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Numerical analysis of stream renovation using MIKE 11-GIS and HEC-RAS5

Abolfazl NAZARI GIGLOU ✉

Islamic Azad University, Department of Civil Engineering, Parsabad Moghan Branch, Parsabad Moghan, Iran
University of Idaho, Center for Ecohydraulics Research, Department of Civil Engineering, 322 E. Front St., Suite 340 Boise, ID 83702, 83712, Boise, USA

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Abstract

The main purpose of river system is to renovate its old processes. This article represents the results of two numerical models and a field site screening results for the river renovation in Idaho, U.S.A and some restoration methodologies that have been used to better understand possible renovating strategy. Ecological recovery methods using a degraded stream ecosystem have been found after estimating a channel design's capability. Despite these representing methods it is hard to present the most effective method to get efficient renovative outcomes. Two hydrodynamics modelling (MIKE 11-GIS and HEC-RAS5) and field site screening are used to evaluate pre- and post-renovation modifies in 35 laboratory experiments and biological performance indicators. Movement formed between 1994 and 2014 have been considered in this research. Ecosystem improvements have been evaluated to compare the pre-post renovation situations by considering the parameters such as water surface elevation, lower slope, shear stress, depth, wet perimeter, and velocities. The numerical model results for all mentioned parameters show that after the completion of phase I, II, III and IV, the sinuosity of the channel will be very close to the 1986 condition. The sediment carrying capacity and potential use of MIKE 11-GIS, hydrodynamic model for scour has been reduced throughout the lower reaches of the project site, where the channel slope is at its steepest position, and a close match with the field site screening and have been shown and presented as graphs.

Key words: *ecological recovery, field site screening, hydrodynamics modelling, pre-post renovation, stream renovation*

INTRODUCTION

Restoring the natural river channel shape, meander pattern, and substrate condition to enhance the quality and quantity of spawning and rearing habitat are the overall objectives of the most recent river renovation projects [CLAYTON *et al.* 1999]. Measuring and documentation progress in satisfying short- and long-term project goals, objectives, and outcomes are the main topics in the international scientific scale. Some other essential subjects in most renovation projects included restoring meadow and riparian plant communities to enhance fish and wildlife habitat, stabilizing stream banks, and reducing water temperatures. A number of experimental and numerical research works have been done in past and recent years and have focused on studying of the aquatic ecosystem restoration [BERNHARDT *et al.* 2005; HENRY *et al.* 2002; LAKE 2005; WARD *et al.* 2001], identifying the multidimensional ecological connections and processes attending to a naturally functioning, dynamic, and self-sustaining river ecosystem [BARINAGA 1996; GILLIAN *et al.* 2005; PALMER *et al.* 2005; WOHL *et al.* 2005] and designing a natural channel in order to consider the missing ecosystem elements and to build the necessary parameters for natural hydrologic, geomorphic [BARINAGA 1996; FIRSWG 1998; GREGORY *et al.* 1991; KLEIN *et al.* 2007; PALMER *et al.* 2005].

THOMAS and POLLEN-BANKHEAD [2010] to investigate assumptions underpinning root-reinforcement models represented a research work using sensitivity analysis and a fiber-bundle model (FBM). Their results included the adopted value (1.2) for a term accounting for initial root orientation, shear distortion angle and soil friction angle is too large and is only attained for friction angles >35°. Also the pointed out to obtain the correct dynamics, equal load apportionment must be used in FBMs. Their finding support that loading curve shape affected by root architecture and a root bundle may help to the peak load. Furthermore they added stabilizing different features need plants with different root architectures.

TAL and PAOLA [2010] did some physical investigations and demonstrated that riparian vegetation can cause a braided channel to self-organize to, and maintain, a dynamic, single-thread channel. They showed that the sinuosity and migrate of the channel improved laterally by matching of deposition along the point bar with erosion along the outer bend while suppressing channel splitting and the creation of new channel width.

RAMSTEAD *et al*. [2012] in their research figured out the effects of wet meadow restoration projects in the southwestern United States on geomorphology, hydrology, soils and plant species composition. They also investigated the effects of wet meadow restoration projects on wildlife.

LONG and POPE [2014] in their investigation focused on high-elevation wet meadows which related to streams. Their monitoring showed to eliminate the losses of socio-ecological values in stream and meadow ecosystems related to erosion and lowering of water tables, the rate and extent of stream incision is essential. Also, meadow restoration offers productive ground for understanding interactions among a wide range of ecological, social, cultural, and economic values.

In a dynamic system which means drivers of vegetation patterns and diversity along stream riparian gradients, FRAAIJE *et al*. [2015] studied the scattering filtering against to environmental filtering. Their results showed that patterns of plant species distribution and biodiversity affected by both environmental filtering and scattering filtering. Species-rich dynamic habitats are known in stream riparian zones. Their studies showed that environmental filtering improved by steep hydrological gradients, and scattering filtering increased by spatiotemporal variation in the arrival of propagules. Their investigations indicated to characterize the plant community assemblies in early successional dynamic habitats, it should be a formidable patterns of both environmental and scattering filtering.

GURNELL *et al*. [2015] proposed a hypothetical pattern for vegetation–hydrogeomorphology interactions and feedbacks in river corridors, which makes on same hydrogeomorphologically centered patterns which included 1 – incorporating hydrogeomorphological constraints on river corridor vegetation from region to reach scales; 2 – defining five dynamic river corridor zones within; 3 – considering the way in which vegetation-related landforms within each zone may reflect processes of self-organization and the role of particular plant species; 4 – focusing upon a "critical zone" at the leading edge of plant – hydrogeomorphological process interactions and the area that is frequently inundated and subject to both sediment erosion and deposition processes; and 5 – considering the vegetated pioneer landforms.

