DEVELOPMENT OF A THREE-DIMENSIONAL CIRCULATION AND TRANSPORT MODEL FOR EVALUATING FLOODING IN DEVILS LAKE, NORTHEASTERN NORTH DAKOTA

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Abstract

Since 1993, Devils Lake has been experiencing an unprecedented rise (in recorded history) with lake levels rising nearly 28 feet (ft) to a peak level of 1450.5 ft above National Geodetic Vertical Datum of 1929 (NGVD 29) in June 2009. The Devils Lake basin is a 3,810 square mile subbasin of the Red River of the North. The basin is closed when Devils Lake water levels are less than 1,446.5 ft above NGVD 29, but spills to Stump Lake at higher levels, and subsequently spills to a tributary of the Red River of the North at elevations greater than 1,458 ft above NGVD 29. The lake level of Devils Lake has exceeded 1,446 (ft) above NGVD 29 since 1999. Since May of 1995, the surface area of the lake has essentially doubled to the current area of 128,600 acres and the volume of the lake has increased 107 percent to 2,512,000 acre-feet. Hundreds of homes and businesses and thousands of acres of productive farmland have been lost as a result of the lake-level rise. More than 450 million dollars have already been spent relocating roads and bridges and building levees and yet the lake continues to rise. As the lake continues to rise and economic losses increase, the need for hydrologic tools that can be used in planning flood mitigation measures has grown. The three-dimensional UnTRIM model was developed for Devils Lake to evaluate the effects of different inflow scenarios on water levels throughout the lake, circulation, and solute transport.

The magnitude of the differential lake levels and their effects on flooding, water circulation, and solute transport can be simulated using the UnTRIM model. Continuous data were collected throughout the lake in 2006 and were used for model development and calibration. An unstructured orthogonal grid was developed for a shoreline elevation of 1463.78 ft above NGVD 29 to account for possible future flooding. The model was calibrated for existing conditions, and scenarios will be conducted using stochastically-generated inflow to investigate effects of various inflow conditions on flooding and solute transport.

INTRODUCTION

The Devils Lake basin is a 3,810 mi^2 sub-basin of the Red River of the North (fig. 1). About 3,320 mi^2 of the total basin area is tributary to Devils Lake, with the remainder being tributary directly to Stump Lake. The basin is closed at Devils Lake elevations of less than 1446.5 ft above sea level (asl). At elevations greater than 1446.5 ft asl, Devils Lake spills to Stump Lake, and at elevations greater than about 1,458 ft asl, Devils Lake and Stump Lake together begin to spill through the Tolna Coulee to the Sheyenne River. Geologic and other records suggest that

Devils Lake has been a dry lake in the past, but has also spilled to the Sheyenne River at least twice during the last 4,000 years (Bluemle, 1991; Murphy and others, 1997).

