ASSESSMENT OF RESERVOIR TRAP EFFICIENCY METHODS USING THE HYDROLOGIC MODELING SYSTEM (HEC-HMS) FOR THE UPPER NORTH BOSQUE RIVER WATERSHED IN CENTRAL TEXAS

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Abstract The effects of surface erosion, reservoir sedimentation, and in-stream sediment transport have become increasingly important in watershed management and natural resources conservation planning studies and for the evaluation and implementation of water quality best management practices (BMPs) and the evaluation of TMDL's. Many water resources studies must now consider erosion related effects of watershed activities. Surface erosion models describe the detachment, deposition, and transport of soil particles from the land surface by the erosive forces of raindrops and then route the sediment downstream while modeling erosion and deposition within river reaches and reservoirs. The U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is a computer program designed to model watershed hydrology. Historically, HEC-HMS has focused on modeling rainfall-runoff processes; however, new tools have been added for sediment and water quality modeling. Output from these new tools could be used for making informed decisions about managing soil erosion within the watershed.

This paper evaluates the new reservoir sediment modeling capabilities in HEC-HMS. Research has shown that reservoir sedimentation trap efficiency is affected by the detention time of storm runoff and by factors governing sediment particle size. The first trap efficiency method in HEC-HMS was evaluated by developing models for two small reservoirs in the Upper North Bosque River watershed (UNBRW), located in central Texas, where average daily flow and sediment loading data were available. Results show that the HEC-HMS model provided reasonable predictions of accumulated sediment at the reservoir bottom and accumulated sediment loadings from both reservoirs during the simulation period.

INTRODUCTION

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is a computer program designed to model watershed hydrology. Historically, HEC-HMS has focused on modeling rainfall-runoff processes; however, a significant effort is underway to add sediment and water quality modeling capabilities. This paper provides a description and example application of the surface erosion, in-stream sediment routing, and especially the reservoir sediment routing modeling capabilities that are available in version 4.0 of HEC-HMS. The following discussion describes the seven hydrologic elements that are available for developing a hydrologic model and the new sediment modeling capabilities that have been added to the program.

The subbasin element is used to represent a drainage basin where precipitation falls, infiltration occurs, and surface runoff may result. Outflow from the subbasin element is calculated by taking into account losses due to interception by the canopy, storage on the land surface and infiltration. Once losses have been computed, the excess precipitation is treated as surface runoff and transformed to stream flow at the subbasin outlet. Surface runoff is combined with interflow and baseflow to compute the total runoff hydrograph. Two surface erosion methods have been included in the subbasin element: the Modified Universal Soil Loss Equation (MUSLE) and the build-up and wash-off methods. The MUSLE method simulates the sediment yield processes from a pervious land segment and the build-up and wash-off method simulates sediment yield processes from an impervious land segment. Future work will eventually include adding additional erosion methods suitable for both pervious and impervious areas, allowing the engineer to select the best method for a specific watershed study. Before sediment from a subbasin element is available to a downstream element, a sediment enrichment ratio is used to determine the relationship between particle size of watershed sediment and fluvial suspended sediments. The enrichment ratio provides a mechanism to translate the sediment distribution from the source on the land surface to a sediment distribution at the subbasin outlet.

The reach element is used to convey stream flow from upstream to downstream. Inflow into the reach element can come from one or many upstream hydrologic elements. Outflow from the reach is calculated by accounting for translation and attenuation of the inflow hydrograph. Multiple methods for modeling sediment transport and erosion/deposition within a channel have been added to the reach element. Several sediment transport equations are available along with sediment routing methods to route sediment through the stream network. The sediment continuity equation is used in conjunction with a sorting algorithm to solve for the actual volume of deposition or erosion within the reach element. Additionally, temporal entrainment and deposition functions similar to those employed in HEC-RAS have been adapted for use in HEC-HMS.

