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RECLAMATION

Technical Memorandum

Water Temperature Modeling Platform: Model Selection (DRAFT)

Central Valley Project Water Temperature Modeling Platform

California-Great Basin Region



Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Water Temperature Modeling Platform: Model Selection (DRAFT)

**Central Valley Project Water Temperature Modeling Platform
California-Great Basin Region**

prepared by

**United States Department of the Interior Bureau of Reclamation
California-Great Basin**

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Cover Photo: Keswick Dam on the Sacramento River by John Hannon

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Abbreviations and Acronyms

CALSIM	CalSim is the model used to simulate California State Water Project (SWP)/Central Valley Project (CVP) operations
CVP	Central Valley Project
GUI	Graphical User Interface
I/O	Input/Output
QA	Quality Assurance
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
TCD	Temperature Control Device
TMDL	Total Maximum Daily Load
WTMP	Water Temperature Modeling Platform

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Chapter 1 Introduction

Flow and water temperature simulation models are useful and necessary tools to support resource managers in their understanding of temperature dynamics in U.S. Bureau of Reclamation (Reclamation) CVP reservoirs and downstream river reaches. Such tools support evaluation of how operational decisions and various influencing factors can affect water temperature in reservoirs and rivers, and the resulting potential impacts to fishery species that are sensitive to water temperature. The improvement of models, modeling approach, and associated tools to support operational decision making is considered a necessary adaptation strategy that takes advantage of ongoing technological advancement, and additional information and data. Reclamation's objective for the development of the Water Temperature Modeling Platform (WTMP) is the effective and efficient management of resources for downstream regulatory and environmental requirements within the context of an uncertain environment. A primary development goal of the WTMP is to provide realistic predictions of reservoir and downstream river water temperatures with sufficient confidence to carry out the necessary planning for seasonal and real-time applications while also describing situational risk and uncertainty.

Models of large complex reservoir-river systems (flow and water temperature) have been developed for a wide range of applications. Reservoir and river reaches can be modeled as discrete components, with individual models for each reservoir or river reach, or with a modeling system. A modeling system is a single software package (e.g., HEC5Q (HEC 1999, HEC 2000) or HEC-ResSim (HEC 2021)) that incorporates all system components (e.g., discrete reservoirs and river reaches) and their inter-connections in a network setting. For the CVP, there is a need for high resolution, discrete reservoir and/or river element models that can offer more detailed representations, as well as a modeling system that can accommodate system wide operations in a computationally efficient manner. As noted in U.S. Bureau of Reclamation (Reclamation) (2021), a modeling framework (framework) provides a means to represent reservoir-river systems as either a suite of linked but discrete models, with a modeling system, or a combination of the two approaches.

This document describes the process of identifying model selection criteria, potential models for use in the WTMP, and recommendations for reservoir, river, and system models. A systematic process of identifying the aforementioned information to assess a wide range of models is important to identify appropriate models to meet the goals and objectives of Reclamation's modeling needs.

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Chapter 2 Model Selection Criteria

Model selection criteria are typically used to assess a range of potential models to meet the specific project objective and needs (Chinyama et al. 2012, Mateus and Viera 2018, and Sharma and Kansal 2012). For this project this translates to developing models that provide realistic predictions of reservoir and downstream river water temperatures with sufficient confidence to support seasonal planning and real-time applications while also assessing uncertainty. The selected models will be applied in the Sacramento and Trinity River basins, the American River basin, and the Stanislaus River basin, and be specific to CVP operations and associated environmental needs associated with temperature management.

California Water and Environmental Modeling Forum (CWEMF) (2021) provides a wide range of guidance on model development, including a four-phase process of:

- Preliminary analysis (defining questions to be addressed through modeling, identifying available information, model selection, schedule and resource considerations);
- Framing the modeling study (period of analysis, spatial extent, boundary conditions, calibration/validation, sensitivity and uncertainty analysis);
- Application of the model (setting up model applications including planning, real-time operations, science and research); and
- Communicating and documenting results (results presentation, documentation, review of model and study through public participation, technical advisory committee, and/or peer review).

The development of the WTMP encompasses all four phases of this process, and this technical memorandum focuses on model selection (preliminary analysis phase). CWEMF further identifies a range of model questions that can be adapted to assist in model selection. This information, as well as other literature (Ejigu 2021, Loucks and van Beek 2017, Chinyama et al. 2014, Sharma and Kansal 2012) and professional experience were used to select a range of criteria to assist Reclamation in selecting both component models (for discrete reservoirs and selected river reaches) as well as a system model that represents a reservoir-river network. Required model elements and capabilities considered in model selection included (but were not limited to):

- Reservoir or river representation;
- Model capabilities (such as flexibility to represent selective withdrawal, submerged dams, or temperature control curtains for reservoir components) and model performance;
- Model spatial and temporal scales and data needs;
- Ability to interface model with other models in a framework;

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- The resources required to develop and maintain a model and cost assessment (initial cost or annual maintenance fee);
- Active model support, access to the principal code author and/or open-source code (allowing review and modification), and comprehensive documentation and training available;
- User interface for input file quality control;
- Post processors available.

Model criteria were developed to screen potential models for selection and implementation in the Water Temperature Modeling Platform (WTMP) (see Technical Memorandum 5). Criteria were grouped into the following subcategories:

- Numerical Model Criteria – numerical representation of the physical system in a model
- Linkage – addresses if models are WTMP compatible and if models are discrete (reach specific) or system-wide
- Input/Output (I/O) – model pre- and post-processing capability and I/O data structures
- Support – addresses whether or not the model is supported by the developer or some other entity
- Central Valley Project (CVP) Features – ability to represent specific features of the CVP (multiple criteria)
- Additional qualitative criteria

Some approaches to model selection utilize explicit grading or numerical priority (e.g., Mateus et al. 2017) to identify (exclusion/inclusion) and rank selected models. Such a rigid approach was not undertaken herein due to the combination of system specific conditions (e.g., temperature control facilities, unique regulatory temperature management approaches), use of existing models, specific modeling needs (e.g., submerged dams, temperature control curtains), and qualitative criteria where the precision of numerical quantification provides modest benefits for ranking. Rather, Reclamation assessed criteria as high, medium, or low priority based on project objectives, and then examined the global applicability of each model when deciding on a recommended set of models for the WTMP. Six types of model selection criteria and their assigned priorities are presented in Table 2-1 through Table 2-6 (as described below), followed by brief descriptions of each category.

- Criteria for numerical models are listed in Table 2-1.
- Criteria based on model linkage capability are listed in Table 2-2.
- Criteria based on model input and output capabilities are listed in Table 2-3.
- Criteria based on model support are listed in Table 2-4.
- Criteria based on specific features of current or planned CVP facilities are listed in Table 2-5.
- Criteria based on qualitative model elements are listed in Table 2-6.

Table 2-1. Model selection criteria for numerical models, and assigned priority.