Long and Davis have done a research about erosion and restoration of two headwater wetlands following a severe wildfire at Turkey Spring [LONG, DAVIS 2016]. Their study demonstrated the importance of headwater wetlands in this region to excessive incision events following high severity wildfires. Their studies also represented the purposed actions for incising channels could be warranted to conserve wetlands, soils and associated values that have established over thousands of years.

In three countries in north-western Europe, GARSSEN *et al*. [2017] improved the hydrology of five reaches during their investigations. They got better results in riparian plant species richness, biomass, plant-available nitrogen and phosphorus and seed deposition to increased flooding depth and prolonged flooding duration. Their wide studies showed fast changes in reach riparian plant communities by following increased winter flooding, leading to strong reductions in plant species diversity.

Deforestation amount and the average annual rates of riverbank erosion along the freely meandering the Kinabatangan River distribution in Sabah, Malaysia studied by HORTON *et al*. [2017]. Their investigation results pointed out the elimination of deforestation over half of the river's floodplain forest and up to 30% of its riparian cover, which increased rates of riverbank erosion by >23%. In order to build and preserve appropriate riverine habitat for whooping cranes, Farnsworth et al. presented the Flow-Sediment-Mechanical management strategy in the Platte River Recovery Implementation Program's Adaptive Management Plan [FARNSWORTH *et al*. 2018]. Studies of the influence of a range of hydrologic and physical metrics on total unvegetated channel width (TUCW) and maximum unobstructed channel width (MUOCW) indicated uncertainties by tracking the relevance among physical process drivers and species habitat metrics. Their results emphasized considerable positive relevance among peak flows and TUCW and MUOCW in the central Platte River.

The Red River is an excellent example of a degraded natural channel and ecosystem that has undergone holistic restoration to promote ecosystem recovery, and as mentioned there is a serious lack of information about the long-term efficacy of such projects. In this research is evaluated the river's hydrologic regime, which describes the natural cyclic variations it experiences due to changes in, for instance, the seasons. The river's hydraulic characteristics, sediment transport have been described.

MATERIALS AND METHODS

THE STUDY AREA

The data has been collected from Center for Ecohydraulics Research (CER) in north-central Idaho, USA [DHI 2000]. It includes data for flood and sedimentation simulations for three periods (pre-restoration, restoration and post-restoration) and 55 cross sections for the Red River in Idaho (Fig. 1), the length of the reach river about 4400 m, field measurements for the flow-rate at the upstream of the reach, field measurements for gauged water level at the downstream of the reach and the upstream and downstream stage and flow hydrographs at the cross sections. In this research two hydrodynamic models (MIKE 11-GeoRAS and HEC-RAS5) that are used by CER to estimate the water surface elevation and also the flow-rate. These models are used in the Red River numerical surveying to get various purposes including pre-restoration, restoration, and post-restoration.

Fig. 1. Map of the Red River basin; source: Google Earth

MIKE 11

The hydrodynamic numerical model, MIKE 11, which is developed maintained in the DHI Water and Environment used in this research. MIKE 11 is a software that prepared to simulate watersheds, rivers, irrigation networks, and open-channels. This software includes rainfall-runoff, advection-dispersion, sediment transport, morphological and water quality modules. The MIKE 11 object is to solve the fully dynamic, one-dimensional, free surface of flow equations considering the hydrodynamic modelling. Also, MIKE 11 software can use kinematic, diffusive or fully dynamic, the Saint-Venant equations which included the mass and momentum equations [USACE 2015].

The Saint-Venant equations are as below:

Continuity:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (1)$$

Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0 \quad (2)$$

Where: Q = flow-rate ($m^3 \cdot s^{-1}$), A = flow area (m^2), q = lateral inflow ($m^2 \cdot s^{-1}$), h = stage above datum (m), C = Chezy's resistance coefficient ($m^{1/2} \cdot s^{-1}$), R = hydraulic or resistance radius (m), α = momentum distribution coefficient.

The river mesh helps the simulator in 1) preparing the mesh of the reach and defined cross sections along the reach and main hydraulic structures to the river mesh; and 2) get the graphically conspectus of the current numerical model properties (Fig. 2).

