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Simulation of Impacts of Streamflow and Climate Conditions on Amistad Reservoir

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The Rio Grande is the fifth longest river in North America running North-South from its source in the Colorado Rocky Mountains to El Paso, Texas. From there it turns South-East and, for over 800 miles, serves as the border between Mexico and the United States. Amistad Reservoir in the Rio Grande basin is located 12 miles northwest of Del Rio in Val Verde County, Texas. The Rio Grande – Rio Conchos to Amistad Reservoir watershed encompasses a total of 34,630 sq miles of which 13,910 sq miles are in Mexico and 20,720 sq miles are in the United States. The surface water area features include the Rio Grande and three major tributaries: the Rio Conchos from Mexico (26,404 sq miles watershed), the Pecos River (35,308 sq miles watershed), and the Devils River (4,305 sq miles watershed), with the latter two contributing flow directly to Amistad Reservoir. Construction on Amistad Dam and Reservoir began in December 1964 and was completed in November 1969. The dam, located at 29°27'N, 101° 03'W, is an earth fill and concrete structure. Amistad Reservoir was designed as a multipurpose facility with considerations given to water supply, flood control, irrigation, hydroelectric generation and recreational usage. The reservoir and dam are jointly owned by the United States and Mexico and operated by the International Boundary and Water Commission. To provide adequate flood control, the "conservation elevation" for water storage is limited to 1117 feet (340.5 meters) above the mean sea level. The lake covers 89,000 acres (139 sq miles), and its storage capacity is 5,658,600 acre-feet.

The Rio Grande Basin was considered to possess an abundant water supply in the past. However, irrigation, growth of urban centers and industries due to rapid population increase, and prolonged droughts in the 1950s and 1990s have resulted in relatively short supply in the basin. Water shortages that challenged traditional lifestyles in far west Texas have stimulated new research interests in the Rio Grande Basin water resources. A comprehensive water management system is crucial to sustaining agricultural, social, economic, environmental and urban uses of the Rio Grande Basin. This paper presents hydrodynamic and water temperature simulations for Amistad Reservoir using a two-dimensional reservoir water quality model. It includes simulation results for various inflow scenarios due to different water availability and demands upstream of the reservoir as well as for a future climate scenario based on potential global warming. The next step of the study is to simulate water quality conditions in Amistad Reservoir and develop reservoir management strategies or programs for different inflow and climate conditions. Both hydrodynamic and water temperature have significant impacts on dynamics (distribution and movement) and reaction kinetics of many water quality parameters.

Model and Model Calibration

The CE-QUAL-W2 model (Cole and Buchak 1995; Cole and Wells 2003) was selected to simulate water quality in Amistad Reservoir. The CE-QUAL-W2 model is a two dimensional (longitudinal and vertical directions), laterally averaged water quality and hydrodynamic model widely applied to stratified surface water systems such as lakes, reservoirs, and estuaries. The model computes water surface elevation, horizontal and vertical velocities, water temperature and twenty-one other water quality parameters such as dissolved oxygen, nutrients, organic matter, algae, the carbonate cycle, bacteria and dissolved and suspended solids. The model assumes lateral homogeneity, so it is best suited for relatively long and narrow water bodies exhibiting longitudinal and vertical water quality gradients. The CE-QUAL-W2 model has been widely used for reservoirs in the United States and around the world, and is considered the preferred model of choice for reservoir water quality simulation. The model can accurately simulate reservoir density-dependent flow and stratification, as well as temperature and water quality conditions. The original model was known as Laterally Averaged Reservoir Model (LARM), developed by Edinger and Buchak (1975).

