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Predicting Vulnerable Bank Erosion Zones in a Large River Meander

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ABSTRACT: A two dimensional hydrodynamic and morphological river flow model has been developed which solves the continuity and momentum equations. It predicts the rate of bank erosion, bed level changes and so on. The model is used to identify the vulnerable bank erosion zones in a river meander and the performance has been evaluated by comparing with bank line shifting obtained from the multi-date satellite imagery. This paper presents the temporal variation of the erosion rate with the flood flow. A study site has been selected in the River Brahmaputra in Assam, India. The model predicts fairly close erosion zones with the actual field situation.

INTRODUCTION

Change of river planform and high bank erosion in the alluvial rivers has been of great concern, causing serious problems to the habitats and others like loss of fertile land, valuables and life [Muramoto *et al.* (1992), Mosselman *et al.* (1995) and Tingsanchali *et al.* (1997)]. Better understanding of these mechanisms is of major concern for designing a cost-effective bank protection system. Prediction of the vulnerable erosion zone is very important in order to save live and other resources during the flood and regulating the river flow system.

The bank erosion rate depends on several factors like characteristics of the river flow, composition and characteristics of the bank and bed materials, sediment load near the river bank and variation of the bed level at the toe of the bank and so on. Besides this, at the river meander, formation of the secondary (helical) current also accelerates the erosion rate significantly. Being associated with so many controlling variables with uncertainty in measurement, hydrodynamic and morphodynamic process is involved in the bank erosion are difficult to be completely understood in a large river meander.

Several fundamental studies have been carried out to explain the river flow processes in a meander with bank erosion by different researchers in the past few decades. Among them Ikeda *et al.* (1981), Parker *et al.* (1982), Hasegawa (1980) and Odgaard (1986) are important. Ikeda *et al.* (1981) and Parker *et al.* (1982) proposed bend theory for the bend development and a method to predict temporal changes in the plan form of meandering channels. Blondeaux and Seminara (1985) modified the bend theory and derived a solution for the bed configuration of a bend in an equilibrium state.

They found the similar solutions as proposed previously by Hasegawa and Yamaoka (1980). A resonance relationship between a channel bend and its point bar has been established by Blondeaux and Seminara (1985). The same has been confirmed by Parker and Johannesson (1989). All these above mentioned study have been carried out assuming constant width and a simple bank erosion model, which considers the rate of bank erosion is proportional to the excess near bank flow velocity over the mean value. So, this theory can not be applicable for the rivers with various planform. But it can be applicable for fixed river banks.

On the other hand, recent studies consider mobile bed and movable river bank line. Numerical model proposed by Kovacs and Parker (1994) assumes steady flow and geometric conditions along the stream direction. Other numerical models have been proposed by Shimizu *et al.* (1989) and Duan *et al.* (1997) to analyze temporal changes in the channel forms due to bank erosion. But all these models have been applied only for the laboratory flume experiments. Darby and Thorne (1996) and Darby *et al.* (1996) developed a numerical model that can compute bank erosion considering rotational-slip and planar failure of the bank. This process is included for the morphological simulation of the natural river. However, the spatial variation in the bank erosion rate cannot be computed from this model. Very recent studies, researchers are considering the mobile bank line concept. For example,

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Nagata *et al.* (2000) and Darby *et al.* (2002) developed numerical models that calculate 2D bed deformations and bank erosion. These models consider curvilinear mobile grid system to incorporate the variation of bank erosion rate. Although Nagata *et al.* (2000) carried out the studies on the laboratory flume experiments with various steady flow conditions. On contrary, Darby *et al.* (2002) carried out the study by calibrating the model using laboratory experiments followed by evaluating the model's performance for natural river like Goodwin Creek, Mississippi.

None of the research study shows about the temporal variation of the bank erosion for the dynamic alluvial rivers. This paper therefore aims to study the temporal variation of the bank erosion for a large river meander with unsteady flow condition. A 2D numerical model with curvilinear grid system has been used for this study. Using the model vulnerable bank erosion zones has been examined and verified with *in-situ* monitoring condition.

