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COMPARISON OF UNSTEADY AND QUASI-UNSTEADY FLOW MODELS IN SIMULATING SEDIMENT TRANSPORT IN AN EPHEMERAL ARIZONA STREAM[1]

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ABSTRACT: Hydrodynamic and sediment transport models are useful engineering tools for predicting unsteady flood flow and sediment transport. Many models such as HEC-RAS, HEC-6, and IALLUVIAL apply quasi-unsteady flow model, whereas others apply the unsteady flow model. It remains unknown if a quasi-unsteady flow model is sufficiently accurate for simulating sediment transport in rapidly varied unsteady flood events, especially in ephemeral rivers in arid and semiarid regions. This study compared the quasi-unsteady HEC-RAS 4.1 model with one-dimensional (1D) Finite Volume Method (FVM) based model in simulating flood flow and sediment transport in the Pantano Wash, a dryland river in the state of Arizona. The objective is to determine which sediment transport method is appropriate in predicting bed elevation changes in an ephemeral stream, Pantano Wash, and if an unsteady model is more accurate than a quasi-unsteady flow model in predicting sediment transport. Results showed that the quasi-unsteady HEC-RAS model and the 1D FVM yielded similar results of bed degradation and aggradation for this dryland stream, although the FVM model predicted better flood hydrographs. Among the seven sediment transport formulas embedded in HEC-RAS, Yang's and Engelund-Hansen's equations gave the best matches with the field measurements for this particular case study.

(KEY TERMS: sediment transport model; finite volume method; sediment transport; dryland rivers.)

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INTRODUCTION

Many rivers in the arid southwestern United States (U.S.) are not perennial, but ephemeral streams containing streamflow only after large storm events occur. The Pantano Wash in Tucson, Arizona, is an example of an ephemeral river that only has streamflow after large rainfall events such as those caused by the North American monsoon, which normally occurs over the southwestern U.S. beginning in June or July and ending around September or October (NOAA, 2004). Approximately 55% of southeastern Arizona's annual precipitation occurs during this season (Magirl, 2007).

During the last week of July 2006, the Tucson region experienced heavy rainfall lasting for several days, leading to a record flooding in several ephemeral streams in the area (Magirl, 2007). Rivers such as the Rillito, Sabino Creek, and Pantano Wash all saw

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unprecedented streamflows during this period of time, and consequently had the potential to transport large quantities of sediment from one stretch of the river to another due to the forces exerted on bed sediment by the high streamflow. This rapid movement of sediment alters the shape and size of the channel, and could be hazardous depending on where this transport takes place. If sediment is eroded, it may destabilize the channel and lead to failure of the channel banks or hydraulic structures situated in the channel bed (Canfield *et al.*, 2005), whereas the deposition of sediment decreases the size of the channel, which adds stress to the channel banks and raises stream elevation levels, increasing the probability of water overflowing into the floodplain and surrounding areas. Deposition is aided by thick vegetation existing in the floodplains of the rivers being discussed here, which trap the moving sediment as it passes, further decreasing the channel capacity (Salguero, 2008).

It is therefore important for engineers and city planners to understand how this sediment transport is taking place, and to be able to predict where it will occur for different storm events. If erosion is expected, actions should be taken such as implementing grade control structures to limit the amount of elevation change predicted to occur or strengthening the channel banks to improve stability during large events. Likewise, if deposition is predicted, efforts could be made to accurately map floodplains and raise bank and levee heights to prevent flood damage from taking place.

However, sediment transport in unsteady flow is not yet well understood. Most of the existing sediment transport formulas were for predicting equilibrium sediment transport in steady uniform flow. As a consequence, one-dimensional sediment transport model (e.g., HEC-RAS, HEC-6) often adopted the quasi-unsteady flow assumption, although a spatial and temporal lag exists between the flow properties and sediment transport rate in unsteady flows. Sediment transport in unsteady flow is often termed as "the nonequilibrium transport," stemming from the inability of the fluvial sediment to immediately respond to the changing flow condition (Phillips and Sutherland, 1989, 1990). To better simulate the process that the sediment transport rate gradually develops into the transport capacity under a given flow condition, many numerical models adopted the nonequilibrium sediment transport algorithm in which an adaptation length was defined to account for this spatial lag effect (Wu and Wang, 2007; Minh-Duc and Rodi, 2008; El kadi Abderrezzak and Paquier, 2009). Several numerical models (Wu and Wang, 2007; Minh-Duc and Rodi, 2008) have shown that the modeling results are sensitive to the adaptation length, especially in highly unsteady flow such as dam break flow or extreme floods. It remains unknown whether an unsteady flow model is more accurate than a quasi-unsteady flow model in simulating sediment transport. This study compared two one-dimensional models: one is HEC-RAS version 4.1, which stands for the Hydrologic Engineering Center's River Analysis System, developed by the U.S. Army Corps of Engineers (USACE, 2010), and the second is a finite volume method (FVM) program developed using Compaq Visual Fortran Version 6.6 (Compaq Inc., Dallas, TX), which implements the nonequilibrium sediment transport algorithm. There were two main objectives for this study: (1) to determine which of the sediment transport methods gives the most accurate bed elevation change results compared with the observed data, and (2) if an unsteady flow model gives more accurate results of bed elevation changes than a quasi-unsteady flow model.

STUDY SITE

The study site being considered is the entire 22-mile (35.4 km) stretch of the Pantano Wash, reaching from its dam near Vail, Arizona, to its confluence with the Rillito River in Tucson just west of Craycroft Road. The lower reach of the Rincon Creek, a tributary that flows into the Pantano Wash near Drexel Road, is also included in the study. Figure 1 shows a map of the region taken from the Pima County MapGuide (Pima County, 2010). The storm hydrograph used for the modeling was produced by the USGS gauge station 09485450 Pantano Wash at Broadway Boulevard at Tucson, which is found at the bridge at Broadway Boulevard in the lower reach of the Pantano. The hydrologic unit code for the gauge is

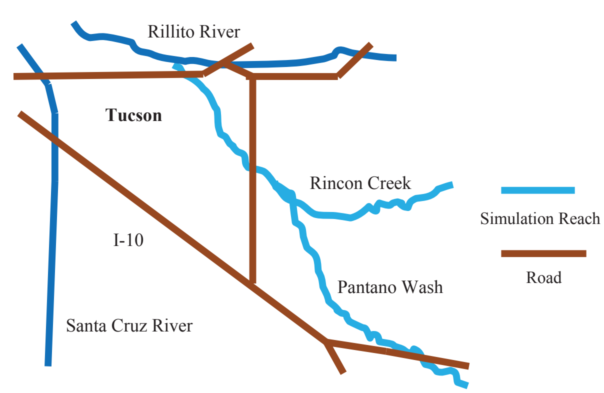

FIGURE 1. Aerial View of Study Site from Pima County MapGuide.

