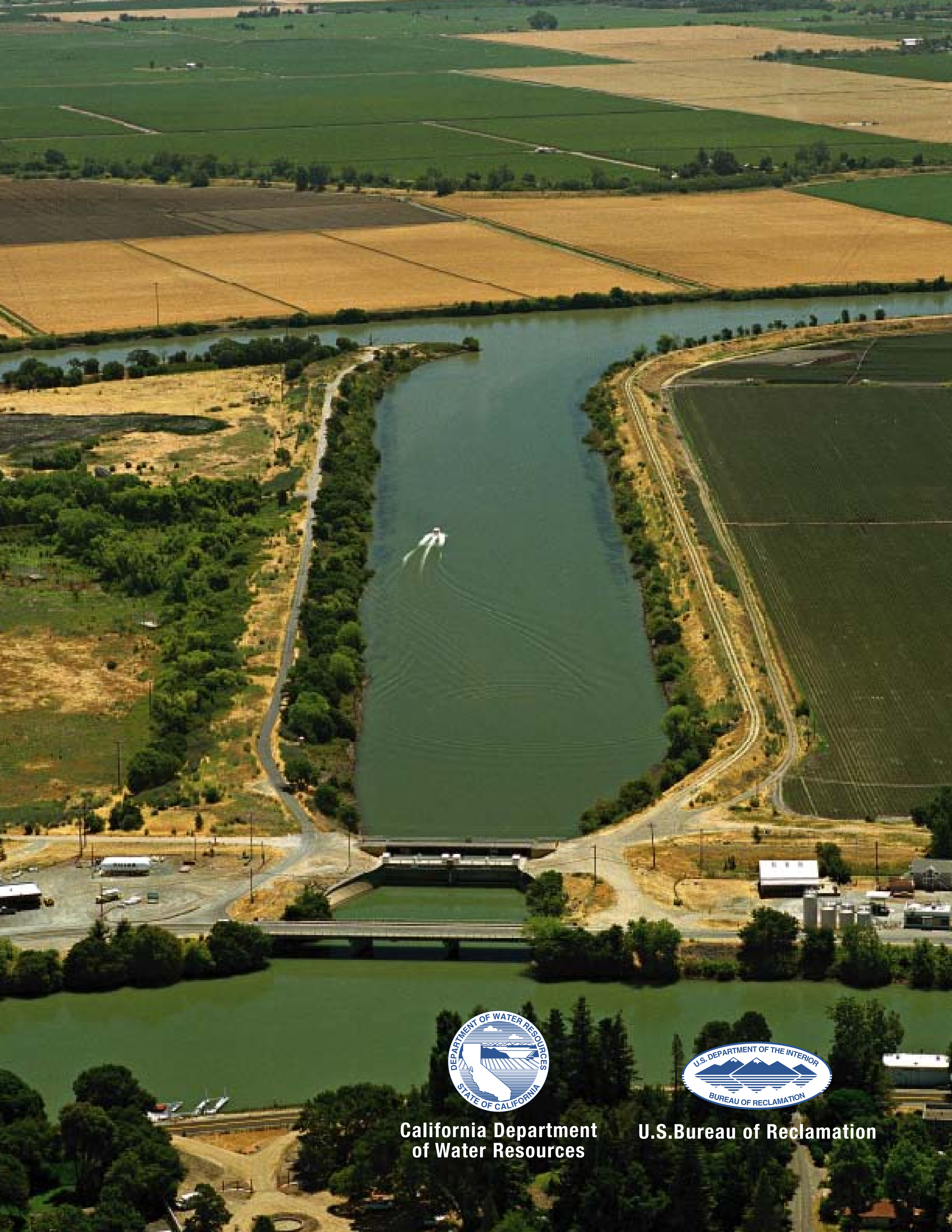
Table 2 Development Priorities

CONCEPTUAL LEVEL				
Task	Current Development	Immediate Needs	Short-Term Development Target January 2007	Long-Term Development Target January 2011
Representation of local projects	Explicitly represent major irrigation districts on the East-Side of the San Joaquin Valley	Explicitly represent major irrigation districts and water agencies in the Sacramento Valley		
Extended geographic scope	Model Friant System			Model Colorado River system
	Model Yuba River			Expand representation of southern California
	Model Bear River		Model Upper Feather River	
	Model Upper American			Tulare Basin
	Model Stony Creek			
Representation of water management options	Develop module for water transfers	Improve capability to model water conservation measures		
		Improve capability to model conjunctive surface water and groundwater operations		
Development of a modular approach		Develop modular approach for irrigation and urban demands in the Sacramento and San Joaquin Valley		
Real-time operations	Integrate planning and operational models	Develop gaming model		
Hydropower	Post-processing of hydropower operations		Add risk-based power capacity evaluation	
Groundwater	Calibration of CVGSM	Refine groundwater representation in the Sacramento Valley	Add groundwater model for the San Joaquin River Valley	
Analyzing Future scenarios			Develop alternate future demand and water use scenarios. Develop ulternate hydrologies	
Operational objectives	Water quality module for the lower San Joaquin River		Use of economic and water quality drivers and performance measures	
Documentation	.	Document applicability and limitations of CalSim-II		
Objective function	Work with operators to define current operating rules and objectives			
Hydrologic uncertainty	Model global climate change study		Develop alternate approaches to representing hydrologic uncertainty and variability	
Groundwater	Develop strategy to more comprehensively model groundwater			
Land use			Dynamic variation of agricultural land use (demand) in response to water supply	

Model improvements		Develop protocols and records for identifying and correcting model errors and making model improvements.		
Daily time step		Assessment of errors due to monthly time step		
Documentation	Document model logic	Document development of rule curves		
IMPLEMENTATION LEVEL				
Numerical Model				
MIP solver	Improve computational efficiency			
Daily operations			Add look ahead optimization functionality	Hydrologic routing
Groundwater model	Link of CalSim-II and CVGSM		Refinement of groundwater model in CalSim-II (unit response function, ANN, or multi-cell model)	
Soil moisture accounting			Replace CU model	
Data				
Required accuracy		Improve CalSim-II's absolute predictive capability		
Data development		Develop protocols for data documentation and development	Develop systematic, transparent and accessible approach to the development of hydrologic data	
Hydrologic Data		Update hydrologic data. Broaden range of expertise involved in hydrology data development. Develop testing regime for data.		
Spatial resolution		Gather data for finer spatial resolution		
Documentation		Document derivation of all data input		
Metadata		Provide metadata for data inputs		
Data Management System				
