Report for 2001SC3781B: Reservoir Shoreline Erosion and Sediment Deposition with Cohesive Sediments

- Water Resources Research Institute Reports:
  - Elci, Sebnem and Paul A. Work, 2002, Prediction of Shoreline Erosion and Sedimentation in Hartwell Lake, SC/GA, Georgia Tech Regional Engineering Program Civil and Environmental Engineering, Report No. GTREP-CEE/2002-1, South Carolina Water Resources Center, Clemson University, Clemson, South Carolina, 97 pages.

Report Follows:

Reservoir Shoreline Erosion and Sediment Deposition with Cohesive Sediments

Statement of critical regional or State water problem

Man-made reservoirs fulfill a variety of needs; those found in the southeastern United States were typically built with flood control, power production, recreation, and water supply needs in mind. Water quality and quantity issues have both become more prominent in recent years as awareness of biological and hydrological issues and limitations have become more recognized.

Reservoir operators or regulatory bodies often impose building limitations to enforce no-development zones, sometimes in the form of buffer strips along the reservoir shoreline. Such setback regulations should consider multiple factors, including regional biology, hydrology, and long-term reservoir evolution, including shoreline erosion. Allowing development in regions with high erosion rates leads to expensive and often unattractive shoreline armoring that may also be detrimental to flora and fauna, terrestrial and aquatic. In coastal settings, setback regulations are common, and are usually based on site-specific, long-term erosion rates, but reservoir regulations rarely consider site-specific erosional conditions.

The proposed project involves development and refinement of techniques for prediction of reservoir shoreline erosion rates and depositional zones. The project is thus relevant to many different problems, related to land use planning, habitat evaluation, contaminant transport, and even real estate development. Although one reservoir will be the focus of the study, the methods applied will be suitable for other sites.

Some previous work on this problem has been done by the principle investigator. A pilot study led to predictions of relative erosion rates for one reservoir (Hartwell Lake, on the Savannah River in the Piedmont region of SC/GA), and an ongoing companion study with colleagues in the biological sciences is investigating grasses, shrubs, trees, and geotextiles suitable for natural-looking erosion control on artificial reservoirs with cohesive sediments and fluctuating water levels. A number of end-users of study findings have been included in discussions of project methods, sites, and results: Soil Conservation Service personnel, landowners (individual homeowners, as well as multi-user properties, such as a local sailing club), State of South Carolina Dept. of Natural Resource employees, U.S. Army Corps of Engineers personnel, representatives from Duke Power, and a local company specializing in shoreline armoring on reservoirs.

The proposed project is also relevant to contaminant transport problems. In addition to investigating long-term shoreline erosion, the fate of the eroded sediments will also be addressed. Predictions of reservoir hydrodynamics will indicate likely zones for deposition of the eroded sediment. This information is relevant for prediction of the fate of any contaminants sorbed onto the sediments, a problem particularly relevant at the chosen study site, where a tributary contributed large amounts of PCB contaminants. The U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, and private contractors have all been involved in predicting the fate of the contaminated sediment, but their predictions have focused primarily on the upper reaches of the lake, and the transport of non-cohesive sediments. The new project will concentrate on the downstream portion of the lake, and the cohesive sediment fraction, which has the potential to travel greater distances.

Statement of results or benefits

The project will yield a method for making objective, quantitative predictions of shoreline evolution on a reservoir featuring cohesive sediments, and describing the fate of the eroded sediment. Site-specific results will be provided for Hartwell Lake, SC/GA, and presented in tabular and graphical form to illustrate long-term erosional risk as a function of location on the lake. Predictions will be calibrated by comparison to available data indicating shoreline change from two sites on the lake.

Nature, scope, and objectives of the research (include a timeline of activities)

Most previous studies for modeling changes in shoreline morphology have addressed erosion and accretion on exposed ocean coasts, typically with non-cohesive sediments in a relatively energetic environment. Reservoir bank erosion is a different process, particularly when the reservoir shoreline is composed of a significant amount of fine, cohesive sediments. Waves strike the shoreline and put the fine sediment into suspension. The fall time for this sediment is much greater than that for sand, so even the slightest current can advect the sediment away from its source. The freshwater environment makes flocculation less significant than in saline water, so the erosion problem may be even more pronounced than in a tidal estuary or coastal setting with a similar energy level.