Development of the computational grid, specification of boundary and initial conditions, and preliminary selection of model parameter values are basic requirements for the implementation of the CE-QUAL-W2 model. The computational grid system requires dividing a reservoir into a number of segments (reaches) in longitudinal direction and layers in vertical (depth) direction. Therefore, the bathymetric data for a reservoir consists of longitudinal segment lengths, vertical layer thickness, segment orientation, water surface elevation at the beginning of the simulation, and segment widths at different depths for each segment. These bathymetric data allow the model to appropriately represent reservoir geometry as a two-dimensional computational grid system. Segment geometry was measured and developed using a 20 feet interval contour map for the Amistad Reservoir from the United States Geological Survey, and each segment was further subdivided or interpolated into 1 m layers. Forty-four computational segments were used along the Rio Grande and thirty-five along the Devils River. In addition, there are seven small branches (five in the Rio Grande and two in the Devils River with total of forty five computational grids) added to associate with the Rio Grande and Devils rivers to preserve reservoir volume. Segment length ranges from 877 m to 1000 m, and segment width at the reservoir surface ranges from 503 m for the upstream segments to 10,232 m for the downstream segments near the dam. With other input data (e.g., control file), the pre-processor program for the model can be run to generate tables for the variations of reservoir storage (volume) and horizontal area with elevation. These bathymetry tables were compared to and have a fairly good agreement with measured relationships (curves) of reservoir volume and area versus elevation, which were obtained from Mr. Cliff Regensberg, hydrologist at the International Boundary and Water Commission. Other input data developed for the model simulation include time series of inflow discharge and temperature from tributaries, outflow from the reservoir, and climate conditions including air temperature, dew point temperature, cloud cover, wind speed, and wind direction.

Model calibration shows that simulated water surface elevation at Amistad Reservoir closely matched observed water surface elevation in 2004 with a root mean square error of 0.07 m (Shrestha 2006). Simulated and observed water surface elevations increased by approximately 7 m from January 2004 to December 2004. Sample results for water temperature calibration at various locations of Amistad Reservoir in June 2004 are given in Figure 1 and results for other months are presented and summarized elsewhere (Shrestha 2006). Overall, the model is capable of accurately reproducing the observed water temperature profiles with root mean square error varying from 0.32 ^{o}C to 1.44 ^{o}C and absolute mean error varying from 0.07 ^{o}C to 2.08 ^{o}C for dates and locations where measured water temperature profiles were available.

Contours of simulated water temperature and velocity vectors in Amistad Reservoir were developed to examine hydrodynamics and water quality conditions at any specified time within the simulation period. For example, on November 17, 2004, there was a relatively low inflow from Rio Grande (150 m^3/s) but very high inflow from Devils River (1054 m^3/s) into Amistad Reservoir. Contour plots of water temperature on November 17 clearly indicate minimal stratification of water temperature in the winter period (Shrestha 2006). A strong density current moving downward in the bottom of the reservoir due to the large inflow from Devils River was depicted by water temperature and velocity vector contour plots (Shrestha 2006).

