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Dear Nick:

This letter summarizes ERM's review of the Lake Powell CE-QUAL-W2 Model. Our review is based on information you provided which consists of the model application (CE-QUAL-W2 executable and input files) and the following documents:

- Background Information for Peer Review of the Lake Powell CE-QUAL-W2 Model

- Modeling Dissolved Oxygen in Lake Powell using CE-QUAL-W2

- Projecting Temperature in Lake Powell and the Glen Canyon Dam Tailrace

- Water Quality Modeling Documentation, especially Chapter C "Reservoir Modeling Using CE-QUAL-W2 - Model Description"

- Glen Canyon Dam Penstock Withdrawal Characteristics, 2007-2008

- Historical Physical and Chemical Data for Water in Lake Powell and from Glen Canyon Dam Releases, Utah-Arizona, 1964–2008

- LPTN 1990-2008 Run Log.xlsx

The review evaluates the model for its suitability for the following purposes:

- assessment of changes in reservoir water quality due to various operational or natural changes, and

- projections of changes in temperature (primarily) and TDS and DO (secondarily) based on forecasts of inflow rates.

The review process consisted of examining input and output files, the latter obtained by executing the model, and studying the provided documents. ERM has familiarity with modeling Lake Powell, having applied an early version of CE-QUAL-W2 to Lake Powell and having reviewed Williams (2007).

In summary, Version 3.2 of CE-QUAL-W2 was used to model water surface elevations, velocities, temperature, TDS, and dissolved oxygen in Lake Powell and was calibrated for a 19-year historical period for these parameters.

The model application consists of the CE-QUAL-W2 executable and a set of input files. The model source code was modified to interface with the AGPM visualizer and to read time-varying gate elevations and time-varying evaporative heat loss coefficients. The input files were developed from the Bureau's comprehensive set of observations and used to construct time-varying boundary and initial conditions for the historical period. Similarly, a significant amount of water quality calibration data exists and was used to assess and correct the model's performance. The calibrated model has been exercised for a number tasks including evaluating the effects of the diversion of up to 100,000 ac-ft per year of storage and estimating temperature, TDS and dissolved oxygen based on forecast inflow rates.

MODEL SELECTION, APPLICATION AND CALIBRATION

CE-QUAL-W2 is the most appropriate time-varying, hydrodynamic and water quality model for Lake Powell inasmuch as its longitudinal dimension accurately and economically maps the long and relatively narrow layout of Lake Powell's main stem and tributary arms to capture longitudinal water quality gradients. The model's vertical dimension allows representation of changes in water quality with depth. The model's assumption of bank-to-bank homogeneity is consistent with the fact that lateral gradients do not appear to be important.

The model's ability to simulate specific events is limited only by the availability of frequent boundary conditions data. The time-varying nature of the model allows diurnal (solar cycle), weekly (weather system), and seasonal changes to be simulated.

The use of CE-QUAL-W2 to study circulation and water quality in Lake Powell has an extended history, beginning with extensive modeling studies of Lakes Mead and Powell using LARM, the initial version of CE-QUAL-W2 (Edinger and Buchak 1982, 1983; Buchak and Edinger 1983).

The Lake Powell application makes use of CE-QUAL-W2, Version 3.2 Version 3.6 of the model is available and Version 3.7 has been released for beta testing. The major differences between 3.2 and 3.6 are the addition of zooplankton, macrophyte, and new state variables and the availability of a more elaborate water balance utility. These additions are not important to the present use of the Lake Powell model, except that the Version 3.6 includes a number of bug fixes that could potentially alter the results. A reasonable approach will be to upgrade the Lake Powell application when Version 3.7 is released. At that time, a comparison of simulations made with Versions 3.2 and 3.7 will be necessary to perform and document.

Model grid

The Lake Powell model application has very good detail spatial: in the longitudinal direction there are nine branches represented by a total of 95 active segments, each 0.8 to 17 km in length. Vertical layers are 1.75 m thick. The bathymetric data used to create the model grid – essentially the widths of each cell defined by longitudinal and vertical spacing – are based on the most recently available datasets.

