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Evaluating Impacts of
Porous Check Dams on Flow Routing and Sediment Transport in Agricultural Ditches

A Case Study in the Mississippi Delta

MAFES

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Evaluating Impacts of
Porous Check Dams on Flow Routing and Sediment Transport in Agricultural Ditches:
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ABSTRACT

Management and reduction of sediments and nutrients reaching water bodies are priorities of several local, state, and federal agencies in the U.S. The main goal of this research was to evaluate hydraulic characteristics and sediment-trapping efficiency of three porous check dams constructed in the main ditch of an agricultural field in Coahoma County, Mississippi. The methods used in this study included field data (land cover, soil characteristics, area size, rainfall, evapotranspiration, cross-section surveys, water levels, and suspended sediment concentrations), geographical information systems (ArcGIS, aerial photos, Google Earth), and modeling tools (USEPA BASINS suite of programs). This approach yielded a Hydrological Simulation Program – FORTRAN (HSPF) processes-based model of rainfall-runoff, soil erosion, hydraulics, and sediment transport of the study area. The model simulated values of observed water-depth values for low and mean conditions well. The model could not adequately represent conditions of high flows due to hydraulic restrictions of the flow (culverts and downstream ponding) that were not input into the HSPF hydraulic processes. After model calibration and verification of water depths were completed, the HSPF model computed 15-minute continuous streamflow, total suspended sediments, rate of change of bed sediments, and sediment loads through the main ditch. Simulated streamflow and total suspended sediments were not evaluated due to lack of observed flow data and short suspended sediment time series. This study assumed that sediment particle distribution in storm runoff was dominated by fine sediments (silt 70% and clay 20%). Considering model uncertainties (e.g., lumped channel discretization, lack of understanding of flow-stage relationships in porous check dams) along with incomplete field data (e.g., two suspended sediment samples during the rising limb of storm hydrographs), the model predicted a moderate sediment trapping efficiency (35%) in the main ditch. Design guidelines of porous check dams suggest low retention values of fine sediments. This study is useful in providing information to improve field-data collection efforts. In addition, this research presents a framework to evaluate sediment control structures like porous check dams in the Mississippi Delta region using the USEPA BASINS/HSPF model.

Evaluating Impacts of

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INTRODUCTION

This research is part of federal and state strategies, along with local farmer efforts, to reduce sediment and nutrient export from agricultural areas that potentially increase eutrophication and reduce dissolved oxygen in the Gulf of Mexico. In a Mississippi Department of Marine Resources research project titled “Watershed Assessment Tools: Mississippi Delta Evaluation,” Mississippi State University researchers used field data and hydrologic and hydraulic models to demonstrate the effectiveness of low weirs (porous check dams) in sediment retention in agricultural drainage ditches in the Mississippi Delta. Porous check dams are built across a given channel cross-section to lower the energy of flowing water. Lowering the energy increases the water residence time, which could increase the accumulation of sediment particles. The ponding area created by the check dams promotes physical and chemical transformation that can improve water infiltration rates, increase groundwater recharge, trap sediment and nutrients, enhance nutrient biogeochemical transformations, and reduce downstream sediment and nutrient loads. The use of porous check dams for channel protection, rehabilitation, and sediment and nutrient reductions is not a new practice. However, it is a novel strategy in agricultural systems, and the effectiveness of this environmental mitigation practice is not well defined.

In this study, continuous water-level time series were recorded in a manmade ditch that transported runoff from a 307-hectare drainage area located in Coahoma County, Mississippi. The 1.4-kilometer main drainage ditch was built in 2010 along with three low-grade weirs (porous check dams). This study uses processes-based watershed models to enhance the field-data-collection efforts. Several watershed hydrologic models have been developed since the 1960s (Singh and Woolhiser 2002). Watershed models such as the Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al. 2001) and the Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2005) are popular continuous simulation models around the world. The HSPF model is one of the most comprehensive, flexible, and modular programs of watershed hydrology and water quality available for applications in rural and agricultural areas (Donigian et al. 1995). HSPF has been applied in different zones around the world since the 1980s (Donigian et al. 1995, Singh and Woolhiser 2002). For instance, HSPF applications in Mississippi and Alabama can be found in Diaz-Ramirez et al. (2011 and 2008) and Duan et al. (2008). The HSPF model was set up and tested to gain more insight about the effectiveness of the low weir system built in Coahoma County.