The reservoir element can be used to model a natural lake, man made reservoir, or small detention pond. Inflow into the reservoir elements can come from one or many upstream hydrologic elements. If there is more than one inflow, all inflow is added together before computing the outflow. It is assumed that the water surface in the reservoir pool is level. Three different routing methods are available for the reservoir elements. One routing method simply represents the reservoir using a user-defined storage and discharge relationship. The second method uses a specified release and computes the storage that would result. This method is useful when observed releases are available and can assist in the calibration of model parameters affecting inflow into the reservoir. The final method is designed to represent individual components of the outlet works. In this case, the user would enter an elevation and storage relationship and supply information about the outlets. The sediment routing option for a reservoir element only works for the first method, the user-defined storage and discharge relationship. The user must define elevation-area-discharge curves in order to use the variable trap efficiency method (Chen’s Method). With this choice, the program automatically transforms the elevation-area curve into an elevation-storage curve using the conic formula (ref HEC-1 manual). The routing is performed using only the storage-discharge curve. After the routing is complete the program will compute the elevation and surface area for each time step. Based on the calculated discharge, surface area and settling velocity, the trap efficiency is then calculated.

Source elements provide a way to add measurement inflows, including water and sediment to the flow network, or to represent upstream boundary conditions. Junction elements are used in the flow network to combine multiple inflows, often at a confluence. The diversion element is used to represent locations where water is withdrawn from the channel. Finally, sink elements are used to represent the outlet of a watershed.

RESERVOIR DESCRIPTIONS AND RELEVANT DATA

The new sediment modeling capabilities were applied and evaluated using observed measurements from two reservoirs (NF030 and SF030) located along the South Fork and North Fork of the North Bosque River near Stephenville, Texas as shown in Figure 1. The SF030 reservoir represents a least impacted site and the NF030 reservoir represents an impacted site with regard to agricultural nonpoint source pollution. The vegetative cover and land-use activities above these two reservoirs are distinctly different as shown in Table 1. The NF030 reservoir has much more intensive agriculture in its drainage basin. There are also three dairies in the watershed above the North Fork reservoir with about 2050 permitted cows during 1994-95 when much of the monitoring occurred (TIAER, 2006).

Table 1 Drainage Area Characteristics of NF030 and SF030 (Source: TIAER, 2006).

Drainage Area Characteristic	North Fork Reservoir (NF030)	South Fork Reservoir (SF030)
Wood & Range (%)	47.3	94.0
Pasture (%)	17.8	3.2
Cropland (%)	9.2	0.9
Dairy Waste Application Fields (%)	24.1	1.0
Other (%)	1.5	1.0
Drainage area (ha)	1560	930

Soils in the UNBRW are classified as fine sandy loams with sandy clay subsoil, calcareous clays, and clay loams (Ward et al., 1992). The watershed receives an average annual precipitation of 750 mm and the average daily temperature ranges from 6^{o}C in winter to 28^{o}C in summer (McFarland and Hauck, 1999). Continental polar fronts produce low-intensity, long-duration storms in winter and fall. Squall-line thunderstorms produce high intensity, short-duration storms in spring and summer.

A monitoring program, including the five gage stations shown in Figure 1, was established in 1993 to provide characterization of stormwater and sediment inflow and outflow through each reservoir. Two gages were monitored for the SF030 reservoir including an inflow gage (SF020) and an outflow gage (SF035). Three gages were monitored for the NF030 reservoir including two inflow gages (NF009 and NF020) and one outflow gage (NF035). Three inflows (SF030, NF009, and NF020) were adjusted for the ungaged area using a drainage area ratio.

The following data were obtained from the Texas Institute for Applied Environmental Research (TIAER), Tarleton State University, Stephenville, TX for the study period 1994-1996: (1) observed stream flow measurements for the NF009, NF020, NF035, SF020, and SF035; (2) observed total suspended solids (TSS) measurements for the NF009, NF020, NF035, SF020, and SF035; (3) drainage area characteristics; (4) elevation and storage relationships for both reservoirs; (5) reservoir design information as shown in Table 2. The Soil Survey Geographic (SSURGO) Database was downloaded from the Natural Resources Conservation Service (NRCS) website: http://www.soils.usda.gov/survey/geography/ssurgo/ and used to estimate the percent sand, silt, and clay for the sediment inflow to each reservoir.