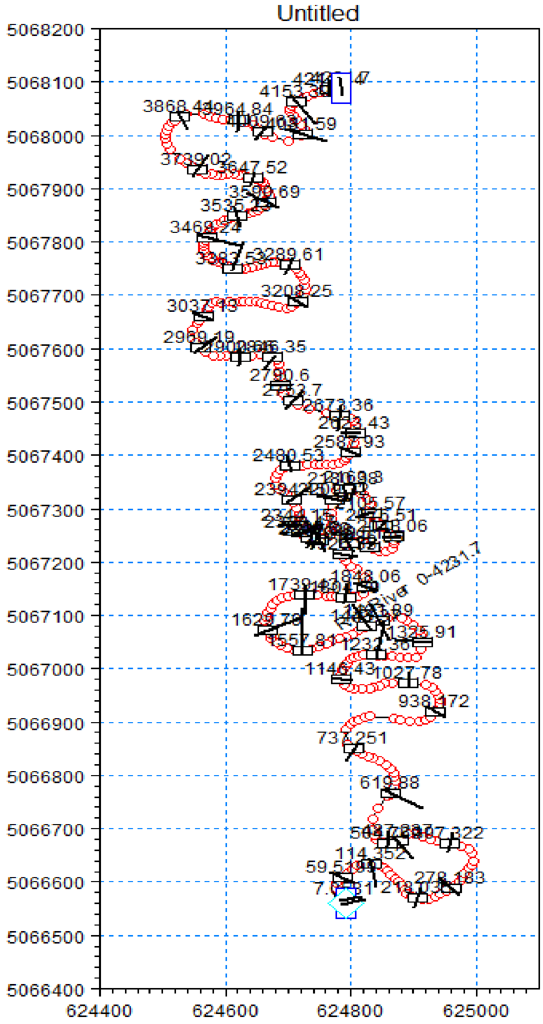

Fig. 2. River mesh and cross sections properties; source: own elaboration

THE HYDRODYNAMIC PARAMETER

To have the river mesh and network, the model need to consider the hydrodynamic parameter, which need to have flood-area and river bed resistance properties (Fig. 3). The distinguish among the river bed and flood-area along with reach net is performed at each cross section.

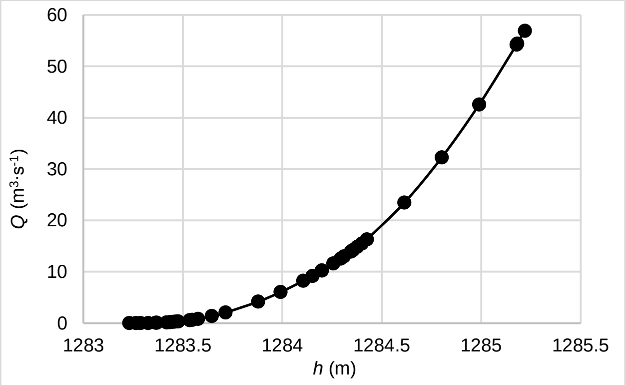

Fig. 3. Downstream boundary conditions; source: own study

HEC-RAS 5

In order to study a simulation of the Red River, the statistical year of (from 1994 to 2014) was selected for HEC--RAS5 simulation model. Also, the cross-sectional data were obtained from 1996 and 1997 survey of the site [CLAYTON *et al*. 1999]. The upstream of the model consisted of the flow boundary, and the downstream boundary was defined as a rating curve. The flow data for upstream boundary were obtained from USDA Forest Service (USFS) measurements [USFS 1992].

Data used for simulation by the hydrodynamic model were acquired by summing mean daily discharge (MDD) values from two USFA gages located approximately 4.83 km upstream of the RRWMA: South and Main Fork of the river [CLAYTON *et al*. 1999]. After setting up the Red River model in HEC-RAS5, to have the model results and measured values matched well and in order to calibrate the model, it is essential to have the water surface elevation and flow-rate data for a specific period of time.

MODELS CALIBRATION: TESTING AND EVALUATION

There is no generally admissible criterion by which a model can be considered plausible. This consideration closely depends on the model's application. Therefore, the hysteresis argument of model evaluation is comparatively general. After developing MIKE 11 for the Red River, the issues needed to be evaluated so as to affirm the model's validity. The virtual test of a model is its capability to predict a system response (gauged data). This test was made by comparison of the gauged data, which was evaluated from MIKE 11 with an observed stage hydrograph at the same river reach (Fig. 4).

There weren't the flow-rate and water surface elevation data for a long period of time on the RRWMA site, so it has been caused difficulties in calibrating the Red River model for extreme flow-rate. Calibration data for extremely high and low flow-rates have been obtained by cross sections studies in 1997.

The most significant variable to be balanced in the numerical models is the roughness coefficient of Manning. The water surface slope of the pools is practically horizontal with a local Manning roughness coefficient of n = 0.045. Calibration of other reaches on the site revealed a Manning's n of approximately 0.045. It was therefore decided to use n = 0.045 for further runs in the models. This value for the roughness coefficient of Manning n should be verified in the future by taking measurements of water level and discharge at higher discharges.

In order to compare the simulated stage to measured stage for different the roughness coefficient of Manning, root mean squared error (*RMSE*) has been used.