Criteria	Notes/Comments	Priority
Model type (River/Reservoir)	Need to effectively predict both reservoir water temperatures (vertical profile and release temperature for selective withdrawal operations) and river temperatures (longitudinal temperature gradients) to manage cold water supplies and downstream river temperatures at appropriate spatial and temporal resolution.	High
Number of dimensions (1, 2)	Consider project objectives, data requirements, and ability to represent physical processes spatially, including potential tradeoffs between lower dimensional representations for computational efficiency and higher dimension for higher spatial resolution/refinement of model results.	High
System geometric representation	Favor greater detail in reservoirs and river reaches in the vicinity of operational control points where physical water temperature processes and biological objectives are most important (e.g., spawning). Improved model accuracy leads to improved estimates of biological models (e.g., Temperature Dependent Mortality on Sacramento River).	High
Dynamic flow model	Desirable over steady-state representations. Hydrology and project operations are complex (e.g., Shasta TCD and Folsom Shuttles) and occur over a range of time scales (hours, days, months).	High
Water temperature representation	Use an approach that provides accurate water temperature modeling, calibration, and validation over a range of conditions, including challenging water temperature compliance conditions. A complete heat budget formulation is necessary.	High
Time step (capable of sub-daily)	Sub-daily required. Aquatic species experience diurnal water temperature signals and there is, in some cases, the need to estimate aquatic species impacts in downstream river reaches based on sub-daily temperature conditions (e.g., maximum daily water temperatures).	High
Computational performance consideration	Computation time is important. Screening or planning level tools might employ models with lower spatial resolution with longer time steps and shorter computational times, while refined tools might employ models with higher spatial resolution and shorter time steps with longer computational times. Screening and refined models will be used to explore an appropriate solution space to examine tradeoffs or to iterate to a desired tradeoff and to evaluate uncertainty in system forcing parameters. Select models for the WTMP that match project objectives (i.e., screening or refined). Screening models would run in seconds or few minutes for an annual simulation, while refined models may run for several minutes up to, say, 100 minutes.	High

Table 2-2. Model selection criteria based on model linkage capability, and assigned priority.

Criteria	Notes/Comments	Priority
Discrete component model or system model	Discrete component model representations (reservoirs or rivers) can be linked together to model a larger reservoir-river system. System models that represent networks of reservoir and river reaches can be used alone or in concert with discrete component models.	Medium
Modeling framework compatible	Model can receive information from other models (i.e., file sharing) and then pass results to other models that will be supported in the WTMP.	High/ Medium

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Table 2-3. Model selection criteria based on model input and output capabilities, and assigned priority.

Criteria	Notes/Comments	Priority
Pre-processor	Prefer models with pre-processors to assess and manage inputs, explore uncertainty, and minimize setup errors.	High
Post-processor	Prefer models with post-processors to assess, visualize, and manipulate output (graphical and tabular).	High
Data structure facilitates model calibration/application	Model includes a data structure that is easily accessible to facilitate input, data storage, and output to facilitate modeling, calibration, and error detection.	Low

Table 2-4. Model selection criteria based on model support and assigned priority.

Criteria	Notes/Comments	Priority
Model applications	Model has been used in applications similar to this project.	High
Actively supported	Actively supported models both in terms of tool usability (e.g., support) and longevity.	High
Public domain, peer reviewed, and accessible model modifications	Software should be in the public domain, peer reviewed, and include a mechanism to assess critical model assumptions and verify model modifications.	High
Free of charge	Model is free or is there a minimal cost for software and/or support.	High
Documentation	Required at a level that allows stakeholder and peer review and that provides a defensible final product. Documentation includes both technical reports on model construction (equations, solution methods) and user manuals.	High
Training and/or user group	For long-term use, available training and/or active user group forums to support ongoing model application.	Medium/ Low

Table 2-5. Model selection criteria based on representation or parameterization of specific features of current or planned CVP facilities, and assigned priority.

Criteria	Notes/Comments	Priority
Temperature control curtains	Lewiston Lake and Whiskeytown Lake contain temperature control curtains.	High
Submerged weirs/dams	There is a submerged dam upstream of New Melones Dam.	High
Selective withdrawal	Shasta Lake and Folsom Lake include selective withdrawal facilities.	High
Automated simulations to meet downstream temperature targets: tailbay	An ability to model target reservoir release temperatures.	High
Automated simulations to meet downstream temperature targets: river reach	An ability to model target downstream river temperatures.	High
Shade	Topographic and/or riparian vegetation shade.	Medium

Table 2-6. Model selection criteria based on qualitative modeling elements, and assigned priority.

Criteria	Notes/Comments	Priority
Ease of use	Model is relatively easily operated by Reclamation operators (data input, model run, and output accessed), i.e., one does not have to be a modeling expert to apply the models.	Medium
Credibility	Final model has sufficient documentation, peer review, application, and stakeholder support to be a credible tool to support temperature management.	High
Easy to incorporate uncertain input parameters	Model can be used to assess uncertainty, i.e., the ability to modify inputs to assess uncertainty preferred over internal logic to assess uncertainty.	Medium
Collaboration with model developers	Model developers have an interest in the model application and potential opportunities to collaborate on model and WTMP development.	Medium

Type (River/Reservoir/System)

Flow and water quality model type is based on aquatic feature type represented: a reservoir, river, or both reservoir and river model domain. The WTMP project requires accurately predicting reservoir vertical profile and dam release temperatures as well as longitudinal river temperatures to guide cold water pool management, selective withdrawal operations, and downstream temperature management actions. There are two distinct requirements for reservoir and river simulation models for the WTMP:

- Model designed for predicting vertical distributions and release water temperatures in a reservoir.
- Model designed for predicting water temperature in a river reach.

Number of Dimensions (1, 2)

A determination of the appropriate model dimensionality should consider project objectives, data requirements, and ability to represent physical processes spatially in the model domain (Ji 2017).

Different model spatial resolutions and representations would be required to address the range of applications addressed by the WTMP. For example, short-term predictive applications may require higher spatial model resolution to capture key infrastructure or system features, such as submerged dams, water temperature control curtains, and selective withdrawal facilities. On the other hand, long time horizon planning studies may utilize less refined spatial representations to reduce computation time. Example representations, listed below, vary depending on modeling objective and type of system.

- Large, seasonally stratified reservoirs:
 - One-dimensional models typically represent vertical temperature gradients but are laterally and longitudinally averaged.

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- Two-dimensional models typically represent vertical and longitudinal temperature gradients, but are laterally averaged.
- Smaller reservoirs (afterbays) that experience weak/intermittent stratification:
 - One-dimensional models typically represent longitudinal temperature gradients but are vertically and laterally averaged (e.g., akin to a slow, deep river).
 - Two-dimensional models may be represented differently:
 - Represent vertical and longitudinal temperature gradients but are laterally averaged.
 - Represent longitudinal and lateral temperature gradients but are vertically averaged.
- Rivers:
 - One-dimensional models typically represent longitudinal temperature gradients but are laterally and vertically averaged.
 - Two-dimensional models typically represent lateral and longitudinal temperature gradients but are vertically averaged.

Three-dimensional models related to flow and temperature have increased complexity in model set-up, calibration, operation, and computational time. Although initially included in the evaluation, three-dimensional models were excluded from final consideration because the potential benefit to CVP systems did not justify the additional time and effort required for additional data collection, implementation, calibration/validation, application, and maintenance of these tools. Therefore, one- and two-dimensional models are included in this assessment and 3-dimensional models are not.