STUDY SITE

For the study of the hydrodynamic and mophodynamic behavior of the natural river, a large river meander site has been chosen in the Brahmaputra river. The study site (26°50′08″ N and 93°46′08″ E) is located about 70 km upstream of the Tezpur town in Assam, India. Figure 1 shows the geographic location of the study site. River flows from east to west at this location. The study location is known locally as Jamuguri. It has been studied from the multi-date satellite imagery (LISS-III) that after 2004 extreme flood a large meander has been formed at the location. Till date the river bank is under severe threat of erosion. It also has been found from the satellite imagery study that a bank area of 2.4 km^2 has been eroded out during the flood period of 2004. The radius of the centerline of the meander is about 2460 m and meander widths at the upstream and downstream are 630 m and 1126 m, respectively.

Detailed hydraulic survey was conducted twice: during the moderate flow condition and during high flood condition (water level nearly 1 m higher than the bank full discharge). The survey includes the data collection like bathymetry using GPS aided Echo-sounder, velocity profile through ADCP, river bed and bank soil samples, depth averaged water samples for suspended sediment concentration. The measuring devices were mounted on an engine propelled vessel. The accuracy of the GPS instrument was +/–1.5 metres. The analysis shows that the average d_{50} value of the river bed material is 0.16 mm. It has been observed that the river bank material is of fine sand (d_{50} = 0.16 mm) type with interlaced clay soil (d_{50} = 0.08 mm). The particle size distribution of the samples is presented in the Figure 2. Detail analysis of the soil samples are presented in Table 1.The longitudinal bed slope is very gentle and about 1 in 5600 (Sarma, 2004).

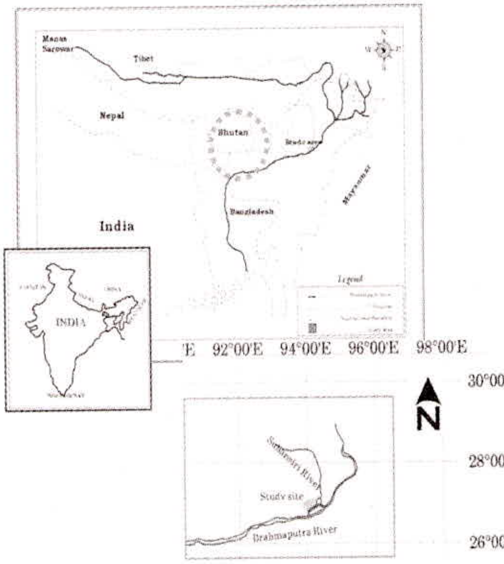

Fig. 1: Location of the study site

Table 1: Characteristics of Soil Sample Collected from Site

Sl. No.	*Parameter*	*Bed Soil Sample 1*	*Bed Soil Sample 2*	*Bed Soil Sample 3*	*River Bank Sample 1*	*River Bank Sample 2*
1.	Specific gravity	2.76	2.80	2.73	2.75	2.72
2.	Porosity	0.73	0.72	0.72	0.67	0.74
3.	d_{90}	0.25	0.25	0.25	0.28	0.22
4.	d_{50}	0.17	0.14	0.16	0.21	0.11

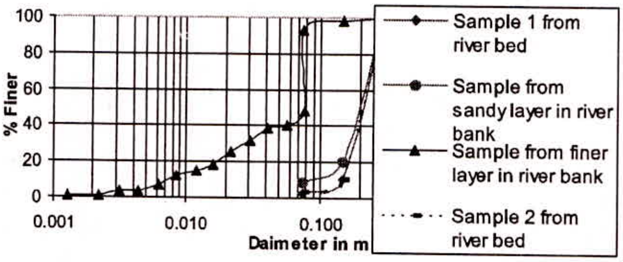

Fig. 2: Particle size distribution of some typical soil sample

METHODOLOGY

Govorning Equation

The hydrodynamic model solves depth integrated shallow water wave equations for continuity and conservation of momentum (Saint-Venant equation) in the two horizontal directions. The equations consider the curvilinear grid system to represent the bank line accurately. In the river meander or flow around an island a three-dimensional flow-field has been created by introducing the secondary (helical) flow. This secondary flow will cause a small deviation δ_s in the direction of flow velocity near the bed and similarly also in the bed shear stress. The deviation of the bed shear stress direction in a curved flow is very important in changing the bed topography especially in the river bend. The bed shear stress direction can be written after Rozowskii (1957), Engulend (1974) and Struiksma *et al.* (1985),

$$\tan\delta_s = -\beta.\frac{h}{R_s} \qquad \text{... (1)}$$

Where, R_s is radius of curvature of flow stream lines, h is the flow depth, δ_s is the angle between bed shear stress and depth averaged shear stress and β is defined as,

$$\beta = \alpha.\frac{2}{\kappa^2}\left(1-\frac{\sqrt{g}}{\kappa C}\right) \qquad \text{... (2)}$$