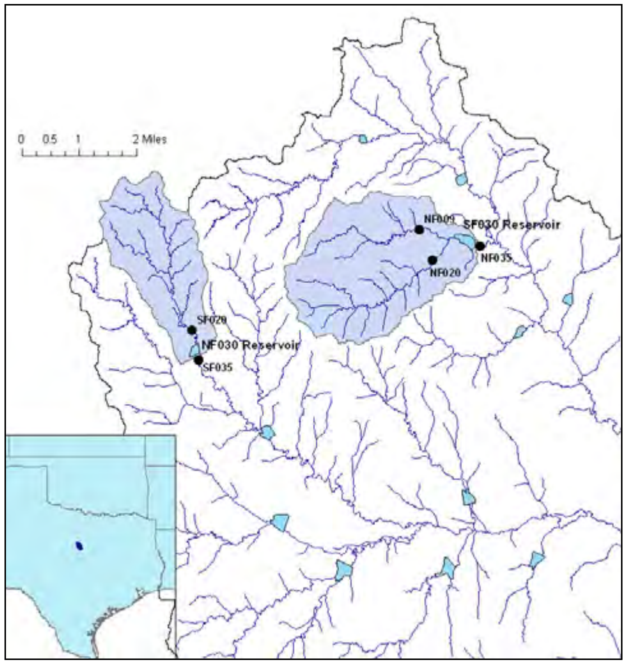


Figure 1 Inflow and outflow monitoring sites for the South and North Forks reservoirs.

Table 2 Reservoir Design Information for NF030 and SF030 (Source: TIAER, 2006).

Parameter	NF030	SF030	Unit	Observations
Principal Spillway	1359.5	1445.8	feet	crest elev.
Hgel elev. At Outlet	1344.3	1434.73	feet	center line
Orifice elev. Of Bar	1350.75	1439.8	feet	center line
Orifice elev. Of Bar	1349.5	1438.8	feet	Invert
Maximum Water Surface	1389.1	1468.5	feet	top of dam (effective) elev.
Weir Length	15	8	feet	
Weir Coefficient	3.1	3.1		Constant
Barrel Orifice (coefficient)	1.1	1.1		Constant (Calibrated Value)
Principal Spillway	1.5	1.5		Constant
Acceleration of Gravity	32.2	32.2	Feet/second	Constant
Riser Area	18.75	8	Square feet	
Area of Pipe	4.9087	3.1416	Square feet	
Emergency Spillway	1377.7	1464.1	feet	crest elev.
Pipe Friction Coef.	0.00786	0.01058		Hydraulics: Head Loss Coefficients table
Pipe Length	230	240	feet	

METHODOLOGY

Significant errors may result if the transportability of sediment is inferred from dispersed particle size distributions rather than actual or effective sediment sizes (Slattery, 1997).

Knowledge of the changes in the particle size distribution from source material at the point of erosion to the watershed outlet is important to understand the comprehensive sediment transport process at work in the watershed. An enrichment ratio option is used in HEC-HMS to convert the watershed particle size distribution into an outlet particle-size distribution before routing the sediment through the stream and reservoir network. The enrichment ratios (*ER*) for each particle size are determined from Eq. 1.

$$ER = \frac{\%\ sediment\ in\ a\ given\ size\ class\ in\ outlet}{\%\ sediment\ in\ a\ given\ size\ class\ in\ watershed} \qquad (1)$$

An *ER* value greater than 1 represents an enrichment condition: a given size class forms a greater percentage of the transported load at the outlet than at the source. An ER value less than 1 represents a depletion condition: a given size class forms a greater percentage at the source than in the transported load at outlet. The SSURGO database was also used to estimate the percent clay, sand, and silt from the subbasins.