System Geometric Representation

For inclusion in the WTMP, model spatial resolution should capture vertical temperature gradients and outflow temperatures in reservoirs and longitudinal temperature gradients in rivers sufficient to support temperature management operations and activities. For reservoirs, geometric representation includes representation of multiple arms or branches, morphology, location of inflow and outflows and regulating structures (spillways, outlet works, and similar facilities). Reservoir models should have sufficient vertical resolution (e.g., on the order of 1.0 to 2.0 meters or less, depending on the system) to represent seasonal stratification under various thermal regimes. For seasonally stratified reservoirs geometric representation includes sufficient spatial resolution to capture isothermal conditions, onset of stratification, persistent seasonal stratification, and fall breakdown of stratification. For smaller reservoirs or systems with short residence times, reservoir models should be able to simulate weak intermittent reservoir stratification. River geometric representations include branching networks, reaches with side channels, variable slopes and complex cross sections, locations of tributaries, and other inflow and outflow locations. Rivers are typically well mixed in the vertical dimension and while lateral variations in temperature can occur, temperature modeling efforts to date in streams below CVP facilities have identified that longitudinal temperature gradients are of principal interest. Longitudinal heating in streams downstream of CVP facilities is generally on the order of 1.0°F (0.5°C) over a few miles during the summer season. A spatial resolution of 1.0 miles (1.6 km) or less would capture longitudinal heating rates appropriately.

Dynamic Flow Model

Dynamic flow models simulate time variable flows while steady state models assume constant flow over time. Dynamic flow models replicate spatially and temporally variable flow conditions in river reaches or in reservoirs with complex flow features. Hydrology and project operations are complex and occur over a range of time scales (hours, days, months) for the WTMP project. Sources of variable flow conditions include hydropower peaking flows, tributary contributions, flows through complex system geometry and temperature control curtains, and dam releases through unconventional outlet structures such as temperature control devices.

Water Temperature Representation

Selected model should employ a comprehensive representation of the heat budget for both river and reservoir systems (see Martin and McCutcheon, 1999). Appropriate meteorological data will be necessary to fully represent the heat budget. Further, features such as riparian shading, topographic shading, wind sheltering, and other attributes may be required to accurately represent the heat budget for certain reaches. This is a required model element.

Sub-Daily Time Step

Models with sub-daily time steps are necessary to simulate dynamic flows (e.g., hydropower peaking flows, tributary inflows) in reservoir reaches as well as dynamic flow conditions and diurnal temperature response in river reaches. A sub-daily time step may require sub-daily flows, operations, inflow temperature boundary conditions, and/or meteorology. Sub-daily temperatures can be used for determining biological metrics or input to biological models. This is a required model attribute.

Computational Performance

Highly detailed and/or computationally intensive models with long run times may not effectively address questions that need to be addressed in a timely manner (e.g., short term forecasts during the temperature management season). There is a trade-off between computational efficiency and system representation (spatial/temporal). Computationally efficient models with lower spatial resolution (e.g., 1-dimensional versus 2- dimensional) are useful for screening or planning activities, while higher spatial resolution models are useful for refined or short-term analysis. Run time is also considered an important attribute because there is often a need to complete multiple simulations relatively quickly to incorporate updated information or to assess uncertainty in model input data (e.g., forecasts).

System Model or Discrete Reach

System models represent a reservoir-river system, while discrete models represent specific system components (for example, individual reservoirs or river reaches). Discrete models can be used to construct a modeling framework. System models can also have component models inserted for

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certain reservoirs or rivers to form a modeling framework. This criterion addresses the use of a single system model and/or a modeling framework that consists of discrete models.

Modeling Framework Compatible

Identified models (system models or component models) should be compatible with the WTMP framework software. To achieve efficiency, standardization, and other purposes, modeling frameworks may require specific formats or information, may have limitations or constraints, or other features that should be considered when selecting models. Models where a GUI is intimately integrated with the model source code can provide challenges for modeling frameworks. Model codes that can readily be accessed through, for example, an executable is more readily included in model frameworks. A modeling framework is a necessary approach to meet overall project objectives.

Pre-Processor

Models with pre-processor tools that allow users to process and analyze inputs, provide quality control, and construct model input files can save a considerable amount of time in the modeling process. Pre-processors vary widely among models with some of the available tools being relatively simple or narrowly focused on selected inputs and assessment methods (e.g., a simple graph of input data for low level quality assessment (QA)). Other, more comprehensive, pre-processors can develop key input information in model-ready formats, check a wide range of model input parameters for appropriate values, or report results to users. Herein, pre-processors are not assessed, but are identified as available or not (or unknown). Pre-processors are a desired attribute of the modeling project, and in Phase II of this project there will be an opportunity to develop pre-processors to meet specific needs of Reclamation.

Post-Processor

Post-processor tools provide efficient methods to examine model output in tabular or graphical form as well as in animations. These tools can also include computation of statistics, development of input files for “downstream” models, and development of specific reports of selected model output. Post-processors can be valuable tools to communicate results to technicians, operators, resource managers, managers, and stakeholders. Post-processors vary widely among models with some of the available tools being relatively simple or narrowly focused on selected outputs and analysis (e.g., a simple graph of output data for low level QA). Other processors include analytical assessment of simulated results (e.g., summary statistics), graphical output, and animation. Certain tools allow for the automating of reports (e.g., QA reports, calibration reports, simulated system status reporting). Herein, post-processors are not assessed in detail, but are identified as available or not (or unknown). Post-processors are a desired attribute of the modeling project, and in Phase II of this project there will be an opportunity to develop post-processors to meet specific needs of Reclamation.

Data Structure Facilitates Model Calibration/Application

Certain models require specific steps to complete simulations. One example is the need to recompile the source code prior to each simulation. Models should have model and data structures that make calibration and application a straightforward process.

Model Applications

Successful application of models to a wide range of systems represents an implicit or informal testing of the model. A further consideration is knowledge of models applied to systems with similar morphology, size, setting, and features found in the project area. Many model applications have reports identifying model calibration and application, and in certain cases include a peer review. If a model has been widely applied and documented, there is a level of confidence that the model will function as planned (although this is not a guarantee). Ratings are “many”, “few”, or “none”. A large number of applications is preferred.

Actively Supported

Actively supported models include up-to-date documentation (including a user guide), a current model version, and a principal contact that is responsible for model maintenance, update, and management. The principal contact may be the model author, model administrator/manager, or a member of a modeling support team. Access to this person or group is a valuable asset when considering any modeling project but is particularly important in model development projects or applications that will have an extended lifespan. This is a required model attribute.

Public Domain, Peer Reviewed, and Accessible Model Modifications

Important considerations for models used in supporting water temperature management for the Sacramento/Trinity, American, and Stanislaus River basins include software accessibility, peer review, and accessibility to or review of model modifications.

For the purposes of this project, software accessibility requirements are largely addressed by considering models that reside in the public domain. Public domain models are considered available for use without restriction or cost and should include the model executable, supporting files necessary for the model to function, and documentation. Conversely, proprietary models typically include a form of licensing with specific terms and conditions that may limit the use, modification, or sharing of software or applications, and may or may not include a one-time or annual subscription fee for use. This is a required consideration.

Model peer review can range from a simple review to a detailed model interrogation. Herein, peer review includes an assessment of the model formulation and an evaluation of the suitability of a model for the intended purpose. Models are often peer reviewed for the specific application of the

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model to assess input and output data, model calibration and validation (and assumed parameter values and model performance), sensitivity analysis, and other model development and application activities. For example, spreadsheets (with proprietary source code) are often used to develop models because these software programs have been widely tested and are accepted. The subsequent spreadsheet “model” can be transparent (formulas, logic, calculation, flow of information), documented, distributable, and peer reviewed. Model peer review is a required consideration.

