Report for 2004SC9B: Modeling the Impact of Reservoir Management Regimes on Important Ecosystems in the Santee River Basin

- Dissertations:
  - Cai, Zongshou, 2005, "Multiple Input Transfer Function Model with Missing Data, "MS Thesis", Statistics, College of Arts and Sciences, University of South Carolina, Columbia, SC, 63 pp.

Report Follows

Modeling the Impact of Reservoir Management Regimes on Important Ecosystems in the Santee River Basin

Statement of critical regional or State water problem.

With an area of 16,000 mi^2, the Santee River Basin is the second largest Atlantic watershed in the coterminous United States. Although the majority of the basin is located within South Carolina, the basin also includes a North Carolina headwaters region where reservoir management decisions influence conditions downstream. Over the past century the dominant management strategy within the watershed has been the development of hydropower resources. Watershed-wide, all of the basin's major rivers, the Broad, Saluda, Congaree, Catawba, Wateree and Santee, have been altered by the construction of hydropower facilities, including storage reservoirs. As a result, only three unimpounded river segments greater than 3 river-miles in length remain along the basin's significant rivers. Further, the basin's flow regime is now governed largely by the instantaneous value of electricity, which is related to demographic and economic development trends in the state. Historically few, if any, operational rules for reservoirs in the basin have been established specifically to improve ecosystems that have been altered or diminished by departures from the natural hydrology in the basin.

In the period up to 2010, three utilities that operate significant hydropower facilities in the basin will undergo re-licensing processes before the Federal Energy Regulatory Commission (FERC). FERC holds the licensing authority over non-federal hydropower projects with a generating capacity above 5 megawatts. Licenses typically are granted for 30 to 50 years of operation and define operating constraints, often based on meeting water-quality and environmental objectives, which must be met in order to maintain a license. The FERC re-licensing process creates an opportunity to factor management objectives into a license that may have emerged in the decades since the current license was issued. In many river basins, including the Santee, this includes greater consideration of environmental objectives.

Several conservation groups in South Carolina have asserted that ecological interests are under-represented in the licenses currently governing the operation of the Catawba-Wateree Project (operated by Duke Power), the Saluda Project upstream of Columbia (operated by South Carolina Electricity and Gas), and the Santee-Cooper Project (operated the South Carolina Public Services Authority). Ecosystems of interest include the habitat quality and availability in river reaches used for spawning by the endangered short-nosed sturgeon and the biologically important swamplands supported by river stage conditions in the basin, including South Carolina's newly created Congaree National Park.

The wetlands in the Congaree National Park (COSW) represent the last vestiges of a once vast and undisturbed ecosystem, and they function as an outdoor laboratory for the study of physical, biological, and cultural systems and their components. All the benefits derived from the COSW are tied to a highly specialized ecosystem whose unique flora and fauna are sensitive to the extent, duration, and timing of floodplain inundation. Further, the Congaree River's 53 miles provide for sixteen percent of the Santee River basin's 17,600 acres of potential diadromous fish spawning habitat. Given the importance of these resources and the opportunity offered by upcoming FERC re-licensing, research is needed to determine how to characterize the Park's wetlands in the context of a basin-wide hydropower planning model that will be used to explore alternative management regimes that could accommodate new management objects into economically viable hydropower operations.

Statement of results or benefits.

To address re-licensing issues, members of the conservation community in South Carolina are financially supporting the development of a basin-wide hydropower planning tool to assess ecological conditions under several different management regimes, and to thereby describe potentially viable operational changes during FERC re-licensing processes. These organizations have already committed the funds necessary to develop this model and a first phase of model development has been completed for the Santee-Cooper Project which is the furthest along in the FERC re-licensing process. The model currently relies upon historic flow data from the USGS *Wateree at Camden* and *Congaree at Columbia* gauges to provide the inflow that drives project operations. The use of historic data implies that the management regimes of upstream projects will remain unchanged over the life of the new Santee-Cooper license and eliminates the possibility for exploring whether coordinated operations of all projects could enhance the ability to meet South Carolina's increasingly diverse water management objectives.

The model will next be extended basin-wide to cover the Catawba-Wateree and Saluda Projects. At this point the function of the wetlands in COSW becomes an important consideration for two reasons. First, an assessment of inundation at the COSW is one of the more complex metrics which the conservation community wants included in negotiations for FERC re-licensure. The Congaree River has two major, tributaries: the Broad and Saluda Rivers that are regulated by the operations of the Saluda Project. The effects of inflow from these tributaries on floodplain inundation in COSW are not currently well documented or defined, although the effect of upstream river regulation is easily perceptible. Saluda River flows are controlled at Lake Murray, which has a substantial storage capacity (2.1 million acre-feet) in relation to its mean annual flow (1.8 million acre-feet). Although no large storages exist upon the Broad River, the pumping station at the Monticello Project is capable of effectively retaining small to moderate events to augment storages during periods when hydropower is cheap (at night and on the weekend) in order to provide a greater generation during peak demand periods (week-days). Second, the outflow from the wetlands to the downstream Santee-Cooper project is attenuated and potentially depleted by the wetlands. Once again, the relationship between inflow and outflow is not currently well documented. Funds are being sought from the South Carolina Water Resources Center Competitive Grants Program to support the development of a stochastic model of wetlands function in the COSW, and its integration into the basin-wide planning model already under development.