15050302, and it is located at latitude 32°13′14″, longitude 110°49′44″ NAD83/WGS84, gauge datum 2,568.83 ft above sea level NGVD29 (USGS, 2008). The USGS has other gauge stations usually located in the upper section of the Pantano near Vail and in the Rincon Creek; however, these gauges were blown out by the size and force of the event being modeled here, so no record from these gauges is available.

The geometry of the channel was divided up into 662 cross-sections and three reaches (274 in the upper reach of the Pantano, 355 in the lower reach of the Pantano, and 33 in Rincon Creek), each spaced approximately 200 ft (60.96 m) apart. Five bridges were modeled as well (Tanque Verde, Speedway, Broadway, Houghton, and Cave Creek), based on the design plans for the bridges supplied by the Pima County Regional Flood Control District (RFCD). Sediment samples were collected from 15 locations along the river, with one sample being taken from the surface of the channel bed and a substrate sample being taken from approximately one foot below the surface at each sample site. A sieve analysis was conducted to determine the sediment sizes at each location, and these results were interpolated to estimate the sediment sizes at locations between the sample sites.

ONE-DIMENSIONAL FINITE VOLUME METHOD MODEL

Flow Model Description

A one-dimensional FVM model was constructed using Compaq Visual Fortran, which will simulate the same event through the Pantano Wash as was done in the HEC-RAS simulation. The governing equations for this model are the Saint-Venant equations, which can be used to represent shallow and unsteady open channel flow (Zhang and Duan, 2011). The Saint-Venant equations are shown below, where the first equation (Equation 1) represents the continuity equation, and the second (Equation 2) shows the momentum equation.

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho Q)}{\partial x} + \frac{\partial(\rho_b A_b)}{\partial t} = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\rho Q) + \frac{\partial}{\partial x}\left(\rho \frac{Q^2}{A}\right) + \rho g A \frac{\partial z_s}{\partial x} + \rho g \frac{n^2 Q|Q|}{AR^{4/3}} = 0, \quad (2)$$

where t is the time, x is the longitudinal coordinate, ρ is the density of the water-sediment mixture, A is the cross-sectional flow area, Q is the flow discharge, g is the gravitational acceleration, z_s is the water-surface elevation, n is the Manning roughness, and R is the hydraulic radius. The FVM generates a grid along the flow path and then, for each node on the grid, creates a volume centered on the node extending to the nodes directly before and after it. The Saint-Venant equations are integrated over the volume created around the node. The cross-sectional area at each node can be obtained by solving the continuity equation, whereas flow discharge was solved by the momentum equation. The solutions of cross-sectional area and discharge can then be used to determine water depth, flow velocity, energy slope, etc., at the node.

Sediment Transport Model

The FVM model adopted the nonequilibrium sediment transport model. As mentioned earlier, an equilibrium sediment load condition means that the volumetric sediment discharge is assumed equal to the transport capacity everywhere in the reach. To determine the bed elevation changes, sediment continuity equation for the bed surface layer is needed to calculate the rate of bed deformation:

$$(1 - p_m)\frac{\partial A_b}{\partial t} = -\Gamma_s, \quad (3)$$

where p_m is the porosity of water-sediment mixture in bed surface layer, A_b is the area of bed surface layer, and Γ_S is the net mass flux from bed surface to the bed load layer. The sediment mass conservation equation can be written as

$$\frac{\partial}{\partial t}(A_s \overline{C_s}) + \frac{\partial Q_s}{\partial x} = \Gamma_s, \quad (4)$$

where A_δ is the total sediment area in a cross-section, $\overline{C_s}$ is the mean concentration of the total sediment load, and Q_s is the total sediment transport rate. Substituting Equation (4) into Equation (3), the mass conservation equation can be written as

$$(1 - p_m)\frac{\partial A_b}{\partial t} + \frac{\partial Q_s}{\partial x} = -\frac{\partial}{\partial t}(A_s \overline{C_s}). \quad (5)$$

At the equilibrium transport condition, the unsteady term or source term is zero. Equation (5) can be expressed by the following equation:

$$(1 - p_m)\frac{\partial A_b}{\partial t} + \frac{\partial Q_s}{\partial x} = 0. \quad (6)$$

At the nonequilibrium condition, the net sediment flux, the mass exchange from the bed surface layer to the sediment layer, can be approximated by the difference between the volumetric sediment discharge and the transport capacity, Q_s^{cap}, divided by a lag distance, L. This gives the equation below, as formulated by Daubert and Lebreton (1967):

$$(1-p_{\mathrm{m}})\frac{\partial A_{\mathrm{b}}}{\partial t}+\frac{\partial Q_{\mathrm{s}}}{\partial x}=\frac{Q_{\mathrm{s}}^{\mathrm{Cap}}-Q_{\mathrm{s}}}{L}. \tag{7}$$

The lag distance parameter has been estimated by several different researchers; however, instead of being able to derive a general formula, they have all suggested that the parameter should be case-dependent and selected based on the user's intentions (Wu and Wang, 2007; El kadi Abderrezzak and Paquier, 2009). Furthermore, the estimations of L were based on flume experiments, and would likely not be applicable to long natural rivers such as the Pantano Wash. In general, the lag distance should be larger than the distance between two consecutive cross-sections; the typical distance between two cross-sections is 200 ft in this study. Therefore, a minimum lag distance should be 200 ft. For this study, simulations were run for various lag distances to find the most realistic value for this system. The results of bed elevation changes varied considerably with changes in lag distances, as seen later in this article in Figures 6 and 7.