At times, model modifications are undertaken to adapt a code to a specific condition or incorporate representations that are needed. Accessible source code is defined as portions of a model code that are available for review. For the purposes of this project, accessible source code includes code modifications to the parent (original) code. Certain software, modeling codes, or modeling approaches have been widely applied and “time tested” (e.g., numerical solution approaches to solving governing equations). However, any modifications to source codes require transparency and an opportunity to be peer reviewed. Accessibility of source code is a required condition.

Documentation

Model documentation can take several forms. Ideally, documentation includes both a technical report (model description, structure, process representation, governing equations and numerical solution methods, etc.) and a user guide (input structures, control parameters, model process parameters, constants, and coefficients). Certain model documentation includes a report, publications and/or example applications that allow the user to run the model and confirm model outputs. As noted above, documentation should be actively supported. Model documentation is required.

Training and/or User Group

Models with currently active training workshops and/or user groups can be valuable resources. Training courses may require a fee. User groups are typically available to modelers without charge. Certain user groups are more formal than others. Access to training or user groups is a preferred model attribute.

Specific CVP System Features

Certain specific features are important for water temperature management in the CVP systems. These structures and features should be represented in the models developed for the WTMP. These include:

- Temperature Control Curtains: temperature control curtains exist in Lewiston Reservoir and Whiskeytown Lake. Reservoir models should be able to accommodate existing and potential future use of temperature control curtains.
- Submerged Weirs/Dams: submerged dams and other underwater features that can potentially impact in-reservoir downstream temperature dynamics occur in some system

reservoirs. Reservoir models should be able to accommodate submerged dams and weirs. One example is a submerged dam in New Melones Reservoir on the Stanislaus River.

- Selective Withdrawal: several reservoirs rely on selective withdrawal operations to conserve cold water pool volume and manage downstream water temperature. Any selected model will be required to include selective withdrawal logic to assess various operational assumptions as well as predict potential operations in response to forecast conditions and associated temperatures. Both Shasta and Folsom have selective withdrawal operational capabilities.
- Automated simulations to meet downstream temperature targets - tailbay: logic to guide operations to meet tailbay temperature targets (dam release temperatures). This is coupled with selective withdrawal because selective withdrawal operations will be based on reservoir tailbay temperature targets.
- Automated simulations to meet downstream temperature targets - downstream river reach: logic to guide operations to meet downstream temperature targets in river reaches, e.g., compliance locations.
- Shade (topographic, riparian vegetation): potential to include topographic and/or riparian shading. Riparian shade may be important in selected river reaches and is a preferred river model attribute. Topographic and riparian shading for reservoirs in the project area is not necessary.

These unique features may require customized treatments in model specifications that may not be readily available in the existing models. Therefore, assessing the ability to adapt the model (including potentially modifications of the source codes) for the particular need is necessary. A related consideration is the ability to provide public accessibility of the implemented modifications to maintain transparency and the status of peer review and public acceptance.

Qualitative Criteria

Additional criteria were identified in this process that address qualitative modeling elements. These include:

- Ease of use: models will be used by technical personnel ranging from model experts to model users and operators. Models should be appropriately accessible for this range of users. This criterion is simply listed as “more difficult” or “less difficult.” Entries left blank indicate the model is relatively straightforward to use. Ease of use is a desired model attribute.
- Credibility: general acceptance of a model by a broader community of modelers, decisionmakers and stakeholders. Credibility is a required model attribute.
- Uncertainty: model users should be able to input different input parameters to readily assess the implications of those parameters on model results, to assist in decision making. Managing uncertainty externally is preferred to incorporating this into the model (internally)

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because an external process is easier to customize for Reclamation and provides transparency to the approach.

- Model developer collaboration: the ability to collaborate with model developers is a preferred outcome. Access to model developers was identified as feasible for all identified models. However, this specific criterion was added to identify the potential for more active collaboration with model developers. Specifically, collaboration should focus on the potential to share project details and approach and engage with model developers to add value to the development of a temperature modeling platform for the CVP.

Chapter 3 System Models, Reservoir and River Models

A variety of system models and reservoir and river models were considered for use in development of the WTMP. Considered reservoir and system models are listed in Table 3-1, and river models are listed in Table 3-2. Information for each model under consideration includes the model sponsor, a URL for the model website, and citations for model development documents or user's guides. System models that incorporate both reservoir and river reaches are included in the reservoir model table.

Model Review

Models included in this review were considered if they were generally consistent with the criteria (e.g., could be assessed using the criteria) identified in Table 2-1 through Table 2-6. Other models were examined in this effort, and several models or types of models were not included because they lacked the necessary representations or were inconsistent with the project objective of developing a temperature modeling platform that conformed with the above criteria. Types of models not included in the initial assessment are outlined below:

- Research models were not included because they typically lack documentation and ongoing support, are often applied to a narrow suite of systems or questions, may not be easy to apply, and other limitations.
- Statistical or stochastic models were not included in the assessment. Such models are often system specific, and performance is based on available data to derive statistical relationships. Ultimately, statistical or stochastic models may be incorporated into the WTMP, where justified with adequate validation and review, and be used independently or in conjunction with other physically-based models. However, the evaluation of such models is separate and different from the focus herein for physically-based models.
- Watershed models were not included in the assessment because the objective of those models is different than that of Reclamation temperature management operations. Specifically, watershed models aim to encompass a much broader domain – both within river-reservoir systems and their associated watershed and the various activities that occur in that watershed (agriculture, urban, forestry, etc.) These are valuable tools to assess a different set of questions.
- Water quality models that include sediment transport processes were not included in the assessment because the objective of those models is different than the objective of the WTMP. Further, the addition of sediment transport to the model process would increase the data needs, model set-up and calibration, and computation time. Selected sediment transport models initially examined are listed in Table 3-3.

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- Purely proprietary codes were excluded from consideration. These models are typically costly to purchase and maintain support. These costs and lack of transparency would not be consistent with the project objective of developing stakeholder buy-in and model credibility.
- Three-dimensional reservoir models were not included in the final assessment for reasons similar to those mentioned for watershed and sediment transport models: different objectives, increased data needs, model set-up and calibration efforts, and computational time. Three-dimensional models were explored in the initial review are shown in Table 3-4. A common attribute of these models is the ability to model complex, multi-dimensional conditions, typical of coastal and estuary systems, as well as streams and lakes. Some of these models can also be applied in one or two dimensions (or have one- or two-dimensional representations included). From a reservoir modeling perspective, reservoir operational elements, such as selective withdrawal to meet target temperatures, are not typically included in these models and would have to be developed. Although they are powerful tools, the excessive complexity of these multidimensional models precluded their inclusion in the final selection process.

Table 3-1. Reservoir and system models reviewed for WTMP application.