STUDY AREA

The study area is located about 10 kilometers northwest of Clarksdale, Coahoma County, Mississippi. Land cover distribution is 52% soybeans and winter wheat, 25% soybeans, and 23% deciduous forest. Table 1 shows land cover and soil distribution by field within the site. In addition, the table shows the 22 hydrologic response units simulated by HSPF. Soils in the study area are characterized by large amounts of silt and clay in proportion to sand particles.

Table 1. Land cover and soil distribution within the Coahoma County field site.

Map unit symbol	Map unit name	Hydrologic soil group	Land cover	Area (Ha)
Dg	Dundee silt loam, 0–3% slopes	C	Forest	4.38
Dg	Dundee silt loam, 0–3% slopes	C	Forest	2.27
Dd	Dubbs very fine sandy loam, 0–3% slopes	B	Soybeans/Winter Wheat	14.84
Dd	Dubbs very fine sandy loam, 0–3% slopes	B	Soybeans/Winter Wheat	2.37
Dd	Dubbs very fine sandy loam, 0–3% slopes	B	Soybeans/Winter Wheat	7.25
Do	Dundee very fine sandy loam, 0–3% slopes	C	Soybeans/Winter Wheat	20.03
Da	Dowling clay (sharkey)	D	Soybeans	24.48
Da	Dowling clay (sharkey)	D	Soybeans/Winter Wheat	28.88
Dd	Dubbs very fine sandy loam, 0–3% slopes	B	Forest	3.94
Dd	Dubbs very fine sandy loam, 0–3% slopes	B	Forest	1.73
Fh	Forestdale silty clay loam, 0.5–3% slopes	D	Soybeans/Winter Wheat	24.53
Fh	Forestdale silty clay loam, 0.5–3% slopes	D	Forest	37.13
Fh	Forestdale silty clay loam, 0.5–3% slopes	D	Soybeans	37.5
Fh	Forestdale silty clay loam, 0.5–3% slopes	D	Soybeans	12.88
Fh	Forestdale silty clay loam, 0.5–3% slopes	D	Soybeans/Winter Wheat	15.41
Da	Dowling clay (sharkey)	D	Soybeans/Winter Wheat	0.94
Da	Dowling clay (sharkey)	D	Ditch	1.63
Dm	Dundee silty clay loam, 0.5–3% slopes	C	Forest	22.53
Dg	Dundee silt loam, 0–3% slopes	C	Soybeans/Winter Wheat	31.04
Dg	Dundee silt loam, 0–3% slopes	C	Soybeans/Winter Wheat	7.92
Do	Dundee very fine sandy loam, 0–3% slopes	C	Soybeans/Winter Wheat	1.67
Dg	Dundee silt loam, 0–3% slopes	C	Soybeans/Winter Wheat	3.68

METHODS

Figure 1. Water level recorder (Level Troll 300, In Situ, Loveland Colorado) (left) and TSS sample devices (right) in the east ditch of the site in Coahoma County, Mississippi.

Data Sources

Time series used in this study included 15-minute rainfall and potential evapotranspiration continuous values between April 1, 2010, and July 31, 2011, 15-minute water levels at two cross-sections along the main ditch collected from February 1, 2011, to May 31, 2011, and discrete total suspended sediment (TSS) samples at four cross-sections along the drainage ditch measured between January 1, 2011, and April 30, 2011. The HSPF model was set up to run from April 1, 2010, to July 31, 2011. Figure 1 shows location of the water level loggers and sampling stations. TSS samples were analyzed using the SM – 2540D method (APHA 1998).

Rainfall data were collected by the U.S Geological Survey at station 341550090391300 Overcup Slough Tributary No. 2 near Farrell, Mississippi (Figure 2). Monthly rainfall and potential evapotranspiration values are shown in Figure 3. Potential evapotranspiration was calculated using temperature data from the NOAA Clarksdale station and the Hamon method (Hamon 1963) implemented in the BASINS program (USEPA 2012). Drainage area boundaries were established using ground truthing and aerial photos (Figure 4). Soil characteristics (infiltration, soil erosion, and sediment transport parameters) were extracted from the SSURGO soils database of the USDA (USDA-

Figure 2. USGS station 341550090391300 Overcup Slough Tributary No. 2 Near Farrell, Mississippi.

Table 2. Datasets and methods used in this study.