Bathymetry, and water level time histories will differ significantly between the reservoir and coastal settings as well. Reservoirs are optimally quite deep to achieve suitable flood protection and power generation benefits, with bathymetry that is much steeper than the typical nearshore coastal region. Water level fluctuations on reservoirs may be greater than the tide range in most coastal regions, and the time scale of the fluctuation is typically much longer. Severe storm surge at a coastal site might elevate the mean water level by several meters for several hours (e.g. Garcia 1995), whereas a severe flood in a watershed might increase the water level in a reservoir by meters for days to weeks. Lastly, there are obviously significant differences between waves on a reservoir and those at a coastal site, primarily because of the vast difference in fetch. Because of the reduced fetch in the reservoir setting, wave heights and periods will be substantially less. Short period waves in deep water are unaffected by bathymetrically induced wave transformation (shoaling, diffraction and refraction). Wave transformation should therefore be largely negligible on most reservoirs, compared to the coastal setting.

The proposed project has three primary objectives:

1) Refine and calibrate an objective technique for prediction of long-term shoreline evolution on man-made reservoirs featuring cohesive sediments.
2) Make predictions of erosion hazard zones for the test case of Hartwell Lake, SC/GA and present in an easy-to-interpret format.

3) Use an existing three-dimensional, numerical, hydrodynamic model to make predictions of depositional zones for fine sediments within Hartwell Lake, SC/GA.

The project timetable is as follows:
Month 1: Acquire all necessary data to drive the hydrodynamic model and to make predictions of shoreline change.
Months 2-3: Make predictions of long-term shoreline change for the two chosen verification sites, including the influences of water level fluctuations and spatial variations in scarp height and beach slope. Develop computational mesh for hydrodynamic model.
Months 4-6: Refine and calibrate shoreline change prediction methodology. Perform initial hydrodynamic model runs.
Months 6-10: Make predictions of shoreline change for selected sites around the downstream (largest) portion of Hartwell Lake. Perform hydrodynamic model runs for selected forcing conditions and determine depositional zones.
Months 10-12: Perform final model runs and develop project report and journal and conference publications.

Methods, procedures, and facilities

Two modeling procedures will be employed to generate project results. One will provide predictions of erosion rates at chosen locations around a reservoir, based on reservoir and shoreline geometry, sediment type, and wind and water level conditions. The second model will yield predictions of zones where fine sediments either eroded from the shoreline or carried into the reservoir by tributaries will be deposited.

The approach to shoreline change prediction is adopted from similar studies of coastal shoreline change. Bank erosion is assumed to be driven primarily by breaking waves, as mean flows are typically too slow to put consolidated, cohesive sediments into suspension, although these mean currents (caused by horizontal pressure gradients arising from inflows and wind) are important in controlling where the eroded sediment is later deposited.

Sediment transport rate is assumed proportional to the power of the flow or waves (e.g. Bagnold 1966). This approach has been used for both longshore sediment transport (Watts 1953, Caldwell 1956, Komar and Inman 1970) and for cross-shore sediment transport (Kriebel and Dean 1985, Larson and Kraus, 1987). Longshore sediment transport predictive equations typically involve the longshore component of wave power, which is zero for shore-normal waves. For waves incident on a cohesive shoreline, however, even shore-normal waves will put material into suspension. If the fall time for the sediment is large and a mean flow is present, the sediment will be carried away before falling back to the bed.

Wave power at breaking may be shown to be proportional to wave height to the 5/2 power. It is therefore assumed that erosion rate would be proportional to this quantity.

$$\textit{Erosion rate} \propto H_b^{5/2} \tag{1}$$

where H_b is wave height at breaking. Obviously prediction of quantitative erosion rates requires knowledge of the coefficient of proportionality.

Since the exponent appearing in Equation (1) is not unity, one cannot simply use the mean wave height to make predictions of long-term erosion rate. Instead, a summation will be employed to capture this time dependency:

$$\textit{Erosion Rate} = \sum_{n=1}^{N} k_n H_{b_n}^{5/2} \tag{2}$$

where N denotes the number of observations and k_n is a coefficient of proportionality. Of course this approach does not explicitly include any dependence on reservoir bathymetry, water level (stage), sediment type or size, presence of vegetation, or shoreline geometry. But most of these factors will also be incorporated into the model.

If wind speed and duration, fetch, and water depth are known, wave height and period can be computed using wave forecasting equations (U.S. Army Corps of Engineers 1984). “Deep water” is a relative term, implying that wavelength is no more than twice the water depth. This condition is met for most waves on most hydropower reservoirs, except very close to the shoreline. For this project, wave forecasting equations for deep water conditions will be employed to determine wave heights away from the shoreline, and then shoaling and refraction processes will be included analytically (Dean and Dalrymple 1984) to determine wave heights at breaking.