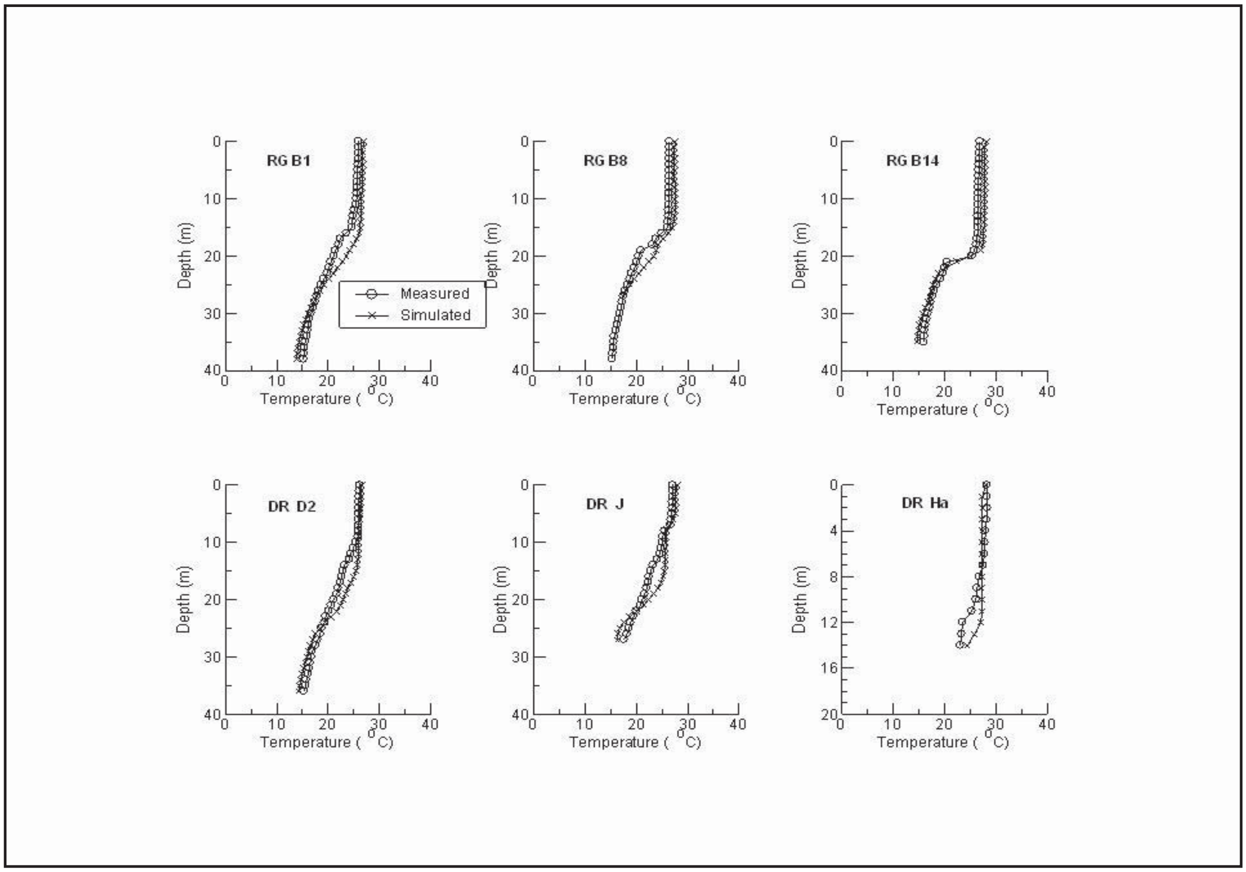

Figure 1. Simulated versus observed water temperature profiles at various locations of Amistad Reservoir on June 15-16, 2004.

Results and Discussion

One of the purposes of this study is to project the water quality conditions under a future scenario where twice the current CO_2 concentration ($2xCO_2$) is present in the atmosphere, and under various future inflow scenarios. Different inflow scenarios were chosen because of potentially different future water usage upstream of the Amistad Reservoir (i.e., different water availability to the reservoir), and the uncertainty that future climate may have on runoff in Texas (Groeger and Bass 2005; Groeger et al. 2005). Model runs were conducted for different scenarios after model calibration was completed, and results and discussion are presented below.

Impacts of Water Availability

There are three inflows from Pecos River, Rio Grande, and Devils River into Amistad Reservoir. The historical records of streamflow indicate that the combined annual average inflow of the three rivers into the reservoir ranges from 24.9 m^3/s (occurred in 2001) to 126.7 m^3/s (occurred in 1991) with an average inflow of 56.4 m^3/s. Combined annual average inflow in 2004 was 59.1 m^3/s and is used as the base year for the analysis of different inflow scenarios. Five inflow scenarios were considered: (1) 25 percent, (2) 50 percent, (3) 75 percent, (4) 150 percent, and (5) 175 percent of measured daily inflows in 2004. Annual average inflows for the five scenarios are 14.8 m^3/s, 29.6 m^3/s, 44.3 m^3/s, 88.7 m^3/s, and 103.4 m^3/s, respectively. For model simulations under different inflow scenarios, the outflow was assumed unchanged. In reality, the outflow rate from Amistad Reservoir is relatively constant. For example, the average outflow in 2004 is 13.8 m^3/s with a standard deviation of 3 m^3/s (70 percent of the time the outflow is between 13 and 14 m^3/s). This outflow is necessary to maintain the ecological health of the river downstream of the reservoir.