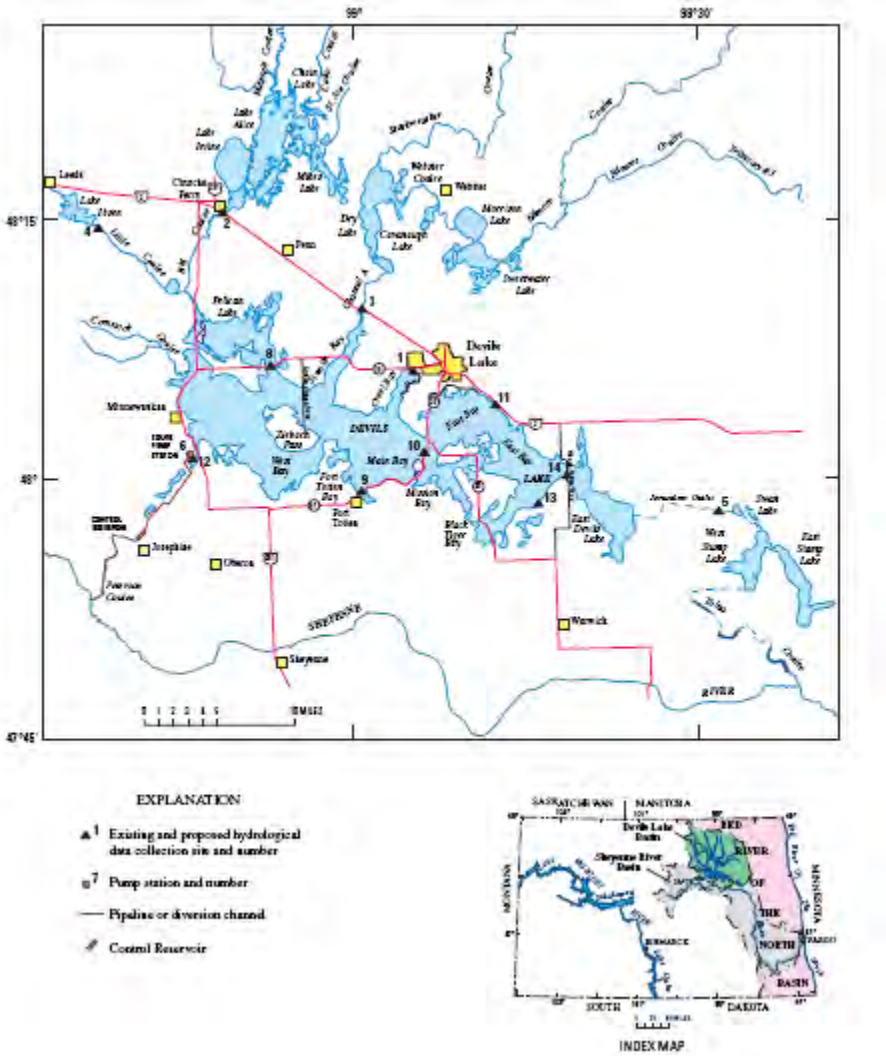

Figure 1 Location of monitoring sites in Devils Lake, North Dakota.

Lake-levels were measured occasionally between 1867 and 1901, but regularly since 1901 (fig. 2). The minimum recorded Devils Lake elevation of 1,400.9 ft asl occurred in 1940, with a corresponding surface area of 10 mi^2. Since 1993, Devils Lake has been experiencing an unprecedented (in recorded history) rise (fig. 2). The Devils Lake-level has exceeded 1,446 ft asl (spill elevation to Stump Lake) more or less continuously since May 1999. In June 2009, the lake-level peaked at 1,450.5 ft asl.