Reservoir sediment routing methods have been developed starting first with steady-state models and moving then to non-steady-state models. The sedimentation in an ideal rectangular flow basin was studied by Camp (1945). The model was developed under three assumptions; a quiescent and steady flow, complete mixing of water and sediment, and no resuspension. When sediment is flowing into the tank, the sediment particles settle with a settling velocity (v_s), which is dependent on particle size. The critical settling velocity (v_c) is defined as the velocity allowing particles to settle in an ideal pond. The critical settling velocity is a function of the water depth (*d*) and the water travel time through the pond (*T*);

$$v_c = \frac{d}{T} = \frac{d}{1/v} = \frac{dv}{1} = \frac{dvb}{1b} = \frac{Q}{A} = overflow\ rate \qquad (2)$$

where:

1 and *b* are the length and width of the rectangular settling basin
v is the water velocity through the pond
A is the surface area of the pond
Q is the in- or outflowing discharge.

The critical settling velocity is equal to the overflow rate of the pond. For an ideal rectangular pond, the fraction of particles trapped with v_s less than v_c is given by the trap efficiency (TE) as shown in Equation (3):

$$TE = 100\frac{v_s}{v_c} = 100\frac{A}{Q}v_s \qquad \text{for quiescent flow} \qquad (3)$$

$$TE = 100\left[1 - e^{-\frac{v_s}{v_c}}\right]_s \qquad \text{for turbulent flow condition} \qquad (4)$$

The Equation (4) was developed from Equation (3) by Chen (1975) in order to have a formulation for turbulent flow conditions. Equation (4) was implemented into HEC-HMS as the first TE estimation method. After calculating the TE, the sediment routing through the reservoir is calculated as shown in Equations (5), (6) and (7):

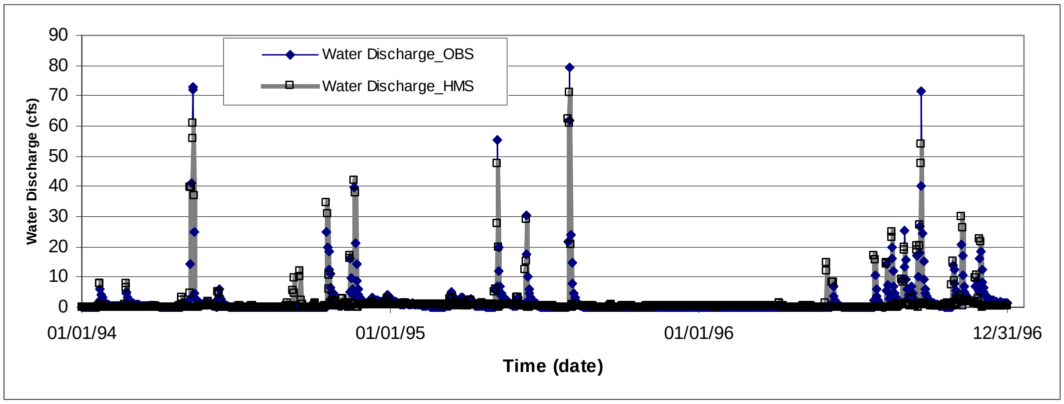
$$Sediment\ Deposition = Sediment\ Inflow \times TE \tag{5}$$

$$Suspended\ Sediment\ in\ reservoir = Sediment\ \ Inflow - Sediment\ Deposition \tag{6}$$

