FORECASTING POTENTIAL IMPACTS OF DEVELOPMENT AND CLIMATE VARIABILITY ON SEDIMENTATION OF A HYDROPOWER RESERVOIR

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Abstract As part of the relicensing of a large Hydroelectric Project in the central Appalachians, large scale watershed and reservoir sedimentation models were developed to forecast potential sedimentation scenarios. The GIS-based watershed model was spatially explicit and calibrated to long term observed data. Potential socioeconomic development scenarios were used to construct future watershed disturbance and land cover scenarios. Climatic variability and potential change analysis were used to identify future climate regimes and shifts in precipitation and temperature patterns. Permutations of these development and climate changes were used to estimate 50 year sediment yield forecasts to the project reservoir.

Extensive field work and reservoir surveys, including wave and current instrumentation, were used to characterize the project watershed, rivers and reservoir hydrodynamics. A fully three-dimensional hydrodynamic reservoir sedimentation model was developed for the project and calibrated to observed data. Hydrologic and sedimentation results from watershed forecasting provided boundary conditions for reservoir inputs. The calibrated reservoir model was then used to forecast changes in reservoir sedimentation and storage capacity under the future scenarios. Results indicated unique zones of advancing sediment deltas and temporary storage areas. Forecasted changes in reservoir bathymetry and sedimentation patterns were also developed for the various climate change scenarios using the model results. The wet climate scenario produced sedimentation impacts similar to extensive development under no climate change. The results of these analyses are being used to guide collaborative watershed and soil conservation partnerships to reduce future soil losses and reservoir sedimentation from projected development.

INTRODUCTION

Claytor Lake is a hydropower reservoir formed by the impoundment of the New River behind Claytor Dam near Radford, VA (Figure 1). The reservoir encompasses portions of Pulaski County and is part of the Claytor Hydroelectric Project (built in 1939). Claytor has four generating units, with a combined generating capacity of 75 MW. The Claytor Dam is approximately 1,140 ft. in length and has a maximum height of approximately 140 ft. above the streambed. Claytor Lake has a surface area of 4,500 acres and approximately 100 miles of shoreline at normal operating pool elevation, 1,846 ft. (National Geodetic Vertical Datum, NGVD). At that elevation, the estimated storage volume of Claytor Lake is 225,000 acre-feet (Appalachian, 2006).

Setting High Appalachian mountain ridges form the New River watershed boundary and delineate a watershed area for Claytor Lake of 2,380 mi² (Figure 2). The project boundary generally follows the reservoir at the 1,850 ft. (NGVD) elevation. Headwaters and tributary streams of the New River are in the Valley and Ridge province of the central Appalachian Mountains in western North Carolina and southwestern Virginia (VDEQ, 2004). From here, the river flows in a northerly direction into Virginia and continues in West Virginia. In North
Carolina and Virginia, the terrain consists of mountains and rolling hills. In West Virginia, the New River enters steep, entrenched gorges and is dominated by higher gradient, whitewater conditions of the New River Gorge National River. The New River then joins the Gauley River and forms the Kanawha River, a tributary of the Ohio River. Land cover in the watershed is 59% forested, 35% agricultural, and 3% residential/developed (Appalachian, 2008).

Figure 1 Claytor Lake Dam, near Radford, VA (photo source unknown).

Figure 2 Claytor Lake Watershed (2,380 mi²) in the Central Appalachians, NC and VA, U.S.A. Reeds Creek watershed (260 mi²) was used for watershed model calibration.

**Climate** Elevation gradients influence climate, soils, and vegetation of the Claytor Lake watershed. Consistent precipitation distributed throughout the year, mild temperatures, and marine climatic influence place this region in Koppen’s warm summer continental and maritime
temperate regimes, types Cfb and Dwb respectively (Riedel, et. al. 2006; McKnight and Hess, 2000). Temperatures are moderate; average annual maximum and minimum daily temperatures are 65°F and 41°F, respectively. The growing season typically lasts from early May through early October. There is no pronounced dry season, and average annual precipitation is approximately 38 inches. Average annual snowfall is 23 inches (SERCC 2003). Marine climate and the North Atlantic Oscillation (NAO) influence long-term precipitation and streamflow in this region (Figure 3) (Riedel, 2006; Greenland, 2001; Portis, et. al., 2001). From the mid 1970’s through present, the NAO has had a generally positive bias and winter precipitation (as rain) has also increased, as compared to the historical record (Boyles and Raman, 2003; Hayden and Hayden, 2003; Greeland, 2001). With a shift to greater winter precipitation, summer thunderstorms have declined and overall storm intensity has decreased slightly (Figure 4).