Model runs were made for the five inflow scenarios using the same initial and boundary conditions, such as the same climate data. In the lowest inflow scenario (25 percent of the inflow measured in 2004), there is scarcity of inflow into Amistad Reservoir due to the assumption of water usage upstream for industrial and agriculture purposes, and the projected increase of the water surface elevation would be only 0.6 m. The maximum water surface elevation of 343.2 m is predicted at the end of the year in the case of the largest inflow scenario (175 percent of the inflow measured in 2004). This is close to the maximum flood control pool level of 347.6 m above mean sea level. Figure 2 shows the simulated surface (all five scenarios) and bottom (only three scenarios as examples) water temperatures near the dam of Amistad Reservoir. There is little variation of surface water temperature for the different inflow scenarios due to the same meteorological conditions being applied for all inflow scenarios. The surface water temperature depends on the air temperature (Shrestha 2006). The bottom water temperature gradually increases from early March to early November due to absorption of radiation energy penetrating through the water column and weak mixing in the hypolimnion. The bottom water temperature near the dam continues to rise even when surface water temperature starts to decline from August toward the end of the year, corresponding to the cooling of atmospheric air temperature (Figure 2). This is because bottom water has no direct heat exchange with the atmosphere but continues to receive solar energy even during the cooling period. Warming of the bottom waters in November is caused by the entrainment and downward mixing of warmer surface waters as the reservoir nears fall turnover. The bottom water temperature near the dam before the fall turnover (Figure 2) shows almost no difference for all inflow scenarios because inflow entering the reservoir is about 38 km upstream of the dam. Difference in bottom water temperature for the five inflow scenarios does occur during the period of the fall turnover from stratification to more or less isothermal conditions (Figure 2). This is in strong contrast to Canyon Reservoir, located about 280 km to the east, where the hypolimnetic