Accountability and Quality Control		Develop version control for model input data		
		Develop an explicit quality control program		
Model runs		Archive data sets from model runs in a central location		

Software				
Error checking			Automate mass balance checking procedure	
			Add automated algorithms for checking input and output	
Simulation			Improve simulation functionality	
Public domain software	Elimination of FORTRAN compiler			
	Adoption of public domain solver.			
Multi-period optimization		Add automated multi-period optimization functionality		
Modularity		Facilitate ability to change geographic scope, spatial and temporal resolution		
Documentation	Add ability to store metadata	Update and expand user's manual		
GUI	Create geo-referenced network schematic	Develop GUI for constructing and editing river basin system topology, facilitating model input, displaying results		
Time-step	Increase flexibility to switch between daily and monthly time steps			
Post-processing		Improve third-party post-processing tools		
Version control	Use version control for text based inputs	Create centralized database for version control management		
Weights	Add functionality for ynamic conditional setting of weights	Develop automated weight generating algorithm		
Run-time	Restructure WRESL code to eliminate redundant/repetitive calculations			
	Add capability to output intermediate of state variables (rather than their addition to MIP problem)			
	Improve solver computational efficiency			
Gaming		Create gaming model for stakeholder participation		
Output		Output of (Lagrange multipliers, basic and non-basic variables, including slack variables		
		Develop more comprehensive standard output of model variables		
Water quality		Add water quality input tables and post-processor	Add functionality to specify water quality objectives	
Infeasibilities	Automate debugging of solver infeasibilities			

Administrative				
Peer Review		Complete technical reviews of CalSim-II components		
Sustainability			Develop strategy on how to sustain software development.	
		Produce strategic document that outlines short-term and long-term efforts, budgets, and responsibilities for model and data improvements		
Public Involvement			Actively engage local agencies, system operators, and consulting firms in the development and application of CalSim-II.	
Financing			Seek wider financing for CalSim/CalSim-II development	
Model Management	CWEMF modeling strategic vision committee		Create broader interagency modeling consortium for developing operations planning models.	
Training &		Hold seminars on use and interpretation of CalSim-II for managers and policy staff		
Education		Develop a formal common regimen to train CalSim-II users.		
		Provide centralized support.		
		Develop a users group		
MISCELLANEOUS				
Supporting Models	Create documentation of model linkages (model map)	Documentation, calibration, testing, and peer review of supporting models		
	Facilitate communication between models (CalSim-II-CALAG translator)			
CALIBRATION AND VERIFICATION				
Calibration		Calibrate hydrologic parameters using historical data		
Sensitivity Analysis	Carry-out sensitivity analysis	Carry-out uncertainty analysis.		



California Department
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