COUPLING WATERSHED SEDIMENT YIELD MODEL WITH INSTREAM SEDIMENT TRANSPORT MODEL: AN EXAMPLE OF MIDDLE RIO GRANDE

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Abstract The Middle Rio Grande (MRG) in Central New Mexico was suffering severe bed aggradation in the history which caused serious flooding problem. Among others, inflow from the Calabacillas Arroyo, a tributary of MRG downstream of the Albuquerque Diversion Dam delivers a large amount of sediment, manifested by the delta formation and the narrowing of the main channel Rio Grande. It implies significant erosion and sediment yield from the surrounding watershed. The goal of this research was to investigate the impact of tributary sediment on the channel geomorphology of main stream MRG. To achieve the goal, we used KINEROS2, a watershed hydrology and sediment yield model, to coupled with CCHE2D, a depth-averaged two-dimensional hydrodynamic and sediment transport model to study the sedimentation process in the whole watershed. The combined model was used to predict the bedform change of main stream under various hydrology scenarios (annual mean flow, 10-year, 25-year, and 100-year floods) by considering concurrent sediment input from the tributary for episodic events (10-year, 25-year, and 100-year storm events). The modeling results indicated that the sediment input from the Calabacillas Arroyo during rainfall events has a strong influence on channel geomorphology of MRG.

INTRODUCTION

Study Area The Middle Rio Grande (MRG) is located in Central New Mexico (Figure 1 insert). As one of the most historically documented rivers in the United States, MRG is under constant supervision from regulatory agencies such as the U.S. Bureau of Reclamation (USBR) and U.S. Army Corps of Engineers (USACE) (Albert, 2004). MRG was historically characterized as an aggrading sand bed channel with extensive lateral bank movement (Richard et al., 2005; Sixta, 2004).

The reach of this study is the diversion dam reach of the middle Rio Grande, which spans from Alameda Blvd bridge to Paseo Del Norte bridge including the Calabacillas Arroyo (Figure 1). There are two USGS gauges located at the Alameda Blvd bridge and Paseo Del Norte bridge, respectively. The Calabacillas Arroyo (CA) is located in Northwestern Bernalillo and South-central Sandoval counties. The CA is a steep, relatively straight channel with a large width-to-depth ratio and has significant potential for lateral and vertical instability. It drains a watershed with a total area of approximately 220 square kilometers and enters the MRG about 70 km downstream of Cochiti Dam. In addition to the CA watershed, the arroyo also discharges water from portions of the Black’s Arroyo watershed due to contributions from the concrete-lined Black Diversion Channel, the only significant tributary of the CA. The drainage area of the Black’s Arroyo is approximately 25 square kilometers (Mussetter, 1996).

Purpose of the Study The purpose of this study is to examine how the sediment input from the CA, a tributary to the Middle Rio Grande affects the geomorphology in the main stream. As shown in Figure 1, a huge alluvial fan at the confluence has resulted from sediment outflows from the CA during extreme flood events, which has reduced the main MRG channel width by approximately one half and significantly affected the sediment transport capacity of the stream. The large amount of sediment input breaks the sediment balance in the MRG and may result a number of hydrological and ecological consequences, such as the channel geometry, flood frequency and changes in aquatic habitat.

Approach Our approach is to conduct a combined modeling study to investigate the watershed sediment yield, tributary sediment transport and mainstream geomorphic changes with sediment input from the tributary during typical storm events. The whole study will include three major parts: the watershed sediment yield, the tributary sediment transport and the main stream sedimentation. Firstly, the Kinematic Runoff and Erosion Model (KINEROS2) model was used to estimate sediment yield from the CA watershed during different storm events. Secondly, analysis of sediment transport in the channel was performed using the HEC-RAS program developed by Hydraulic Engineering Center (HEC) of U. S. Army Corps of Engineers. Thirdly, The main stream sedimentation process was modeled with a two-dimensional sediment transport program CCHE2D.