An examination of the grid in the immediate vicinity of Glen Canyon Dam indicates complex connections between the Colorado River Channel and Wahweap and Warm Creek Bays (see Figure 3 in Williams 2010). The model represents the two bays as connected only to the Colorado River Channel whereas they are also be connected to one another through the Castle Rock Cut. The model will allow doubly-connected branches, but will not disconnect them when water surface elevations decline to the point where the branches are not connected. Disconnection occurs when water surface elevations fell below 3615 ft, a frequent occurrence in recent years. It is unknown if this possibility has been evaluated or whether the dynamics of the connection are important to the purposes of the model. An alternative if circulation and water quality in the immediate vicinity of Glen Canyon Dam and these bays are significant is to run a spatially-detailed model like CE-QUAL-W2's three-dimensional counterpart GEMSS (the Generalized Environmental Modeling System for Surfacewaters). GEMSS can make use of information provided by CE-QUAL-W2 at the boundaries of the three-dimensional model on a time-varying basis.

Time-varying boundary and initial condition data

As noted, time-varying boundary condition datasets have been assembled for a 19-year period. These datasets generally consist of daily values (sub-hourly for meteorological parameters). For nutrient concentrations, the values are constant through time.

The sources of the datasets are described in several of the provided documents. The boundary condition datasets consist of the following types:

- Inflow rates at the head of each branch and tributary; the larger inflows are well known from observations.

- Inflow temperatures and TDS values for each branch and tributary; these are measured at sporadic intervals.

- Inflow nutrient values for each branch and tributary; the model assumes constant concentrations for phosphorus, nitrate/nitrite, and ammonia; this approach is consistent with the limited availability of data.

- Glen Canyon Dam outflow rates; well known from observations.

- Meteorological data from Page, Arizona, just south of Glen Canyon Dam, with cloud cover data from Hanksville, located to 110 mi to the northeast of Page.

The model would benefit from meteorological data more representative of conditions immediately above the water surface and from direct measurement of solar radiation. Although the water temperature calibration is within accepted error bounds (<1°C AME), it is possible that the goodness-of-fit relies on a combination of evaporative heat loss formula and wind stress coefficient tuning.

The ideal meteorological dataset would include hourly observations of all parameters including solar radiation from instrumentation placed on rafts, the locations of which would be selected to represent Lake Powell's surface area in an economical fashion. A less expensive, but entirely satisfactory alternative would be similarly situated land-based stations. Compact stations of the type required are not expensive, although operation, security, and maintenance in remote locations would be a consideration. ERM strongly recommends that the minimum effort would be to deploy a solar radiation instrument.

A second approach, which would also allow recovery of meteorological data for the entire historical period and as far back as 1948, would be to make use of prognostic meteorological such as MM5. MM5 is a widely-used three-dimensional numerical meteorological model which contains non-hydrostatic dynamics, a variety of physics options for parameterizing cumulus clouds, microphysics, the planetary boundary layer and atmospheric radiation. MM5 is used to generate three dimensional gridded meteorological data, including the parameters required by CE-QUAL-W2 for surface heat exchange and wind stress computations, through sophisticated treatment and assimilation of available surface/upper air/precipitation observations.

MM5 uses 1km by 1km gridded land use to estimate surface properties within the domain. It also uses the pre-processed wind field from global weather simulations to obtain the initial and boundary conditions.

A typical MM5 domain is approximately 240 km in both the north-south and east-west directions. These dimensions correspond roughly to the dimensions of Lake Powell and its immediate drainage basin. Downscaling is used to estimate the required meteorological parameters at finer resolutions, e.g., 36, 12 or 4 km. CE-QUAL-W2 could be coded to used these downscaled parameter values at individual segments.

- Initial temperature, TDS and dissolved oxygen values; interpolated longitudinal and vertical.

