# Optimally Managing Water Resources in Large River Basins for an Uncertain Future

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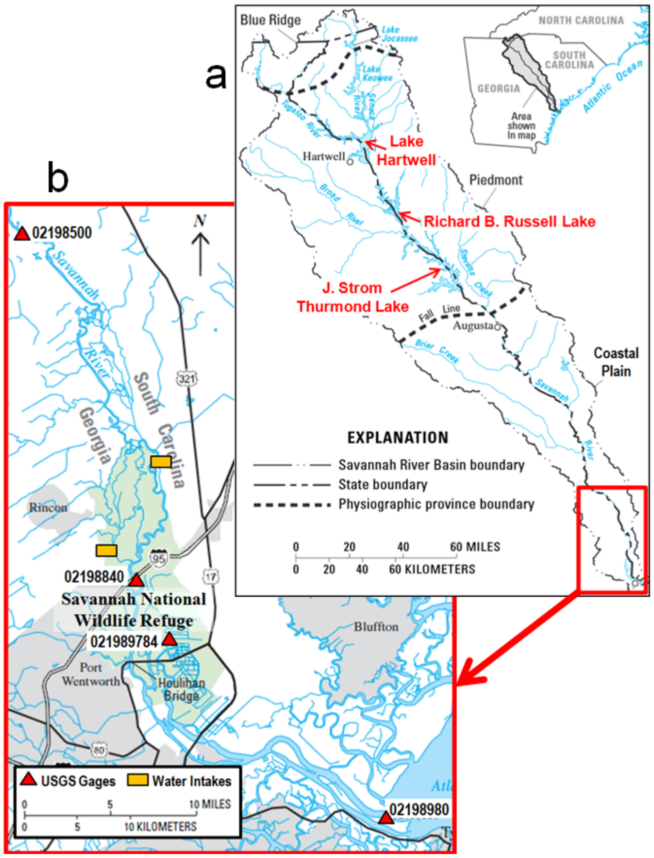

**Figure 1.** Maps showing the a) Savannah River Basin and b) lower Savannah River.

**ABSTRACT**. Managers of large river basins face conflicting needs for water resources such as wildlife habitat, water supply, wastewater assimilative capacity, flood control, hydroelectricity, and recreation. The Savannah River Basin for example, has experienced three major droughts since 2000 that resulted in record low water levels in its reservoirs, impacting local economies for years. The Savannah River Basin's coastal area contains municipal water intakes and the ecologically sensitive freshwater tidal marshes of the Savannah National Wildlife Refuge. The Port of Savannah is the fourth busiest in the United States, and modifications to the harbor have caused saltwater to migrate upstream, reducing the freshwater marsh's acreage more than 50 percent since the 1970s. There is a planned deepening of the harbor that includes flow-alteration features to minimize further migration of salinity. The effectiveness of the flow-alteration features will only be known after they are constructed.

One of the challenges of basin management is the optimization of water use through ongoing development, droughts, and climate change. This paper describes a model of the Savannah River Basin designed to continuously optimize regulated flow to meet prioritized objectives set by resource managers and stakeholders. The model was developed from historical data by using machine learning, making it more accurate and adaptable to changing conditions than traditional models. The model is coupled to an optimization routine that computes the daily flow needed to most efficiently meet the water-resource management objectives. The model and optimization routine are packaged in a decision support system that makes it easy for managers and stakeholders to use. Simulation results show that flow can be regulated to substantially reduce salinity intrusions in the Savannah National Wildlife Refuge while conserving more water in the reservoirs. A method for using the model to assess the effectiveness of the flow-alteration features after the deepening also is demonstrated.

## INTRODUCTION

The Savannah River Basin (basin; fig. 1a) is a prototypical large basin whose water-resource managers face conflicting needs, such as wildlife habitat, water supply, wastewater assimilative capacity, flood control, hydroelectricity, and recreation. In the upper basin, the U.S. Army Corps of Engineers (USACE) controls three large reservoirs - Lake Hartwell, Richard B. Russell Lake (Lake Russell), and J. Strom Thurmond Lake (Lake Thurmond). Lake Russell has comparatively little storage, leaving Lakes Hartwell and Thurmond to provide most of the regulated flow to the coast. Since 2000 the upper basin has experienced three major droughts, resulting in record and near-record low reservoir water-level elevations that impacted local economies.