Model	Sponsor ¹	URL	Citation(s)
CE-QUAL-W2	PSU, USACOE	http://cee.pdx.edu/w2/	Cole, T. M., & Wells, S. A. 2008. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.6. Prepared for U.S. Army Corps of Engineers, Washington, DC 20314-1000. Wells, S. A., Editor. 2020. "CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.2, user manual part 1, introduction," Department of Civil and Environmental Engineering, Portland State University, Portland, OR. Wells, S. A. 2020. "CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.2.2, user manual part 5, model utilities and release notes," Department of Civil and Environmental Engineering, Portland State University, Portland, OR
DYRESM	CWR-UWA	http://www.colby.edu/chemistry/EastPond/East_Pond/DYRESM_Model.html	Antenucci, J., and A. Imerito. 2003. The CWR Dynamic Reservoir Simulation Model DYRESM: User Manual. Centre for Water Research: The University of Western Australia.
HEC-5Q	USACOE	(unsupported)	U.S. Army Corps of Engineers, Hydrologic Engineering Center. 1986. HEC-5Q: System Water Quality Modeling. TP-111. January. (HEC-5Q Model Application) U.S. Army Corps of Engineers, Hydrologic Engineering Center. 1986. HEC-5Q: Simulation of Flood Control and Conservation Systems – Appendix on Water Quality Analysis. CPD-5Q. January. (HEC-5Q User's Manual)
HEC-ResSim	USACOE	https://www.hec.usace.army.mil/software/hec-ressim/	U.S. Army Corps of Engineers, Hydrologic Engineering Center. 2021. HEC-ResSim: Reservoir System Simulation – User's Manual (Version 3.3). CPD-82. February. (HEC-ResSim User's Manual) Additional citations can be accessed at HEC-ResSim Documentation
Riverware	CADSWES	http://cadswes.colorado.edu/riverware/	Zagona, E., T. Magee, D. Frevert, T. Fulp, M. Goranflo and J. Cotter (2005). "RiverWare." In: V. Singh & D. Frevert (Eds.), <i>Watershed Models</i> , Taylor & Francis/CRC Press: Boca Raton, Florida, pp. 527–548. Zagona, E., T. Fulp, R. Shane, T. Magee, and H. Goranflo (2001), "RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling," <i>Journal of the American Water Resources Association</i> , AWRA 37(4):913–929.

¹Sponsors:

CADWES: Center for Advanced Decision Support for Water and Environmental Systems

CWR-UWA: Center for Water Resources, University of Western Australia

PSU: Portland State University

USACOE: US Army Corps of Engineers

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Table 3-2. River models reviewed for WTMP application.

Model	Sponsor ¹	URL	Citation(s)
CE-QUAL-RIV1	USACOE	https://erdc-library.erdc.dren.mil/jspui/handle/11681/4352	Army Corps of Engineers. 1990. CE-QUAL-RIV1: A Dynamic, One-Dimensional (Longitudinal) Water Quality Model for Streams, User's Manual. Instruction Report E-90-1
EPD-RIV1	GEPD	http://epdsoftware.wileng.com/	Martin, J.L and T. Wool. 2001. Dynamic One-Dimensional Model of Hydrodynamics and Water Quality - EPD-RIV1 User's Manual (Version 1.0). Prepared for Georgia Environmental Protection Division, Atlanta, Georgia.
Heat Source	ODEQ	https://www.oregon.gov/deq/wq/tmdls/Pages/TMDLs-Tools.aspx	Boyd, M., and Kasper, B. 2003. Analytical methods for dynamic open channel heat and mass transfer: Methodology for heat source model Version 7.0.
HEC-5Q	USACOE	(unsupported)	U.S. Army Corps of Engineers, Hydrologic Engineering Center. 1986. HEC-5Q: System Water Quality Modeling. TP-111. January. (HEC-5Q Application) U.S. Army Corps of Engineers, Hydrologic Engineering Center. 1986. HEC-5: Simulation of Flood Control and Conservation Systems – Appendix on Water Quality Analysis. CPD-5Q. January. (HEC-5Q User's Manual)
HEC-RAS	USACOE	https://www.hec.usace.army.mil/software/hec-ras/	U.S. Army Corps of Engineers, Hydrologic Engineering Center. 2021. HEC-RAS River Analysis System, User's Manual (Version 6.0). CPD-68. May. (HEC-RAS User's Manual) Additional citations for HEC-RAS Historical Documentation and Recent HEC-RAS Model Documentation
HEC-ResSim	USACOE	https://www.hec.usace.army.mil/software/hec-ressim/	U.S. Army Corps of Engineers, Hydrologic Engineering Center. 2021. HEC-ResSim: Reservoir System Simulation – User's Manual (Version 3.3). CPD-82. February. (HEC-ResSim User's Manual) Additional citations for HEC-ResSim Documentation
QUAL2K	Tufts Univ., USEPA, WDOE	http://www.qual2k.com/home/default.html	Chapra, S.C., Pelletier, G.J. and Tao, H. 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.11: Documentation and User's Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA., Steven.Chapra@tufts.edu (QUAL 2K Documentation and User's Manual)
RAFT	NOAA-SFSC	https://oceanview.pfeg.noaa.gov/CVTEMP/river/model	Daniels, Miles E., V.K. Sridharan, S.N. John, and E.M. Danner. 2018. Calibration and validation of linked water temperature models for the Shasta Reservoir and the Sacramento River from 2000 to 2015. NOAA Technical Memorandum NMFS-SWFSC-597. 60 p. Additional references for RAFT model
RBM10	USEPA	n/a	U.S. Environmental Protection Agency. 2018. EPA Fact Sheet: River Basin Model-10. (RBM10 Fact Sheet) Contact: Ben Cope U.S. EPA Region 10 Modeling Lead cope.ben@epa.gov (206) 553-1442 Jones, E.C., Perry, R.W., Risley, J.C., Som, N.A., and Hetrick, N.J., 2016, Construction, calibration, and validation of the RBM10 water temperature model for the Trinity River, northern California: U.S. Geological Survey Open-File Report 2016–1056, 46 p. (Trinity River RBM10 Model Documentation)

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Model	Sponsor ¹	URL	Citation(s)
River Modeling System (ADYN/RQUAL)	Loginetics	http://www.loginetics.com/index.html	Hauser, G.E. and Walters, M. 1995. User's Manual for One-Dimensional Unsteady Flow and Water Quality Modeling in River Systems with Dynamic Tributaries. WR28-3-590-135. TVA Engineering Laboratory. Norris, Tennessee. July.
Riverware	CADSWES	http://cadswes.colorado.edu/riverware/	Zagona, E., T. Magee, D. Frevert, T. Fulp, M. Goranflo and J. Cotter (2005). "RiverWare." In: V. Singh & D. Frevert (Eds.), Watershed Models, Taylor & Francis/CRC Press: Boca Raton, Florida, pp. 527–548. Zagona, E., T. Fulp, R. Shane, T. Magee, and H. Goranflo (2001), "RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling," Journal of the American Water Resources Association, AWRA 37(4):913–929.
RMA2/ RMA4	Aqueveo	https://www.aquaveo.com/	Donnell, B. P., Joseph V., W. H. McAnally, and others. 2011. "Users Guide for RMA2 Version 4.5," 27 Sept (RMA2 User's Manual) Joseph V., Donnell, B.P., and others. 2008 "Users Guide for RMA4 Version 4.5", 14 Aug (RMA4 User's Manual)

¹Sponsors:

CADWES: Center for Advanced Decision Support for Water and Environmental Systems

GEPD: Georgia Environmental Protection Division

NOAA-SFSC: National Oceanic and Atmospheric Administration-Southwest Fisheries Science Center

ODEQ: Oregon Department of Environmental Quality

USACOE: US Army Corps of Engineers

USEPA: US Environmental Protection Agency

WDOE: Washington Department of Ecology

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Table 3-3. Sediment transport models that were reviewed but excluded from WTMP applications.