κ is the Van Karman constant, C is Chezy's number and α is the calibration constant. The approximate value of β is 10. The secondary flow will develop gradually along with the changes in the curvature of the streamlines. This change will be faster near the bottom than upper part. Thus this phenomenon can not be characterized by using only one length scale. The adaptation length is a function of water depth and the friction facter. In the morphological model, the following differential length scale λ_{sf} is applied after Struiksma *et al.* (1985) and Olesen (1987),

$$\lambda_{sf} = \frac{1.2hC}{\sqrt{g}} \qquad \text{... (3)}$$

The actual direction of the bed shear stress in case of continuously varlying curvature in steady flow conditions are found by solving the transport equation where S_s is the streamwise co-ordinate along the streamline and R_s is the radius of curvature of the streamlines,

$$\lambda_{sf}\frac{\partial(\tan\delta_s)}{\partial S_s} + \tan\delta_s = -\beta\frac{h}{R_s} \qquad \text{... (4)}$$

Sediment Transport

The sediment transport process includes two parts, bed load and suspended load. Asymptotic approximation technique suggested by Galappatti *et al.* (1985) is incorporated to describe the vertical concentration profile. The depth-averaged equation for the concentration of suspended sediment emerges by combining the vertical velocity (primary and secondary) and concentration profiles can be given as,

$$\gamma_t\frac{\partial\bar{C}}{\partial t} + \gamma_1\bar{u}\frac{\partial\bar{C}}{\partial S_s} + \gamma_2\bar{u}\frac{h}{R_s}\frac{\partial\bar{C}}{\partial n_s} = \gamma_0\frac{w_s}{h}\left(\bar{C}_e - \bar{C}\right) \qquad \text{... (5)}$$

Where, R_s is the radius of curvature of the streamlines, S_s is the streamwise coordinate along the streamline, n_s the transverse coordinate on right angles with the main streamline, $\bar{C}$ is the depth-averaged concentration of suspended sediment, $\bar{C}_e$ is the depth-averaged equilibrium concentration as obtained from a sediment transport formula, w_s is the fall velocity of the sediment grains under consideration, γ_i profile functions representing dispersion and lag time. The profile function γ depends on the friction factor and rouse parameter as well. Additional dispersion, if any, from the observation data may be included during solving the above equation. The equilibrium concentration is obtained from empirical sediment transport formulas for sand transport, e.g. van Rijn (1984a, 1984b) or Engelund-Fredsøe (1976). After mean concentration is found the suspended load is calculated by integrating the velocity and concentration profiles.

Empirical sediment transport formulas have been applied for bed load calculation. Assumption has been made that the bed load responses immediately with the change in the hydraulic conditions. Two important factors, (1) the deviation of the direction of the bed shear stress from the mean flow direction due to secondary flow at the meander and (2) effect of a sloping river bed, are considered. The following relationship after Olesen (1987) and Talmon (1992) is implemented in the model,

$$S_n = \left(\tan \delta_s - G.\theta^{-a}.\frac{\partial z^*}{\partial n} \right) S_{bl} \qquad \dots (6)$$

Where, G is the bed slope calibration parameter (approximate value is 0.6), a is bed slope calibration parameter (approximately 0.5), is bed shear direction change due to helical flow strength, S_{bl} is the bed load as calculated from an empirical sediment transport formula, S_n is the bed load transport in the transverse direction compared to main flow direction.

Based on the calculated suspended load and bed load, the net bed level change can be determined by solving the continuity equation,

$$(1-n)\frac{\partial z}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = \Delta S_e \qquad \dots (7)$$

Where, S_x is the total sediment transport in x-direction and S_y is the total sediment transport in y-direction, n is the sediment porosity, z is bed level, t is time, x and y are Cartesian coordinate system, ΔS_e is the lateral sediment supply due to bank erosion. The rate of erosion can be estimated from the empirical equation,

$$E_b = -\alpha_b \frac{\partial z}{\partial t} + \beta_b \frac{S}{h} + \gamma_b \qquad \dots (8)$$

Where, E_b is the rate of bank erosion in m/s, z is the local bed level near the bank, S is near bank sediment transport, h is the local water depth near the bank, α_b and β_b are the calibration co-efficients to be specified in the model. Theoretically, α_b is the transverse slope of the bank but needs to be calibrated for the model. β_b is the fraction of sediment capacity that is used for transporting the material eroded from the bank. Instead of the detailed calibration data, a constant bank erosion rate can be used as γ_b (m/s) depending on the actual erosion rate.