The lower Savannah River (fig. 1b) contains two municipal water intakes and ecologically sensitive freshwater tidal marshes in the Savannah National Wildlife Refuge (Refuge). The interaction of regulated streamflow, tides, and weather produces salinity intrusions more than 25 miles upstream at U.S. Geological Survey (USGS) gage 02198840. Modifications to the harbor have caused saltwater to migrate upstream, reducing the freshwater marsh acreage more than 50 percent since the late 1970s (Conrads and others, 2006).

The complexity of the water-resource issues suggests that basin water management is a problem of optimizing water use for ongoing development, droughts, and sea-level rise. A solution is to save water “for later” by limiting regulated flows to the minimums needed to meet objectives prioritized by resource managers and stakeholders. This solution requires daily data updates that describe changing conditions, and leveraging them with a model that reliably predicts the requisite flows.

## PROJECT DESCRIPTION

This project built upon two previous studies. The first developed a hydrodynamic and water-quality model of the lower Savannah River to estimate the impacts of the planned harbor deepening on the Refuge (Conrads and others, 2006). The model was developed from historical data using artificial neural networks (ANN; Jensen, 1995), a form of machine learning that allows models to adapt to changing conditions. The model was packaged in a spreadsheet-based decision support system (DSS; Roehl and others, 2006), making it easy for managers and stakeholders to use. It was named the Model-to-Marsh DSS (M2M-DSS) because it connected two other models together, one of the hydrodynamics of the estuarine channel and the other of the marsh plant populations in the Refuge.

A second study modified the M2M-DSS, renamed M2M2-DSS, to estimate how sea-level rise and climate change would affect the magnitudes, frequencies, and durations of salinity intrusion events in the lower Savannah River (Conrads and others, 2013). This project developed a third version of the M2M-DSS, named M2M3-DSS, to study how the water resources of the upstream reservoirs could be managed differently to better protect the Refuge from salinity migration and conserve water.

Figure 2a shows the normalized (N) measured (m) water-level elevations (ELV) of Lakes Hartwell and Thurmond (HART, THUR) in feet (ft), labeled ELV_N-HARTm and ELV_N-THURm, for the February 10, 2007, to January 8, 2012 study period. All time series presented herein use a daily time step. Normalization was performed by subtracting the full pool elevations from the measured elevations. The maximum normalized full pond elevation during the study period was 2.6 ft. Lakes Hartwell and Thurmond reached their all time lowest and second lowest elevations, respectively, during the winter of 2008.

Figure 2b shows the measured regulated outflow (QOUT) of Lake Thurmond (QOUT-THURm) and the streamflow (Q) at USGS gage 02198500 (Q8500m). The study period represents the climatic extremes of two severe droughts and an El Niño episode. QOUT-THURm contributes most of the flow to Q8500m, with the additional flow due to rainfall and groundwater discharge originating between the gaging sites. During the droughts, QOUT-THURm was nearly constant, at the regulatory minimum flow deemed necessary to protect downstream water intakes and the Refuge. Figure 2c shows the measured maximum and minimum water levels (WL) at USGS gage 02198980 (WL8980MAXm and WL8980MINm, respectively). The major factors causing the water-level variability at this location are periodic tidal forcing, weather, and streamflow.

Figure 2d shows the measured maximum specific conductance (SC), the field measurement used to compute salinity, at USGS gages 021989784 and 02198840 (SC89784MAXm and SC8840MAXm, respectively). The spikes indicate intrusion events that occur during spring tides of the new moon when tidal ranges are greatest. Tides having a low range are called neap tides. Annual specific conductance cycles coincide with those of the water levels in Figure 2c. The specific conductance values also are modulated by weather and streamflow, causing spike magnitudes and durations to vary.

## METHODS

ANN models synthesize nonlinear functions to fit multivariate calibration data rather than use predefined functions like mechanistic and statistical models. Conrads and Roehl (1999) and Conrads and Greenfield (2010) found that ANN models had prediction errors that were significantly lower than those of mechanistic models of the Cooper and Savannah River estuaries, respectively. In addition, ANN models have fast

