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Modeling Hydrologic Regime of a Terminal Lake Basin with GCM Down-scaled Scenarios

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Abstract: A dramatic phenomenon has been occurring in Devils Lake, a terminal lake in North Dakota: its inundated area has continually expanded since reaching its extreme low in the 1940s. Devils Lake’s continual rise in water level has created immediate hardships for local residents, particularly farmers who have lost large parcels of productive land and properties. The search for solutions to the problems caused by the unique lake flooding has motivated our modeling of the lake basin’s hydrology, the lake processes, and climatic change impacts. A distributed rainfall runoff model, HEC-HMS, has been calibrated for several major sub-basins that drain into the lake. A significant challenge has been the implementation of Arc-Hydro within ArcGIS for a basin with relatively flat terrain (using the best available DEM of the region) which has undergone a lot of land-use changes in the past century. Further complexities in modeling are introduced by a pumped-drainage scheme implemented by the state’s water commission to lower the lake level by pumping and draining into an adjacent stream. The scheme operates whenever the stream’s water quality is favorable. A reservoir simulation model, HEC-ResSim, which is coupled with the HEC-HMS model, is calibrated for the lake for a short period of time. For the model calibration, NASA’s remote sensing data, including the TRMM Multi-Satellite Precipitation Analysis (TMPA) data, are used to supplement the limited ground data. The coupled, calibrated hydrologic-reservoir model allows a series of comprehensive climatic-scenario simulations to be carried out, a key feature of which is the use of future regional climatic conditions derived from GCM down-scaled ensembles. The described modeling is expected to yield useful and usable results for planners and decision makers who set long-term sustainability plans for the Devils Lake region.

Keywords: hydrologic, HEC-HMS; HEC-ResSim, lake flooding; terminal lake

1. PHENOMENON OF DEVILS LAKE

A unique lake-flooding phenomenon is the ongoing situation in Devils Lake of North Dakota, which has engaged many stakeholders, both locally and internationally. Being a terminal lake, its inundated area has continually expanded since reaching its record low in the 1940s. The lake has more than tripled in size since the early 1990s, which can be attributed to a series of wet years. Figure 1 shows an infamous plot of the lake level, with a very clear trend showing a continual rise in water level since the early 1990s. The slow but persistent rise in water level has inundated large parcels of productive agricultural land, properties, and civil infrastructures (including roads and water and public utilities). Unlike a river flooding which typically ends in days, lake inundation like that in Devils Lake can continue for years. It has created immediate hardships for many local residents, particularly farmers. Affected counties have been building higher dikes and re-routing numerous flooded highways and local roads. The cost associated with all these mitigation efforts is approaching half a billion dollars.
The U.S. Northern Great Plains, which includes the Dakotas, is predicted by GCM models to have greater amounts of precipitation in various simulation scenarios (IPCC, 2000). In addition to these model predictions, there are many regional hydrologic factors which have to be fully understood, such as evapotranspiration and seepage of the lake, and basin runoff characteristics. A companion paper in this volume by Zhang (2010) covers the present problem of Devils Lake, while another paper by Kirilenko (2010) presents the climate change impacts on agriculture in the Devils Lake Basin. We postulate that a fully distributed hydrologic model, combined with a reservoir simulation model, and used together with downscaled-GCM ensembles, can predict future lake levels under various climate change scenarios. The search for solutions to the problems caused by the unique Devils Lake flooding has motivated our modeling of the lake basin’s hydrology, the lake processes, and climatic change impacts.

2. HYDROLOGIC MODELING

The hydrologic modeling consists of two components: (1) modeling the generation of runoffs from the sub-basins into Devils Lake at seven locations and (2) modeling the water balance of the lake itself.

DEM and Delineations

Digital delineations of watersheds that flow into Devils Lake comprise the first step in the hydrologic modeling. 150 DEMs from the United States Geological Survey (USGS) were input to ArcGIS (from ESRI with Arc-Hydro extension) to delineate the sub-basins (see Figure 2). The total number of cells used varied according to the basin size. The model for Mauvais Coulee basin, e.g., is made up of half a million cells, each of size 10m x 10m.
The delineation using ArcGIS consisted of (1) merging all the DEMs together; (2) filling in the many small pot holes, to allow water to flow; (3) identifying flow direction once the direction of water flow from each cell is determined; (4) identifying points where water will accumulate (flow accumulation) and, hence, outlining the streams and rivers; and (5) constructing the stream network by setting the number of cells used to define a stream. The number of cells is determined not only by the size of the watersheds but also by the total number of watersheds and streams. ArcGIS’ stream link tool connects the streams by helping to define the nodes, junctions, and reaches of the streams; the catchment delineation tool defines the watershed for each stream section. The implementation of Arc-Hydro extension within ArcGIS for a basin with relatively flat terrain could have caused the formation of tiny holes (groups of cells) in the delineated watersheds. An approximation solution was adopted by adding the relatively small areas to the adjacent basins.