BANK MIGRATION MAPPING USING SATELLITE IMAGERY

Out of several methods of bank line survey like erosion pin data, PEEP (Photo Electric Erosion Pin) system, land survey after certain interval of time, aerial photography and satellite imagery study are the most convenient way of determining the bank erosion rate and vulnerable erosion zones in a river reach. In the present study, multi-date satellite imagery has been analysed and the model has been evaluated for the vulnerable erosion zone. The satellite imagery of the study site in December 2005 is shown in Figure 3. The bank lines from 2002 to 2007 of the river at the location is digitised and depicted in Figure 4. It can be seen that after 2004 flood period sudden change had occurred. The migration rate is about 1.07 km in one year. For the present study, bank line migrations after 2004 till 2006 have been considered. For each flood year, the area subscribed by the two outer bank lines is divided into 20 equal spaced segments along the bank. The area of the each segment divided by the segment length along the bank will give the average bank erosion rate in that segment for that flood year. Then the segments are ranked according to the bank erosion rate, thus vulnerability ranks have been estimated. Following this procedure, vulnerable bank erosion zones along the outer bank of the meander were mapped in the satellite imagery.

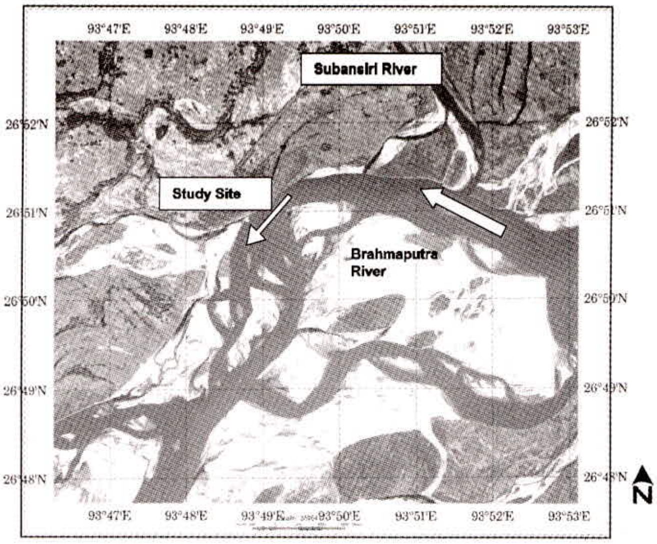

Fig. 3: Satellite imagery of the study Site

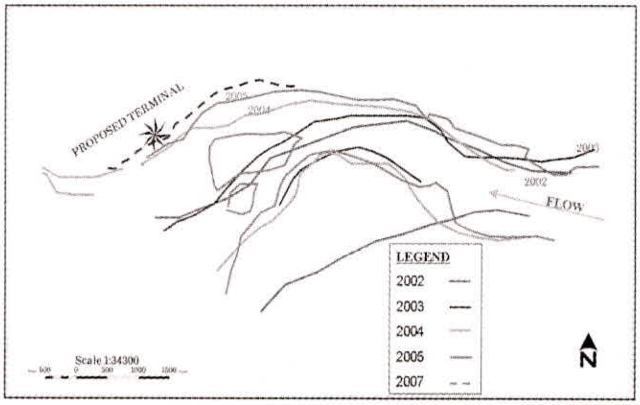

Fig. 4: Bank lines of the river meander at the study location of proposed terminal