Dataset	Comments
Soil map	USDA SSURGO
Land use	Groundtruthing and aerial photos
Rainfall	USGS station 341550090391300
Potential evapotranspiration	NOAA Clarksdale temperature time series and Hamon temperature method
Ditch hydraulic characteristics (FTABLE)	Four reaches computed using surveying and flow measurements at USGS station 341550090391300
Hydrologic respond units	Twenty-two units discretized using land cover and soil data
Watershed boundaries	Groundtruthing and aerial photos

NRCS 2012). HSPF also requires a tabular characterization of stream geometry (FTABLE) with relationships among area, volume, and flow in a river cross-section. Depth, area, and volume relationships were computed by using surveying data and the HSPF BMP Tool (http://www.epa.gov/athens/research/modeling/HSPF-WebTools/). Flow data were not available at the outlet of the study area. Flow data required in the FTABLE were computed using field measures by USGS at USGS 341550090391300 Overcup Slough Tributary No. 2 near Farrell. This station is located 260 meters downstream of the study area's outlet, and it is assumed that the study area is three-quarters of the USGS gaged drainage area. In other words, HSPF FTABLE flows were computed by multiplying USGS flows times three-quarters. Table 2 shows a summary of datasets and methods used in this study.

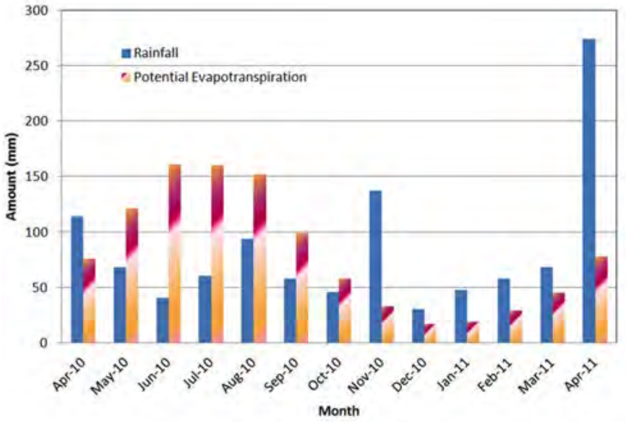

Figure 3. Monthly rainfall and potential evapotranspiration values for the study area.