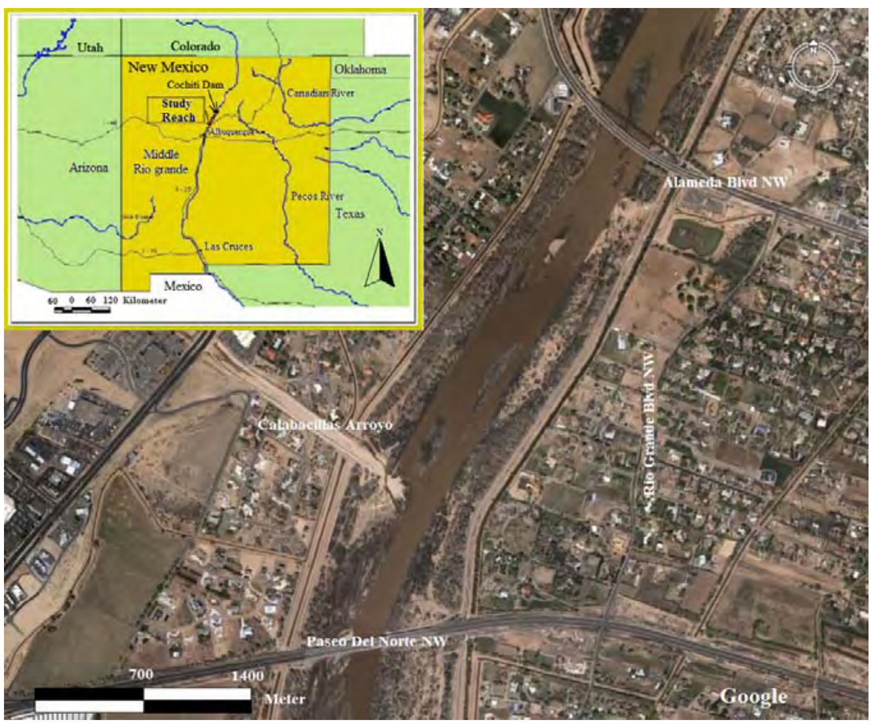

Figure 1 Map of the Study Site.

MODEL DESCRIPTION

Introduction to KINEROS2 Model The KINEROS2 model has been undergone long term development in the US Department of Agriculture, Agriculture Research Service (USDA-ARS). It describes the physical processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds and uses physically-based approach to simulate dynamics of short duration rainfall-runoff processes in watersheds. In this model, a watershed is represented by a series of planes (hill-slopes) and channels. Interception, infiltration and overland flows are simulated for planes to generate runoff, and channel routing is simulated to transport runoff to the outlet of the watershed with the consideration of transmission loss. Infiltration on planes as well as in channels is modeled using a three-parameter general infiltration model. Technical details can be found from the KINEROS2 website http://www.tucson.ars.ag.gov/kineros/.

Introduction to HEC-RAS Model HEC-RAS program was developed by Hydraulic Engineering Center (HEC) of U. S. Army Corps of Engineers. The latest HEC-RAS model provides a module for sediment transport analysis. This model was designed for modeling one-dimensional sediment transport, and can simulate trends of scour and deposition typically over periods of years or alternatively, for single flow events. For unsteady flow events, it segments the hydrograph into small time periods and simulates the channel flow for each time interval assuming a steady state flow in the whole channel. The non-equilibrium sediment transport approach included in the module makes the sediment transport process more realistic. The sediment transport potential is computed by grain size fraction so that the non-uniform sediment can be represented more accurately. The model can be used for evaluating sedimentation in fixed channels and estimating maximum scour during large flood events among other purposes (Hydrologic Engineering Center, 2008). The HEC-RAS sediment transport module provides the option of several different sediment transport functions, thus users can select the most appropriate function according to the site conditions. This module also has the ability to limit degradation to specified elevations/depths at individual cross-sections which allows for the representation of Grade Control Structures (GCS) in the arroyo for the modeling study.