Besides the sediment boundary conditions, the FVM model was programmed so as to duplicate the HEC-RAS program as closely as possible. Hydrograph and sediment input data, geometry structure, parameter values, and time steps were the same in both models; however, it was still necessary to make two exceptions. First, HEC-RAS allows for the Manning's roughness values to vary within a cross-section, whereas the FVM model does not, so although the n-values were set as 0.035 in the channel and 0.045 in the overbanks for every cross-section in the HEC-RAS model, they were set at 0.040 throughout the entire reach in the FVM model. Upon completing the FVM simulations, an experimental simulation was conducted for one of the transport methods using a Manning's roughness of 0.035, and the results were found to vary only slightly from those computed with a roughness of 0.040. Secondly, the FVM model was incapable of including bridges in the geometry file, so although there are five bridges in the HEC-RAS model, none of these appear in the FVM model. The FVM model was also only run for the lower reach of the Pantano Wash, to simplify the computational process, so that is the only reach in which results between the two models are compared.

MODEL INPUT DATA

Geometry Data

Information needs to be input by the user regarding the geometry of the study site, the hydrology data being used, and the sediment data for the site. For HEC-RAS, the geometry file requires a river path with cross-sections along it. For this project, the cross-sections were created using the HEC-GeoRAS model embedded in ArcGIS and the actual LiDAR data from 2005, obtained from the Pima County RFCD. Shape files were created in ArcGIS from the LiDAR data with a resolution of 1×1 ft spatially and a vertical accuracy of within 0.50 ft at a 95% confidence interval. Cross-sections were cut from these shape files, and oriented along a stream pathway. Bank stations at each cross-section were set at the elevations of bankfull flow, at which the river would be full of water to the bank height. Areas of the cross-section outside the bank stations were defined as the floodplains. HEC-GeoRAS allows to create the geometry files in it, and then be exported to HEC-RAS. After being exported, the geometry file can be opened in HEC-RAS with the flow paths, cross-section locations and elevations, and bank stations. In HEC-RAS, the Manning's roughness values within cross-sections are allowed to be varied, so the roughness was set as 0.035 for the main channel nearly free of vegetation, and 0.045 for the channel floodplain with shrubs. These values were selected based on table 4-1 in Sturm (2001) for wide, irregular cross-sections with existing brush in the floodplains. Those values are also used in a prior study of the Rillito River (JE Fuller, Inc., 2006).

Hydrologic Data

The upstream flow boundary condition used for this study was an input hydrograph. As the HEC-RAS sediment model requires the use of quasi-unsteady flow, the hydrograph is converted into a series of intervals consisting of a steady flow for each time step. Each time step was 15 min long for this project. As mentioned earlier, the only gauge data available for this reach over the desired time period was at the Broadway Bridge. As this bridge is located in the downstream end of the channel, a new scaled input hydrograph was created for the upstream boundary condition, in such a way that when the model was run, the simulated flow seen at the Broadway Bridge agreed with the gauged data. Figure 2 shows the quasi-unsteady input hydrographs at the Pantano Wash and the Rincon Creek used by

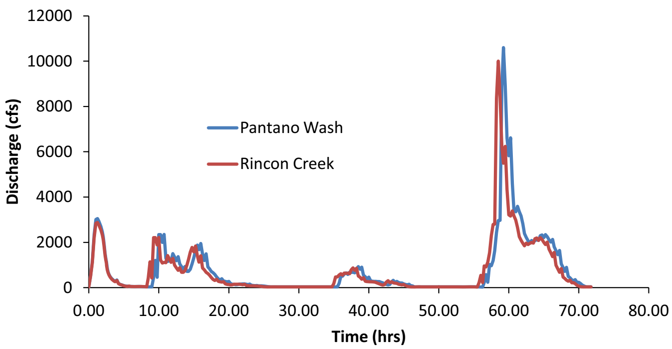

FIGURE 2. HEC-RAS Input Hydrograph at the Pantano Wash and Rincon Creek.

HEC-RAS. The actual duration of the storm event was about four days; however, for this project, long periods of little to no flow were removed from the hydrograph, to both speed up the modeling process and increase model stability. The downstream boundary condition of the flow data used here was at a normal depth, which requires an input of the channel slope and calculates the flow values based on Manning's equation. The slope of the channel was approximated at 0.005 ft/ft based on a profile plot of the measured bed elevations along the channel. As there is no gauge at the Rincon Creek, the hydrograph at the Rincon Creek was created based on the hydrograph observed in the Broadway gauge. According to field observations, the source water at Rincon Creek has the similar flood peak as in the Pantano Wash during the event, and the ratio of this estimated peak to the peak flow of the Pantano Wash was used to create a hydrograph for Rincon Creek scaled by this ratio. The FVM model hydrograph was made by taking the HEC-RAS hydrograph (with data points at 15 min intervals), and using a linear interpolation between the points, although again only the lower reach of the Pantano Wash was modeled in the FVM program. The same boundary conditions were used in both models.

Sediment Data

The final input data needed by the models to run a sediment analysis are the sediment data. Bed gradation data at each sample site were entered into HEC-RAS based on the sieve analyses of the sediment taken from the 15 sample sites, and the data were interpolated for cross-sections between the sample sites. Results from the sieve analysis for the 15 sample sites are shown in Table 1. The average d_{50} value for the entire reach was 1.34 mm. Maximum erodible depth values were set at 10 ft (3.048 m) for each

TABLE 1. Sieve Analysis Results.