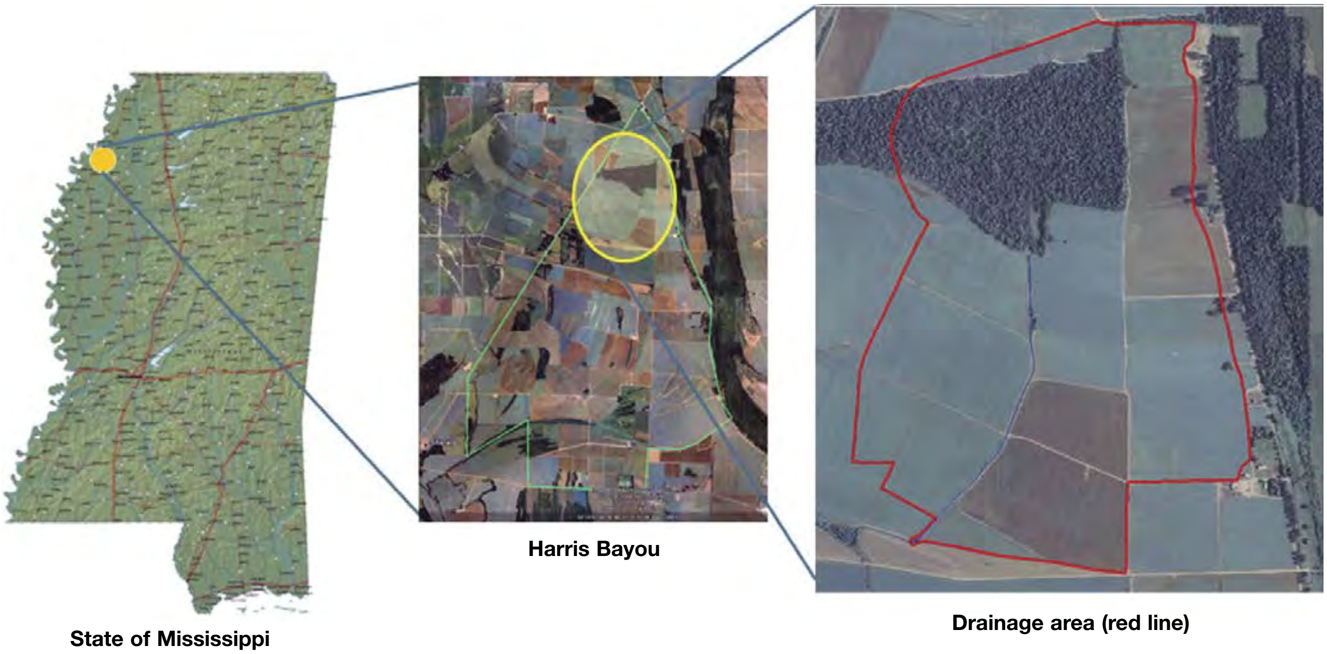

Figure 4. Map of study area.

Hydrology and Flow Routing Modeling

This study used the HSPF model to compute continuous hydrology and flow routing processes in the Harris Bayou drainage area and drainage ditch, respectively. Rainfall-runoff modeling from the watershed area was done to compute 15-minute runoff, interflow, and baseflow time series. Runoff time series are required to simulate soil erosion processes. Flow routing in the main channel was computed to simulate water depth, flow velocity, and shear stress continuous variables. The main ditch was divided into four reaches (from upstream: inflow, weir 1, weir 2, and weir 3) (Figure 5). Fifteen-minute shear-stress data were computed at every reach (four in total) of the main ditch to estimate sediment transport processes (critical scour and deposition values). Simulated 15-minute water levels were evaluated against observed time series at the outlets of inflow and weir 3 reaches from February 1, 2011, to May 31, 2011. This period covered the wet season along with most of the available observed data.

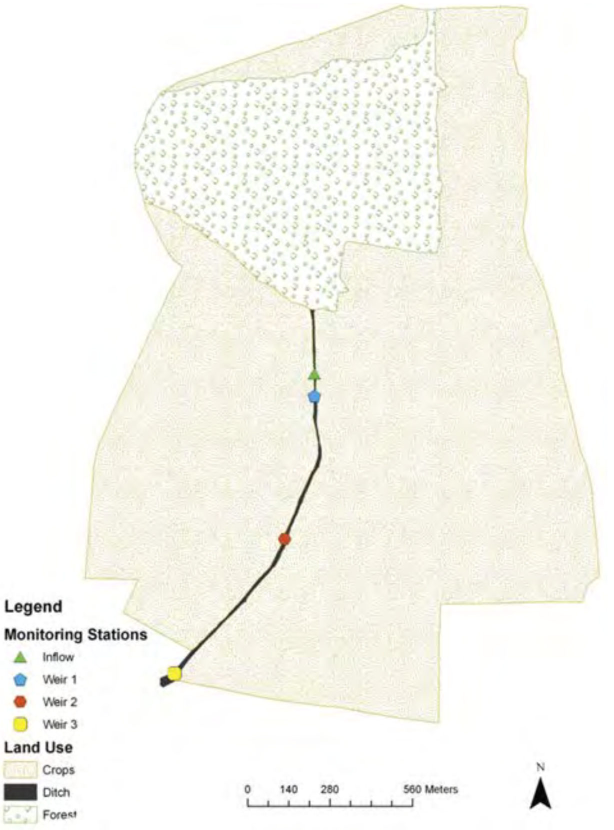

Figure 5. Harris Bayou catchment and main ditch characteristics

Manual calibration was done by perturbing select HSPF parameters defined in Table 3. Calibration consisted of adjusting the parameters that govern water balance, seasonal flows, and storm events following the HSPF author's guidelines (USEPA 2000). The calibration process was completed when error measures (root mean square error - RMSE and mean relative error - MRE) were minimized, efficiency criteria (Nash and Sutcliffe - NS and coefficient of determination - R^2) were maximized (Krause et al. 2005, Legates and McCabe 1999, Moriasi et al. 2007, Nash and Sutcliffe 1970), and the parameter values were within the range specified by the literature and supported by the knowledge of catchment physiographic characteristics (USEPA 2000, USEPA 2006). Model verification was not performed because of the short period of available water level time series.

Table 3. HSPF hydrologic parameter definition (USEPA 2000).