Introduction to CCHE2D Model CCHE2D is an integrated software package for two-dimensional simulation for analysis of river flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport and water quality developed at the National Center for Computational Hydro-Science and Engineering at the University of Mississippi. These processes in the model are solved using the depth integrated Reynolds equations, transport equations, sediment sorting equation, bed load and bed deformation equations. The model is based on Efficient Element Method, a collocation approach of the Weighted Residual Method. Internal hydraulic structures, such as dams, gates and weirs, can be formulated and simulated synchronously with the flow. A dry and wetting capability enables one to simulate flows with complex topography. There are three turbulence closure schemes in the model, depth-averaged parabolic, mixing length eddy viscosity models and k-ε model. The numerical scheme can handle subcritical, supercritical, and transitional flows (NCCHE, 2009).

Modeling Procedure The modeling system described in this article uses an aggregated approach to model watershed sediment yield, stream sediment transport and bedform change. As shown in figure 2, the HEC-1 and KINEROS2 results provide the flow and sediment boundary conditions (BCs) for HEC-RAS CA channel model, respectively. The HEC-RAS model result is further used as the tributary flow and sediment boundary conditions (BCs) for the CCHE2D main stream model.

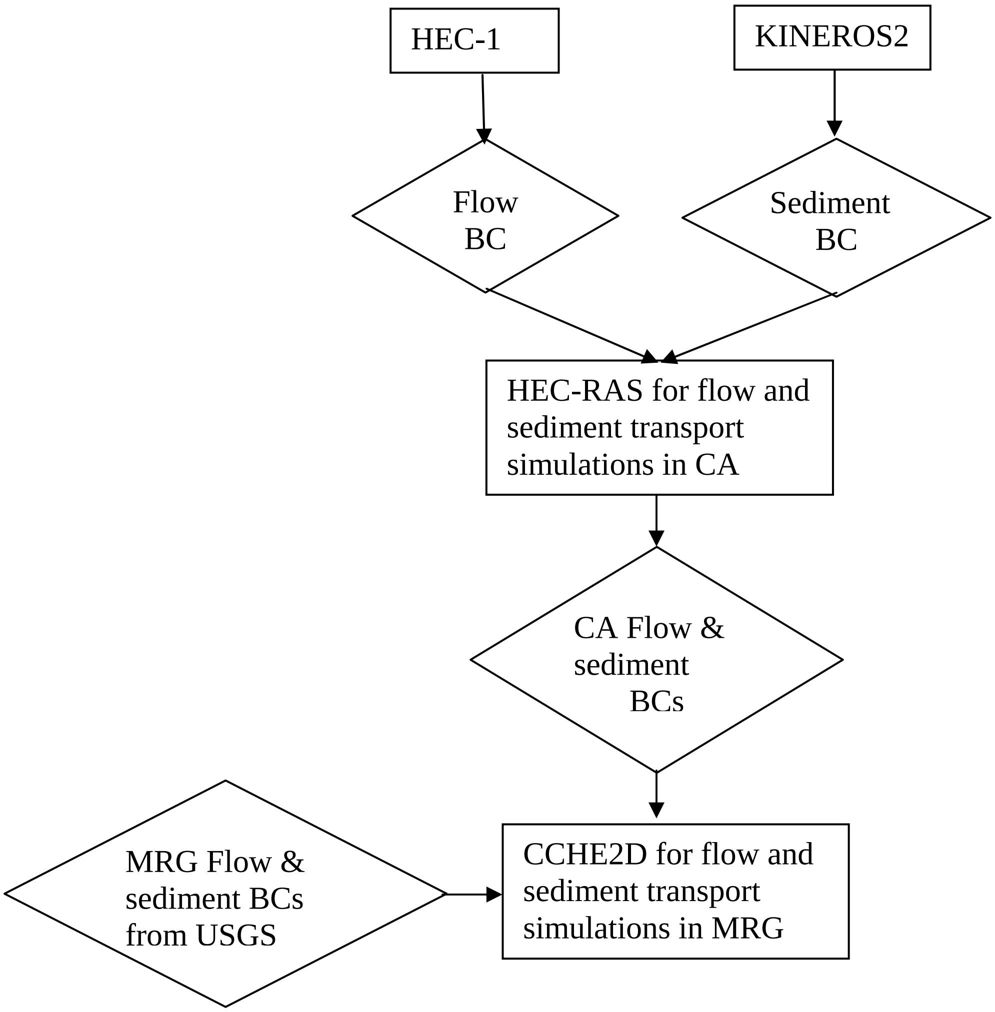

Figure 2 Flowchart for modeling system.

DATA PREPRATION

CA Watershed Sediment Yield For the watershed sediment yield analysis we need the topographic data, soil data and land cover data. All of these data sets can be downloaded from the public available internet sites. A ten-meter digital elevation model (DEM) data used for watershed delineation and 2001 land cover data were obtained from the U. S. Geological Survey (USGS) via internet. SSURGO soil data was obtained from the U. S. Department of Agriculture Soil Data Mart site. Using the topographic data, we can delineate the watershed via the AGWA extension in the ArcGIS environment. The soil data and land cover data were used to parameterize the model, which can be done within the AGWA interface. Meteorological data for different storm events were shapefiles of precipitation-frequency grids from NOAA. These grids are based on high-resolution (~800 m) NOAA Atlas 14 precipitation frequency estimates that were calculated from the analysis of partial duration series (see hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html).