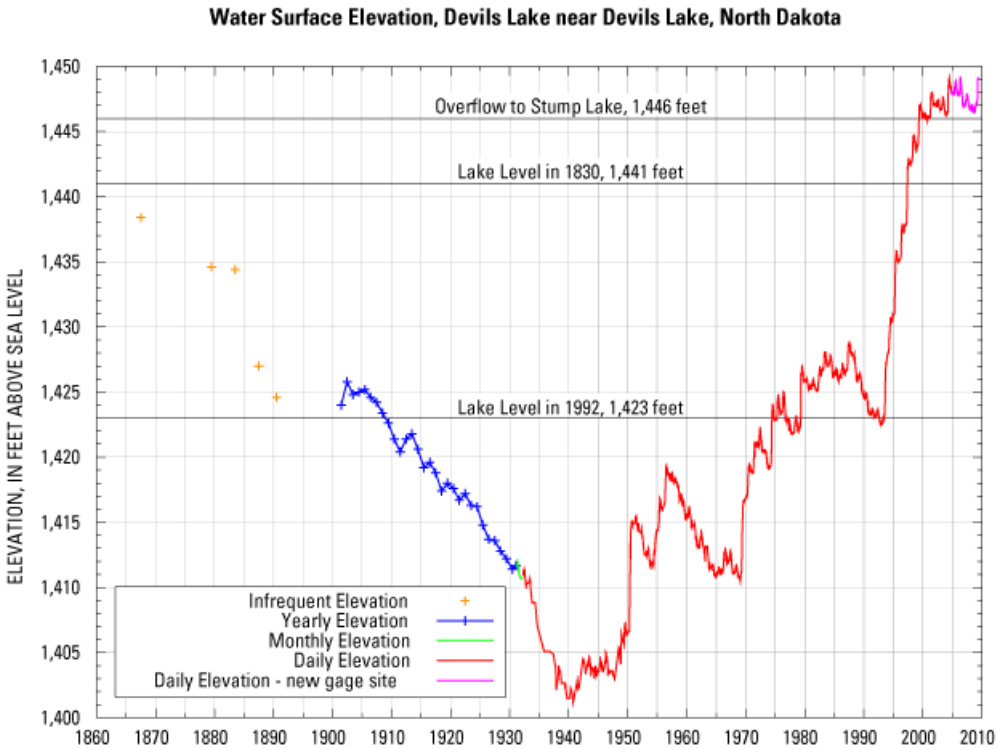

Figure 2 Historic water elevation for USGS gaging station, 05056500, Devils Lake near Devils Lake, ND.

The surface area of the lake has essentially doubled since May 1995 to the current area of 128,600 acres, and the volume of the lake has increased 107 percent to 2,512,000 acre- feet.

Direct flood damages and flood mitigation measures associated with the rise in Devils Lake have been in the hundreds of millions of dollars. Farmland has been lost, the dike protecting the town of Devils Lake has been raised and lengthened, the communities of Creel and Minnewauken are threatened, roads have been inundated or raised, and transportation patterns have been disrupted. As the lake continues to rise and economic loss increases, the need for hydrologic tools that can be used in planning flood mitigation measures has grown. A hydrodynamic model can be used to evaluate the effects of different inflow scenarios on water levels throughout the lake, circulation, and solute transport, regardless of whether the lake is rising or falling.

MODEL DESCRIPTION

UnTRIM Numerical Model

The UnTRIM model, developed by the U.S. Geological Survey, solves the unsteady (time-varying) shallow-water equations on a boundary fitted unstructured orthogonal grid (Casulli and Walters, 2000). The computational scheme used in UnTRIM is based on the method first proposed by Casulli (1990) for two-dimensional hydrodynamic equations, and later extended to

three-dimensional equations. The model is unconditionally stable, computationally efficient, and wetting and drying of computational cells is treated correctly. The model has been applied in a variety of waterbodies, successfully tested for extreme hydraulic conditions, including simulation of dam break flow in a laboratory flume (Fulford, 2003), and has been extensively applied to San Francisco Bay (Cheng and others, 1993) in both the two-dimensional and three-dimensional form.

Model Domain

The computational domain, or model domain includes the Devils Lake/Stump Lake hydrologic system. Big Coulee (site 2) upstream to the gaging station, and Channel A (site 3) upstream to the gaging station (fig. 1) are included. Little Coulee inflow measured at site 4 is assumed to occur at the confluence of Big Coulee and Little Coulee (fig. 1). A shoreline elevation of 1463.78 ft NGVD 29 was used to develop an unstructured orthogonal grid of Devils Lake and Stump Lake (fig. 3).