Name	Definition	Range
LZSN (mm)	Lower zone nominal soil moisture storage	50.8–381.0
INFILT (mm/h)	Index to infiltration capacity	0.25–25.0
SLSUR (%)	Slope of overland flow plane	0.1–30.0
NSUR	Manning's n (roughness) for overland flow	0.05–0.50
LSUR (m)	Length of overland flow	30.5–213.4
KVARY (per mm)	Variable groundwater recession	0.0–127.0
AGWRC	Base groundwater recession	0.92–0.999
DEEPFR	Fraction of groundwater inflow to deep recharge	0.0–0.5
BASETP	Fraction of remaining evapotranspiration from baseflow	0.0–0.2
AGWETP	Fraction of remaining evapotranspiration from active groundwater	0.0–0.2
CEPSC (mm)	Interception storage capacity	0.0–10.2
UZSN (mm)	Upper zone nominal soil moisture storage	1.27–50.8
INTFW	Interflow inflow parameter	1.0–10.0
IRC	Interflow recession parameter	0.3–0.85
LZETP	Lower zone evapotranspiration parameter	0.0–0.9

Soil Erosion and Sediment Transport Modeling

Soil erosion modeling from the drainage area was performed to compute the soil erosion rates coming into the main ditch. Sediment transport modeling in the main ditch was accomplished to determine effectiveness of the low weir (porous check dam) system. Soil erosion and sediment transport modeling was done using the algorithms coded in the HSPF model.

Soil erosion and sediment transport calibration and verification were not performed in this project because of lack of observed data (crop management, long continuous TSS series, and sediment particle size distribution). However, model parameters were set in the ranges suggested by the HSPF developers (USEPA 2006) for row crop, bare areas, and forest areas. In addition, runoff-time series and shear-stress values computed previously were used in this section. The drainage ditch was segmented into four reaches (Figure 5). This discretization allowed the model to use a better spatial discretization of the system and its components.

RESULTS AND DISCUSSION

Hydrology and Flow Routing Modeling

Figure 6 shows simulated and observed continuous water depths at the outlet of inflow reach. The HSPF model underpredicted values (negative relative errors) for water depths less than 0.5 meter. Water depths of large events were overpredicted by the model (Table 4 and Figure 6). In general, the HSPF model poorly simulated larges events recorded in April and May. Site information about soil-infiltration rates in the drainage area and ditch is required to improve model results.

Figure 7 depicts simulated and observed continuous water depths at the outlet of weir 3 reach. In general, the HSPF model showed fair results with a tendency of underpredicting water depths less than 0.5 meter (Table 5). Simulated hydrograph volumes were less than the observed ones for events larger than 0.5

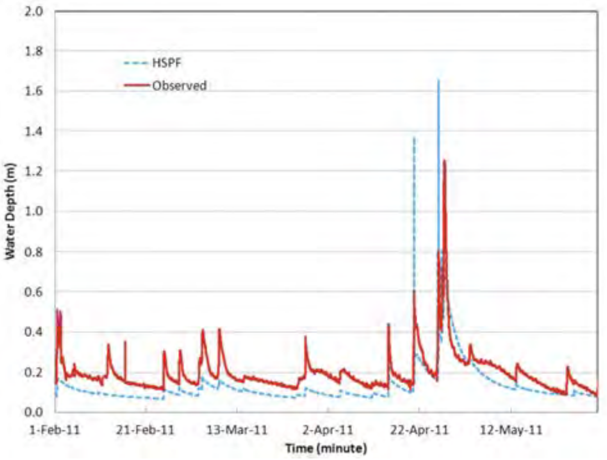

Figure 6. Fifteen-minute data of observed and simulated water levels at the outlet of inflow reach

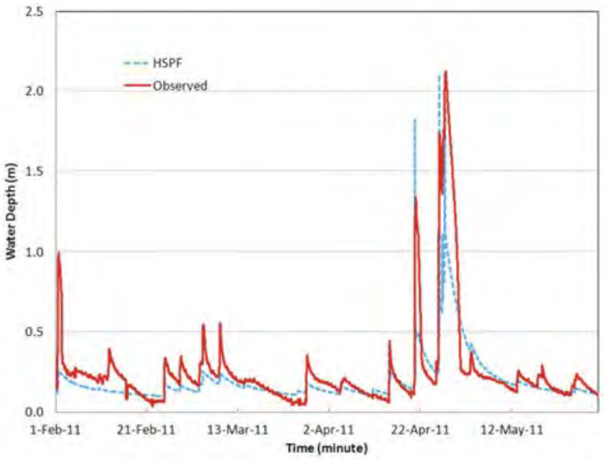

Figure 7. Fifteen-minute data of observed and simulated water levels at the outlet of weir 3 reach.