The small watersheds were combined to form the six large basins (Figure 2). These large basins were then input as background maps into HEC-HMS (USACE-HEC, 2009) to assist in creating a HEC-HMS model. The dendritic network of channels was modeled mainly by considering its main channel lengths, slopes, and routing parameters. The channel lags were estimated using the SCS Soil Curve Number and the empirical equation of SCS (SCS is now NRCS). 20 sub-basins were used for modeling the Mouvais Coulee, with the details shown in Table 1. It can be seen that the basin topography is very gentle, with slopes (10-80) in the range of 0.00015 to 0.0015 for major portions of the basin. Figure 3 shows the model setup for the Mouvais Coulee, featuring the interconnections of sub-basins, channel reaches, junctions, and a sink.

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3. CALIBRATION OF THE HEC-HMS MODEL

A calibration of the hydrologic model for the Mauvais Coulee basin involved an event from 6/13/2001 to 6/20/2001. The flow gauging station at USGS station 05056100 had been in operation from 06/01/1956 to 12/30/2009. The precipitation data from the North Dakota State Water Commission (NDSWC) station 848 operated by volunteers include rainfall. The results of calibration for that storm event, which include discounting the baseflows, are shown in Figure 4. Various initial loss and continuous loss values were used. Initial loss ranging from 0.04 to 0.2 in. (1 to 5 mm) was found acceptable, while the continuous loss is more sensitive. The model performed the best in the range of 0.037 to 0.039 in/day.

Improving the calibration of the Mauvais Coulee basin is important, because it is the only basin with significant discharge data, which will help make our model more accurate. The completed calibration attributes can subsequently be applied to the other six basins.
Precipitation data derived from NASA Tropical Rainfall Measuring Mission (TRMM) satellite were converted into grid files which were input into the HEC-HMS model. These supplementary data helped the calibration process, because only one ground-based rainfall
gauge over the entire basin was available. A uniform rainfall was assumed, even though, in reality, a storm system moving through a basin is often very unevenly distributed. With only one ground station within the basin, an error estimate for this assumption was not possible. Using grid data in the HEC-HMS model will, in theory, make our model more accurate due to the more accurate rainfall measurements. However, there were significant differences in terms of storm magnitude and temporal distributions.

The use of grid input to HEC-HMS encountered a problem. The approach was to treat each grid cell data as if they were observed by a ground station located at the center of the grid cell. The grid cell data was provided in ASCII format. Initially, it was input into ArcGIS as point data, which were then converted to grid format by adding a cell size. When added to the basin file, the grid did not overlap due to ArcGIS interpreting the longitude and latitude as meters instead of degrees. To overcome this, we input the grid data into a separate file and converted the degrees to meters. The saved file is imported into the basin file of HEC-HMS, with the grid overlapping the delineated basins.

4. USE OF NASA DATA IN MODEL CALIBRATION

Sources of NASA satellite and model data used in this study include (1) for precipitation, the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2007); (2) for surface air temperature, the Atmospheric Infrared Sounder (AIRS) (Aumann et al., 2003); (3) for soil moisture, the Land Parameter Retrieval Model (LPRM) applied to brightness temperatures from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) and the TRMM Microwave Imager (TMI) (Owe et al., 2008); and (4) for solar radiation and snow water equivalent, the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). Brief descriptions of these data follow. The TRMM product, 3B42 (V6), is an “organic” merged product, with new sensor data incorporated as they become available. It uses an optimal combination of microwave-based precipitation estimates to adjust the infrared (IR) estimates from geostationary observations. The resulting global precipitation estimates are then scaled to match the monthly rain gauge analyses. The surface air temperature is part of the AIRS L2 Standard Retrieval Product (AIRX2RET), which includes profiles of retrieved temperature. LPRM data provide global soil moisture for the top few centimeters of the soil column. LRPM is a three-parameter retrieval model for passive microwave data and is based on a microwave radiative transfer model that links surface geophysical variables (i.e., soil moisture, vegetation water content, and soil/canopy temperature) to the observed brightness temperatures. GLDAS drives multiple, offline (not coupled to the atmosphere) land surface models, integrates a large quantity of observation-based data, and executes globally enabled by the Land Information System (Kumar et al., 2006). Time series of the above data are prepared for input to HEC-HMS and GCM simulations. NASA data offer a denser and more uniform spatial coverage, which is required to drive the hydrologic models. An isolated rainstorm event recorded at the NDSWC station 848 in the Mauvais Coulee basin was compared with the TRMM data. The TRMM data indicated less precipitation total by up to 13% over a grid area (25 x 25 km). More elaborate comparisons will be carried out for more ground stations located in proximity of the Devils Lake basin.

TRMM Data Input Scheme

TRMM data available on the grid pattern were prepared for entry into HEC-HMS. However, that turned out to be inefficient because there are only 13 grid cells overlying the Mauvais Coulee, the largest of the six basins. Due to the grid format of HEC-HMS, input of data in a time series can be cumbersome, given the small grid size with which we are dealing. To be able to use the grid data, we set up a precipitation gauge weight time series component. Each grid cell has a gauge applied to the model to represent the cell. The precipitation gauge weight storm setup was deemed satisfactory.