Sample No.	River Station	Location	Depth	d_{50} (mm)
1	501.4311	Craycroft	Surface	1.05
2	5,499.269	Glenn	Surface	1.54
3	12,122.57	Tanque Verde	Surface	1.11
4	18,089.49	Speedway	Surface	0.95
5	24,186.59	Broadway	Surface	5.68
6	29,783.48	22nd	Surface	0.95
7	37,015.51	Golf Links	Surface	1.11
8	47,330.07	Harrison	Surface	1.50
9	54,014.55	Houghton	Surface	0.92
10	0.01 (Rincon Creek)	Drexel-Rincon Creek	Surface	1.15
11	65,699.2	Drexel-Pantano	Surface	1.19
12	78,697.14	Valencia	Surface	0.64
13	97,209.34	Leon	Surface	0.74
14	104,279	Almond Crest	Surface	0.84
15	109,903	Colossal Cave	Surface	0.77

cross-section based on observed data, and the entire extent of each cross-section was allowed to erode. The five transport methods being tested by HEC-RAS were those proposed by Laursen (1958), Engelund and Hansen (1967), Toffaleti (1968), Ackers and White (1973), and Yang (1973).

For the FVM model, the d_{50} and d_{90} of each cross-section were given in the input file. The d_{50} values were taken from Table 1, and interpolated for cross-sections between the sites. d_{90} Values were estimated from the bed gradation curves for each location, and once again interpolated for sections between two consecutive sample sites. Sample bed gradation curves for the upper and lower Pantano Wash are shown in Figure 3. Although no maximum erodible depths were entered into the code, the maximum erosion depth from the FVM model is much <10 ft. The entire extent of the cross-sections was allowed to erode, like in HEC-RAS. Only five transport methods were tested by this method to compare with the HEC-RAS results. As described in the previous sections,

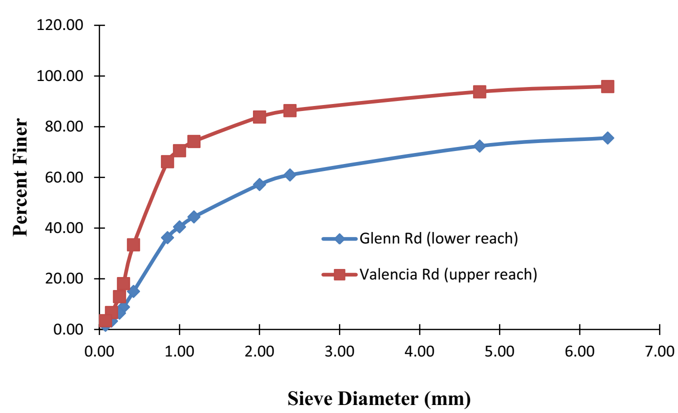

FIGURE 3. Bed Sediment Gradation Curve for Pantano Wash.

HEC-RAS used an equilibrium sediment transport algorithm, whereas the FVM model used a nonequilibrium transport algorithm. It is important to note that only changes in channel geometry and bed elevation are being compared in this study, and there is no measure of the volumetric sediment transport taking place.

RESULTS

Flow Results

The first test of the modeling procedure was to determine whether the flow output matched with the observed flow data. As mentioned earlier, the only gauge data available were at the Broadway Bridge. Flow at this location was therefore verified using the model output data. The input hydrograph was rescaled and the simulations repeated until the model flow data agreed with the observed gauge data. Results from this procedure are shown in Figure 4, showing only minor differences in the two hydrographs. Now that the input flow data were determined to be reasonable to what was actually seen in the reach, sediment transport results could be obtained.

HEC-RAS Sediment Model

The HEC-RAS sediment analysis of this river generates a mean effective invert change for each cross-section, representing the averaged bed elevation change, which was then compared with observed results for the river. Invert, in this article, refers to the lowest elevation point in a channel cross-section, also called the thalweg. The observed results were calculated by first creating separate raster files in ArcGIS for the 2005 and 2008 LiDAR data, then creating shape files of all of the cross-sections in the study area of each raster and subtracting the 2005 cross-section shape files from the 2008 ones. An assumption was made that this 2006 event was the only significant rainfall event during the 2005-2008 time period resulting in changes to bed elevation. Upon observing the gauge data, this assumption is reasonable due to the fact that the peak discharge recorded during this storm was 15,900 cubic feet per second (cfs), and the largest discharge recorded over this time period not occurring during this 2006 event was only 2,750 cfs, occurring July 23, 2007 (USGS, 2008). The results of the simulation are shown graphically in Figure 5. The simulation reach was divided into two reaches to show the differences by using five different sediment transport equations.

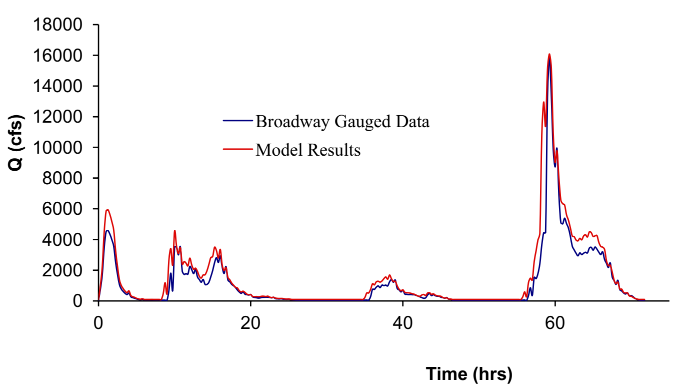

FIGURE 4. Comparison of Hydrographs at Broadway Road.

Finite Volume Method Model

The results of the simulation using the FVM are presented in Figures 6 and 7 in which the nonequilibrium sediment is simulated using Yang's and Engelund-Hansen's sediment transport methods for multiple lag distances and compared with the observed measurements. The lag distance of 3,000 ft yielded the best matches with measured elevation changes for Yang's method and 1,000 ft for Engelund-Hansen's method.

Sample cross-section elevation changes calculated by the two models are shown in Figure 8. These plots demonstrate that the predicted change from the FVM model is often very similar to the HEC-RAS predictions, although this was not always the case. When looking at these figures, it is important to remember that the methods used to calculate the observed results only generated an average bed elevation change across each cross-section, so the actual observed changes seen in these plots is that average value added or subtracted from the initial bed elevation value corresponding to each station.