![Figure 3: Annual NAO, precipitation and water yield from the New River, just upstream of Claytor Lake. Lines are 5-year moving averages.](image)

![Figure 4: Winter NAO and rainfall intensity (erosivity) from long-term gauge records in the southern Appalachian Mountains, North Carolina. Lines are 5-year moving averages.](image)

**Geology and Soils** The bedrock of the Valley and Ridge province is typically thick, folded Palaeozoic sedimentary rock. The elongate parallel ridges and valleys in the province are the result of differential weathering that has been repeated by folding and faulting (VDEQ, 2004).
Cambrian clastic sediments characteristic of the eastern portion of the province are overlain by carbonates that are exposed in the Great Valley sub province (Appalachian, 2008). Soils vary with slope location and parent material. Soils on steeper slopes are generally formed of residual materials from weathered shale, siltstone and fine-grained sandstone. Permeability is moderate to moderately high. Soils in flatter areas are generally of colluvial or fluvial origin having low to moderately low permeability. They are highly erodible containing silts, sands, and fine clays (Appalachian, 2008).

METHODS

Three main types of methods were used in this study: field reconnaissance, watershed modeling, and hydrodynamic reservoir modeling. Field reconnaissance provided data to support the modeling efforts. Watershed modeling, hydrology and sedimentation, was used to assess changes in sediment yield and to provide boundary conditions for the hydrodynamic reservoir model. The reservoir model was used to predict how potential changes in water and sediment influx might alter reservoir sedimentation processes. These are fully described below.

**Field Reconnaissance** Field reconnaissance was conducted to validate remotely sensed MRLC (multi-resolution land characteristics) digital land cover data, inspect existing dams, gather sediment samples, survey model domain, and instrument Claytor Lake for current and wave data. Validation of land use data was conducted at 10 locations across the Claytor Lake watershed and included the full range of land uses and geographic settings (e.g. valley, mountains). The MRLC data were very consistent with observed conditions with one exception; low density and rural lands that had transportation corridors. MRLC data processing methods assigned impervious surfaces for fixed right-of-way widths that were greater than actual road widths and assigned turf-grass for pervious right-of-ways. To correct for this, adjustments were made to SWAT land cover parameters to reduce the impervious road widths and allow for forested right-of-ways.

Sediment samples were gathered from shoreline and bed sediments at a number of locations around Claytor Lake. These were analyzed for physical properties (size, cohesion, etc) and used to develop the digital representation of the lake bed and parameterize the sediment transport model. Mapping and identification of the model domain and shoreline conditions (e.g. bank material, bank protection, etc) was conducted for Claytor Lake and its major bays and tributaries. Model domain, shoreline condition, and lake level elevations were used to define the boundary of the reservoir model and relative elevations of where lake level intersected the shoreline.

Instrumentation of Claytor Lake included deployment of in-situ ADCP (acoustic Doppler current profiler) and AWAC (acoustic wave and current) instruments at seven locations (Figure 5). These instruments monitored continuous temperature, wave condition, and current velocity and direction data throughout the entire depth of the water column. Deployment locations provided representative coverage of the wind, current, and wave climate of Claytor Lake as well as appropriate boundary conditions for the hydrodynamic model.

**Watershed Modeling** There are numerous watershed hydrology and sedimentation models that can be used to simulate water and sediment fluxes from watersheds. Due to the large watershed scale, differences in land use, and presence of multiple hydropower reservoirs, ArcSWAT, the GIS (geographic information system) version of SWAT (Soil and Water Assessment Tool), was
selected for this project. SWAT allows for inclusion of climatic stations across physiographic regions, inclusion of multiple dams and reservoirs, simulation of sediment transport through fluvial networks, and can be calibrated and validated over large model domains. SWAT is a physically based, watershed-scale numerical model for the simulation of water, sediment, nutrient, and pesticide movement in surface and subsurface systems. It is a continuous model that runs on various time steps from observed and simulated climatic data and was developed for the prediction of long-term water and sediment yields from a watershed (Neitsch, et al., 2002).