CA Channel Sediment Transport Channel sediment transport modeling is based on the channel hydraulic conditions which can be simulated by HEC-RAS. The hydraulics and sediment transport are both based on channel geometry. For this task, the first step is to generate cross sections to define the channel. This was done using the high resolution (2-ft contour) digital terrain model (DTM) data provided by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) within the HEC-GeoRAS software for ArcGIS environment developed by HEC, USACE. The CA channel was modeled from Swinburne Dam down to the confluence of the arroyo at the MRG. A total of 114 cross sections were extracted from the DTM data. Of these, 17 designate the approximate locations of existing grade control/soil cement structures. Locations of these structures were estimated using engineering drawings provided by AMAFCA. The elevations of the bases of the grade control structures were determined from engineering drawings and entered into HEC-RAS as minimum elevations (elevation below which the model will not erode at that cross section).

HEC-1 hydrograph data for existing conditions from a previous study for AMAFCA was used to create the upstream flow boundary condition in HEC-RAS. The peak flow values for the 100-year, 25-year, and 10-year 24-hour storms were calculated as 12,302 cfs, 7,921 cfs, and 5,391 cfs, respectively. The downstream flow boundary condition was set to normal depth, which was based on the friction slope (0.0105 ft/ft) calculated from the cross sections in the most downstream 400 feet of the channel. Sediment bed gradation characteristics for the channel bed were based on those provided in the *Calabacillas Arroyo Prudent Line Study and Related Work* (Mussetter Engineering, Inc., 1998). The computed sediment yield totals from KINEROS2 were used as the sediment boundary conditions in the HEC-RAS analysis. These values were the upstream sediment boundary condition input at Swinburne Dam. The sediment size distribution used for this modeling study was based on the sediment sampling work in the 1998 report from Mussetter Engineering.

Main Stream Sediment Transport A 2-D computational mesh was generated based on channel topography data extracted from a digital contour map which was produced using the cross section data from HEC-RAS model (downstream of the diversion dam) and measurement by AMAFCA (arroyo) and University of New Mexico (upstream of the diversion dam). Bed material gradations were obtained from textural analyses of in-Channel Cored Samples taken by Sandia National Laboratories (SNL). The original data include bed material gradation in five layers at 27 sampling sites along the reach. For the simplification and requirement by CCHE2D, we reduced it to three layers and applied an averaged bed material gradation for each layer.