Water level plays an important role in the reservoir erosion problem by moving the shoreline back and forth as the water moves up and down. A steep, eroding scarp often develops. Erosion at the toe of the scarp leads to slumping and potential rapid erosion. In order to incorporate this process into the model, a simplified geometric representation of the situation has been developed, in terms of two slopes:

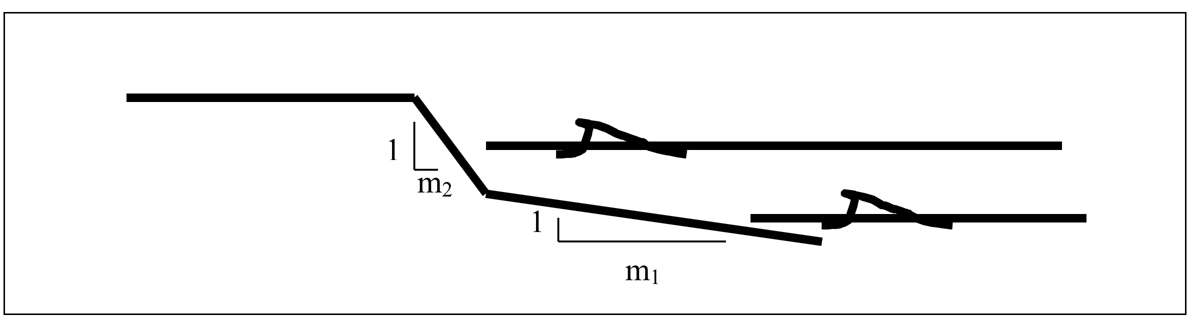

Figure 1. Geometric representation of beach profile.

A description of the erosion rate as a function of the two slopes m_1 and m_2 has been developed so that both water level and wave height are explicitly factored into the calculation. This will allow inclusion of important seasonal variations in both water level and wind characteristics. Previous work has revealed strong seasonal variations in both parameters at the chosen study site.

Two sites on Hartwell Lake, SC/GA, have been surveyed previously with topographic surveying equipment, providing some data on shoreline change. A one-day field trip will be made to visit both sites and collect sediment samples and shoreline position data for model calibration. The sediment samples will be analyzed to determine shear strength and non-cohesive fraction.

Hartwell Lake is a man-made reservoir on the Savannah River, bordering both Georgia and South Carolina. It covers 56,000 acres and has a shoreline of 962 miles (Figure 2). It was built between 1955 and 1963, by the U.S. Army Corps of Engineers, for flood protection, power production, water supply, and recreation purposes. Two additional Corps of Engineers dams (Russell and Thurmond) are located further downstream, and three Duke Power reservoirs (Keowee, Jocassee, and Bad Creek) are located upstream. Hartwell Lake is one of the top 3 most visited Corps lakes in the nation, serving about 10 million visitors annually. It was selected for several reasons: it is widely used, features a large and growing number of residential properties, is convenient for study, and historical data (water levels, discharges, and aerial photographs) are readily available.

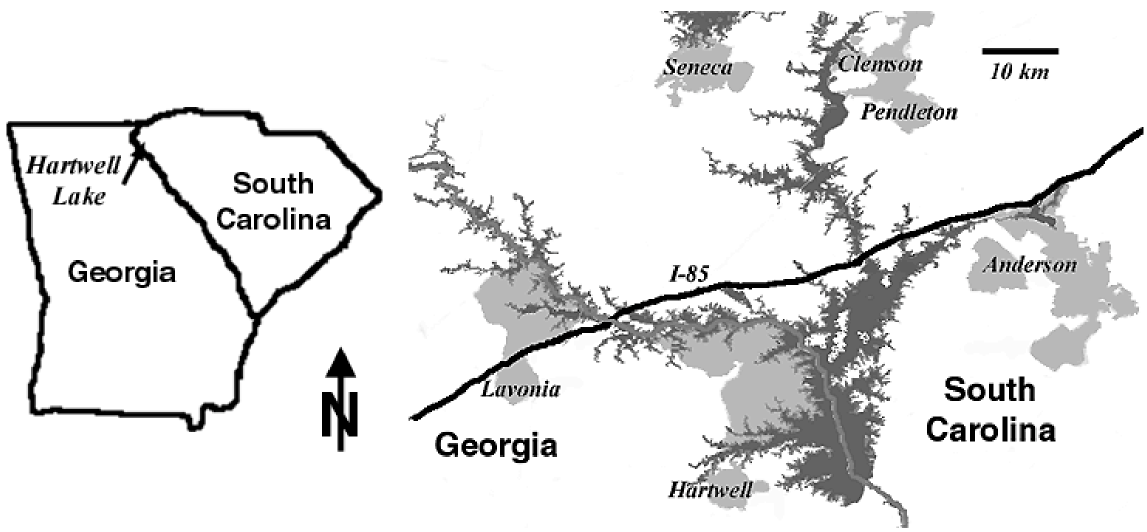

Figure 2. Maps of study area, showing Hartwell Lake on the Savannah River.