![Map of Claytor Lake with ADCP and Wave gauges](image)

**Figure 5 Locations of ADCP and Wave gauges deployed on the bottom of Claytor Lake.**

**Watershed Modeling - Development:** Manual editing of the climate station database was required to allow additional climatic data. Observed temperature, precipitation, and wind data were used for modeling while relative humidity and solar insolation were estimated using the stochastic weather generator in SWAT. Observed precipitation and discharge data, when filtered using a five-year moving average, cycled with the ten year NAO cycle (Figure 3). The historical weather data were analyzed for significant departures from average conditions and used as surrogates for future climate change scenarios. The scenarios included a historical wetter NAO phase (> 90% of observed data), historical drier NAO conditions (≤10% of observed data), and the median condition (50% conditions). This approach was selected because future climate scenarios are expected to be governed by changes in the NAO (Hurrell, et. al., 2003; Hurrell, 2000). Water and sediment yield results were used to develop boundary conditions to Claytor Lake under the simulated NAO shifts. The wet scenario represents the typical “global warming” scenario anticipated for the Appalachian Mountains and includes increased winter precipitation from remnant hurricane/tropical depressions (Riedel, 2006; SERCC, 2003).
MRLC Land cover data from 2001 were used for calibration and status quo scenario. Future land cover scenarios were developed from published population and land development forecasts (Table 1) (Weir and Greis, 2002). Development was simulated by changing land use in the 2001 MRLC data to residential and commercial uses in the areas most likely to experience growth. Field surveys of construction site and soil conservation best management practices (BMP’s) were used to determine compliance with existing regulations; less than 80% of all sites were in full compliance. Future growth scenarios were analyzed to assess the role of BMP compliance on sediment yield using status quo, growth (population growth, no change in BMP’s), growth with 50% increase in BMP compliance, and growth with 80% increase in BMP compliance scenarios.

Soils data were obtained from the State Soil Geographic (STATSGO) database (1:250,000). Higher resolution Soil Survey Geographic Database (SSURGO) soils data were not complete for the Claytor Lake watershed. Digital elevation data were obtained from the U.S. Geological Survey at 1/3 arc-second resolution (10m) and used to build the watershed terrain model.

Table 1 Population projections (VAWC, 2007)*

<table>
<thead>
<tr>
<th>Year</th>
<th>Pulaski County Population</th>
<th>New River/Mount Rogers Population</th>
<th>Virginia Population</th>
</tr>
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<tr>
<td>1990</td>
<td>34,621</td>
<td>331,770</td>
<td>6,216,884</td>
</tr>
<tr>
<td>2000</td>
<td>35,139</td>
<td>354,310</td>
<td>7,104,078</td>
</tr>
<tr>
<td>2010</td>
<td>35,025</td>
<td>364,797</td>
<td>8,010,342</td>
</tr>
<tr>
<td>2020</td>
<td>35,125</td>
<td>374,950</td>
<td>8,917,575</td>
</tr>
<tr>
<td>2030</td>
<td>35,148</td>
<td>388,129</td>
<td>9,825,288</td>
</tr>
<tr>
<td>2040</td>
<td>35,540</td>
<td>402,799</td>
<td>10,723,925</td>
</tr>
<tr>
<td>2050</td>
<td>35,698</td>
<td>416,134</td>
<td>11,626,955</td>
</tr>
</tbody>
</table>

*Bold values represent linear growth projections from past decades

Over 60 dams were identified from the National Inventory of Dams. The majority were small sediment filled conservation dams from the mid 20th century. These were not included in the watershed modeling because, relative to Claytor Lake, any remaining sediment trapping in these small dams would not be discernable. However, there were three large dams upstream of Claytor Lake. These were Fries, Buck, and Billsby Dams. Specifications for these dams (e.g. stage/storage, release rates, configuration, etc.) were used to “build” the dams in ARCSWAT.