Comparison of Models

A statistical analysis of the data was then conducted to evaluate the models. Calculations were conducted to find the mean error, the correlation factor, and the root mean square error (RMSE) of each transport method compared with the observed mean bed elevation change data of the river. "Mean effective invert change" refers to average change in bed elevation at a cross-section after the flow event occurs. The following equations were used in the analysis, where C_i represents each calculated sample, $\overline{C}$ represents the average of the calculated samples, O_i represents each observed sample, $\overline{O}$

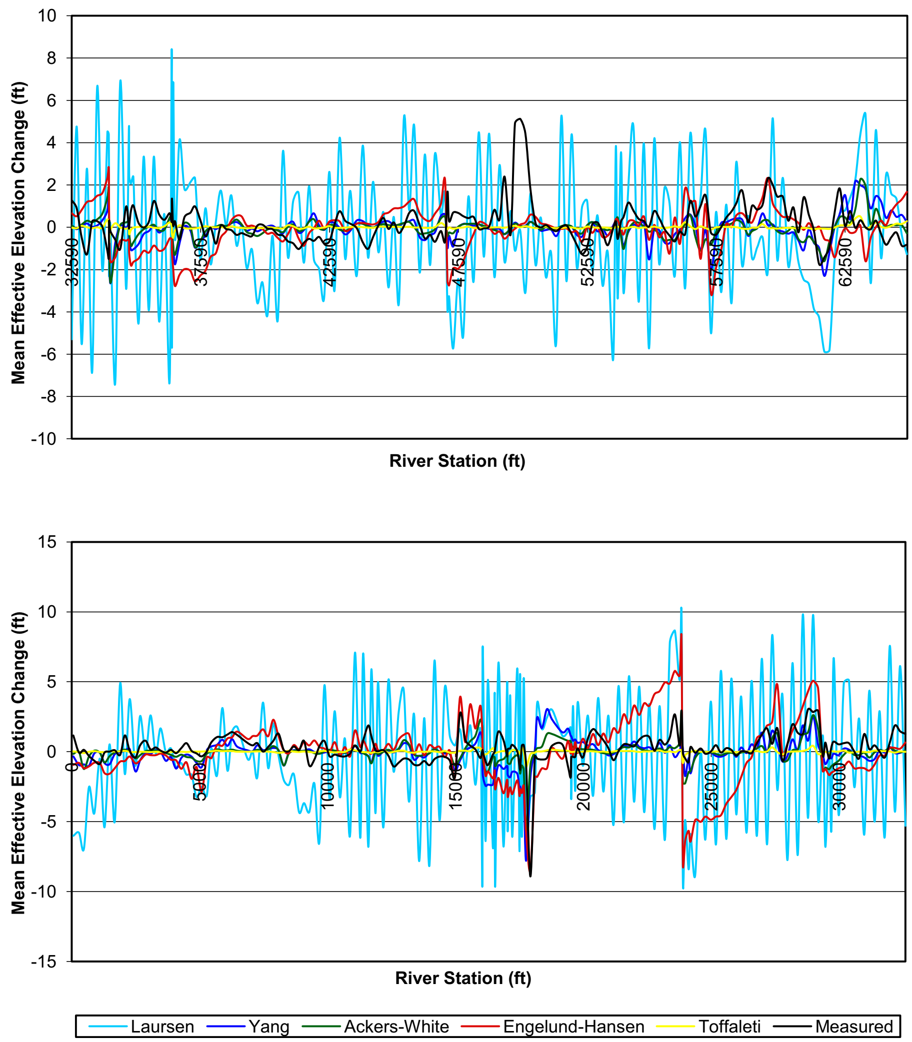

FIGURE 5. Averaged Bed Elevation Change from HEC-RAS Model.

represents the average of the observed samples, and n is the total number of samples.

$$\text{Mean error} = \frac{\sum_{i=1}^{n}(C_i - O_i)}{n}. \tag{8}$$

$$\text{Correlation factor} = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(C_i - \overline{C})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(C_i - \overline{C})^2}}. \tag{9}$$

$$\text{Root mean square error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(C_i - O_i) - (\overline{C - O})\right]^2}. \tag{10}$$

By using Equations (5-7), the statistical parameters of simulated results for the Pantano Wash and Rincon Creek using HEC-RAS model are summarized in Table 2, whereas those from FVM model are shown in Table 3.

DISCUSSION

The plots in Figure 5 demonstrate how the results from the HEC-RAS sediment analysis are compared with the observed data (shown on these figures in black). Table 2 then shows the quantitative comparisons of the results. As can clearly be seen by the graphs, Laursen's transport method gives a severe overestimate of the amount of bed scour taking place in the channel, whereas Toffaleti's method gives a