MODELING RESULTS

<u>CA Watershed Sediment Yield</u> We used KINEROS2 model to calculate the sediment yield of the watershed for 100-year, 25-year, and 10-year recurrence interval 24-hour storms. The model calculated sediment yield at each element. The sediment yield calculated at the watershed outlet for the whole watershed (area in the KINEROS2 model = 20077.16 hectares) is summarized in the following table.

Table 1 Sediment yield estimates from KINEROS2 for the entire watershed.

Event	Yield (kg/hectare)	Yield (kg)	Yield (short tons)
10year-24hour	0.0036	73.24	0.0807
25year-24hour	0.6886	13,825.14	15.24
100year-24hour	333.41	6,693,968.04	7,378.84

* 1 US short ton = 2,000 lbs

Figure 3 shows the calculated spatial distribution of sediment yield from KINEROS2 model for the 100-year event. This may provide useful information for future watershed management.

CA Channel Sediment Transport Table 2 shows the cumulative mass out near the confluence of the CA from different design storm events from the HEC-RAS simulations (with non-equilibrium sediment inflow boundary condition). The cumulative mass out at the second most downstream cross section was recorded for each simulation. The most downstream cross section was held at a constant elevation (zero bed change) in the boundary condition file. Model runs were made with the selected transport functions, design storm events, and for two different conditions, with and without the presence of grade control structures (GCS). The choice of transport function strongly impacted the totals. The presence or absence of GCS did not lead to large changes in the totals. In some cases, the presence of GCS led to slightly larger sediment totals as compared to runs without GCS.

In the HEC-RAS sediment transport analysis of the CA, three transport functions were used: Engelund-Hansen (EH), Meyer-Peter-Muller (MPM), and Yang. The EH transport equation provided the highest totals and the MPM equation provided the lowest totals. The highest total produced, 284,259 tons (US short tons), was with the EH transport function with GCS for a 24-hour, 100-year storm. The lowest total, 2,430 tons, was produced with the MPM transport function without GCS for a 24-hour, 10-year storm.

Table 2 Cumulative mass out at the most downstream cross section in US short tons.

Function		100year	25year	10year
EH	No GCS	275,928	172,754	120,384
	With GCS	284,259	175,318	118,929
Yang	No GCS	164,184	111,935	86,323
	With GCS	167,549	109,421	87,073
MPM	No GCS	4,490	3,094	2,430
	With GCS	4,489	3,097	2,440