Table 4. Statistical ranking of 15-minute data of observed and simulated water levels at the outlet of inflow reach.

Rank	Simulated (m)	Observed (m)	Relative error (%)
Minimum	0.07	0.08	-18
25th percentile	0.09	0.14	-41
50th percentile	0.10	0.17	-42
75th percentile	0.13	0.21	-39
Maximum	1.65	1.26	32

Table 5. Statistical ranking of 15-minute time series of observed and simulated water levels at the outlet of weir 3 reach.

Rank	Simulated (m)	Observed (m)	Relative error (%)
Minimum	0.10	0.04	184
25th percentile	0.13	0.14	-9
50th percentile	0.15	0.19	-23
75th percentile	0.19	0.24	-20
Maximum	2.11	2.12	-1

meter. Field hydraulic conditions for large events that occurred in April 2011 were not well represented by the model due to hydraulic restrictions of the flow (culverts and downstream ponding) that were not input into the HSPF FTABLE. In general, large peak flows were well simulated, but runoff-volume values were underpredicted.

Results at weir 3 reach were better than those computed at inflow reach, indicating that the model is robust in simulating mean conditions of ditch volumes using porous check dams. However, more field data is required to simulate better hydraulic conditions in the main ditch (flow velocity, downstream conditions, etc.).

After model calibration of water depths was completed, the HSPF model computed continuous flow-time series through the system (Figure 8). Simulated flow-time series were not calibrated due to lack of observed data. Continuous flow data is required to compute the efficiency of the low weir system on trapping sediments. In addition to flow time series generated by HSPF, flow-velocity and shear-stress time series were also simulated. These variables were not evaluated because there was no collected data. Flow-velocity and shear-stress data are required to simulate sediment transport processes.

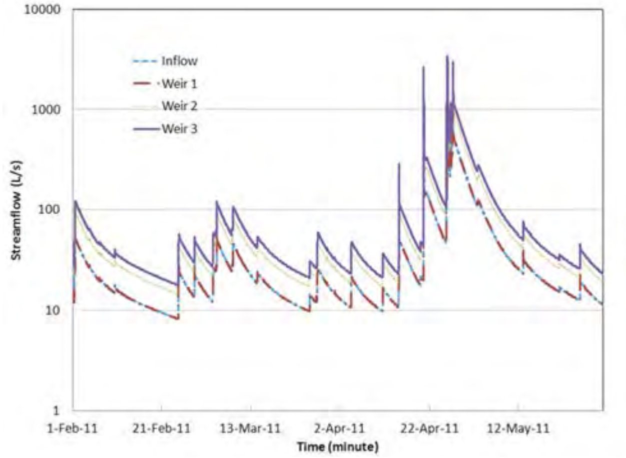

Figure 8. Simulated 15-minute streamflow time series.

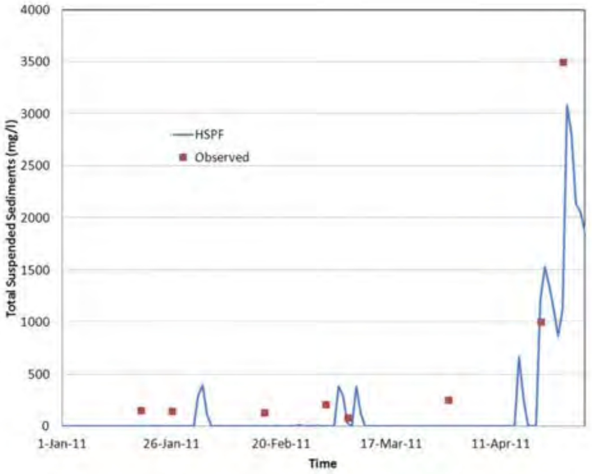

Figure 9. Simulated daily average and instantaneous observed total suspended sediments at inflow station.

Table 6. Performance comparison statistics for 15-minute water levels.