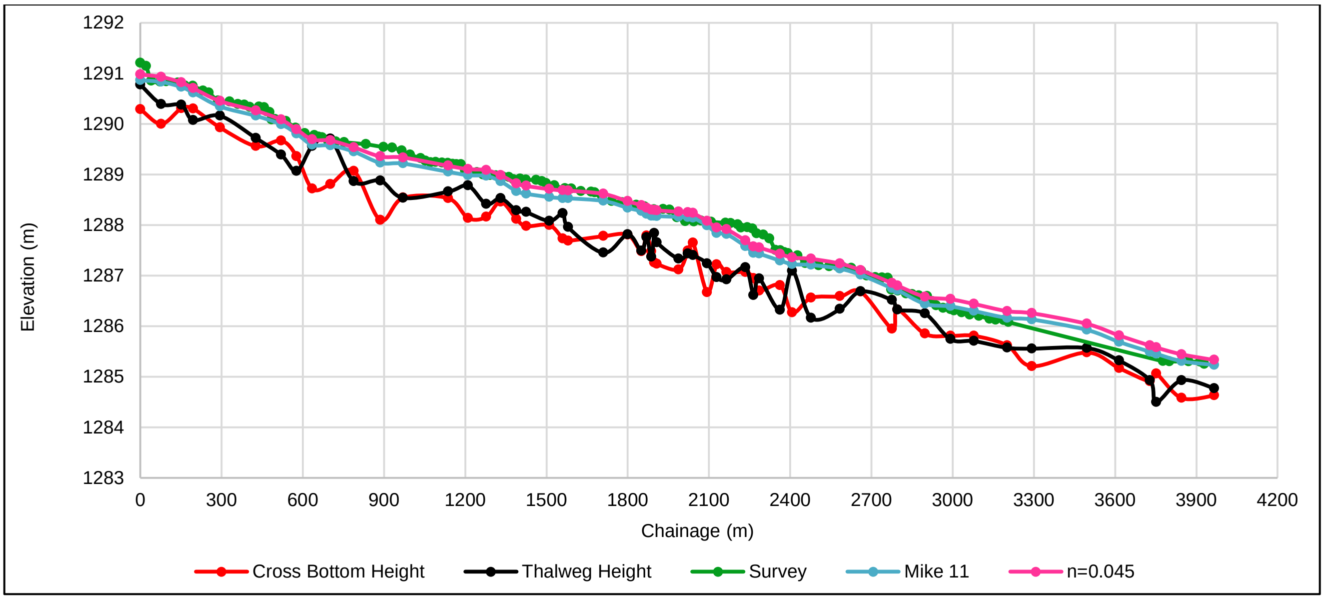

Fig. 4. Model comparison; source: own study

RMSE can be defined as,

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_{pi} - x_{mi})^2}{N}} \qquad (3)$$

Where: x_{mi} = gauged water surface elevation (m), x_{pi} = modelled water surface elevation (m), N = the all numbers of points for reference data.

For this study *RMSE* has been evaluated by 0.5883 m in MIKE 11 and 0.6094 m in HEC-RAS5.

RESULTS AND DISCUSSION

MAIN INFORMATION

Data for numerical modelling and analysis was obtained from the USDA Forest Service (USFS) [USFS 1992]. Data used for design purposes at the project location were acquired by summing mean daily discharge (*MDD*) values from two USFA gauges located approximately 4.83 km upstream of the RRWMA: South and Main Fork of the river [CLAYTON *et al*. 1999]. Both South and Main Fork are gauged only during the spring and summer months and have accurate flow records from 1986–2014. Utilizing the extended data for the period 1986–2014, the design team conducted a flood frequency analysis on the combined data (annual peak *MDD*, not instantaneous peak discharge) using a Log Pearson III distribution (Tab. 1). Because this analysis was conducted using *MDD* and not instantaneous peak, the discharge associated with any particular recurrent interval is an underestimate of the actual peak discharge that may be observed for that recurrent interval. The maximum and minimum observed *MDD* at the project location are 40.66 and 0.31 $m^3 \cdot s^{-1}$, respectively.

Table 1. Flood frequency analysis

Recurrence interval (year)	Probability of exceedance (%)	Mean daily discharge ($m^3 \cdot s^{-1}$)
1.23	96.0	8.44
1.35	92.3	10.59
1.48	82.8	14.02
1.94	69.7	15.91
2.47	54.1	20.73
6.20	24.8	30.84
12.30	14.3	35.34
28.90	8.4	36.73
54.70	7.6	39.39
110.50	4.9	41.46
218.70	1.2	44.88

Source: own study.

GEOMORPHOLOGY

Despite the anthropogenic changes to the project reached over time, the channel has maintained a meandering planform [CLAYTON *et al*. 1999]. However, the incision and reduction in sinuosity that have occurred, resulted in decreased sedimentation, depressed groundwater levels, and reduced hydroperiods through the meadow. These changes combined with altered vegetation and grazing management have led to degradation of aquatic and riparian habitat. Less arbitrary is the relationship between slope and discharge. LEOPOLD and WOLMAN [1957] quantitatively described the distinction between a braided and meandering channel as a function of bankfull discharge (Q) in $m^3 \cdot s^{-1}$ and channel slope (S) as follows: $S = 0.06Q^{-0.44}$. If the actual channel slope is less than the calculated slope, the channel is meandered. If greater, the channel is braided. At the project site, the purposed channel slope 0.0020 is less than a calculated critical of 0.0036 slope (based upon Q = 18.92 $m^3 \cdot s^{-1}$). Therefore, it is expected that the channel should adopt a meandering form through the RRWMA.

DESIGN ELEMENTS OF THE PREFERRED ALTERNATIVE

In past decades, it has been done increasing surveys which is a main factor in identification of ecological renovation of reviver reach systems based on existing physical process which forms the current reach habitats [BARINAGA 1996]. The dominant process includes the cycle of high and low flow-rates, which have the ability of moving the reach bed and scouring the banks, interface among the current reach and its flood-area and the natural geometric characteristics of the reach. It is essential to evaluate the main cross section of a current reach to assist the mentioned physical processes, in the case that the current reach performs dynamic balance. Two key elements for determining the cross section are the bankfull and dominant discharges.

Observations of bankfull discharge

Previous studies have visually estimated the bankfull discharge at these stream gauge sites [CLAYTON *et al*. 1999; WHITNING 1998] to be 9.34 and 7.25 $m^3 \cdot s^{-1}$ at South Fork Red River and Main Fork Red River gages, respectively. Summing these flows leads to an estimated bankfull discharge of 18.92 $m^3 \cdot s^{-1}$ at the RRWMA. In this research flood and bankfull analysis using MIKE 11-GIS and HEC-RAS5 are based on these data. Based on the flood frequency analysis, the flow of 18.92 $m^3 \cdot s^{-1}$ will be expected to occur approximately every 1.8 years (Tab. 1).