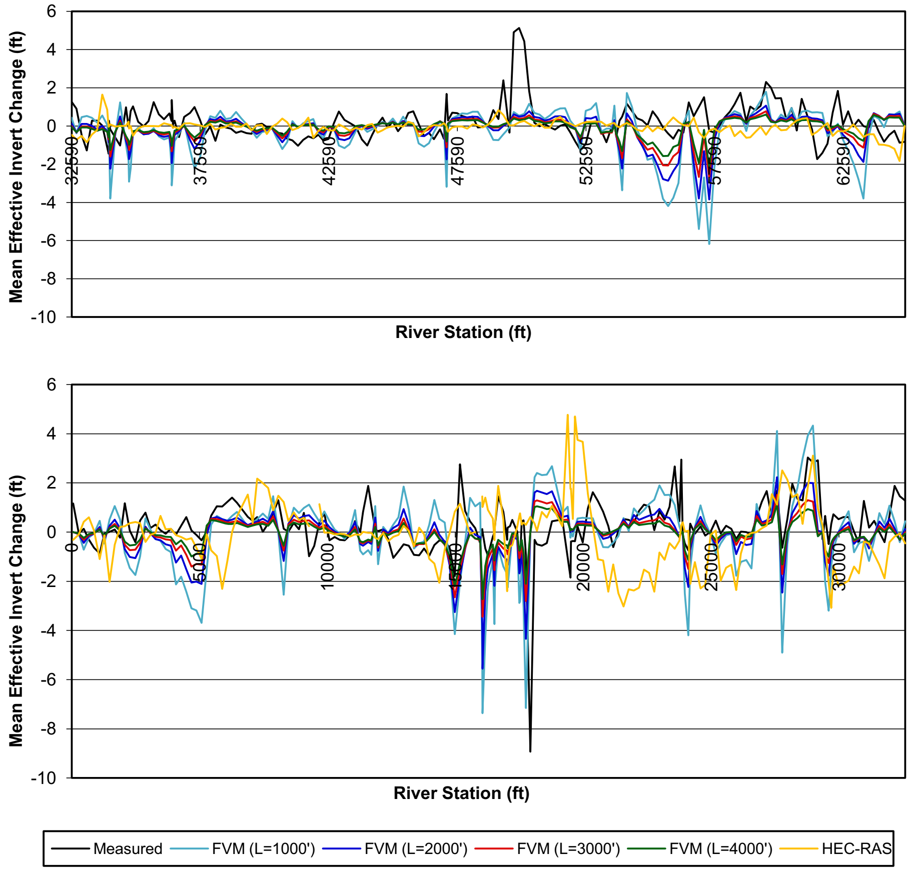

FIGURE 6. Comparison of the Results of FVM Model Using Yang's Method.

consistent underestimation of the actual results. The other three methods correlate much better with the observed data. The Engelund-Hansen method, while having the highest correlation factor of the five methods tested, also shows the greatest magnitude of error besides the Laursen's method. Based on the combination of smaller error with greater correlation factors, Yang's method would most likely be the optimum choice for modeling rivers like the Pantano Wash.

The FVM model was programmed to utilize the Yang and Engelund-Hansen transport methods as they were found to give the best results in HEC-RAS. The results show that the FVM model obtains smaller error compared with the observed values using the Engelund-Hansen equations than HEC-RAS could; however, this model could not duplicate the higher correlation seen in HEC-RAS. The FVM simulations using Yang's method produced the opposite effect; the model error was larger in the FVM model for all lag distances compared with the HEC-RAS results, whereas the correlation of the FVM results was basically around the same value as generated by HEC-RAS. Interestingly, the optimal lag distance was not the same for the two transport methods when using the FVM model. The ideal lag distance for the Engelund-Hansen method is estimated to be around 1,000 ft (304.8 m), whereas the best results for Yang's method came with a lag distance of 3,000 ft (914.4 m). These distances are chosen as optimal due to the combination of small error and highest correlation. Plots comparing the measured data and HEC-RAS results with just the FVM results using these optimal lag distances are shown in Figures 9 and 10.

For the Engelund-Hansen transport method, the HEC-RAS model seems to overestimate the mean bed elevation change more often than the FVM model does. The results in Table 3 definitely show a smaller error in the FVM model, so if willing to accept the lower correlation with the observed results, the FVM model using a nonequilibrium sediment transport load may actually be better suited for predicting sediment transport than HEC-RAS for rivers similar in region and grain size to the Pantano Wash. Qualitatively, this appears to be true by looking at Figures 9 and 10.

Likewise, an argument could be made for the FVM model implementing Yang's transport method being preferable to the HEC-RAS model. Although the mean error is smaller in HEC-RAS, the RMSE of the HEC-RAS results is actually larger than that of the

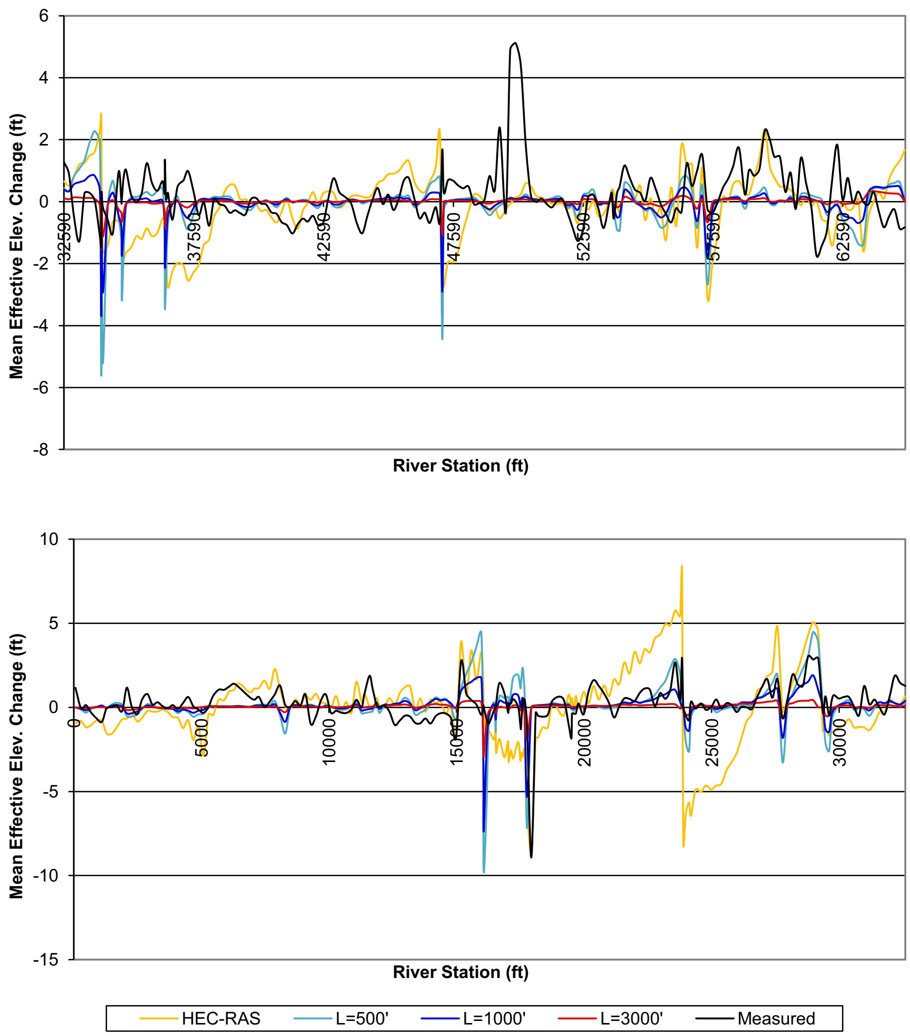

FIGURE 7. Comparison of the Results of FVM Model Using Engelund-Hansen's Transport Method.