Calibration of Multi-year Series

Devils Lake is in a temperate region; hence, it was necessary to calibrate the HEC-HMS model against a continuous flow series covering multiple years, including several winter seasons.
Accumulations of precipitation over the winters and snowmelt runoff processes in the spring were modeled in HEC-HMS. The observed temperature series over the basins was used to determine precipitation type, while a melt-rate function determined the runoff generation from the snowpacks. The melt-rate function allows the HEC-HMS model to interpret how fast the snow will melt, based on the temperature above freezing. This function is described in Dewalle & Rango, 2008 as

\[ M_s = C_m (T_a - T_b) \]  

where \( M_s \) is snowmelt (in/Fo day), \( C_m \) is the melt-rate coefficient which varies between 0.04-0.08, \( T_a \) is the air temperature (Fo), and \( T_b \) is the base temperature (Fo). Along with the ground gauge runoff series at USGS station 05056100 over a four-year period, a project storm derived from TRMM data was created using multiple gauge stations to represent the grid cells. Figure 5 shows a plot of a model simulation over a four-year period using \( C_m \) of 0.04. Generally, the observed storm sequences and the model runoffs coincide very well, though a discrepancy in the peak flow can be seen at the very first run off. The total volume of the observed runoff was 15.19 inches, while the model computed runoff was 10.44 inches or 68 percent of the observed value, for \( C_m \) at 0.04. For \( C_m \) of 0.08, the generated total volume was 10.94 inches or approximately 72 percent of the observed value. The difference is large, but it is acceptable for the present feasibility study purpose. Moreover, the dependency on just one ground observation is the limitation of the comparison.

5. HEC-RESSIM MODEL

Devils Lake resembles a reservoir with incoming flows from the surrounding seven major river basins. A reservoir simulation model, HEC-ResSim (obtained from the U.S. Army Corps), was implemented for the lake and surrounding areas. A schematic of the model setup can be seen in Figure 5. It includes four flow regimes: (1) inflows feeding the lake from the major basins; (2) a pumped outlet scheme, constructed by the North Dakota State Water Commission, that drains the lake, via a series of canals and pumps, into the Sheyenne River; (3) the natural overflow channel that connects Devils Lake to Stump Lake; and (4) the eventual overtopping pathway of Stump Lake into the Toulna Coulee and Sheyenne River.
The estimated pumped volume is almost negligible, because the pumped outlet scheme was operational starting in June 2007 with an original pumping capacity of 100 cfs. The outlet operates from April 1 to November 30, if lake level is over 1446.0 ft amsl. One main problem was the high sulfate concentrations in both the water of the lake and the receiving Sheyenne River, which prevented the pumping at full capacity. The limiting factor is the sulfate class 1A stream standard on Sheyenne River (450 mg/l). However, the pumping rate reached almost the capacity of permit in 2009. The current pumping rate is modified to 250 cfs. The additional pumping capacity is scheduled to begin on July 1, 2010. Recently, the North Dakota Department of Health (NDDH) adjusted the rate to a site-specific standard downstream of Baldhill Dam (750 mg/l). With that adjustment, the pumped volume is likely to be increased. The outlet discharge by pumping, since its implementation in 2007, based on reports submitted by the NDSWC to NDDH, shows an approximate drop in water level in Devils Lake by more than 65 mm (2.5 in). The accounting of current outflows includes pumping of water from the lake, losses through lake evaporation, and losses through the lake’s pool seepage. The pool seepage and lake evaporation, together with the inflows generated by the HEC-HMS models of the river basins, are calibrated against the observed water level series of Devils Lake provided by USGS. For continuous simulation purposes, DSS (a file format used in the suite of HEC software for data storage and transfer) files generated by HEC-HMS for each basin in the continuous period studied are imported into the reservoir model. The lake levels observed for the period are also entered as benchmarking for reservoir calibration.

6. GCM DOWNSCALED SCENARIOS

The GCM downscaling for this project is described in the companion paper by Kililenko et al. (2010). The whole process of deriving GCM downscaled scenarios for running the hydrologic model entails significant data handling and processing. The main outputs from GCM downscaling are precipitation and temperature. The gridded data need to be transformed to the appropriate basin-level or as single site time series data. Figure 7 shows the integration of the hydrologic model, reservoir model, and the downscaled GCM ensembles for hydrologic runoff simulations in the Devils Lake basin.

7. CONCLUSIONS

The calibration of hydrologic models (HEC-HMS) for the upland sub-basins of the Devils Lake Basin has proven to be challenging, because of the absence of sufficient ground-based precipitation data. Several storm events derived from the NASA TRMM satellite data have been processed and used to supplement the calibration process. The calibration of HEC-HMS model was satisfactory and a continuous loss of 0.037 to 0.039 in/day will be used in the simulation models. The use of NASA TRMM data in generation of runoff through calibrated HEC-HMS model has shown certain promising success. The runoff timing in the HEC-HMS model matches up consistently with a ground station when melt rate coefficients of 0.04 and 0.08 are used. The initial reservoir model has been established using HEC-ResSim, but further investigations are required for running the full reservoir model under various GCM down-scaled scenarios.
ACKNOWLEDGMENTS

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