Model	Sponsor ¹	URL
SRH-2D	USBR	https://www.usbr.gov/tsc/techreferences/computer%20software/models/srh2d/index.html
Adaptive Hydraulics Model	USACOE	https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/476708/adaptive-hydraulics-model-system/

¹Sponsors

USBR: US Bureau of Reclamation

USACOE: US Army Corps of Engineers

Table 3-4. Three-dimensional reservoir models that were reviewed but excluded from WTMP applications.

Model	Sponsor ¹	URL
Environmental Fluid Dynamics Code (EFDC)	USEPA	https://www.epa.gov/ceam/environmental-fluid-dynamics-code-efdc
AQUATOX	USEPA	https://www.epa.gov/ceam/aquatox
Delft3D-FM	Deltares	https://oss.deltares.nl/web/delft3d/
Semi-implicit Cross-scale Hydrosience Integrated System Mode (SCHISM)	Virginia Institute of Marine Sciences	https://www.vims.edu/ccrm/research/modeling/schism/index.php
Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (SUNTANS)	Stanford University	https://web.stanford.edu/group/suntans/cgi-bin/documentation/user_guide/user_guide.html

¹Sponsors:

USEPA: US Environmental Protection Agency

Models in Table 3-1 and Table 3-2 were subsequently compared with the criteria in Table 2-1 through Table 2-6 to assist model selection. With the many criteria applied to the model selection process, there were no models that met all criteria. The model selection process used quantitative measures to pare down the list of potential models, and from this subset a final suite of models was selected.

Consistent with the desire of Reclamation to have both a relatively fast calculation model for making suites of simulations as well as having more detailed models for improved system representation, a system model that represents reservoir-river systems and discrete reservoir or river models, respectively, were selected by Reclamation for further consideration. For purposes of this memorandum, a discrete model represents a single component – a single reservoir (e.g., Shasta Lake) or a specific river reach (e.g., Sacramento River from Keswick Dam to Red Bluff). Selection criteria for the system and reservoir models under consideration are included in the following tables:

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- System and discrete reservoir models reviewed based on criteria for numerical models are listed in Table 3-5.
- System and discrete reservoir models reviewed based on criteria based on model linkage capability are listed in Table 3-6.
- System and discrete reservoir models reviewed based on criteria based on model input and output capabilities are listed in Table 3-7.
- System and discrete reservoir models reviewed based on criteria based on model support are listed in Table 3-8.
- System and discrete reservoir models reviewed based on criteria based on specific features of current or planned CVP facilities are listed in.
- System and discrete reservoir models reviewed based on criteria based on qualitative model elements are listed in Table 3-10.

Selection criteria for the river models under consideration are included in the following tables:

- Discrete river models reviewed based on criteria for numerical models are listed in Table 3-11.
- Discrete river models reviewed based on criteria based on model linkage capability are listed in Table 3-12.
- Discrete river models reviewed based on criteria based on model input and output capabilities are listed in Table 3-13.
- Discrete river models reviewed based on criteria based on model support are listed in Table 3-14.
- Discrete river models reviewed based on criteria based on specific features of current or planned CVP facilities are listed in Table 3-15.
- Discrete river models reviewed based on criteria based on qualitative model elements are listed in Table 3-16.

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Table 3-5. System and discrete reservoir models reviewed for WTMP application based on numerical model criteria.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Model type (Discrete/ System)	Is the model a discrete model or a system model?	NA	Discrete	Discrete	System	System	System
Model type (River/ Reservoir)	Is the model designed for predicting vertical distributions and release-water temperatures in a reservoir reach?	Require	Yes	Yes	Yes	Yes	Yes
Short-term forecasting	Within season (days, weeks, months)	Require	Yes	Yes	Yes	Yes	Yes
Long-term planning	Extended simulations (years, decades)	Require	Yes* (*feasible but computationally inefficient)	Yes* (*feasible but computationally inefficient)	Yes	Yes	Yes
Number of dimensions (1, 2)		NA	2	1	1	1	1
System geometric representation	Principal dimension(s): longitudinal/ vertical	NA	Longitudinal/ vertical	Vertical	Vertical	Vertical	Vertical
System geometric representation	Detailed vertical resolution? (Yes/ No)	Require	Yes	Yes	Yes	Yes	No
Dynamic flow model	Yes/ No	Prefer	Yes	No	Yes	Yes	No
Water temperature representation	Full heat budget: Yes/ No	Require	Yes	Yes	No	Yes	Yes
Time step (capable of sub-daily)	Yes/ No	Require	Yes	Yes	Yes	Yes	Yes
Computational performance consideration	Faster/ Slower	NA	Slower	Faster	Faster	Faster	Unknown

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Table 3-6. System and discrete reservoir models reviewed for WTMP application based on criteria for model linkage capabilities.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Discrete component model or system model	Discrete/ System	NA	Discrete	Discrete	System/ Discrete	System/ Discrete	System
Modeling framework compatible	Readily incorporated into a framework. Yes/ No	Prefer	Yes	Unknown	Yes	Yes	Yes

Table 3-7. System and discrete reservoir models reviewed for WTMP application based criteria for model input and output capabilities.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Pre-processor	Yes/ No	Prefer	Yes	Yes	No	Yes	Unknown
Post-processor	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Yes
Data structure facilitates model calibration/application	Yes/ No	Prefer	Yes	Unknown	Yes	Yes	Yes

Table 3-8. System and discrete reservoir models reviewed for WTMP application based on criteria for model support.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Similar model applications	Many/ Few/ None	Prefer	Many	Unknown	Many	Few	Unknown
Actively supported	Yes/ No	Require	Yes	Yes	No	Yes	Yes
Public domain (PD), peer reviewed (PR), or accessible modifications (AM)	PD/ PR/ AM	Require	PD/PR/AM	PR	PD/ AM	PD/ PR/ AM	PR
Documentation	Yes/ No	Require	Yes	Yes	Yes	Yes	Yes
Training and/or user group	Yes/ No	Prefer	Yes	Yes	No	Yes	Yes

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Table 3-9. System and discrete reservoir models reviewed for WTMP application based on criteria for specific features of current or planned CVP facilities.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Temperature control curtains	Yes/ No	Require	Yes	No	No	No	No
Submerged weirs/dams	Yes/ No	Require	Yes	No	Yes	Yes	No
Selective withdrawal	Yes/ No	Require	Yes	Yes	Yes	Yes	Unknown
Automated simulations to meet downstream temperature targets: tailbay	Yes/ No	Require	Yes	Unknown	Yes	Yes	Unknown
Automated simulations to meet downstream temperature targets: river reach	Yes/ No	Prefer	NA	NA	Yes	Yes	Unknown
Shade	Yes/ No (v=vegetation, t=topographic)	Prefer	Yes (t)	Unknown	Yes (v)	Yes (v)	No

Table 3-10. System and discrete reservoir models reviewed for WTMP application based on criteria for qualitative modeling elements.

Criteria	Comments	Need	CE-QUAL-W2	DYRESM	HEC-5Q	HEC-ResSim	Riverware
Ease of use	Less/ More Difficult	Prefer	More	Unknown	More	Unknown	Unknown
Credibility	Yes (supported)/ No (unsupported)	Prefer	Yes	Yes	No	Yes	Yes
Easy to incorporate uncertain input parameters	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Unknown
Collaboration with model developers	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Yes

Table 3-11. Discrete river models reviewed for WTMP application based on numerical model criteria.