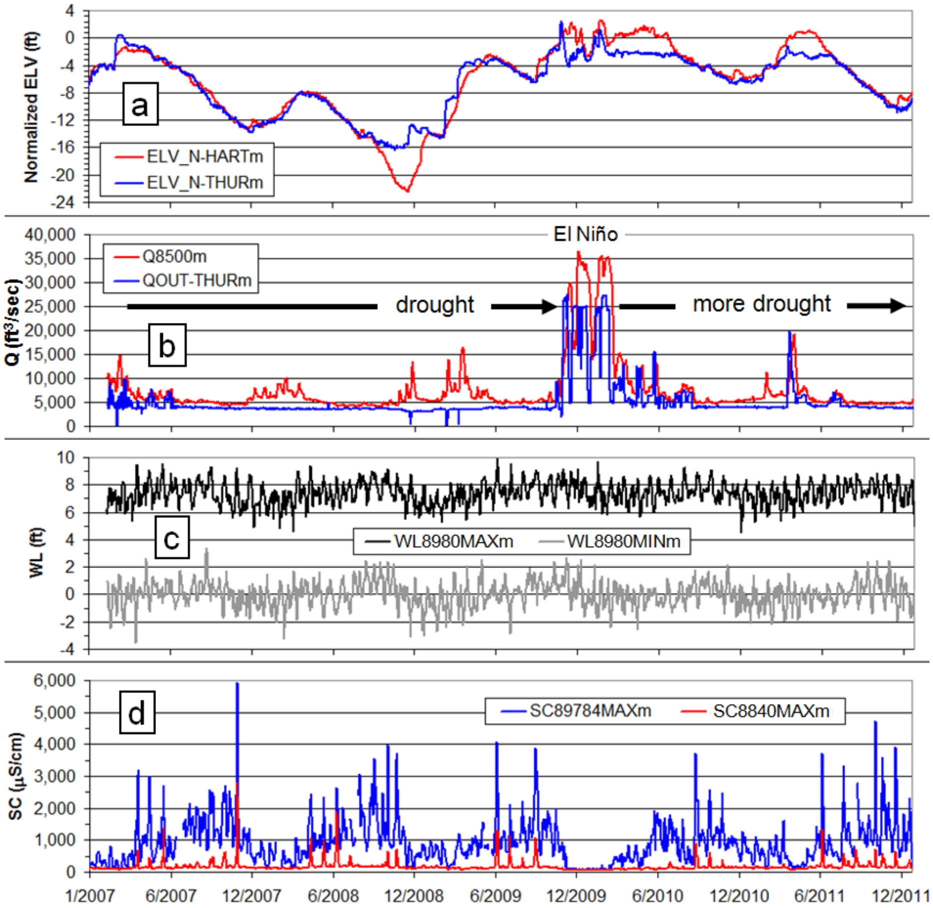

**Figure 2.** Hydrographs showing the measured data used in the study: a) normalized water elevations (ELV) for Lakes Hartwell and Thurmond (ELV_N-HARTm, ELV_N-THURm), b) flow (Q) from Lake Thurmond outflow (QOUT-THURm) and streamflow at USGS gage 02198500 (Q8500m), c) maximum and minimum water levels (WL) at USGS gage 02198980 (WL8980MAXm, WL8980MINm), and d) maximum specific conductance (SC) at USGS gages 021989784 (SC89784MAXm) and 02198840 (SC8840MAXm).

execution times that allow them to be coupled to an optimization routine to automatically predict the values of controllable inputs. For example in this application, the optimization routine predicts the required streamflow (a controllable input) needed to compensate for changing harbor water level (an uncontrollable input) in order for the model to maintain a user-specified specific conductance output value (setpoint). This approach also has been used in models of the Beaufort River and Pee Dee River basin (Conrads and others, 2003; Conrads and Roehl, 2007).

The M2M3-DSS's optimization routine predicts Q8500 values (Q8500p) needed to meet setpoints for ANN models of average (AVG) and maximum (MAX) specific conductance (SC) at USGS gages 021989784 and 02198840 (SC89784AVG, SC89784MAX, SC8840AVG, and SC8840MAX). The predicted QOUT-THUR values (QOUT-THURp) are calculated by subtracting the intervening drainage area flow between Lake Thurmond and USGS gage 02198500 (Q8500m-QOUT-THURm) from Q8500p. Lake elevation setpoints are input to the M2M3-DSS as hydrographs and are used to calculate the flows from each lake needed to meet QOUT-THURp. The user-specified specific conductance setpoints have priority over the elevation setpoints. Flows from Lakes Hartwell and Thurmond are balanced so that they are kept volumetrically equidistant from their elevation setpoints. This approach closely matches the historical practice.

To develop the ANNs, historical USGS data were randomly partitioned into training and testing datasets. The Q8500m, WL8980MAXm, and WL8980MINm signals were decomposed into different frequency components that represent variability on time scales such as daily, weekly, monthly, and seasonal. During training, an ANN effectively selects the frequency components that provide the best fit. Figure 3 shows the measured and predicted maximum specific conductance at USGS gages 021989784 and 02198840. The coefficients of determination ($R^2$) for the testing datasets are 0.71 and 0.72 respectively.