Numerical estimates of dominant discharge

Since the governing flow-rate is a current reach flow-rate which carries the high potential of sediment during the long period of time, so it is supposed this flow-rate applies the most amount of work in the current reach during must responsible for the current dynamic reach. High flow-rate will spread into the flood-area, because low flow-rates will be hold in the current reach The daily flow record for the upstream gages has been reconstructed [WHITING 1998], and, for the purposes of this analysis, the 33-year flow record from 1986–2014 at the RRWMA was obtained by summing the flows at the upstream gauging stations. In this research sediment analysis using MIKE 11-GIS is based on these data. Sediment transport predictors for bed load sediment were obtained from linear regression relation of observed values (Fig. 5).

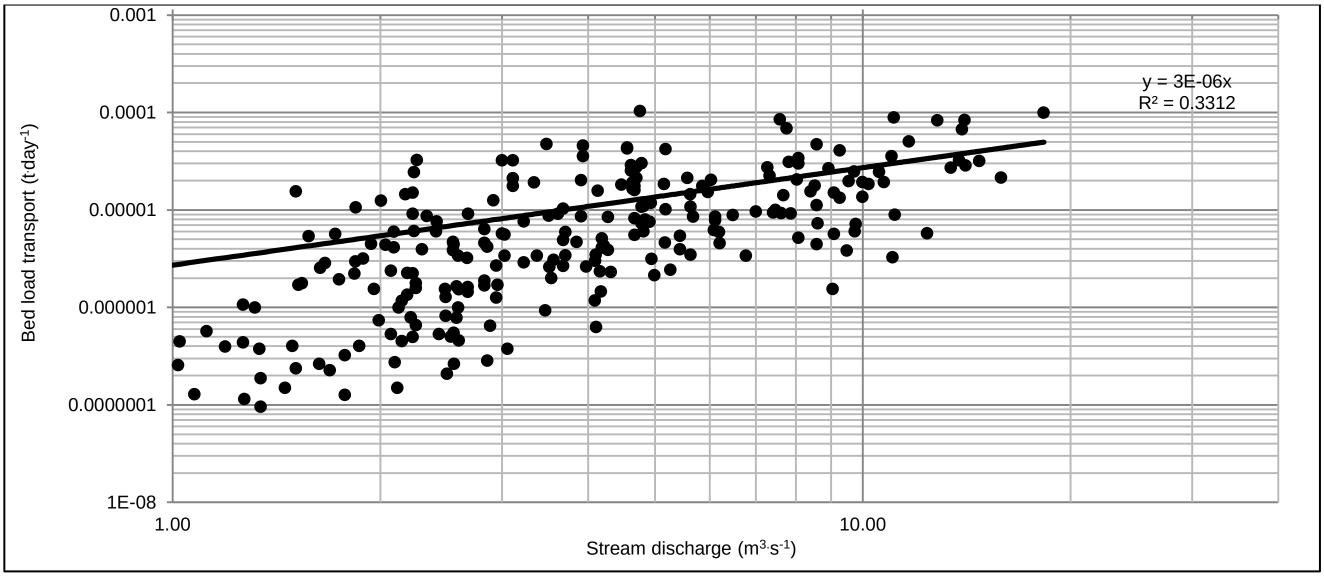

Fig. 5. Bed load calculations for phase I, II, III and IV; source: own study

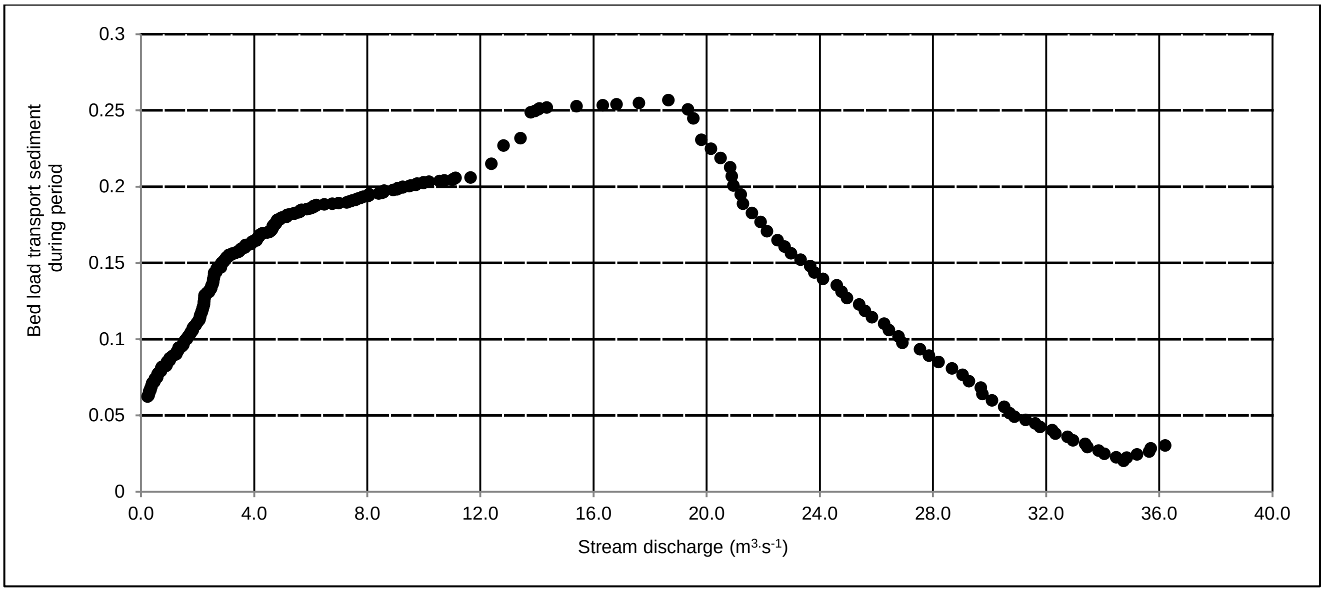

Fig. 6. Dominant discharge estimate for phase I, II, III and IV; source: own study

The built-up of the sediment particles carried by a current flow-rate and frequent registration of flow-rate spreading sediment particles at various flow-rate using MIKE 11-GIS. The top point of the stream flow-rate stands for the dominant flow-rate (Fig. 6). The dominate discharge corresponds to a flow approximately 18.97 $m^3 \cdot s^{-1}$.