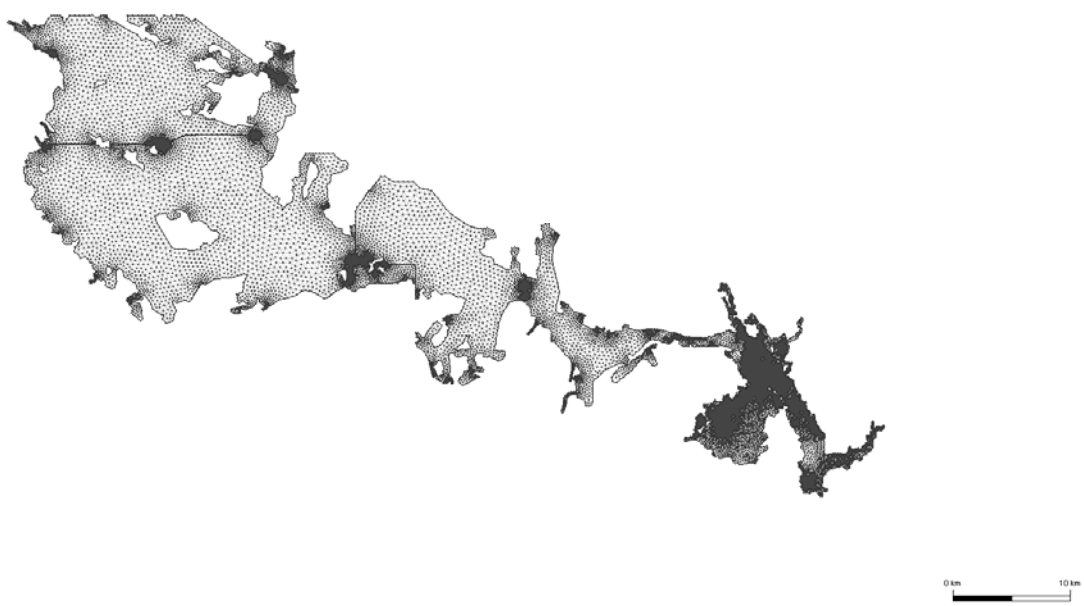

Figure 3 Unstructured orthogonal grid for Devils Lake, North Dakota.

Bathymetry

Bathymetry data from the North Dakota State Water Commission was used to develop the model grid for portions of Devils Lake that are typically inundated. For areas around the lake that are not normally inundated, LiDAR data was available from the Army Corps of Engineers through the Federal Emergency Management Agency. Ten meter Digital Elevation Model (DEM) data

was available from the North Dakota Game and fish and was used in the development of the grid for Stump Lake (http://web.apps.state.nd.us/imf/imf.jsp?site=NDGFGenInfo). It was assumed that the major highways crossing Devils Lake, ND State highway 19 and ND State highway 57, would be maintained to the 1463.78 ft elevation; these roads were defined in the model grid (fig. 1). County Road 4, also known as Woods-Rutten Road, was also assumed to be maintained to a 1463.78 ft elevation; it was defined in the model grid. The bridge openings for these three roadways were defined in the model.

MODEL DEVELOPMENT AND CALIBRATION

Computational grid

The unstructured orthogonal model grid for Devils Lake and Stump Lake (fig. 3) was created and optimized using JANET software (Lippert and Sellerhoff, 2006). The resulting grid for the Devils Lake/Stump Lake hydrologic system contains 32,752 polygons and 18,400 vertices. The length of the sides of the polygons vary from approximately 26 ft in areas around the bridge openings to 260 ft in open areas of the lake.

Datasets

Datasets collected in 2006, were the primary source of data for model development and calibration (fig. 1). Discharge measured in 2006 for the three main inflow sites to Devils Lake (sites 2, 3, and 4) and meteorological data compiled from selected sources were used for boundary conditions in the model. Lake-level data and discharge data for the three bridge openings (sites 8, 10, and 14) on Devils Lake measured in 2006 were used in the model calibration.

Boundary Conditions

Discharge measured by side-looking AVMs in 2006, at sites 2 and 3, were used as inflows to Devils Lake from Big Coulee and Channel A, respectively. Site 4 is an established USGS streamflow gage and discharge was considered to enter the lake at the confluence of Big Coulee and Little Coulee. Ungaged inflows were computed by applying a coefficient to the sum of the measured daily inflows based on Table 2 in Vecchia, 2002. Coefficients are large in early spring due to direct runoff from snowmelt, but taper off in early summer. Groundwater inflow is considered negligible in the water balance for Devils Lake, so a specific groundwater source was not included in the model.

Daily precipitation and evaporation data were compiled from the North Dakota Agricultural Weather Network (NDAWN) stations located at Baker and Crary, ND (fig. 1; NDAWN, 2008). The Penman equation for potential evapotranspiration was used to represent evaporation. Precipitation and evaporation were applied in the model as a net daily evaporation. The net daily evaporation was determined by averaging the daily precipitation and evaporation from Baker and Crary and then subtracting evaporation from precipitation. Average net daily evaporation was applied uniformly over the grid.