**Watershed Modeling - Calibration** Sufficient data did not exist to calibrate the entire watershed model. Consequently, the model was calibrated using the Reeds Creek tributary watershed (Figure 2). This watershed included land uses and terrain representative of the Claytor Lake Watershed. Calibration was conducted over 1974-1995 with 1974-1980 being the “priming” period. The calibration period was representative of the entire record including wet periods in the late 1980’s and drought conditions in the early 1990’s. Baseflow separation was conducted following the comprehensive baseflow analysis of Nelms, et. al., for the Valley and Ridge region (1997). Annual calibration was conducted on water balance basis by adjusting vegetation parameters to best fit published values while maximizing model accuracy (Riedel, et al., 2005; Di Luzio, et. al., 2004; Nietsch, et. al., 2002). Double-mass analysis results indicated the calibrated model explained 99.9% of observed water yield and, over the period of simulation, under-predicted total runoff by an average of 2.3mm/year, or 3% (Figure 6).
Figure 6 Double-mass analysis of daily predicted yield against observed daily yield. The calibrated model underpredicted total runoff by approximately 2.3 mm/yr, or 3%.

Hydrographs were calibrated using channel hydraulics parameters (roughness, channel size, etc.) to represent published values for the region and best match observed hydrograph shape (Keaton, et. al., 2005; Neitsch, et. al, 2002; Barnes, 1987). Iterative calibration optimized SWAT parameters until departure from observed data were minimized and could not be resolved with further model calibration. Hydrographs for large events and seasonal fluctuations trended well with observed data. For smaller events, the results for predicted and observed hydrographs were mixed with predicted peaks tending to be slightly overestimated in the late summer and early fall and underestimated in the late fall and early winter (Figure 7).

Figure 7 Predicted and observed daily discharge for Reed Creek at Graham's Forge, VA.

There were not observed sediment data at Reed’s Creek for sediment calibration. Consequently, predicted sediment yield to Claytor Lake was verified by comparing the total predicted sediment yield to reservoir sedimentation calculations from current and historical bathymetric data. Aggregated over the observed 50 years, the average annual forecasted sedimentation depths ranged from 0.6 to 1.2 inches per year as compared to the observed 0.9 inches/yr.

Reservoir Modeling Literature review and field sediment sampling were used to characterize the sediments within Claytor Lake (Royall, 2003; USACE, 1989). Sediment samples collected
from tributary sources around Claytor Lake and deep sediment cores were analyzed to determine dominant sediment characteristics. A representative sediment fraction of ten μm (0.01mm), in the clay size fraction, was used for the numerical simulations and development of figures showing sediment transport, plume evolution, and sedimentation. Based upon lab results, in situ bulk density of 1.8 g/cc was used for sediment volume estimates and modeling.

A 3D hydrodynamic and sediment transport model was developed for Claytor Lake using MISED. MISED combines efficient computation time with numerical stability and flexible mesh capabilities to simulate currents, temperature, and sediment (Lu and Wai, 1998). Multibeam bathymetric were used to develop the model. Hourly wind data were obtained from airports and National Weather Service climatic stations. Observed current data were processed to remove bad data values and adjust time intervals. The cleaned data were used to calibrate over the period of observation (May - July 2007). A quadrilateral finite element mesh was generated to fit to the complicated shoreline (Figure 8). Model calibration consisted of adjusting roughness and wind drag parameters such that predicted currents best matched observed results.

![Figure 8 Final model mesh and main ADCP stations used in model calibration.](image)

Calibration was performed at a variety of depths and instrument locations with validation checking using other instruments and water depths. Sample results for model calibration of surface vectors near Claytor dam are shown in Figure 9. Predicted vectors matched the majority of observed currents in Claytor Lake with no significant bias to departures (error was randomly distributed). The calibrated model was run for 17 scenarios to cover the range of flows, water levels, and tributary conditions, summarized below:

- High, moderate, and low discharge and sediment events in the New River;
- Various discharge and sediment events in tributaries.
RESULTS

Watershed Sediment Yield  Current sediment yield from individual subwatersheds were 10 to over 300 times pre-settlement rates (Figure 10). Under the status quo condition, future sediment yield averaged tenfold greater than pre-settlement. Sedimentation increased under the population growth and BMP scenarios anywhere from two to over ten times over status quo values (Table 2). Forecasted sediment yields in watersheds and lands adjacent to Claytor Lake far exceeded existing rates under the growth scenario; this was greatly reduced by BMPs (Figure 11).