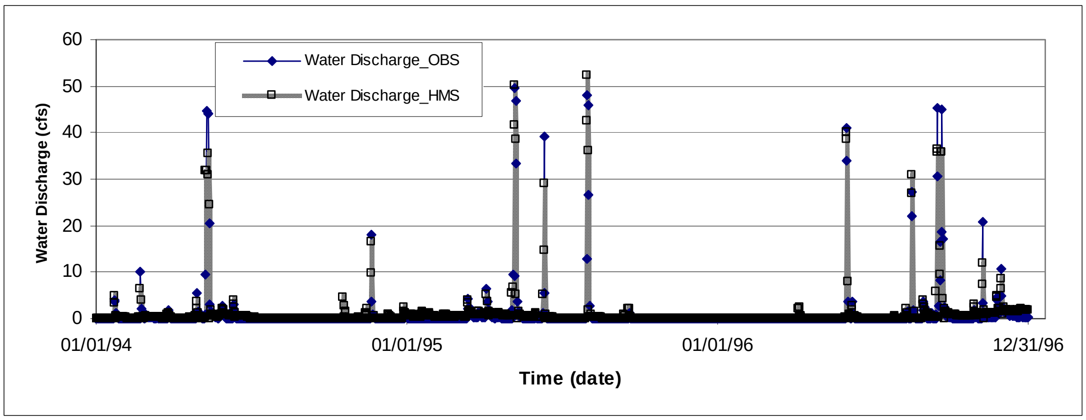
$$Sediment\ \ Outflow = Suspended\ \ Sediment\ \ in\ \ reservoir \times \frac{Water\ Discharge\ \ from\ reservoir}{Water\ Volume\ in\ reservoir} \tag{7}$$

RESULTS AND DISCUSSIONS

For flow reservoir routing, elevation-area-discharge curves were developed using the available information in Table 2. Measured average daily flows at NF035 and SF035 are compared with simulated average daily outflows at reservoirs NF030 and SF030 from the HEC-HMS model for the simulation period (01Jan1994 – 31Dec1996) in Figure 2. Results show that the simulated average daily outflows from the reservoirs are in good agreement with the measured average daily flows at the stream gages (NF035 and SF035).



(a)

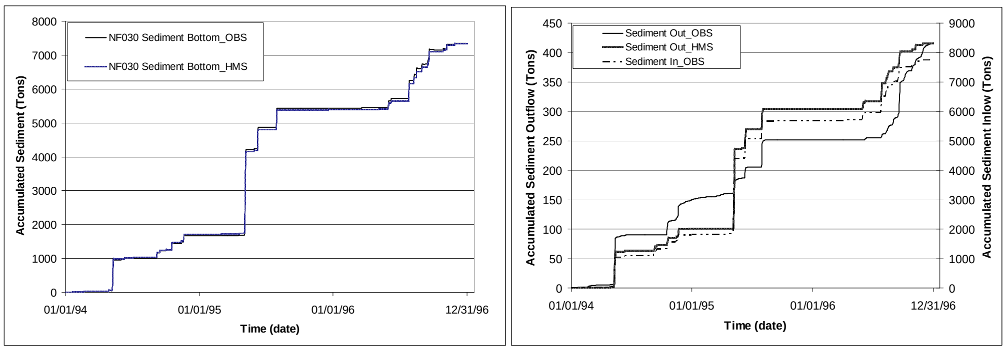


(b)

Figure 2 Reservoir Discharge Routing Results for Reservoirs; (a) Flow Discharge from Reservoir NF030, (b) Flow Discharge from Reservoir SF030.

Simulated accumulated sediment at the reservoir bottom and sediment difference between inflow sediment gages (NF009 and NF020) and outflow sediment gage (NF035) are compared in Figure 3a. The simulated accumulated sediment at the reservoir bottom is generally close to the measured values during the simulation period (01Jan1994 –

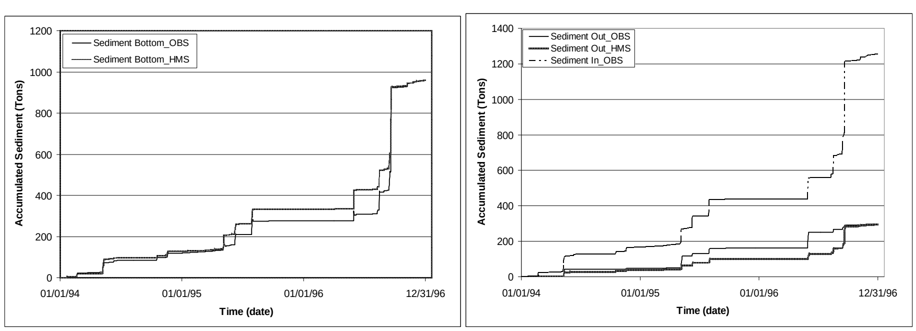
31Dec1996). Simulated accumulated sediment from reservoir NF030 and measured accumulated sediment (NF035) are compared in the Figure 3b for the simulation period (01Jan1994 – 31Dec1996). Simulation results show that 33% of the total estimated accumulated sediment load (416 tons) from reservoir NF030 was generated during a 4 day period (May 05-10, 1995) as shown in Figure 3b. This is caused by the fact that the current sediment trap efficiency method is heavily influenced by the sediment inflow amount during a time step.