There are several uncertainties in the estimate of bankfull discharge and dominating discharge, but the estimates are remarkably similar. Thus, the newly-constructed channel in phases I, II, III and IV will be designed to accommodate 18.92 $m^3 \cdot s^{-1}$ before spilling onto the floodplain.

HYDRAULIC GEOMETRY

Hydraulic geometry is the relation between discharge and cross-sectional area, width, depth, and velocity. These relationships are often expressed as simple power functions of the bankfull discharge. Predictions of the hydraulic geometry using the formulations of WHITING [1998], EMMET [1975], and WILLIAMS [1986] are shown in Table 2. For design purpose using MIKE 11-GIS and HEC-RAS5, the result of WHITING [1998] have been used since his data are based on several similar creeks in the region, including the two upstream gauging stations. The predicted bankfull width from these relationships (17.98 m) shows a close match with field observations (18.29 m) and hydrodynamic models results (18.90 m for MIKE 11-GIS and 19.51 m for HEC-RAS5). These matches give some confidence in the use of the hydraulic geometry relationship for the design newly-excavated channels.

These graphs include drawing of typical cross sections for existing, historic, and new channel reaches. These drawings are based upon field observation notes, field monitoring measurements, hydraulic geometry calculations, and modelling results.

Table 2. Hydraulic geometry dimensions

Data source/equation	Discharge Q ($m^3 \cdot s^{-1}$)	Width b (m)	Depth h (m)	Area S (m^2)
WHITING [1998]	18.92			
Figure 2	18.97			
Application of WHITING [1998] hydraulic equations, for Q = 18.92 $m^3 \cdot s^{-1}$		$b = 2.601Q^{0.48} = 10.67$	$h = 0.234Q^{0.35} = 0.65$	$S = b \cdot h = 6.99$
Application of EMMETT [1975] hydraulic equations, for Q = 18.92 $m^3 \cdot s^{-1}$		$b = 2.601Q^{0.54} = 12.73$	$h = 0.234Q^{0.34} = 0.64$	$S = b \cdot h = 8.09$
WILLIAMS [1986], for R = 3.74 m, R is hydraulic radius, equations are metric; results have been converted		$b = 0.71R^{0.89} = 2.30$	$h = 0.085R^{0.66} = 0.20$	$S = 0.067 \cdot R^{1.53} = 0.50$
Mean value estimated from field measurements and hydrodynamic models	18.92	65 (field), 68 (MIKE 11-GIS), 68.7 (HEC-RAS5)	2.53 (field), 2.65 (MIKE 11-GIS), 2.67 (HEC-RAS5)	173.9 (field), 182.8 (MIKE 11-GIS), 183.5 (HEC-RAS5)

Source: own study.

HYDROPERIOD

The hydroperiod is the depth, frequency, and duration of inundation at any point in the river system [CLAYTON *et al*. 1999]. Under existing conditions, the channel is inside by up to 0.77 m, so the meadow and floodplain are inundated less frequently than in a natural channel in dynamic equilibrium. One of the key design criteria adopted in phase I, II, III and IV was to ensure that the channel cross section is sized to convey the dominant discharge (i.e., the bankfull discharge and dominant discharge are identical). This design feature will ensure that the frequency, depth, and duration of inundation of both the flood-area and bars closely resembles natural conditions.

Another important concern regarding hydroperiod is related to downstream off-site flooding. A critical concern was that the research should not inundate the downstream to landowner's property more frequently than occurs under existing conditions. In the first iteration of the preferred research alternative, the historic meander in the northwest corner of the site was included in phase II and IV. However, this alternative presented concerns that there may be an increase in water surface elevations in the river and overland flow that would raise water elevations under some flood conditions. It is determined that this was unacceptable, and this meander was eliminated from the design of phase II and IV. The hydrodynamic modelling has shown, Figure 7, that the remainder of the phase I, II, III and IV design will not alter the flood characteristics downstream, due primarily to steep channel and floodplain slopes in the lower reaches of the meadow.

REGIONS OF SCOUR AND DEPOSITION

The hydrodynamic model, MIKE 11-GIS was used to assess the deposition and erosion trends throughout the research site. The reach of river comprising phase I, II, III and IV has the steepest slopes within the RRWMA (Fig. 8). Simulations of the existing conditions show reaches subject to deposition, reaches where the sediment carrying capacity of the channel closely matches the incoming sediment, and reaches that will be subject to erosion unless checked by an armouring layer. Phase II and III are located in reaches where the sediment carrying capacity exceeds the up-stream supply of sediment. Thus, under flood conditions when the armour layer is broken up and the local area is not protected by cohesive sediment layers, channel erosion may be expected.