## RESULTS

Two simulations were made to evaluate different resource management issues. The first scenario simulated the optimization of flow from Lake Thurmond to control

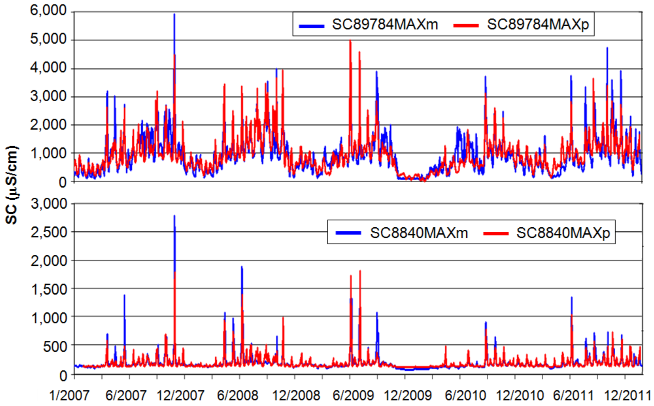

**Figure 3.** Measured (m) and predicted (p) maximum specific conductance at USGS gages 021989784 (SC89784MAXm, SC89784MAXp) and 02198840 (SC8840MAXm, SC8840MAXp).

salinity in the Refuge. The second scenario simulated a substantial change to the harbor (a 2.0 ft increase in sea level) to demonstrate how the M2M3-DSS could be used to monitor salinity effects of alterations to the harbor.

Conrads and Greenfield (2010) had used the M2M-DSS to estimate the effect of a timed streamflow pulse on a large intrusion event at the USGS gage 02198840. Scenario 1 extended this idea to continuously modulating water releases of the appropriate volumes to control salinity at the USGS gage 021989784 in the Refuge and upstream at the USGS gage 02198840, so that water also is conserved in the lakes. The setpoints were: 650 µS/cm for SC89784AVG; 2,000 µS/cm for SC89784MAX; and 1,000 µS/cm for SC8840MAX. Note that 1,000 µS/cm equates to a commonly used upper limit for freshwater of 0.5 practical salinity units. The elevation setpoints for both Lakes Hartwell and Thurmond were full pond + 2.0 ft, elevations that were often exceeded in the historical record.

The Scenario 1 results showed QOUT-THURps1 was much more variable than the historical measured flow (fig. 4a). This eliminated most of the SC89784AVGps1 spiking, but also allowed the specific conductance to rise to the 650 µS/cm setpoint when the measured specific conductance was lower than the setpoint, as seen in December 2007 (fig. 4b). The few predicted values above the setpoint are a consequence of an optimization constraint that limited the 1-day change in Q8500ps1 to dampen flow variability. The number of days exceeding the freshwater limit of 0.5 psu was predicted to decrease from 230 to 34 (-85%). Similarly, the number of days when SC89784MAXps1 exceeded its 2,000 µS/cm setpoint was predicted to decrease from 126 to 10 (-92%; Figure 4c), and the number of days when SC8840MAXps1 exceeded the freshwater limit was predicted to decrease from 16 to 0 (-100%; fig. 4d). Figure 4e shows generally higher water-level elevations for Lakes Hartwell and Thurmond, with the Scenario 1 simulation averages being 2.7 and 3.4 ft higher than the measured values respectively.

Scenario 2 demonstrated that a program like the M2M3-DSS could be used to promptly identify changes after the deepening occurs. A 2.0 ft sea-level rise was simulated to create a surrogate, post-deepening dataset for the estuary. The current deepening plan will increase the depth of the navigation channel by 5.0 ft. The Scenario 2 simulation predicted that the average SC89784AVG for the study period would increase from 562 to 902 µS/cm (+61%), and the number of days exceeding the freshwater limit of 1,000 µS/cm (0.5 psu) would increase 220% (fig. 5a). The surrogate data were labeled SCps2-post. Predictions made from only measured input data, representing pre-deepening conditions, were labeled SCps2-pre.