Station	RE (%)	RMSE (m)	R^2	NS
Inflow	-0.350	0.091	0.67	0.21
Weir 3	-0.048	0.180	0.75	0.67

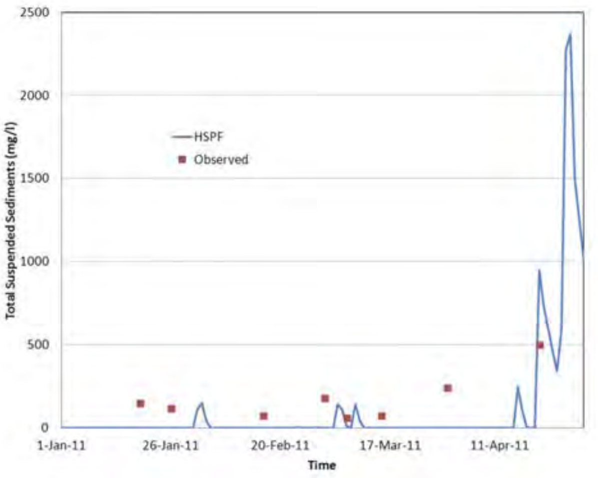

Figure 10. Simulated daily average and instantaneous observed total suspended sediments at weir 1 station.

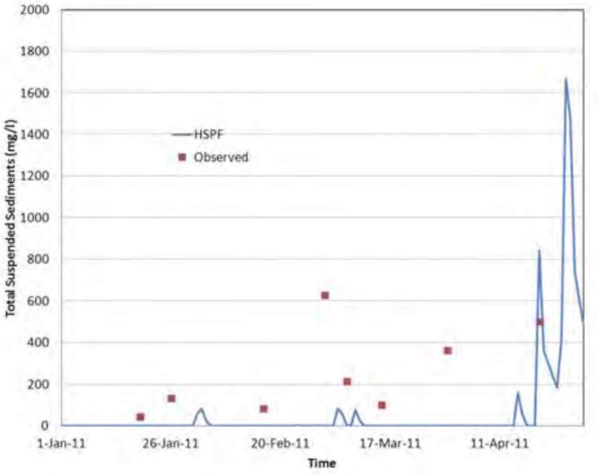

Figure 11. Simulated daily average and instantaneous observed total suspended sediments at weir 2 station.

Soil Erosion and Sediment Transport Modeling

In the study area, observed total suspended sediments were limited to eight samples from January 1 to April 30, 2011. This amount of sampling is not sufficient to evaluate the system performance or to assess the HSPF continuous (every 15 minutes) soil erosion or sediment transport model. The model was set up with available data, but it was neither calibrated nor validated. Figures 9–12 show observed and simulated total suspended sediments from January 1, 2011, to April 30, 2011. These graphs depict that the model and observed data were in the same order of magnitude. The observed data were collected almost instantaneously, and simulated time series were averaged daily from each 15-minute time step. The model can show a better understanding of how the sediments are transported through the system than using only the observed data.

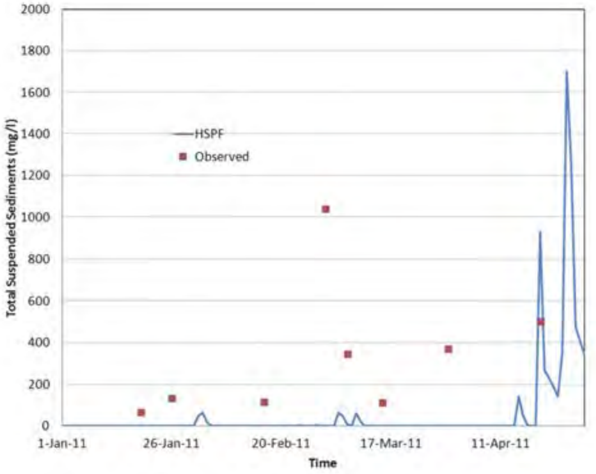

Figure 12. Simulated daily average and instantaneous observed total suspended sediments at weir 3 station.

Efficiency of Low Weir System

After simulating hydrology (rainfall-runoff), soil erosion (detachment and washload), hydraulics (water depths, flow velocities, and shear velocities), and sediment transport (shear stress, suspended sediments, and changes of bed sediments), the model computed sediment loads. The efficiency of the system for trapping sediments was computed using sediment load outputs from the HSPF model from January 1, 2011, to April 30, 2011. It was assumed that the soil-particle distribution reaching the ditch followed this distribution: 10% sand, 70% silt, and 20% clay. This distribution reflects data collected by Dr. Kroger's team (personal communication, February 10, 2012) in different ditches in the Mississippi Delta region. In addition, studies have reported that soils in the area are characterized mainly by fine particles (silt and clay). Figure 13 shows inflows, outflows, deposition, and scour of total sediment loads (metric tonnes). Inflow reach was the only reach that simulated scour. Inflow reach does not have a check dam and promotes more scour than deposition. In other words, 55% of total outflows of sediments in inflow reach were scoured from the channel bed. The critical sheer stress for scour in inflow reach was the lowest for the system.