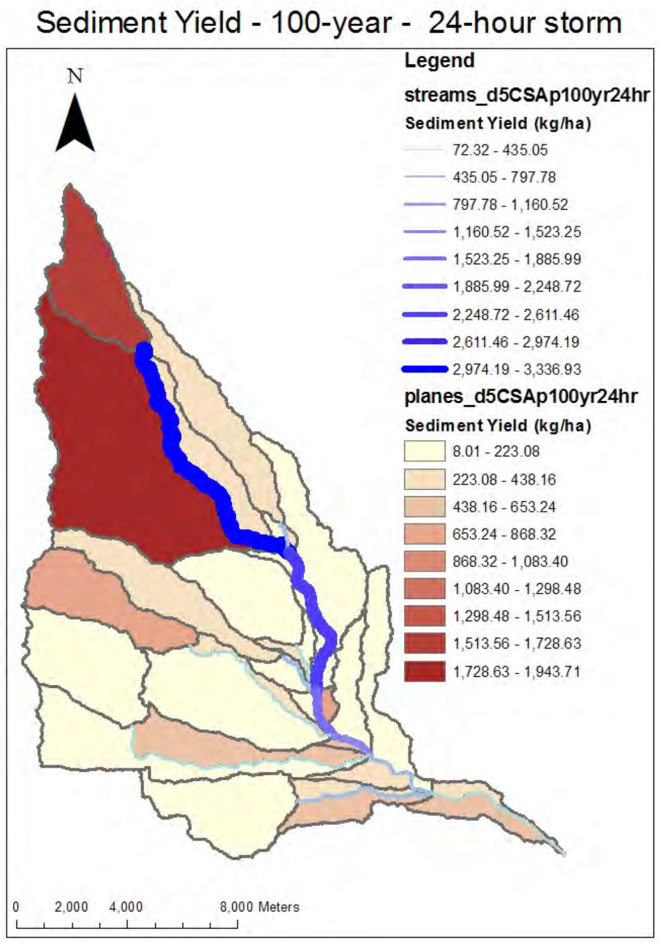

Figure 3 Sediment yield results from KINEROS2 model for 100-year event.

CA Channel Sediment Transport The 2D model for the main stem Rio Grande needs the input data of flow and sediment from both the main stream and the tributary Calabacillas Arroyo. In this modeling work, the equilibrium sediment boundary was adopted for the main stream MRG, while both equilibrium and non-equilibrium upstream sediment input conditions were applied for the tributary CA. The incoming sediment load based on equilibrium upstream sediment condition was calculated with the Yang formula, while EH function with GCS was adopted for the non-equilibrium upstream sediment boundary condition.

Non-equilibrium sediment boundary condition at CA inlet Figure 4 shows the bed elevation changes at two extreme scenarios: (a) 100-year flood occurs in the MRG with synchronous 10-year flood in the tributary; (b) 100-year flood occurs in the tributary with based flow in the MRG. Figure 4a represents a favorable condition for river maintenance: although the whole channel system was an aggrading system in the past (Chen et al., 2007), sedimentation was minimal under those conditions. In contrast, Figure 4b represents the worst case: a heavy rainstorm has been restricted to the upper watershed of the Calabacillas Arroyo which results in a 100-year flood in the tributary and huge sediment load, while the flow in the main stem of MRG remains around 25m3/s (base flow). In the case of Figure 4b, a great amount of sediment has settled around the confluence area which indicates that base flow in the main stem does not have enough hydraulic power to transport the deposited sediment to downstream reaches. Most serious deposition (around 1m) is located a bit downstream of the confluence, while depositing depths elsewhere are less than 0.5m.

In addition, it could be observed that sedimentation in Figure 4b traces toward the upstream along the right bank for several hundred meters, which is believed due to the ponding effect produced by excessive downstream aggradation.

Equilibrium sediment boundary condition at CA inlet To better understand the impact of CA inflow sediment on the evolution of main stream geomorphology, scenarios with equilibrium sediment boundary condition at CA inlet was also simulated to provide a most extreme condition.

Figure 5 shows the bed elevation changes at two scenarios: (a) 100-year flood occurs in the tributary (equilibrium sediment inflow at the CA inlet) with the based flow (25 m3/s) in the MRG; (b) 100-year flood occurs in the MRG with synchronous 100-year flood in the tributary (equilibrium sediment inflow at the upstream boundary of the tributary). The crucial role of sediment source from the tributary can also be revealed when comparing Figure 4b with Figure 5a and comparing Figure 4a with 5b. There is more inflow sediment from the CA under the equilibrium boundary scenarios which will bring more serious deposition in the main stream. Even the 100-year flood in the MRG has limited ability to flush away the sand bar formed along the right bank. Unlike the non-equilibrium sediment boundary scenarios, the most serious deposition area located just upstream the confluence which indicates stronger ponding effects.