Hourly wind data from the Crary weather station was applied uniformly over the grid.

Calibration data

Lake-levels measured in 2006 at sites 1, 9, 11, 12, and 13, were used to compare with simulated lake-levels. Because of accuracy limitations in surveying, lake-levels measured in 2006 do not correlate well with each other. In order to compare lake-levels with one another, site 1 was assumed to be the base lake-level, and all sites were corrected to site 1. An average correction was applied to daily lake-levels for each site based on three calm periods with little to no inflow. The corrected lake-levels were used for comparison with simulated lake-levels.

Discharge measured in 2006 through bridge openings at sites 8, 10, and 14 was used to compare with simulated discharge. In 2006, up-looking AVMs were used to collect velocity data through the three bridge openings. The index-velocity method was then used to determine discharge through these openings (Morlock and others, 2002).

Hydrodynamic calibration

The hydrodynamic model was calibrated for 2006 by adjusting model parameters *a*, a constant in the equation for surface drag coefficient and z_o, the bottom roughness height. After calibration, a value of 0.00056 $(m\ s^{-1})^{-0.5}$ was used for *a* and a value of 0.0005 m was used for z_o. In addition to the model parameters, a coefficient, *b*, was applied to the daily evaporation before computing net evaporation. An initial *b* was specified based on monthly coefficients in Table 2 of Vecchia, 2002. Using the measured daily lake-level at Site 1, and the volume of the lake as a function of lake-level (based on the same bathymetry used for the model grid) a simple mass balance was used to compute daily lake-levels. The simple mass balance for Devils Lake can be calculated by:

(1) $\sum \Delta V = \sum$ inflows (gaged and ungaged) - $\sum$ outflows + net evaporation

Using *b* the net evaporation term in equation (1) was adjusted until the sum of the differences between measured lake-level and lake-level computed by mass balance equaled zero. The same net evaporation was applied uniformly over the Stump Lake portion of the grid.

The model simulates the measured elevations reasonably well (fig. 4). Wind induced peaks and valleys are captured well by the model.