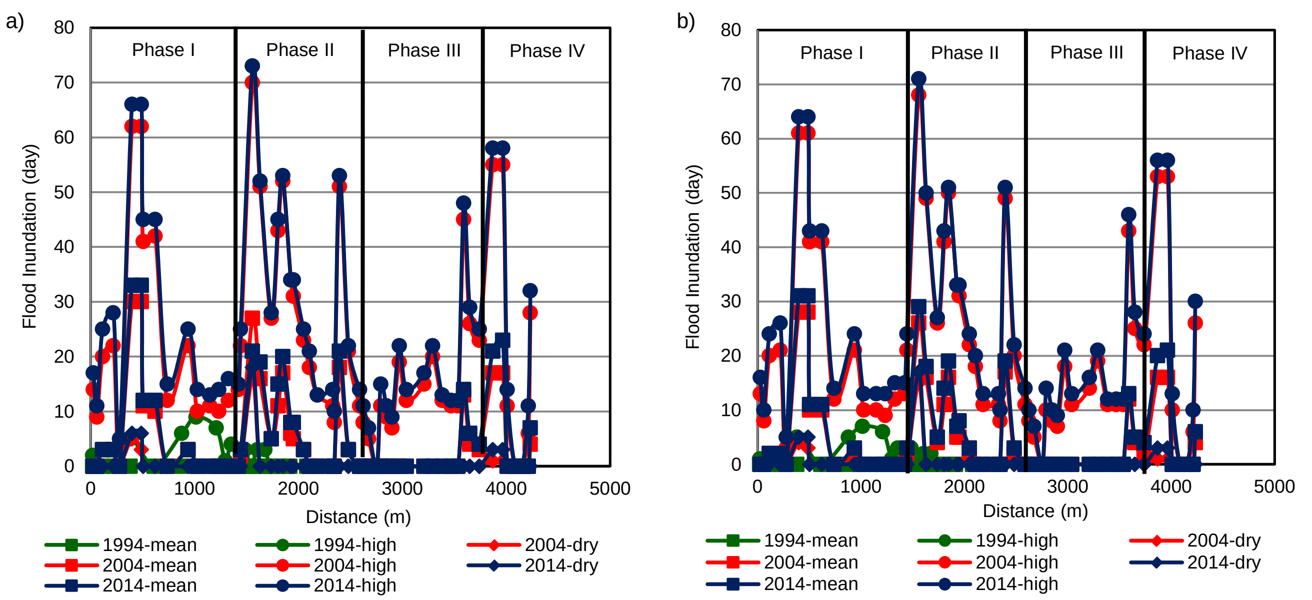

Fig. 7. Flood inundation for dry, mean and high flow period acc. to two models: a) MIKE 11-GIS, b) HEC-RAS5; source: own study