Figure 5b shows SCps2-post, and SCps2-pre plus 348 µS/cm, the amount of the 95th percentile prediction error of the model of SC89784AVG. The running percentage of days from the start of the study period when SCps2-post exceeded SCps2-pre + 348 µS/cm also is shown as Running%. Running% generally followed the annual specific conductance trend, and stabilized to a range between 40% and 50%. The higher SCps2-post values shown in Figure 5a are apparent in the Running% within the first three months of the study period. Discriminating the higher values was made possible by the accuracy of the model's representation of the pre-deepened system behavior. Detecting and correcting adverse consequences of actions quickly is necessary to manage the resource most effectively.

The M2M3-DSS could be deployed for automated daily (or more frequent) simulations. In Figure 6, current data from the USGS, USACE, and weather stations are input (fig. 6a) to the M2M3-DSS's database (fig. 6b) and then processed for quality assurance and input to the M2M3-DSS's predictive models. These data also can represent near-term weather and tidal forecasts. Constraints on the regulated streamflows, such as the minimums required for scheduled hydropower generation, are entered and stored in the database (fig. 6c) and the specific conductance and elevation setpoints (fig. 6d) are similarly entered. The M2M3-DSS computes "suggested" regulated flows that are optimized for the current and near-term forecasted conditions and outputs these flows to resource management personnel (fig. 6e).

## CONCLUSIONS

Meeting the increasing and often conflicting usage demands in a constantly changing hydrologic system like