(a) (b)

Figure 3 Reservoir Sediment Routing Results for Reservoir NF030; (a) Accumulated sediment at the Reservoir Bottom, (b) Accumulated Sediment from the Reservoir.

Simulated accumulated sediment at the reservoir bottom and sediment difference between inflow sediment gage (SF020) and outflow sediment gage (SF035) are compared in Figure 4a. The simulated accumulated sediment at the reservoir bottom is in good agreement with the measured values during the simulation period (01Jan1994 – 31Dec1996). Estimated accumulated sediment load from the reservoir SF030 and measured accumulated sediment load (SF035) are compared in Figure 4b for the simulation period (01Jan1994 – 31Dec1996). Simulation results reveal that 42% of total estimated accumulated sediment (296 tons) from reservoir SF030 was generated during a 10 day period (September 14-23, 1995) as shown in Figure 4b. As mentioned above, the current sediment trap efficiency method is heavily influenced by the sediment inflow amount as shown in Equation 4.



(a) (b)

Figure 4 Reservoir Sediment Routing Results for Reservoir SF030; (a) Accumulated sediment at the Reservoir Bottom, (b) Accumulated Sediment from the Reservoir.

Measured and simulated mean and standard deviation values of average daily flows and total suspended solid (TSS) loads from the two reservoirs (NF030 and SF030) are compared in Table 3. The simulated average daily flows and TSS loads from the two reservoirs are generally close to measured values as shown in Table 3.

Table 3 Measured and Simulated Mean, Standard Deviation (SD) of Daily Flow and TSS Loading During 01Jan1994 – 31Dec 1996.

Reservoir		Flow (cfs)		Sediment (tons)	
		Mean	SD[1]	Mean	SD[1]
NF030	Measured	1.99	6.48	0.34	1.80
	HMS	1.76	5.33	0.38	2.39
SF030	Measured	1.15	6.69	0.25	2.39
	HMS	0.98	4.12	0.27	2.46

SD[1] – Standard Deviation

SUMMARY AND CONCLUSIONS

This paper presents a brief description and a simple application of the new sediment reservoir routing method that available HEC-HMS Version 4.0. The new modeling tool will make it possible to use HEC-HMS for the assessment of sediment reservoir routing and reservoir siltation. These estimates can be used in reservoir siltation studies for watersheds containing significant non-point sources of sediment. HEC-HMS can be used to model the amount of sediment from pervious and impervious areas in a watershed and route the sediment downstream through the stream and reservoir network. In the future, HEC-HMS will provide more trap efficiency methods for users to implement more detailed sediment reservoir routing processes.

In the example test case, output from an HEC-HMS model was compared to measured sediment and stream flow data for two reservoirs. The HEC-HMS model provided reasonable predictions of average daily flow and TSS loadings during the simulation period for the two reservoirs within the UNBRW. It is important to note the evaluation of the new sediment reservoir routing method in HEC-HMS was limited to the two small reservoirs in UNBRW study area. Expanded use of this model for other study areas requires calibration and validation with site specific field measurements in order for the model to be applied with confidence.

Limitations of the current trap efficiency method are that the model is not designed to model resuspension of sediment from the reservoir bottom and the trap efficiency is only a function of reservoir inflow and surface area. As the results show, these limitations have little effect on the long term simulation results; however, results for a specific flood event can vary significantly from observed measurements.

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