<table>
<thead>
<tr>
<th></th>
<th>Pre-Settlement</th>
<th>Status Quo</th>
<th>Growth</th>
<th>+50% BMPs</th>
<th>+80% BMPs</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>22,000</td>
<td>240,000</td>
<td>2,272,000</td>
<td>1,118,000</td>
<td>455,000</td>
</tr>
</tbody>
</table>

Claytor Lake Sedimentation  Sedimentation and future loss of volume were strongly dependent on the land use scenarios. Long term reductions in reservoir volume ranged from < 2% to
>5% for the status quo and growth scenarios, respectively (Figure 11). The +80% BMP scenario resulted in sedimentation values <2% greater than status quo conditions.

![Figure 11](image1.png)

Figure 11 Forecasted reduction in Claytor Lake volume due to sedimentation under status quo, 50 year population growth, and 50% and 80% increased BMP compliance scenarios.

Results for sediment yield under the future climatic scenario are shown in Figure 12. In comparison to the median, which is similar to current conditions, the wetter future condition resulted in > 60% increase in sedimentation for the long-term average represented by the status quo condition. For the reduced precipitation scenario, sedimentation was 25% lower than the long-term average rate.

![Figure 12](image2.png)

Figure 12 Forecasted annual reduction in Claytor Lake volume under future climatic scenarios. Wet, median, and dry scenarios represent future NAO that will bias towards wetter, current, or drier conditions.

Historically, sedimentation in Claytor Lake has been most extensive at the upstream end (southeastern tip) where the New River enters the reservoir. The numerical results for typical flow (460 cfs to 4,600 cfs) and water levels were used to develop estimates of average daily sedimentation rates (Figure 13a). Most of the sediment deposited in the upper section of Claytor Lake. These would be remobilized during storm events (e.g. 2+ year event, > 6,000 cfs) and transport further into Claytor Lake. Increased water and sediment discharge from the wetter climate scenario increased sediment loading to Zone 1. However, higher sustained flows under the wet scenario would push sediments to Zone 2. During high discharge events (> 99% of average, 46,000 cfs) re-mobilized sediments from Zones 1 and 2 push to deeper quiescent waters.
of Zone 3 (Figure 13b). Only under the most extreme flow condition (e.g. 50+ year event) was significant plume transport and sedimentation predicted to occur in Zone 4, the deepest water portions of Claytor Lake. Events of this magnitude advance the subaqueous sediment delta in Claytor Lake past Lowman’s Ferry Bridge (past Zone 2).

Figure 13a Average daily sedimentation in Claytor Lake occurs in Zone 1 and Zone 2.

Figure 13b Fifty year Claytor Lake sedimentation depths under alternative scenarios with specific zones of changing sediment dynamics. Under wetter and stormier conditions, sediments move into Zones 3 and 4.

CONCLUSIONS

A combination of observed field data, watershed hydrology, sedimentation, and reservoir hydrodynamic modeling was used to develop water and sediment yield forecasts for the Claytor Lake hydroelectric reservoir in the central Appalachian Mountains. Results from combinations of future land use change with development, best management practices, and shifts in future climate regime were compared to determine how these would affect reservoir sedimentation. Increased enforcement and compliance with BMPs would produce a dramatic decrease in long-term sedimentation predicted with typical population growth and development scenarios.

Existing sediment yields and reservoir sedimentation values were higher than those predicted for pre-settlement conditions. Future trends in sediment yield and reservoir sedimentation were predicted to worsen under land use development and climate change scenarios. During relatively low flow periods, most sedimentation occurred in the upstream extent of Claytor Lake, above Lowman’s Ferry Bridge. During moderate and large flow events, these sediments were re-mobilized and flushed further into Claytor Lake – extending the sediment “delta” face, that area of most rapid change in depth with sedimentation. The absolute rate of delta progression will generally decrease as it encounters deeper and wider portions of the reservoir; it will take more sediment to fill that larger volume and advance the delta face. With increased precipitation and sediment yield, an asymmetrical delta face is predicted to push past Lowman’s Ferry Bridge into the deepwater portion of Claytor Lake.
REFERENCES