An integral outcome of this effort is the development of reliable performance measures, or metrics, for representing ecological benefits. By comparison, economic metrics are straightforward to develop: powerhouse releases are instantaneous and well defined, as are general market prices. Environmental conditions are seldom as easy to quantify, and are generally based upon both instantaneous and antecedent hydrologic conditions within the system. For instance, providing enough flow to increase fish spawning area achieves little if the additional habitat is allowed to go dry before the fry can hatch. Thus, designing methods to enhance the environment becomes a complex process, highly dependant upon an accurate relationship between in-stream flows and important biological indicators.

In order to clearly understand the relationship between management costs (potentially foregone power production) in order to reach different ecological goals at COSW, it is imperative that a reliable relationship be drawn between managed upstream flows and river elevations at the Congaree Swamp. Development of this model will then be used to enhance the basin-wide model, so that historical gauge data inputs can be replaced with modeled inputs that can then be used to study the entire Santee system under different regulatory schemes.

Nature, scope, and objectives of the research.

The primary goal of the PI's research is to deliver stochastic models for various reaches of the basin-wide model. The Natural Heritage Institute anticipates completion of the basin-wide model using historical streamflows in the second quarter of 2004. As stochastic models are developed, they can be used to study the effect of manipulated input flows for the basin-wide model.

Methods, procedures, and facilities.

Basin-wide methods. Central to this effort is the development of a basin-wide reservoir model, capable of demonstrating operational impacts on both the economics of hydropower generation and the viability of the basin's environmental goals. The principles behind the basin-wide model are relatively simple: a mass balance is maintained between inflows, releases, diversions, and losses at each reservoir; inflows are initially defined by the historic records in the Santee River basin; the timing and quantity of releases is calculated within the model's operational logic to reflect objectives and constraints such as minimum flow requirements and rule curves; lastly, the timing, quantity and duration of releases is used to quantify benefits among the basin's many uses, such as hydropower profits, lake levels, and riverine habitat.

The model will be created using Extend simulation software, a visually communicative, object-oriented programming environment that can easily represent the number of facilities in the Santee River Basin and produce an analytical framework for the analysis of basin-wide planning criteria.

The evaluation of ecologically important metrics within the Congaree National Park and the Upper Santee Swamp requires, first, the development of a reliable and comprehensive model for translating inflow from the Saluda, Broad, and Wateree Rivers into river stages, quantifications of inundated areas, and outflows to Lake Marion, followed by its implementation into the basin-wide planning model environment elaborated above. The proposed approach for this component is an extension of previous work by the PI in the Four Holes Swamp. The Four Holes model used stochastic transfer function models to predict downstream gauge flows from an upstream gauge (the residual standard error in a 1-day ahead forecast was 2.6 cm in a system that could fluctuate by several feet; the residual standard error for a 10-day ahead forecast was 8.1 cm). Four Holes Swamp personnel can use the prediction to study inundation throughout the Four Holes system; as a practical matter, it relieves staff from checking the downstream gauge every day, which was inconveniently located.

Stochastic transfer function models. To allow more flexible modeling of inflows, stochastic transfer function models will be used to model reservoir inflows. This will allow researchers to study the effect of reservoir operations, *as manipulated by the researcher,* beyond conditions available in the historical record. Deterministic transfer function models have long been used by process engineers to study dynamic continuous systems. Discretized versions of these continuous systems can be studied using difference equations.

Typically, an output in these discrete transfer function systems depends on an input variable, a delay between the input and output variable, first- and higher-order differences for the input variable, and first- and higher-order differences for the output variables. Each of these effects can be related to physical characteristics of the system, such as backwater and reservoir effects. While an entirely empirical approach can be taken to stochastic transfer function modeling, it is useful to include known physical effects in the model, so that the model has a theoretical, as well as an empirical, basis.

Transfer function models can be enhanced by modeling residual correlations between the input and output variables using ARIMA (AutoRegressive Integrated Moving Average) Autoregressive terms account for correlations between current stage data and past stage data—multiple AR terms in stochastic transfer function models developed for Four Holes Swamp, for instance, suggested the presence of more than one mechanism for upstream flood events. Moving average terms relate current stage data to past forecast errors. In an earlier project modeling Lake Murray Dam outflows for an analysis of recreational flow on the Saluda River conducted for the River Alliance, moving average terms were needed to compensate for forecasts that tended to underpredict the rapid increase in stage typical of releases from Lake Murray. Integrated terms include first- and higher-order differencing; first-order differencing removes trend effects, while higher-order differencing can be used for smoothing.

Structural similarities between ARIMA and transfer function models facilitate incorporating the stochastic ARIMA models into the deterministic transfer function models. In the case of multiple inputs, stochastic transfer function models can be written as vector ARIMA models. Off-the-shelf software includes numerous useful algorithms and diagnostics for developing single-input stochastic transfer function models. Specialized software packages for multiple-input models are not available, though methodology for vector ARIMA models is well established in the statistical literature.

Related Research.

The first reference contains an in-depth summary of stochastic transfer function modeling, while the second reference extends stochastic transfer function models to multiple inputs using Vector ARIMA time series models. The first reference in particular contains an extensive bibliography on transfer function models.

Box, G.E.P., G.M. Jenkins, and G.E. Reinsel, *Time Series Analysis, Forecasting and Control, 3rd edition,* Prentice Hall, Englewood Cliffs, N.J., 1994.

Astakie, T. and W.E. Watt, Multiple-input transfer function modeling of daily streamflow series using nonlinear inputs, *Water Resources Research, 34,* 2717-2725, 1998.