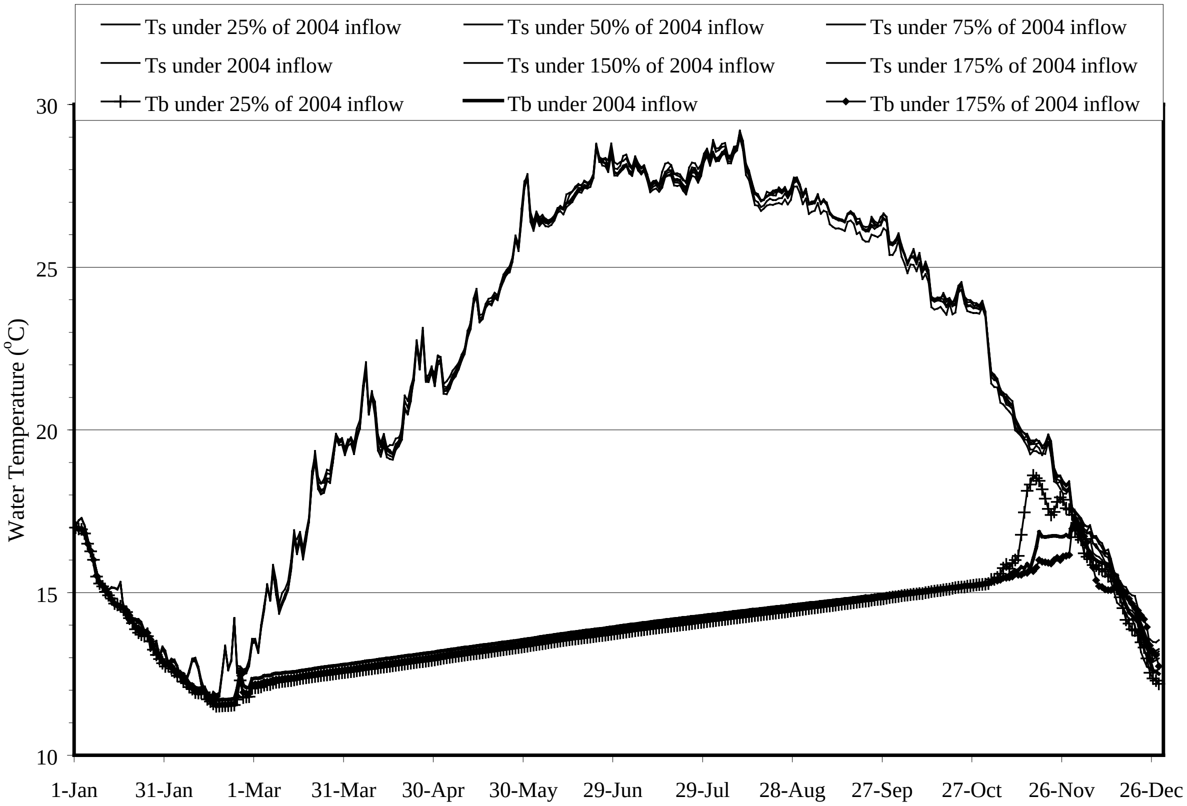

Figure 2. Simulated surface (Ts) and bottom (Tb) water temperatures near the dam of Amistad Reservoir under different inflow scenarios.

temperature is highly variable between years, and is closely and positively correlated to the inflow regime (Groeger and Bass 2005). The management scheme in Canyon Reservoir has been to largely keep the volume as close to conservation elevation as possible, so when inflows are high, the outflows coming from the hypolimnion are also high. Therefore, during wet years, all or most of the cold winter water found in the bottom of Canyon Reservoir in the spring is replaced by warmer inflows before the summer is over (Groeger and Bass 2005).

For the 25 percent inflow scenario for Amistad Reservoir, the fall turnover starts on November 2 (Figure 2) due to lower water storage depth and strong wind (maximum wind speed of 12.86 knots on November 2), but for the 175 percent inflow scenario the fall turnover starts on November 28 (4 weeks later) in spite of high wind on November 2 which does not cause the fall turnover due to a deeper water column (Figure 2). Impacts of the varied inflow on water quality conditions in the reservoir should be further examined in the region where the inflow enters the reservoir.

Impact of Future Climate Scenario

To examine the impact of future climate scenarios, projected changes in climate conditions were obtained from the output of the Canadian Climate Centre General Circulation Model (CCC GCM) (Second Generation) at doubling the atmospheric CO_2 concentration (using an increase of CO_2 at a rate of 1 percent per year). Predicted mean monthly increase for air temperature and the ratios for solar radiation, wind speed, and relative humidity between $2xCO_2$ (future) and $1xCO_2$ (current) climate scenarios were applied to measured 2004 daily climate conditions to generate the projected $2xCO_2$ climate scenario. This protocol eliminates the effect of any General Circulation Model biases in the current ($1xCO_2$) climate, and was proposed by the United States Environmental Protection Agency (Smith and Tirpak 1989). Projected monthly air temperature under future climate has an average increase of 3.4°C with a standard deviation of 0.9°C and ranges from 1.95°C to 6.5°C. Projected specific humidity has an average increase of 23 percent while wind speed has an average decrease of 3 percent. Figure 3 shows simulated