FVM model using an optimal lag distance of 3,000 ft. The correlation of the FVM model for this lag distance is slightly higher than the HEC-RAS correlation, although they are very similar. Again, the FVM model appears to be the model of choice when looking at Figure 10, although the HEC-RAS simulation using Yang's method does perform very well for short stretches of the reach.

Ultimately, there is bound to be a lot of errors made when trying to model a reach of this size (~22 miles for the whole Pantano Wash, ~12 miles for the lower reach). There are some areas of the river, especially around the middle of the study area where the upper and lower reaches meet and connect with the Rincon Creek tributary (mostly between river stations 40,000 to 80,000), where there are large aggradations or degradations in the observed data that were not predicted by the HEC-RAS simulations. This is most likely due to changes occurring to the actual site which were not caused by streamflow. As alluded to in an earlier section of this report, there are gravel pits and other construction projects existing near this part of the river. The proceedings of these projects likely caused changes in elevations to areas that lay right up against the reach being considered, and would create differences in the 2005 and 2008 geometry files in ArcGIS that are not seen in the HEC-RAS model because they are not caused by the streamflow generated by the input event. The cross-sections of the model were cut in a way to minimize this effect and reduce as much overlap with these construction areas as possible without removing sections of the channel necessary to contain flow; however, this was not possible at all locations. Near station 77,787.19, for example, a dirt road exists directly on top of the river bed. The spike in the mean elevation invert change seen in the observed results around river station 50,000 may be due to similar circumstances, as none of the models picked up on this observed bed increase.

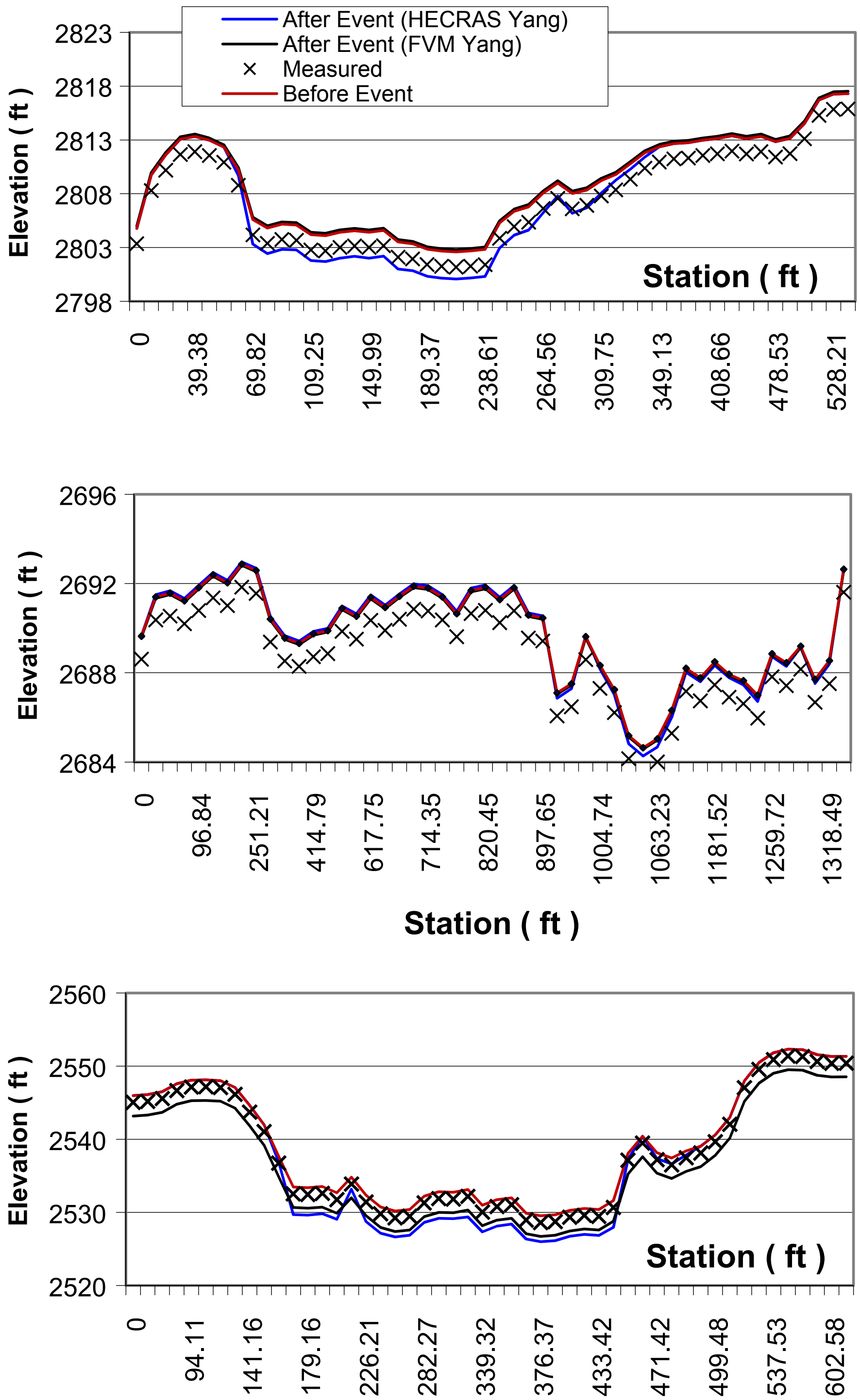

FIGURE 8. Samples of Cross-Section Changes Using HEC-RAS and FVM 1D Model.

CONCLUSIONS

In summary, a sediment analysis was conducted on the Pantano Wash and one of its tributaries in Tucson, to determine whether two different sediment models could accurately estimate bed elevation change after a storm event. Cross-sections were created for the models using actual LiDAR data of the study site, and the flow inputs to the system were based on a real gauged hydrograph. A HEC-RAS (version 4.1) analysis considered five of the transport

TABLE 2. HEC-RAS Statistical Analysis.