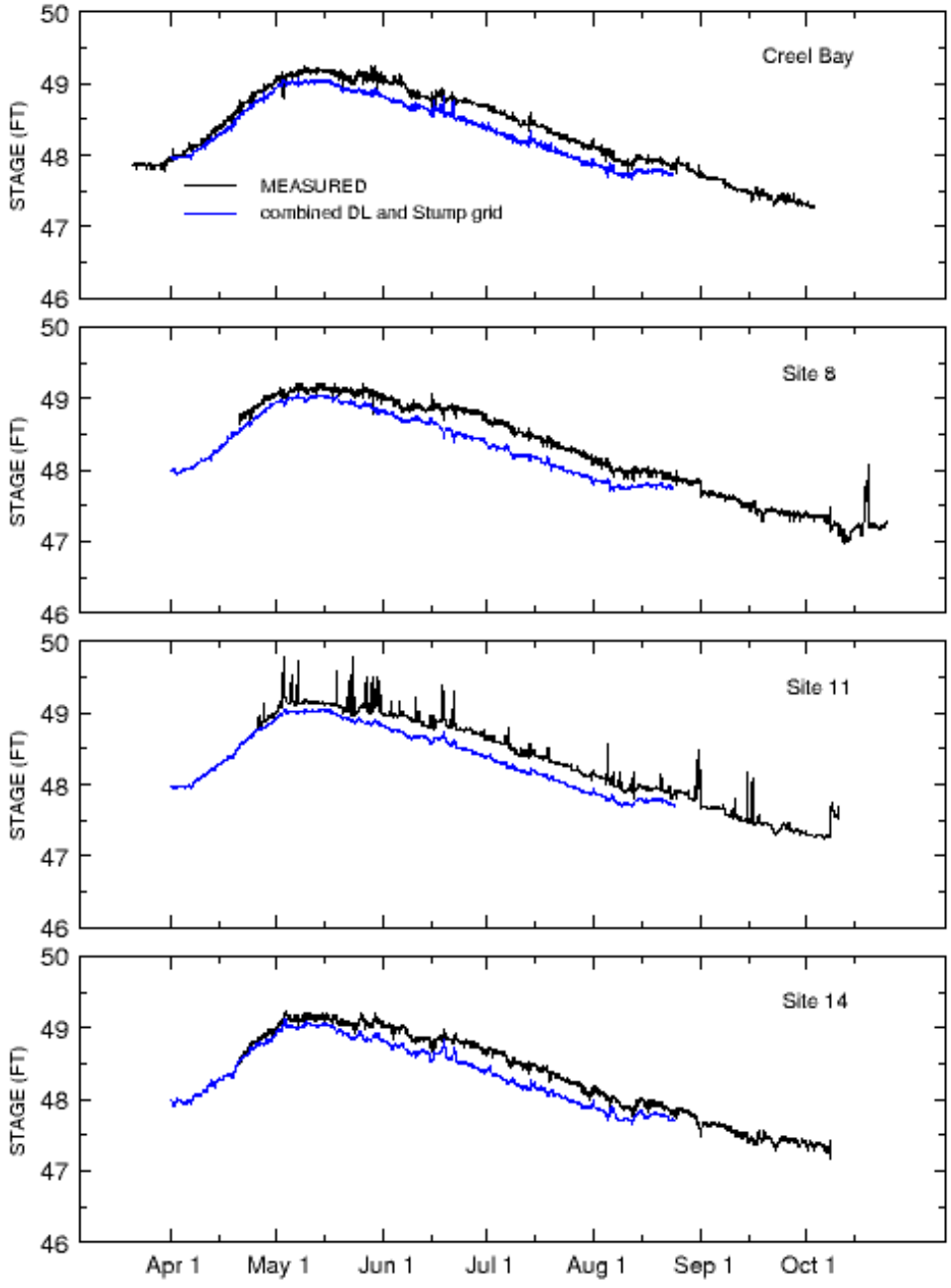

Figure 4 Measured and simulated lake-levels at for sites in Devils Lake, North Dakota, 2006.

The mean error (ME) in the simulated lake-levels at all of the lake sites are provided as a measure in the bias of the simulation (table 1).

Table 1 Goodness-of-fit lake-level statistics for the UnTRIM model of Devils Lake, ND, 2006.

Site	Mean of measured lake-level	Mean error (ft)	Root mean square error (ft)
1	1448.37	0.05	0.15
9	1448.32	0.07	0.19
11	1448.39	-0.15	0.05
12	1448.37	0.13	0.12
13	1448.46	-0.11	0.30

Errors are calculated as the measured value minus the simulated value; a positive ME indicates simulated values less than measured. As indicated by the ME, lake-levels are overestimated at site 1, 9, and 12. At sites, 11, and 13 lake-levels are underestimated. The root mean square error (RMSE) is provided as a measure of overall goodness-of-fit of the simulated lake-levels to measured lake-levels. The RMSE is low for all sites indicating a good fit between measured and simulated lake-levels.

In the model grid, the channel geometry at the bridge openings was modified to closely match the measured cross-sectional area. The model simulates discharge well at site 14, but not as well at sites 8 and 10 (fig. 5).