Criteria	Comment	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Model type (River/Reservoir)	Is the model designed for predicting vertical distributions and release-water temperatures in a reservoir reach?	Require	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Short-term forecasting	Within season (days, weeks, months)	Require	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Long-term planning	Extended simulations (years, decades)	Require	No	No	No	No	Yes	No	Yes	No	Unknown	Yes	No	Yes	No
Number of dimensions (1, 2)	1/ 2	NA	1	1, 2	1	1	1	1	1	1	1	1	1, 2	1	1
System geometric representation	Principal dimension(s): longitudinal (Long.)/ lateral (Lat.)/ vertical (Vert.)	NA	Long.	Long./ Vert.	Long.	Long.	Long.	Long.	Long.	Long.	Long.	Long.	Long./ Lat.	Long.	Long.
Dynamic flow model	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
Water temperature representation	Full heat budget: Yes/ No	Require	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time step (capable of sub-daily)	Yes/ No	Require	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

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Criteria	Comment	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Computational performance consideration	Faster/ Slower	NA	Faster	Slower	Faster	Faster	Faster	Faster	Faster	Faster	Faster	Faster	Slower	Unknown	Faster

Table 3-12. Discrete river models reviewed for WTMP application based on criteria for model linkage capabilities.

Criteria	Comments	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
System model or discrete reach	System/ Discrete	NA	Discrete	Discrete	Discrete	Discrete	System/ Discrete	Discrete	System/ Discrete	Discrete	Discrete	Discrete	Discrete	System/ Discrete	Discrete
Modeling framework compatible	Readily incorporated into a framework: Yes/ No	Prefer	Yes	Yes	Unknown	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 3-13. Discrete river models reviewed for WTMP application based criteria for model input and output capabilities.

Criteria	Comments	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Pre-processor	Yes/ No	Prefer	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Unknown	Yes	Yes	Unknown	Unknown
Post processor	Yes/ No	Prefer	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unknown	Yes	Yes	Yes
Data structure facilitates model calibration/ application	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 3-14. Discrete river models reviewed for WTMP application based on criteria for model support.

Criteria	Comments	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Similar model applications	Many/ Few	Prefer	Few	Many	Few	Many	Many	Few	Few	Many	Few	Few	Many	Unknown	Many
Actively supported	Yes/ No	Require	No	Yes	Unknown	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Public Domain (PD), Peer Reviewed (PR), or Accessible Modifications (AM)	PD/ PR/ AM	Require	PD/ PR/ AM	PD/ PR/ AM	PD/ PR/ AM	PD/ PR/ AM	PD/ AM	PD/ PR/ AM	PD/ PR/ AM	PD/ PR/ AM	PD/ PR	PD/ PR/ AM	PR	PR	PR
Documentation	Yes/ No	Require	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Training and/or User Group	Yes/ No	Prefer	No	Yes	No	No	No	Yes	Yes	Yes	No	No	No	Yes	No

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Table 3-15. Discrete river models reviewed for WTMP application based on criteria for model support.

Criteria	Comments	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Temperature control curtains	Yes/ No	Require	NA	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Submerged weirs/dams	Yes/ No	Require	NA	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Selective withdrawal	Yes/ No	Require	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Automated simulations to meet downstream temperature targets: tailbay	Yes/ No	Require	NA	NA	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Automated simulations to meet downstream temperature targets: river reach	Yes/ No	Prefer	NA	NA	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Shade	Yes/ No (v=vegetation, t=topographic)	Prefer	No	Yes (t)	No	Yes (v,t)	Yes (v)	Yes (v)	Unknown	Yes (v)	Unknown	No	Yes (v,t)	No	Yes (v)

Table 3-16. Discrete river models reviewed for WTMP application based on criteria for qualitative modeling elements.

Criteria	Comments	Need	CE-QUAL-RIV1	CE-QUAL-W2	EPD-Riv1	Heat Source	HEC-5Q	HEC-RAS	HEC-ResSim	QUAL-2K	RAFT	RBM10	RMA2/RMA4	Riverware	RMS (ADYN/RQUAL)
Ease of use	Less/More Difficult	Prefer	More	More	More	Unknown	More	Unknown	Unknown	Unknown	Unknown	Unknown	More	Unknown	Unknown
Credibility	Yes/ No (supported/ unsupported)	Prefer	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Model developer collaboration	Yes/ No	Prefer	Unknown	Yes	Unknown	Unknown	Yes	Yes	Yes	Unknown	Yes	Unknown	Yes	Unknown	Unknown
Uncertainty incorporation	Yes/ No	Prefer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Chapter 4 Initial Model Selection

Model selection criteria were applied to the identified system, reservoir, and river models and an initial model selection was made for each category for inclusion into the WTMP.

System Model Selection

The only system model that generally met all required criteria was HEC-ResSim. Other system models (e.g., Riverware, HEC-5Q) lacked support, were proprietary, included a notable cost, or have other factors which make them unsuitable.

Features of HEC-ResSim that warrant further discussion are addressed below:

- HEC-ResSim represents unsteady flow using hydrologic routing methods that have been used effectively in both reservoir and river temperature models (DeGeorge et al. 2018, USACE 2016, Goode et al. 2010, and Modini 2010).
- HEC-ResSim has been widely applied as a reservoir-river operations model; however, the number of applications for temperature modeling is limited, but expanding. The model representation of water temperature fate and transport in reservoir and river systems is drawn from other, long-standing models (see Zhang and Johnson 2016).
- At this time, the model does not include temperature control curtains or submerged dams, elements that are important to certain CVP facilities. These logic elements are readily available in other models (e.g., CE-QUAL-W2, HEC-5Q) and adding such representation to HEC-ResSim will be examined as part of this project.

A unique attribute of HEC-ResSim is the ability to not only simulate operating to reservoir tailbay temperature targets, but also to assess needed operations to meet downstream river temperature targets in model simulations using a built in function. Overall, HEC-ResSim fulfills the role of a computationally efficient reservoir-river system model that would be effective in the Sacramento/Trinity, American, and Stanislaus River basins.

Reservoir Model Selection

For certain systems Reclamation desires to have access to more detailed representations of reservoirs and specific attributes. For example, assessing longitudinal thermal gradients, as well as vertical temperature stratification in larger reservoirs, can identify when cold water pool segregates from surface inflows, providing useful information for system operators and decision makers. Other examples include representing branching reservoirs with differing tributary inflows and temperatures, the spatial representation of temperature control curtains (e.g., Whiskeytown Lake, Lewiston Lake), and other features.

Chapter 4 Initial Model Selection

CE-QUAL-W2 meets the majority of the criteria identified in Table 3-4 and was selected for the detailed reservoir model. CE-QUAL-W2 applications exist for several CVP reservoirs (Shasta Lake (Watercourse 2020), Keswick Reservoir (Watercourse 2020), Lewiston Lake (Jayasundara and Deas 2012), Folsom Lake (Cardno, 2021)) and can be developed for other CVP reservoirs as needed. In addition to CE-QUAL-W2, the HEC-ResSim model can also be used to represent a discrete component model (or represent several discrete components) where appropriate.