MATHEMATICAL MODEL SETUP

A numerical river model has been setup for the study site with sandy river bed. Figure 5 shows the mathematical model domain. The curvilinear model grid consists of 151 nodes along longitudinal direction and 78 nodes along the transverse direction. The length of the reach considered for the model is about 4 km. The grid near the meander was made finer than the other part. The sizes of the grid vary from 80 to 20 m in longitudinal direction and 40 to 20 m in transverse direction. The bathymetry of the river has been set up with the survey data obtained in the moderate flow situation (water level is about 2.5 m below the river bank). At the upstream (east) discharge hydrograph and for the downstream (west) stage hydrograph are assigned as the boundary conditions. For the simulation, a seasonal flood hydrograph with similar water level variation as observed in the gauging station near the study location has been considered (Figure 6). For obtaining the upstream boundary conditions, 1D river flow model has set up and with hit and trial method, a discharge time series data has been obtained. The initial water level data also obtained from this 1D model and applied to the 2D model. The grain roughness of the river bed has been determined with the Mayer-Peter and Muller (1948) formula,

$$n = \frac{(d_{90})^{\frac{1}{6}}}{26} \qquad \dots (9)$$

Where, n is the Manning's roughness and d_{90} is the size of the bed material with 90% finer. A constant inflow sediment concentration of 400 mg/l is applied at the inlet boundary. The time step considered for the hydrodynamic simulation is 30 sec, while the sediment time step was 20 times (600 secs) of the hydrodynamic time step.

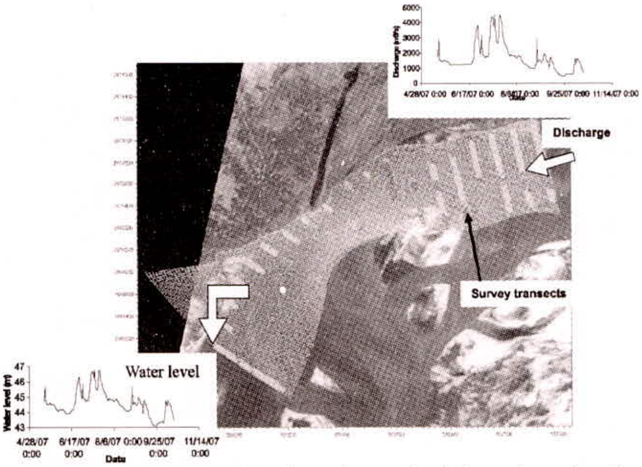

Fig. 5: Two-dimensional mathematical flow domain of study area with boundary conditions

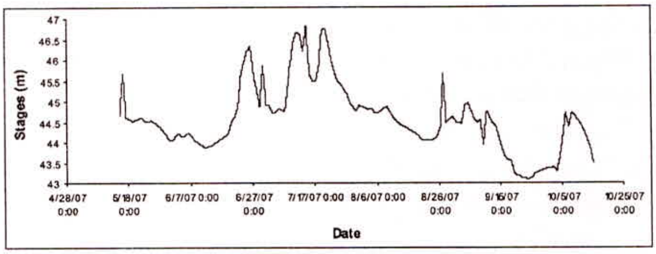

Fig. 6: Typical stage hydrograph data of the study site

RESULTS AND DISCUSSION

Calibration and Validation of the Model

The simulation results at the similar condition of high flood time (water level 1m above the river bank) have been compared for the calibration of the model. Table 2 shows the observed and simulated water level and flow velocity at the different locations. Due to error and uncertainty involved in collecting field data, it is not possible to compare the result point to point basis. But the simulated and observed data are within the range.

Table 2: Measured *versus* Simulated Flow Parameters

Parameter	*Simulated*	*Measured*
Velocity	0.3–2.6 m/s	0.44–2.337 m/s
Water depth		
at U/S of terminal	4–13 m	2.5–16.9 m
at Centre of terminal	4–7 m	3.0–7.1 m
at D/S of terminal	1.5–7.5 m	1.8–7.6 m

The calibrated model used to determine the outer bank erosion. The results obtained from the satellite imagery analysis show the longitudinal shifting of the vulnerable erosion zones towards the downstream. The simulated results also show the same trend and vulnerable erosion zones moves further downstream. The simulated erosion zone based on their vulnerability is also ranked. The river bank line survey was again conducted after the flood period. The simulated vulnerable bank erosion zones and the post flood bank survey data has been plotted in Figures 7 and 8. It shows the model's prediction matches fairly close to the field observation.

At the vulnerable bank site, the time series erosion rate can be plotted. Almost all cases number of erosion cycle is more during the receding phase than the rising phase. This shows that the bank is more prone to erosion during the receding phase of the hydrograph. It can be concluded that the bank erosion with non-cohesive materials usually follows a cyclic process [Nagata *et al.* (2000)]:

1. Bed scouring at the bank side
2. Bank collapse due to instability of the scoured bank
3. Deposition of the collapsed bank materials at the front of the bank
4. Transportation of the deposited materials.