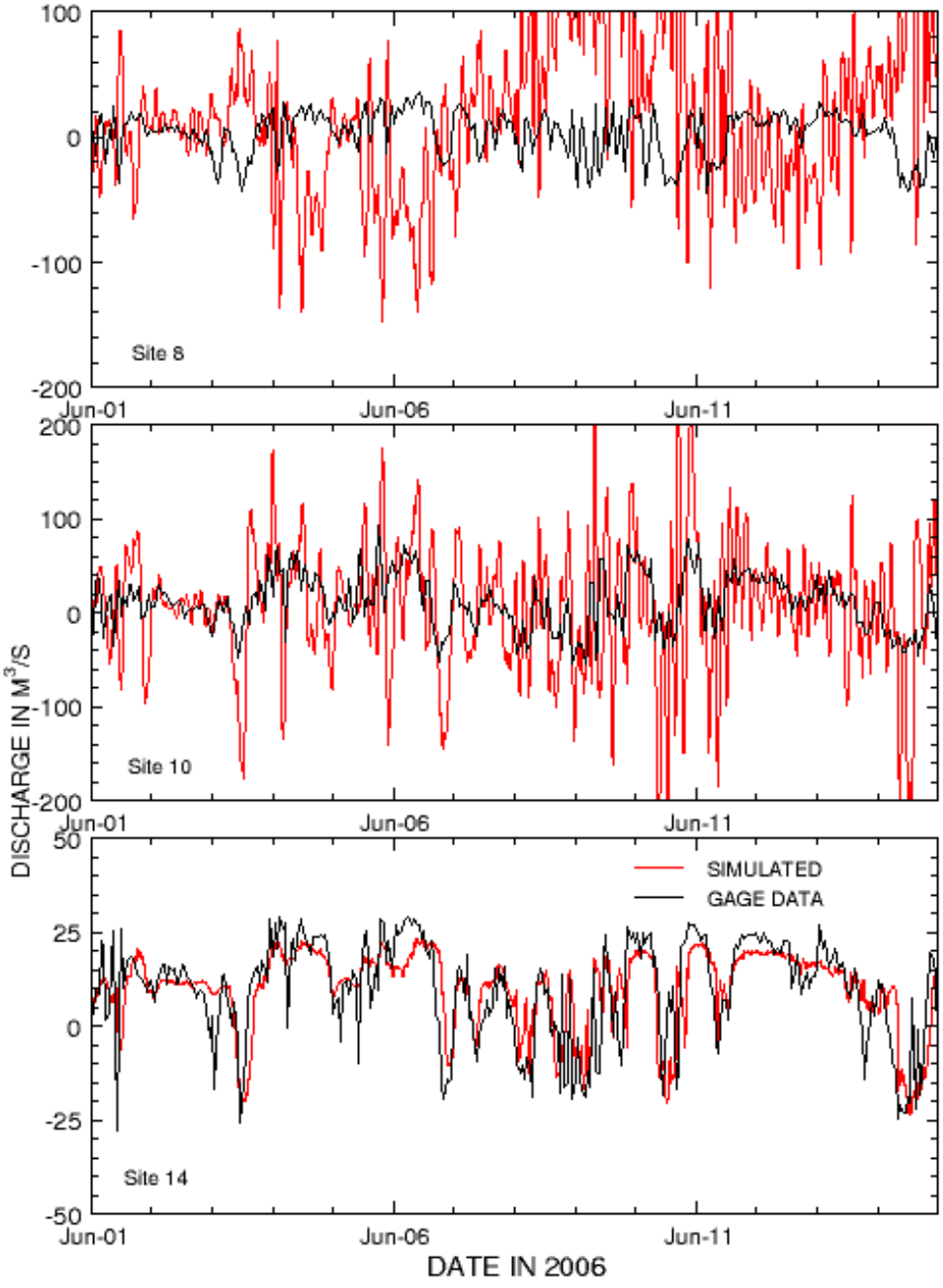

Figure 5 Measured and simulated discharge at three bridge openings in Devils Lake, North Dakota, 2006

The ME for site 14 is the lowest at 3 cfs. For all sites discharge is overestimated as indicated by the positive ME. The RMSE is low, overall indicating a good fit for all sites.

Table 2 Goodness-of-fit discharge statistics for the UnTRIM model of Devils Lake, ND, 2006.

Site	Mean of measured discharge	Mean error (cfs)	Root mean square error (cfs)
8	248	5	7
10	266	7	15
14	212	3	5

Further calibration of the circulation and transport is needed. Data is available from 2006 to aid in further calibration. The UnTRIM model of Devils Lake, ND can

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