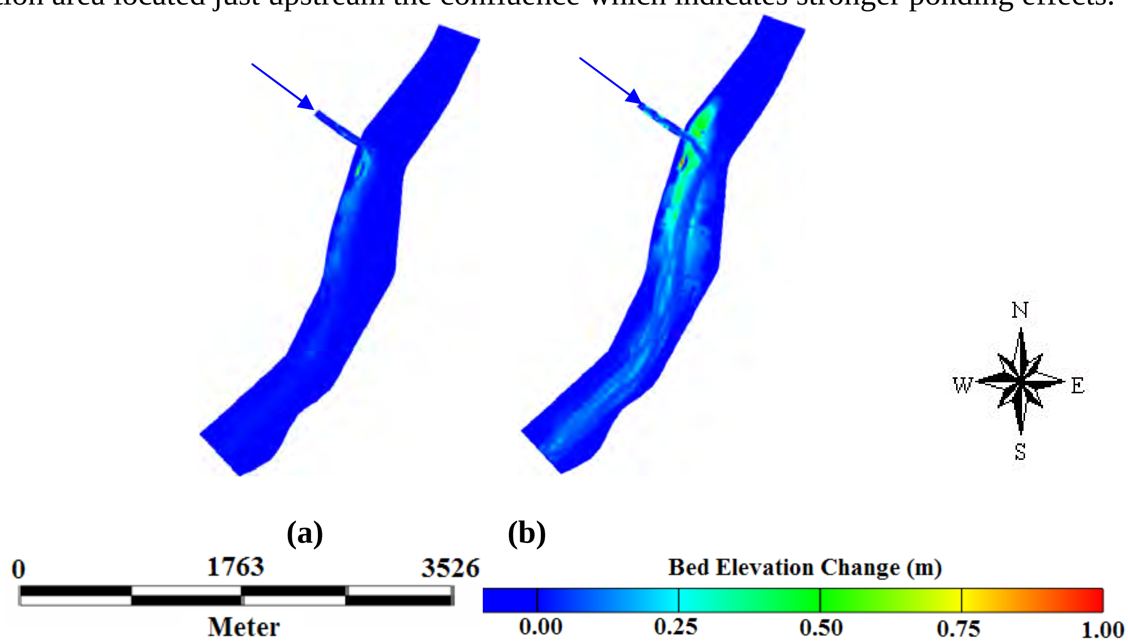

Figure 4 Bed elevation change after combined flood events: (a) 10-year flood in the tributary with synchronous 100-year flood occurs in the MRG; (b) 100-year flood occurs in the tributary with based flow (25m^3/s) in the MRG.