In general, reaches with check dams trapped between 3% (weir 1 reach) and 25% (weir 2 reach) of

Figure 13. Sediment load budget (all values in metric tonnes).

the total sediment loads. These sediment-trapping values could be considered low to moderate efficiencies, but check dams are not particularly effective for trapping small particles (silts or clays) (Metropolitan Council 2012). Soils in the study are mainly characterized by silt and clay fractions. The total efficiency of the system was computed as follows:

$$\text{Sediment Load Efficiency} = \left[\frac{\text{Inputs-Outputs}}{\text{Inputs}}\right]$$

$$\text{Sediment Load Efficiency} = \left[\frac{(284+342+285+236\ )-742}{(284+342+285+236)}\right] \text{x } 100{=}35\%$$

The current model can be used to create different scenarios. For example, what happens if the system soil particle distribution was 25% sand, 55% silt, and 20% clay? Figure 14 shows results using this hypothetical scenario. The total efficiency of the system will increase to 41%. The sediments will fill up about 0.5 feet from weir 1 reach to weir 3 reach.

Figure 14. Sediment load budget (all values in metric tonnes) for a case scenario.

CONCLUSIONS

A mechanistic model that includes hydrology, soil erosion, hydraulics, and sediment transport processes was developed for the Harris Bayou drainage area in Coahoma County, Mississippi. The 307-hectare drainage area was cropped with soybeans and winter wheat. Three porous check dams were built along the main ditch to improve sediment and nutrient retention. Field data (water levels and grab samples) were collected along the main ditch. Although these data are useful, the field data were not conclusive about the efficiency of the porous check dams in the study area. Therefore, a modeling approach was required to improve our knowledge of these kinds of systems under Mississippi Delta conditions.

The USEPA HSPF model was set up and evaluated with available data from the Harris Bayou drainage area. Due to the lack of available data (crop management, flow velocities, particle size, distribution of soil) and limited data (streamflow time series, suspended sediment concentrations for rising and falling storm events, rate of change of bed sediments, soil infiltration rates), this study could not make a rigorous calibration and verification of modeling processes. The current model provides continuous 15-minute time series from April 1, 2010, to July 31, 2011, of runoff, interflow, baseflow, water levels, streamflow, flow velocities, shear velocities, suspended sediment concentrations, sediment loads, and changes in bed sediments. Using these physics-based data, sediment-trapping efficiencies in the system were computed. This study assumed that runoff was carried to the main ditch on large amounts of fine particles (70% silt and 20% clay). The HSPF model computed a total trapping efficiency of 35%. This efficiency could be moderate due to high amounts of fine particles on the water that pass over or though the voids on the check dams.

The HSPF model was used to develop a scenario where sand particles account for up to 25% of the total suspended sediments. This scenario yielded sediment trap efficiency of 41%. From the literature, it was found that check dams do not provide good performance when runoff transports large amounts of fine particles (silt and clay). This study is useful in providing information to improve field-data collection efforts. In addition, this research presents a framework to evaluate sediment control structures like porous check dams in the Mississippi Delta using the USEPA BASINS/HSPF model.

IMPLICATIONS FOR FUTURE RESEARCH

The results obtained in this research are promising and should be extended to include a larger sample of hydrological conditions. More specifically, future investigations could include these goals:

- Evaluate the models using a separated set of data for validation purposes;
- Test the model using available data from Porters Bayou, Sunflower County, Mississippi;
- Evaluate the efficiency of porous check dams in removing nitrogen and phosphorus;
- Evaluate effects of input data and parameter uncertainty on model results;
- Define and incorporate crop-management practices;
- Collect site-specific data, including median diameter of bed material, flow velocities, particle-size distribution in suspended sediments, changes in bed sediments, and soil-infiltration rates;
- Evaluate different riprap materials in building check dams for sediment and nutrient trapping; and
- Develop model scenarios to evaluate the impact of drainage ditches without check dams, with more check dams, or with different check dam designs (dimensions).

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