The terrain of Hartwell Lake consists primarily of gentle rolling hills and pine forest near the southern terminus of the Appalachian mountain chain. Sediments contain high fractions of silt and clay. Portions of the lake's shores are eroding severely. Vertical bluffs have been carved gradually and are threatening public and private lands (Figure 3).

Figure 3. Erosion at Hartwell Lake, October 1997, resulting in loss of trees. East side of lake.

The methodology described above will be applied to calculate shoreline change at the two chosen calibration locations on Hartwell Lake, and the measurements will be used to calibrate the predictive equation. The approach will then be used to model shoreline change at approximately 25 sites along the shoreline of the main pool of Hartwell Lake. Results will be presented in tabular and graphical form.

The last project objective is related to fate of the eroded sediment, and any other sediment that might be carried to the lake by overland flow or tributaries. A three-dimensional hydrodynamic model of flow within the reservoir will be used. The EFDC (Environmental Fluid Dynamics Code) model (Hamrick, 1996) was chosen for the purposes of this study. This model solves the three-dimensional, vertically hydrostatic equations of motion for a variable density fluid. The model has been successfully applied to Chesapeake Bay, James River, Indian River Lagoon, and the Florida Everglades, as well as several lakes, to investigate transport of sediment, heat, salt, larvae, etc.

Input to the hydrodynamic model includes basin geometry, inflow locations and strengths, and wind forcing. The hydrodynamic model will be used to predict deposition zones for sediment suspended within the water column. Several representative cases will be considered: 1) no wind, low inflow, 2) fall/winter wind, low inflow, 3) fall/winter wind, 10-year inflow, 4) spring/summer wind, low inflow.

The data necessary to run the models are available from the U.S. Army Corps of Engineers, National Weather Service, and published sources. Published topographic maps are suitable for specification of geometry of the lake. Inflow, outflow, and stage data are available from the Corps of Engineers. Long-term wind data are available for Athens Municipal Airport, GA, and Greenville-Spartanburg (GSP) Airport (65 km west and 90 km east of Hartwell Dam, respectively.) Available data include average and peak daily wind speed and corresponding direction, and cover the period 1948-present (Athens) and 1962-present (GSP).

Related Research

Reservoir sedimentation has been the subject of many studies from the standpoint of reservoir operation, efficiency and lifetime (e.g. Arnold et al., 1987; Lo, 1994). Bank erosion will contribute to this problem, but may also be considered as a separate issue (e.g. Penner, 1993). Ferguson and Overend (1998) performed an inventory of erosion problem sites on Clark's Hill/Thurmond Lake, a U.S. Army Corps of Engineers reservoir near Augusta, Georgia, on the Savannah River.

There have been many studies of the erosion resistance of cohesive soils to flowing water (e.g. Mehta et al., 1989). Few studies have focused on erosion of cohesive sediments from reservoir shorelines, however, in a freshwater environment, and clay behavior is quite sensitive to the absence or presence of salts in solution.

Annandale (1996) described an empirical relationship between threshold stream power for erosion of cohesive sediments and an erodibility index. For clay materials the erodibility index is primarily a function of the shear strength of the soil. Kamphuis (1990) and Parson, Morang, and Nairn (1996) describe other empirical techniques for describing sediment erodibility. In these tests, undisturbed samples of consolidated sediment were placed in a drop section of the floor of a high-velocity, unidirectional flow flume. The average rate of erosion was determined by measuring the volumetric loss from the sediment sample within a test period (U.S. Army Corps of Engineers, 1998).

The complexities of the hydrodynamic processes on a reservoir suggest use of numerical modeling approaches to simulate erosion of consolidated sediments. Penner (1993) described an approach to estimate future bank recession rates on Western Canadian lakes and reservoirs. He used a wave hindcast to determine the amount of energy reaching a bluff face, together with an erodibility coefficient to determine the future rate of shoreline recession. The erodibility coefficient is calculated through model calibration for a location with a known history of erosion. Nairn, Pinchin and Philpott (1986), described another approach where downcutting is related to the shear stress generated by orbital velocities under unbroken waves, and to the wave energy dissipation for breaking waves. The predicted downcutting determines the profile retreat rate, which is assumed to determine the bluff retreat rate above water. A more detailed version of this model is described in Nairn and Southgate (1993) and has been applied to sites on the Great Lakes.