These stages repeated in a cycle. So, at the receding phase, there will be extra pull of water away from the river bank. This will cause more collapsed material to move from the bank, and as the material will transported away, then again step one will start and it will go on.

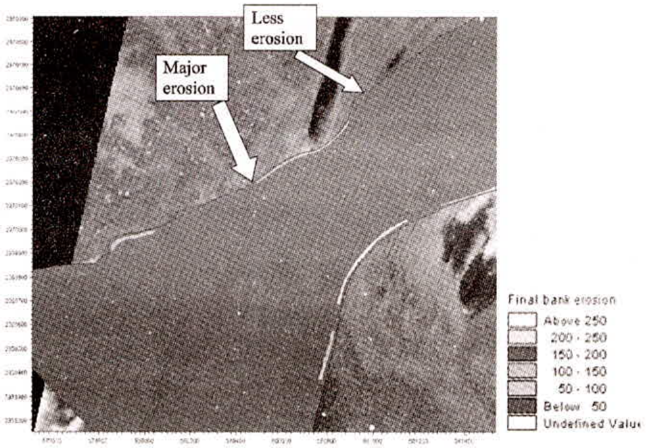

Fig. 7: Simulated vulnerable erosion zones

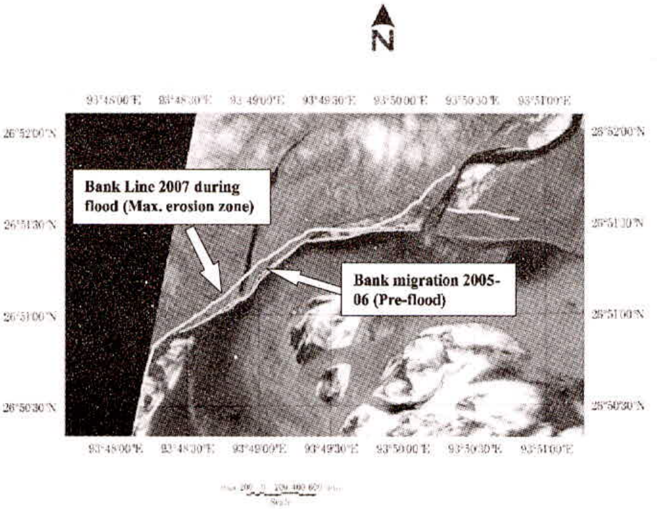

Fig. 8: Bank line migration from 2005 to 2007 (during flood)

CONCLUSIONS

Two dimensional mathematical river model for the simulation of the river bank erosion has been described for a large meander in a braided river. River with only sandy bed material as in case of River Brahmaputra has been simulated in the present study. Short term simulation for a flood year predicts fairly close vulnerable erosion zones. Frequency of maximum erosion during the flood period also has been predicted and confirms the hypothesis given by Nagata *et al.* (2000).

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REFERENCES

Blondeaux, P. and Seminara, G. (1985). "A unified bar-bend theoryof river meander". *J. Fluid Mech.*, Cambridge, U.K., 157, 449–470.

Darby, S.E., Alabyan, Wiel, A.M. and M.J.V. (2002). "Numerical simulation of bank erosion and channel migration in meandering rivers". *Water Resour. Res.*, A.G.U., 38(9), 2/1–21

Darby, S.E. and Thorne, C.R. (1996). "Numerical simulation of widening and bed deformation of straight sand-bed rivers. I: Model development". *J. Hydr. Engg.*, ASCE, 122(4), 184–193.

Darby, S.E., Thorne, C.R. and Simon, A. (1996). "Numerical simulation of widening and bed deformation of sand-bed rivers. II: Model evaluation". *J. Hydr. Engg.*, ASCE, 122(4), 194–202.

Duan, G., Jia, Y. and Wang, S. (1997). "Meander process simulation with a two dimensional numerical model". *Proc., Conf. on Mgmt. of Landscapes Distributed by Channel Incision*, University of Mississippi, Miss., 389–394.

Enggrob, H.G. and Tjerry, S. (1999). "Simulation of morphological characteristics of a braided river". *I.A.H.R. Symposium on River, Coastal and Estuarine Morphodynamics*, Genova, Italy, 585–594.