The interpolated initial conditions likely result in the setup of small density currents because temperature- and TDS-dependent densities are not in static balance. Because the model results are only used after an initial spin-up period, these small density currents as well as the initial conditions themselves, are eventually supplanted by values closely related to the time-varying boundary condition data. However, it would be instructive to assess the magnitude of these small currents, which can be done by running the model for a short period with unchanging the boundary conditions (CE-QUAL-W2's dead sea case) and examining the velocity fields in the first few minutes of the simulation. Furthermore, because of the long residence time in Lake Powell, a formal assessment of the effects of initial conditions on constituent concentrations should be made by testing the sensitivity of results each time the model is used in operational or forecast mode.

Model calibration

The model was calibrated for the 19 year period, 1990-2008. The calibration quality is very good and the fact that the calibration period extends over 19 years, while somewhat dictated by Lake Powell's long residence time and by the availability of calibration data, is remarkable relative to common practice.

The main calibration targets were temperature, TDS and DO profiles for in-reservoir stations and for release time-series. All comparisons were quantified by station in terms of AME.

To calibrate temperatures, two related parameters were adjusted: segment-by-segment wind sheltering coefficients (the wsc.npt file) and the coefficients of the evaporative heat loss equation (the Wind Coefficients.npt file). The former represent segment-by-segment modifications of the wind that reflect physical wind sheltering effects, not unlike solar shading applied to each segment that reflects orientation and canyon wall height. Many CE-QUAL-W2 modelers use the wind sheltering coefficients to tune specific temperature profiles and therefore would a separate set of coefficients for each of the observed profiles. The Lake Powell model application applies a single set of coefficients over the entire 19-year period, a very robust approach.

Similarly, the model varies the evaporative heat loss equation coefficients seasonally, but repeats the seasonal cycle each year, once again eschewing the opportunity to tune individual computed profiles.

For this review, the kinetic rates were compared with CE-QUAL-W2's default values and no values are outside acceptable limits.

RECOMMENDATIONS FOR MODEL ENHANCEMENTS

Working from the list of potential updates and enhancements provided in Williams (2011), these are listed below in priority order:

- Update historic, or calibrated, model through the present – recommended, perhaps in conjunction with the annual forecasting process.

- Update the method from simulating dissolved oxygen to incorporate DO demand increases at lower pool elevations – recommended.

- Extend the historic model to the early 1980's which precedes a historic wet period in the Colorado River Basin and which includes spills from Lake Powell – recommended.

- Update to CE-QUAL-W2 to the latest version – recommended when Version 3.7 is released.

- Develop a model of tributary inflow temperatures to Lake Powell – only necessary if the current temperature forecasts are unsatisfactory and if tests are made to quantify the sensitivity to tributary temperatures. A one-dimensional tributary inflow model can be used to generate temperatures and to estimate gauge lag times. However, Water Temp Pro recording thermistors by Onset (or similar) should be deployed to provide data for calibration of a selected model and for direct use in the Lake Powell model. The remote locations of potential sites, the large and rapid changes in water surface elevation, and flood events combine to make installation and maintenance difficult.

- Calibrate the model for nutrients – only necessary if nutrients themselves become an issue or if the current DO results become unsatisfactory for future use; only possible if more frequent inflow nutrient data become available and the nutrient dynamics of delta formation and destruction are clarified.

- Add zooplankton to the model – not needed at the present time.

In addition, the following tests should be made:

- The importance of initial conditions can be assessed with simulations in which these are changed and changes in release temperatures as a function of time and inflow rate are noted.

- The use of several bounding meteorological dataset for annual projections instead of a single average year sets is recommended; years can be characterized based on response temperature or inflow temperature observations.

CONCLUSION

The Lake Powell modeling effort reflects exhaustive use of available data and a quantitative approach to calibration. Two important features of the model that support its credible use for the stated purposes are (1) the calibration data covered an usually long period – 19 years and (2) the fact that the model has been in continuous use for at least six years. The modeling effort used best practices and demonstrated utility of the calibrated model in both forecast and assessment modes. The 19-year calibration period means that the model is able to cover a large range of in-reservoir and release temperatures and TDS values. Additional datasets became available when the model was used to project these parameters from hydrologic forecasts; when forecast conditions are modified to reflect actual conditions, the model performed as well as during the calibration period.

Sincerely,

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Partner

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