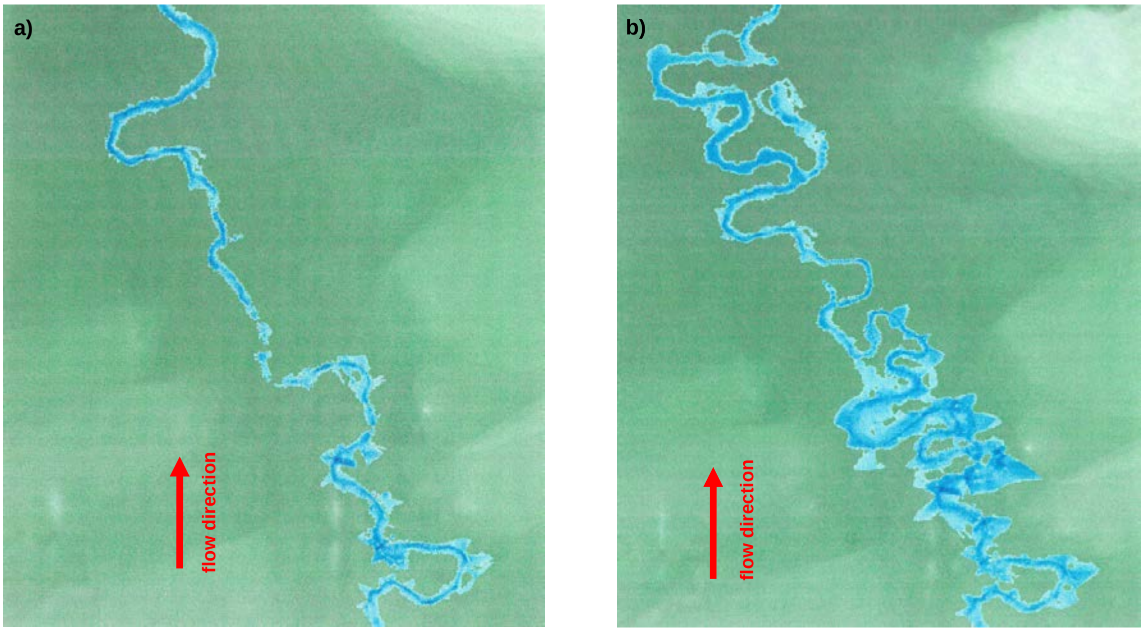

Fig. 8. Flood plain for high flow period: a) 1994, b) 2014; source: own study

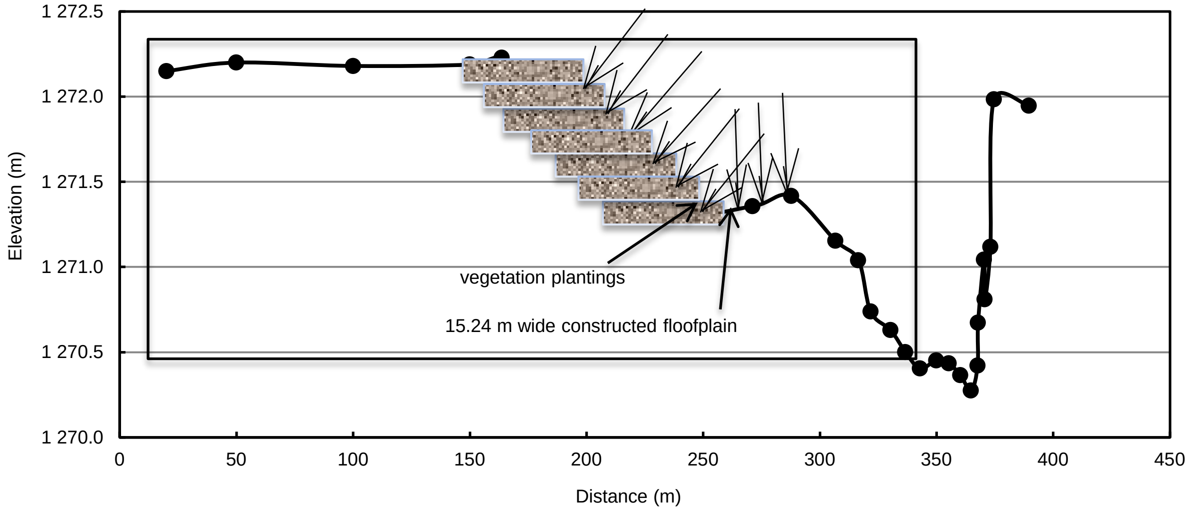

Fig. 9. Typical bank stabilization treatment; source: own study

In these reaches, the design criterion was to reduce the potential scour, by reducing bed shear stress, velocities, and sediment transport capacity of the channel. Additional protection against incision is provided at strategically located grade control structures.

BANK STABILIZATION AND RECONTOURING OF HIGH BANK BEND

Although the channel through high bank has remained in essentially the same planform position since at least 1986, the incision that has occurred has resulted in loss of habitat. Because the bank terrace is as high as 3.66 m above the thalweg and because the existing bank slope is nearly steep, the potential for riparian vegetation to naturally establish along this bank is very low. Based upon these conditions, it is better to take a special approach to improve habitat by creating an environment more suitable for riparian vegetation along this 198.12 m reach of the channel (Fig. 9).

The bank will be recontoured to create a floodplain bench on the outside of the meander, and the bank will be stabilized using a bio-stabilization treatment. The excavation will be above the level of the existing clay layer. Figure 9 depicts a typical bank stabilization treatment that consists of building a floodplain approximately 15.240 m wide on the outside of the meander at the same level as the floodplain on the inside of the meander. At the outside edge of the floodplain, the bank is resloped to a 3*H*:1*V* slope and reinforced with terraced wraps of coir erosion control fabric around dirt fill. The fabric is designed to degrade after several years which allows the vegetation time to establish and protect the bank naturally with its deep, binding root mass.

A previous study in this field shows [CLAYTON *et al.* 1999], and that outside meanders on rivers such as the Red

River are often vertical and that this bank will one day again be vertical or, more preferably, undercut with overhanging vegetation. However, it is worth to mention that without "jump starting" the process, it would be extremely difficult to establish vegetation on the vertical banks that are as high as 1.83 m above the baseflow water level. The vegetation will play an important role in stabilizing the bank in the future as well as providing overhead cover for habitat and stream temperature reduction.

CONCLUSIONS

Using two hydrodynamic models and a conceptual design has been developed for phase I, II, III and IV of the Red River renovation research. The design is based upon the historic 1986–2014 conditions as an initial rough template. These initial templates have been modified to account for current hydrology conditions and geomorphic characteristics of the site, and to link with upstream and downstream properties. Using the application of Whiting hydraulic equations shows a close match with field observations and hydrodynamic models results. Also, including of the historic meander in the northwest corner of the site in phase II and IV, caused concerns in which there may be an increase in water surface elevations in the river and overland flow that would raise water elevations under some flood conditions. So, the hydrodynamic modelling shows that the remainder of the phase I, II, III and IV design will not alter the downstream flood characteristics. Models results show, reaches subject to deposition, will be subject to erosion unless checked by an armouring layer. The geomorphology analysis using two hydrodynamic models show that after the completion of phase I, II, III and IV, the sinuosity of the channel will be very close to the 1986 condition. The design length and sinuosity are slightly greater than the 1986 condition because there appears to be some evidence of channel straightening prior to 1986.

The main goal of the design is to satisfy the project objectives related to renovating a natural habitat and channel form for fish species and wildlife. Key elements of the project design include:

– the design should be sustainable with minimum maintenance and artificial intervention in the future.
– there should be no significant adverse impacts to adjacent property owners (e.g., increased flooding).

Also, the proposed design results in a slightly greater sinuosity of the river compared to the 1986 conditions, and bank stabilization measures are restricted to one existing bend and areas where the river is to be diverted into or out of its historic alignment. The sediment carrying capacity and potential using MIKE 11-GIS, hydrodynamic model for scour has been reduced throughout the lower reaches of the project site, where the channel slope is at its steepest position. Channel erosion may be expected in phase II and III, where the armour layer is broken up and the local area is not protected by cohesive sediment layers. The enhanced channel alignment and proposed planting program will restore diversity to the instream habitat, riparian corridor, and meadow vegetation.

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