Engulund, F. (1974). "Flow and bed topography in channel bends". *J. Hydr. Div.*, ASCE, 100(HY11), 1631–1648.

Engelund, F. and Fredsøe, J. (1976). "A sediment transport model for straight alluvial channels". *Nordic Hydrology*, 7(5), 293–306.

Galappatti, R. and Vreugdenhil, C.B. (1985). "A depth-integrated model for suspended transport". *J. Hydr. Res.*, I.A.H.R.., 23(4), 359–377.

Hasegawa, K. and Yamaoka, I. (1980), "The effect of plane and bed forms of channels upon the meander development". *Proc. JSCE*, Tokyo, 296, 143–152.

Ikeda, S., Parker, G. and Sawai, K. (1981). "Bend theory of river meanders. Part 1. Linear development". *J. Fluid Mech.*, Cambridge, U.K., 112, 363–377.

Kovacs, A. and Parker, G. (1994). "A new vectorial bedload formulation and its application to the time evolution of straight river channels". *J. Fluid Mech.*, Cambridge, U. K., 267, 153–183.

Meyer-Peter, E. and Muller, R. (1948). "Formulas for bed load transport". *Proc. Second Meeting Int. Assoc. Hydraul. Res.*, 39–64.

Mike 21C user guide and Scientific documentation (2007). DHI Water & Environment, Danish Hydraulic Institute, Denmark.

Mosselman, E., Huisink, M., Koomen, E. and Seijmonsbergen, A.C. (1995). "Morphological changes in a large braided sand-bed river". *River Geomorphology*, E. J. Hickin, ed., Wiely, Chiehester, U.K., 235–247.

Muramoto, Y. and Fujita, Y. (1992). "Recent channel processes of the major rivers in Bangladesh". *Annuals of the Disaster Prevention Res. Inst.*, Kyoto, Japan, 35 B-2, 89–114 (in Japanese).

Nagata, N., Hosoda, T. and Muramoto, Y. (2000). "Numerical analysis of river channel processes with bank erosion". *J. Hydr. Engrg.*, ASCE, 126(4), 243–252.

Odgaard, A.J. (1986). "Meander flow model I: Development". *J. Hydr. Engrg.*, ASCE, 112(12), 1117–1136.

Olesen, K.W. (1987). "Bed topography in shallow river bends". *Commun. Hydraul. Geotech. Engrg.,* Delft University of Tech., 87(1).

Parker, G. and Johannesson, H. (1989). "Observation on several recent theories of resonance and over deepening in meandering channels". *River Meandering, Water Resources Monograph 12*, American Geophysical Union, Washington, D.C., 379–415.

Parker, G., Sawai, K. and Ikeda, S. (1982). "Bend theory of river meanders. Part 2. Nonlinear deformation of finite-amplitude bends". *J. Fluid Mech.*, Cambridge, U.K., 115, 303–314.

Rozovskii, I.L. (1957). "Flow of water in bends of open channels". *Israel Progr. for Scientific Transl.*, Jerusalem, 233.

Sarma, J.N. (2004). "An overview of Brahmaputra river system". *The Brahmaputra Basin Water Resources*, V.P. Singh, N. Sharma and C.S.P. Ojha, ed., Kluwer Academic Publishers, Netherlands, 72–87.

Shimizu, Y. and Itakura, T. (1989). "Calculation of bed variation in alluvial channels". *J. Hydr. Engrg.*, ASCE, 115(3), 367–384.

Struiksma, N., Olesen, K.W., Flokstra, C. and de Vriend, H.J. (1985). "Bed deformation in curved alluvial channels". *J. Hydr. Res.*, I.A.H.R., 23(1), 57–78.

Talmon, A.M. (1992). "Bed topography of river bends with suspended sediment transport". *Ph.D Thesis*, Delft Univ. of Tech, Netherland.

Tingsanchali, T. and Chinnarasri, C. (1997). "Design of Mekong river bank protection". *Proc. Conf. on Mgmt. of Landscapes Distributed by Channel Incision,* University of Mississippi, Miss., 345–348.

van Rijn, L.C. (1984a). "Sediment transport: Bed load transport". *J. Hydr. Engrg.*, ASCE, 110(10), 1431–1456.

van Rijn, L.C. (1984b). "Sediment transport II: Suspended load transport". *J. Hydr. Engrg.*, ASCE, 110(11), 1613–1641.