	Mean Error (ft)	RMSE (ft)	Correlation
Pantano Wash and Rincon Creek			
Ackers-White	−0.280	1.387	0.243
Engelund-Hansen	−0.386	1.968	0.349
Laursen	−0.440	3.725	0.108
Toffaleti	−0.219	1.382	0.131
Yang	−0.313	1.449	0.273
Lower Pantano Wash			
Ackers-White	−0.273	1.104	0.210
Engelund-Hansen	−0.365	1.798	0.355
Laursen	−0.497	4.174	0.081
Toffaleti	−0.218	1.016	0.109
Yang	−0.307	1.232	0.176

TABLE 3. Statistical Analysis of FVM Model, Compared with HEC-RAS Results.

	Mean Error (ft)	RMSE (ft)	Correlation
Engelund-Hansen			
HEC-RAS	−0.365	1.798	0.355
FVM L = 250′	−0.181	2.147	0.157
FVM L = 500′	−0.223	1.460	0.173
FVM L = 1,000′	−0.234	1.176	0.150
FVM L = 2,000′	−0.223	1.051	0.131
FVM L = 3,000′	−0.217	1.027	0.124
Yang			
HEC-RAS	−0.307	1.232	0.176
FVM L = 1,000′	−0.512	1.676	0.179
FVM L = 2,000′	−0.422	1.269	0.175
FVM L = 3,000′	−0.360	1.118	0.179
FVM L = 4,000′	−0.322	1.061	0.178

methods provided by the program, concluding that using Engelund-Hansen's and Yang's methods generated the mean effective bed elevation change for each cross-section with the smallest error and greatest correlation to those seen in the observed elevation changes. If one were to attempt to model sediment transport in a semiarid ephemeral stream such as the Pantano Wash using HEC-RAS, it would be advisable to use one of these two transport methods.

These two methods were then further analyzed using an FVM model that applied a nonequilibrium sediment algorithm to the system. Based on a statistical analysis of the two models, it was found that for some stretches of the reach being studied, the FVM was able to produce results with smaller error and higher correlation to the observed results than were seen in HEC-RAS. Use of this model requires experimentally determining the lag distance used to estimate the volumetric sediment transport rate. Modeling rivers of this size is not without its difficulties; however, if the system is able to be adequately defined, the results of this project show that there are models available that can provide knowledge of how sediment transport in the river is taking place.

However, the results showed that the unsteady nonequilibrium sediment transport has not significantly improved the accuracy of modeling results. This is attributed to two factors: one is the uncertainty and errors of input geometric data, and the other is the nonequilibrium sediment model. As stated in the article, the nonequilibrium sediment source term was approximated using the adaptation length, an empirical parameter, which may not represent the physical process of nonequilibrium sediment transport. Although current sediment transport knowledge is based on equilibrium transport, this study illustrated the needs of theoretically sound and practically feasible nonequilibrium sediment transport models to better simulate the sediment transport in unsteady flow.

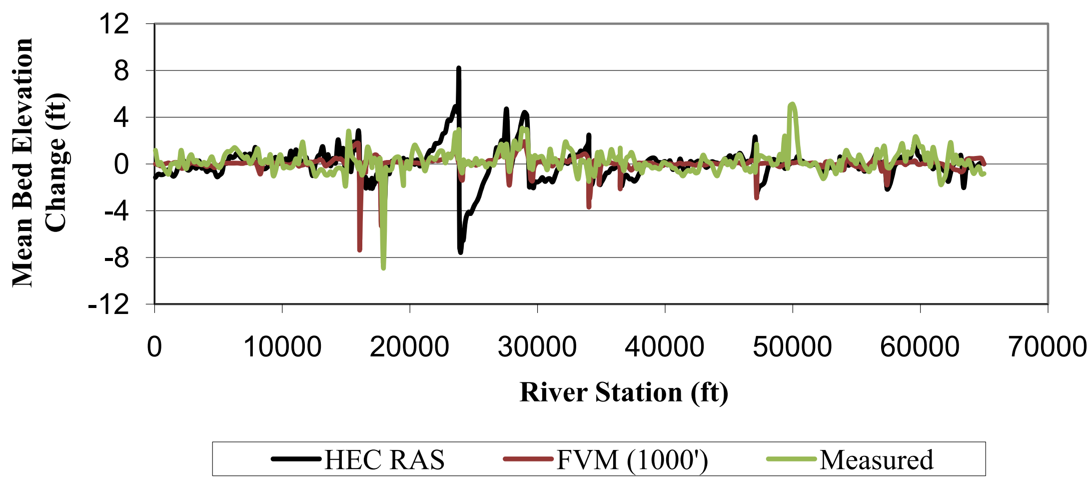

FIGURE 9. Comparison of Results from FVM and HEC-RAS Model (Engelund and Hansen's Method).

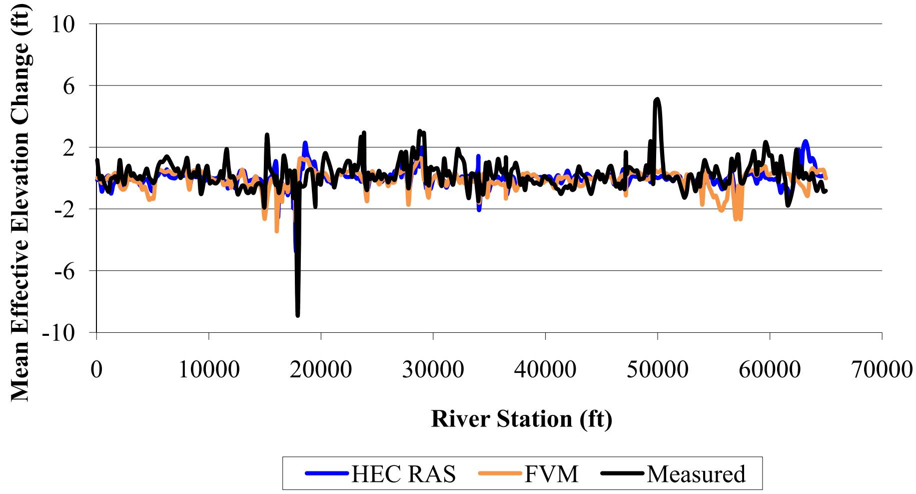

FIGURE 10. Comparison of Results from FVM and HEC-RAS Model (Yang's Method).

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