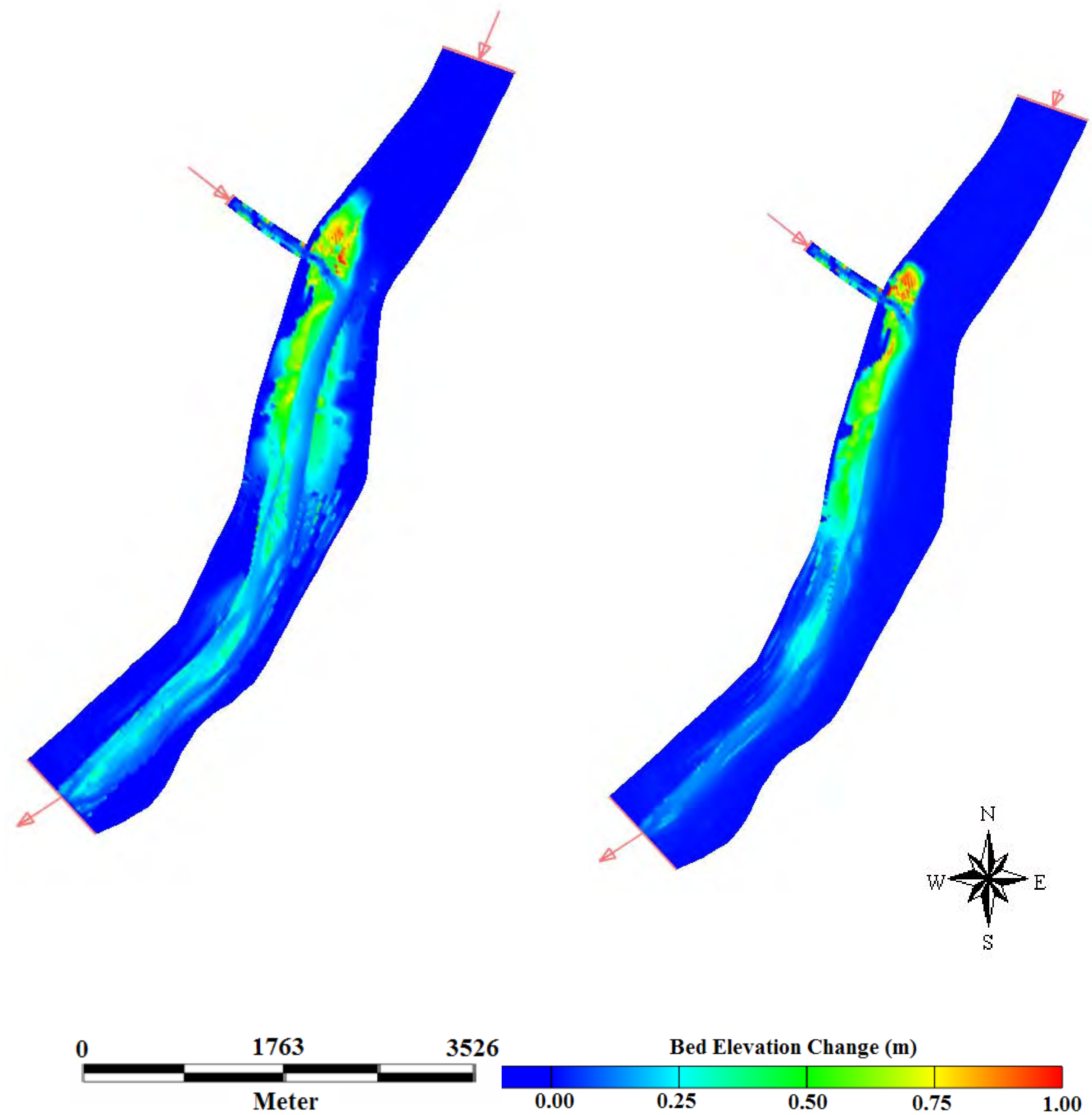

Figure 5 Bed elevation change after combined flood events: (a) 100-year flood occurs in the tributary (equilibrium sediment inflow at the inlet) with based flow (25 m^3/s) in the MRG; (b) 100-year flood occurs in the MRG with synchronous 100-year flood in the tributary (equilibrium sediment inflow at the upstream boundary of the tributary).

CONCLUSIONS

Three models have been applied in this project to conduct a combined study of watershed sediment yield, tributary sediment transport and main channel sedimentation modeling. The following conclusions can be drawn from the study:

1) Significant amount of sediment (7,378 US tons) can be eroded from the watershed and enter the CA channel during a 100-year, 24-hour storm event. However, this portion of the sediment is relatively small compared with the amount of sediment that can be transported to the MRG through CA;
2) Large amount of sediment (ranging 167,549 - 519,967 US tons) will be scoured from the CA channel to supply the main stream MRG during a 100-year flood. The GCSs will have limited impact on the sediment transport process under the current situation;
3) According to research in literature and the current study, EH and Yang sediment transport functions are better applicable for the CA site. MPM function should be used with care because it is limited for bedload prediction;
4) The 25-year and 10-year floods will produce about 60% and 40% of sediment transported by a 100-year flood, respectively, which are also significant sediment amounts to the MRG;
5) The sediment input from the CA channel can significantly affect the geomorphic features in the main stream MRG. Serious deposition will happen in the main stream mainly in the downstream reach of the confluence and also in a short reach upstream. The worst situation happens when large events occur in the tributary coincident with low flows in the main stream.

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