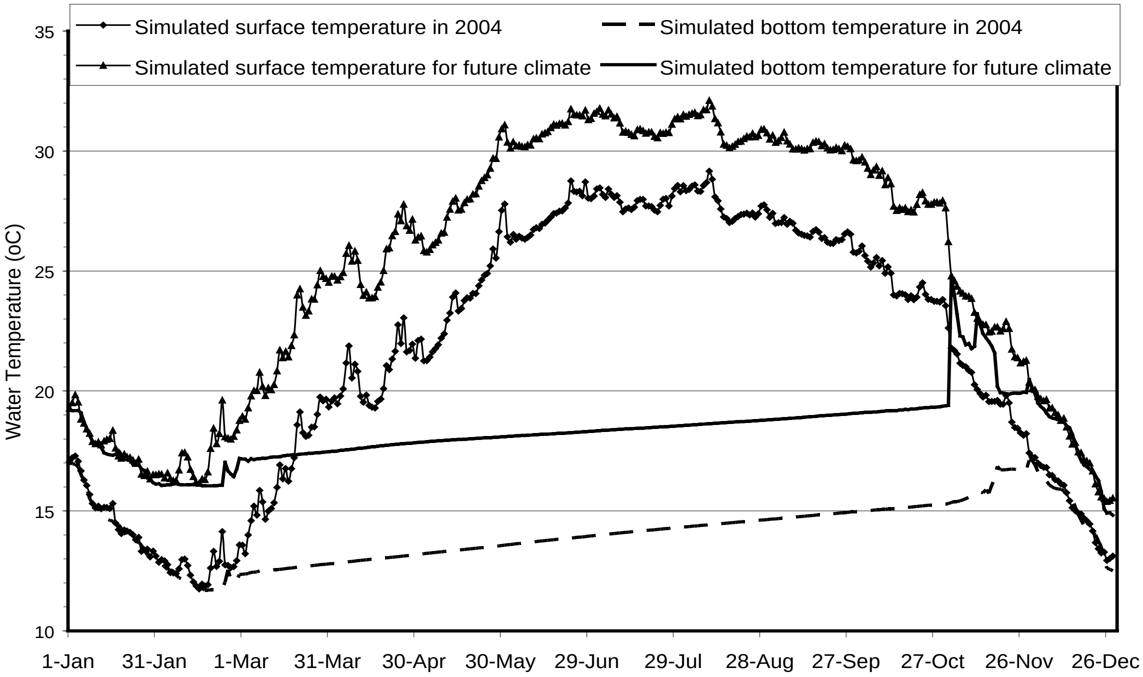

Figure 3. Simulated surface and bottom water temperatures near the dam of Amistad Reservoir under 2004 climate condition and $2xCO_2$ future climate scenario.

surface and bottom water temperatures near the dam in 2004 (modern) and under future ($2xCO_2$) climate conditions. It indicates that surface and bottom water temperatures are projected to have average increases of 3.7°C and 4.2°C, respectively. Increase of surface water temperature ranges from 2.2°C to 5.6°C and from 2.2°C to 9.5°C for bottom water temperature. Simulation results using the future climate scenario show that stratification of water temperature lasts longer (about three weeks) while strength of stratification after May is reduced compared to results under 2004 climate conditions (Shrestha 2006). This weaker stratification with the strong wind in early November results in the fall turnover occurring more than two weeks earlier (Figure 3), and leads to a maximum bottom temperature difference (9.5°C) between the two climate scenarios. The weaker stratification for Amistad Reservoir under the projected future climate scenario is different from projected water temperature characteristics in lakes in the northern U.S. (Minnesota) and the continental U.S. (Stefan et al. 1998; Fang and Stefan 1999). This is because lakes in these earlier studies (lake types), have no inflow and outflow. With inflow into and outflow leaving Amistad Reservoir, turbulent mixing below the mixed layer is much stronger. Therefore, water temperature near the reservoir bottom is projected to increase to a similar magnitude as surface water temperature (Figure 3). This leads to the same or weaker stratification strength for water temperate near the dam in Amistad Reservoir under the future climate scenario.

Summary and Conclusions

A two-dimensional reservoir water quality model CE-QUAL-W2 has been used to simulate water temperature characteristics in Amistad Reservoir on the Rio Grande under current and future climate conditions and under various inflow scenarios. The base-case model simulation shows good agreement with observed water surface elevation (root mean square error of 0.07 m) and measured water temperature profiles at various locations and dates (root mean square error varying from 0.32°C to 1.44°C). Changes of inflow discharges show significant impact on water storage (increase water depth with inflow) but limited impact on surface and bottom water temperatures near the dam. The future climate scenario shows a strong impact on both surface and bottom water temperature in the reservoir. The stratification of temperature under doubling CO_2 concentration is projected to last for a longer period (about three weeks), but strength of stratification is reduced. Elevated water temperatures in the reservoir will alter water quality (e.g., higher oxygen demand and lower dissolved oxygen concentrations), and impact reservoir management strategies in the future. Other water quality parameters such as dissolved oxygen are currently being examined.

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