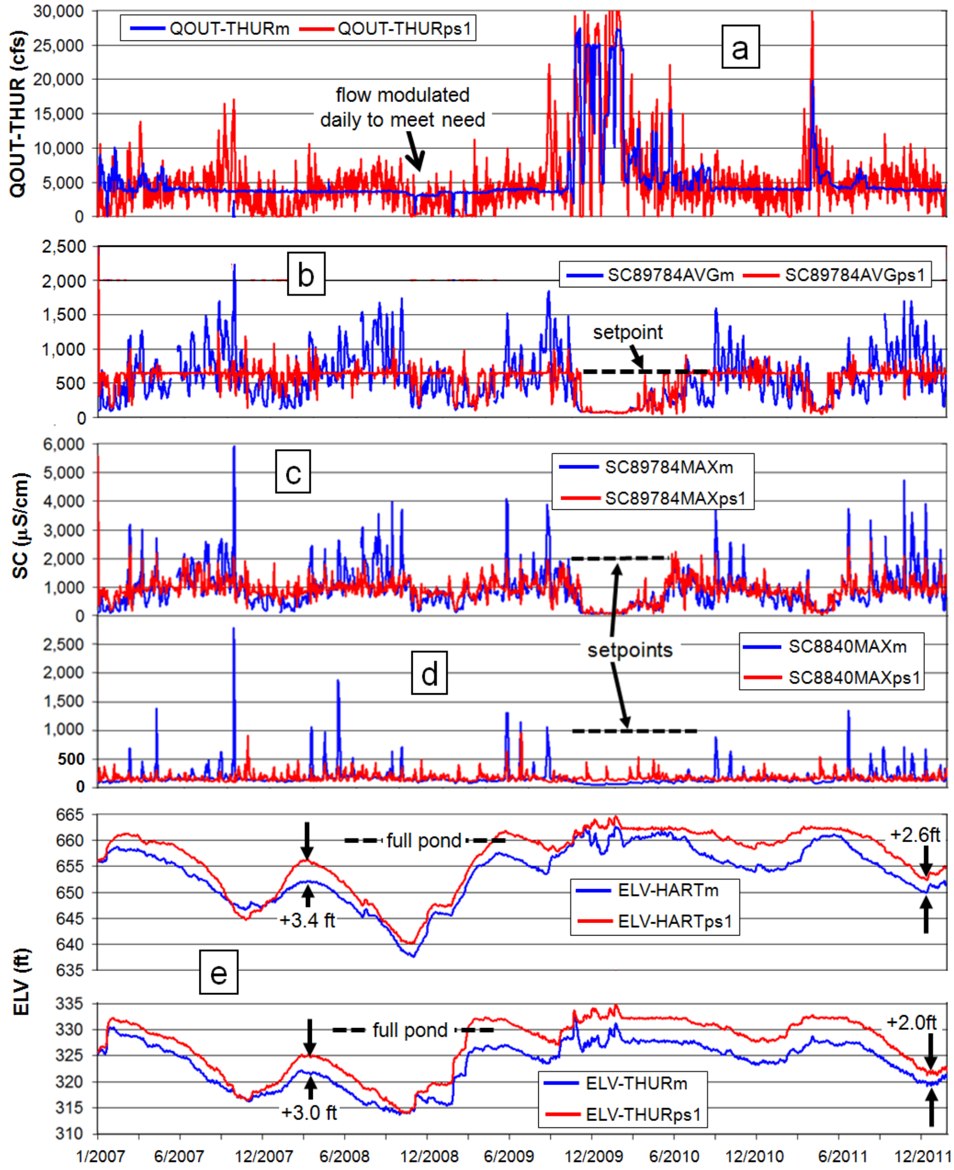

**Figure 4.** Hydrographs showing measured (m) and simulation Scenario 1 (s1) data of a) Lake Thurmond outflows (QOUT-THURm, QOUT-THURps1), b) average specific conductances at USGS gage 021989784 (SC89784AVGm, SC89784AVGps1), maximum specific conductance at USGS gage 021989784 (SC89784AVGm, SC89784AVGps1), d) maximum specific conductances at USGS gage 02198840 (SC8840AVGm, SC8840AVGps1), and e) Lakes Hartwell and Thurmond water elevations (ELV-HARTm, ELV-HARTps1, ELV-THURm, ELV-THURps1).

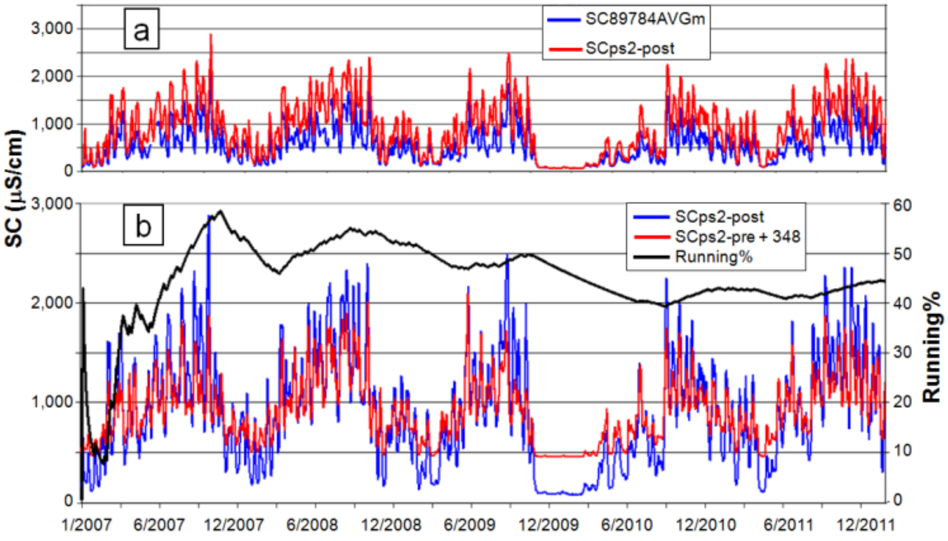

**Figure 5.** Hydrographs showing Scenario 2 results: a) measured and simulated average specific conductance at USGS gage 021989784 (SC89784AVGm, SCps2-post) and b) simulated pre-deepening average specific conductance at USGS gage 021989784 + 348 µS/cm (SCs2-pre + 348), surrogate post-deepening measured specific conductance at the same gage (SCps2-post), and running percent of days when SCps2-post exceeded SCs2-pre + 348 (Running%).

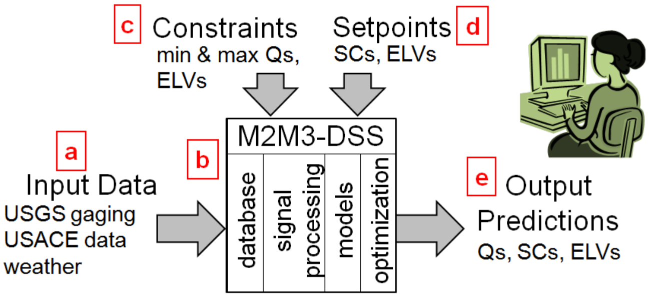

**Figure 6.** M2M3-DSS deployment schematic.

the Savannah River Basin is an ongoing, multi-objective optimization problem. The conflicting demands can be addressed by a decision support system like the M2M3-DSS, which incorporates accurate predictive models and other capabilities. The M2M3-DSS indicates that a management approach that continuously optimizes water releases might substantially reduce salinity in the Refuge and near municipal intakes, and increase lake water-level elevations. M2M3-DSS also indicates that the effects of changes in salinity such as the harbor deepening could be promptly quantified so that flow-alteration features can be proactively evaluated.

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