River Model Selection

River model selection required identifying a model that can effectively represent variable flow, depth, and surface area, as well as simulate water temperature on a sub-daily basis in response to meteorological conditions. Data needs, computational considerations, and current modeling needs indicate that a one-dimensional model is sufficient to meet current water temperature modeling needs in the river reaches downstream of CVP facilities. As a result, two-dimensional models were not considered.

Of the one-dimensional models considered for the WTMP, the following were removed from consideration: CE-QUAL-RIV1, EPD-Riv1, HEC-5Q, QUAL2K, RBM-10, and RMA2/4. Reasons included lack of active support, lack of short-term forecasting or long-term simulation, time step, inability to model varying flows, lack of model accessibility (modifications) and/or public domain considerations, and other issues. The remaining models (Heat Source, HEC-RAS, HEC-ResSim, and RAFT) are all one-dimensional models that generally met the basic criteria.

However, HEC-ResSim was selected for the river model because the tool meets all the criteria including: previous wide applications, extensive selective withdrawal flexibility, can provide options for reservoir release temperature targets as well as downstream river temperature targets (as a system model), readily fits into the HEC-WAT framework (selected framework for the WTMP), model and pre- and post-processors are well documented and in the public domain, model developers are interested in collaboration, and several other beneficial features. Water temperature specific applications of the model at this time include the Merced River system and the Russian River basin, with applications currently being considered for temperature and/or water quality for reservoir-river systems in the Columbia River basin, Osage River basin (tributary to the Missouri River), and the Salt River basin (tributary to the Mississippi River).

Chapter 5 WTMP Model Recommendation Summary

Reclamation’s objective for the development of the Water Temperature Modeling Platform (WTMP) is the effective and efficient management of CVP resources for downstream regulatory and environmental requirements within the context of an uncertain environment. The primary development goal of these computational tools is to produce trusted, reasonable predictions of downstream water temperatures for planning, seasonal, and real-time applications while also describing situational risk and uncertainty.

For the CVP, there is a need for both a broader network model that can accommodate the large complex reservoir-river networks for temperature management purposes and a framework that can accommodate the more detailed models that represent specific operation of facilities (including the applicable temperature management infrastructure). This document presents Reclamation’s requirements for a WTMP system model as well for discrete reservoir and river models that can be used together in a modeling framework (see Technical Memorandum 5: Model Framework Selection and Design). Model selection criteria that were developed based on those requirements, and an evaluation of potential models based on those criteria.

A summary of the recommended models is included in Table 5-1. These models will reside in a modeling framework (See Technical Memorandum 5) that will form the WTMP and undergo additional assessment and testing prior to being applied to the Sacramento/Trinity, American, and Stanislaus River basins.

Table 5-1. System, Reservoir, and River Temperature Models Recommended for WTMP.

Type	Selected Model
System Model	HEC-ResSim
Discrete Model – Reservoir	CE-QUAL-W2 (HEC-ResSim is also available)
Discrete Model – River	HEC-ResSim

Chapter 5 WTMP Model Recommendation Summary

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Chapter 6 References

- California Water and Environmental Modeling Forum (CWEMF). 2021. Protocols for Water and Environmental Modeling – Final Draft. April 7.
- Cardno. 2021. Technical Memorandum 5 Folsom Reservoir CE-QUAL-W2 Temperature Model. Prepared for Placer County Water Agency. 2021.
- Chinyama, A., G.M. Ochieng, I. Nhapi, and F.A.O. Otieno. 2014. A simple framework for selection of water quality models. *Reviews in Environmental Science and Bio/Technology*. 13. 10.1007/s11157-013-9321-3.
- DeGeorge, J., S. Andrews, T. Steissberg, Z. Zhang. 2018. Development and an Integrated Water Quality Modeling Engine for HEC-RAS, HEC-ResSim, and HEC-HMS. Presentation at the 13th International Conference on Hydrosience & Engineering. Chongqing, China. June 18-22, 2018.
- Ejigu, M.T. 2021. Overview of water quality modeling, *Cogent Engineering*, 8:1, DOI: 10.1080/23311916.2021.1891711.
- Goode, D.J., E.H. Koerkle, S.A. Hoffman, R.S. Regan, L.E. Hay, and S.L. Markstrom. 2010. Simulation of runoff and reservoir inflow for use in a flood-analysis model for the Delaware River, Pennsylvania, New Jersey, and New York, 2004-2006: U.S. Geological Survey Open-File Report 2010-1014, 68 p.
- HEC (U.S. Army Corps of Engineers, Institute for Water Resources – Hydrologic Engineering Center). 2021. HEC-ResSim Reservoir System Simulation: User's Manual. V3.3. CPD-82. Davis, CA.
- HEC (U.S. Army Corps of Engineers, Institute for Water Resources – Hydrologic Engineering Center). 2000. HEC-5, Simulation of Flood Control and Conservation Systems, Appendix on Water Quality Analysis. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.
- HEC (U.S. Army Corps of Engineers, Institute for Water Resources – Hydrologic Engineering Center). 2016. Missouri River Recovery Management Plan Time Series Data Development for Hydrologic Modeling (Draft). Prepared by the Northwestern Division Omaha and Kansas City Districts, Hydrologic Engineering Branch, Engineering Division. September.
- HEC (U.S. Army Corps of Engineers, Institute for Water Resources – Hydrologic Engineering Center). 1999. Water Quality Modeling of Reservoir System Operations Using HEC-5, Training Document. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis CA.
- Jayasundara, N. and M.L. Deas. 2012. Lewiston Reservoir Water Temperature Modeling. Prepared for the U.S. Bureau of Reclamation. December.
- Ji, Zhen-Gang. 2017. *Hydrodynamics and Water Quality, Modeling Rivers, lakes, and Estuaries*. John Wiley and Sons Inc. Hoboken New Jersey. 581 pp.

Chapter 6 References

- Loucks D.P., E. van Beek. 2017. Water Quality Modeling and Prediction. In: Water Resource Systems Planning and Management. Springer, Cham. https://doi.org/10.1007/978-3-319-44234-1_10.
- Martin, J.L. and S.C. McCutcheon. 1999. Hydrodynamics and Transport for Water Quality Modeling. Lewis Publishers. New York. 794 pp.
- Mateus, M., R. da Silva Vieira, C. Almeida, M. Silva, and F. Reis. 2018. ScoRE—A Simple Approach to Select a Water Quality Model. *Water*. 10. 1811. 10.3390/w10121811.
- Modini, C. 2010. Using HEC-ResSim for Columbia River Treaty Flood Control. Presentation at 2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 - July 1, 2010.
- Sharma, D., A. Kansal. 2012. Assessment of river quality models. *Rev Environ Sci Biotechnol*. 12:285-311. DOI 10.1007//s11157-012-9285-8.
- U.S. Bureau of Reclamation (Reclamation). 2021. Technical Memorandum: Model Framework Selection and Design (DRAFT). September.
- Watercourse Engineering, Inc. (Watercourse). 2020. Shasta Lake and Keswick Reservoir Flow and Temperature Modeling – Development Report. Prepared for the Sacramento River Settlement Contractors. December.
- Zhang. Z. and B.E. Johnson. 2016. Aquatic Nutrient Simulation Modules (NSMs) Developed for Hydrologic and Hydraulic Models. Prepared by the U.S. Army Corps of Engineers (USACE) Ecosystem Management and Restoration Research Program at the Research and Development Center (ERDC). ERDC/EL TR-16-1. February.