MATHEMATICAL MODEL OF RIVER BED VARIATION PREDICTION AT ALLUVIAL RIVERS UNDER GRADUALLY VARIED FLOW CONDITION

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Abstract: *In this research a mathematical model was developed to study bed elevation variation of alluvial rivers. It utilizes two principal modules of hydraulics and sediment transport for simulation purposes. SDAR (Scour and Deposition model of Alluvial Rivers) is a new model with both one and semi-two dimensional(S-2D) computational schemes. It is regarded S-2D in a sence that lateral variation of velocity, hydraulic stresses, and geometrical specifications are achieved by dividing the main channel into serveral stream tubes. In order to overcome the existing limitations, a new idea of reachwise stream tube concept was also introduced. This allows to include branch connections and withdrawal points across the tube barriers. Sediment routing and bed variation calculations are accomplished along each river strip desigated by virtual interfaces of the tubes. Presently, quasi-steady gradually varied flows are processed by the model. It should also be emphasised that this version is only valid for alluvial rivers composed of noncohesive bed material. To assess the model, several river cases and laboratory data base were used. During calibration runs, the ability of model in longitudinal and transversal bed profile simulation and armor layer development predection were especially detected. Results of simulation are also compared with the results of well-known models, e.g. HEC-6, GSTARS-2, and FLUVIAL-12. It was found that the ability of model in simulating bed variation is noticeably increased when S-2D concept is introduced. Indeed, the comparative validity tests confirm SDAR's promising functioning in facing with complex real engineering cases. Obviously more article discussions would bring oppurtunities to demonestrate it's technical cappabilities profoundaly.*

Keywords: *Mathematical model, Stream tube, Sediment routing, Simulation.*

1. INTRODUCTION

Because of probabalistic nature of hydrological events, river processes are inherntly time dependent phenomena. Contrary to solid bed catagory, in moveable bed domain a change in flow conditions , such as depth or velocity, influences fluvial interactions. This causes a systematic changes of channel specifications and morphological prospections. Accordingly rivers are faced with continuous adjustment of bed profile, channel deformation, sediment regradation and transport capacity adaptation, to be mentioned among others. Quantitatively, however, the propagation of bed variations and morphological features, is small enough to consider flow characteristics uninfluenced by bed moveability, within a sufficiently small time increment, as pointed out by De Vries and other pioneers in this field[1]. This postulation allows to solve momentum and continuity equations for water and sediment independently, a basis for developing numerical schemes in loose boundary environment.

Following this concept, two principal algorithms of SDAR model, e.g., hydraulics and sediment transport, was formulated to appraise river response to flow stresses.

These algorithms work independently, during a computational time step, but their results are fed back to each other. The portion of model belonging to hydraulic scheme provides full information necessary to simulate bed variation as well as inspecting basic flow properties. As a matter of fact, the model simultaneously is able to analyse both one–dimensional (1-D) and semi–two dimentsional (S2-D) features of flow events. In the course of calculation backwater computation is first accomplished, which implies a 1-D process. At the second stage, the main

channel is divided into several stream tubes, each carrying equal discharge, as introduced by Yang et al. [2]. This provides opportunity to manipulate the variation of transversal velocity and hydraulic stresses in the model, simulating S2-D flow condition herewith. Details are described by Yang and Co-workers [2].

In SDAR model the concept of stream tube is further enhanced by introducing reachwise stream tube criteria. Such specialty makes it possible to connect branches, and introduce lateral water and sediment inflows or outflows. Equal distribution of water and sediment inflow or extraction from stream tubes is assumed in this case.

Sediment routing is fulfilled along each conceptual tube using a sophistcated sediment transport algorithm. It should be mentioned that for hydraulic routing under solid bed catagory, up to ten stream tubes may be introduced, but for river bed prediction it is restricted to only three strips at present. Obviously for one stream tube case, the model reduces to 1-D stage. S2-D model has the advantage of simulating not only longitudinal bed variations, but also acquiring the influence of transversial flow characteristics on sediment transport intensity.

Erosion and sedimentation handling requires several steps among them determination of ***active*** and ***inactive layer***, as proposed by Bennet and Nordin [3], ***residual transport capacity*** according to Boreh et al. [4], formation and destruction of ***armor layer*** and consideration of ***nonequilibrium transport*** play important role in modeling senario.

Model validity tests or calibration runs are also vital notions in modeling strategy. In SDAR model several validity tests were conducted using field and experimental data. The scope of studies cover wide ranges of grain sizes, channel geometry, flow duration, reach lengths and plan forms. Results of validity tests and comparisons with existing models such as HEC-6, GSTARS-2, and FLUVIAL-12 are illustrated to some extent, [8], [2], [11].

2. GOVERNING EQUATIONS

Movement of sediment particles is directly related to flow intensity, channel geometry and pertinent hydraulic properties. In SDAR model channel specifications is established by introducing three groups of equations:

Momentum and continuity equations for water.

$$(1-\propto Q^2B/gA^3)\frac{dh}{dx}+(S_f-S_o)=0 \qquad (1)$$

$$Q=f(x) \qquad (2)$$

continuity equation and conveyance factors for stream tubes.

$$Q_{st}=(Q-Q_f)/JST \qquad (3)$$

$$K_{st}=K_{mc}/JST \qquad (4)$$

$$K_{st}=\frac{1}{n}A_{st}(A_{st}/P_{st})^{2/3} \qquad (5)$$

$$K_{mc}=\frac{1}{n}A(A/P)^{2/3} \qquad (6)$$

continuity and transport equations for sediment.

$$\frac{\partial Q_s}{\partial x}+(1-\theta)B\frac{\partial Z_b}{\partial t}=q_{sl} \qquad (7)$$

$$Q_s=f(V,D,G_s,Y,S_f,S_o,\gamma) \qquad (8)$$

In which Q= the flow rate; B= the channel width; g= the acceleration of gravity; A= the flow cross sectional area ; $\propto$ = velocity correction factor; h= water depth; x= distance along the channel; S_f= the friction slope; S_o= the channel slope; Q_{st} = discharge in the stream tube; Q_f = discharge on the flood plain; JST = number of stream tubes ; K_{st} = the conveyance factor for the stream tube; K_{mc} = total conveyance factor of the channel ; n=Manning's roughness coefficient; A= The flow area of main channel; P= the wetted perimeter of main channel; Q_s = the sediment discharge; θ = the bed porosity ; Z_b = the local bed elevation; t = time; V = the mean flow velocity; D= bed material size; q_{sl} = the lateral sediment discharge per unit channel length; A_{st} = the stream tube cross sectional area ; P_{st} = the stream tube peremeter, G_s= specific gravity of grains, Y= the flow depth, γ = specific weight of water.

Equation (1) is generally applicable for both sub and super critical steady flow depending whether the magnitude of Q^2 B/gA^3 , implying Froud number , is less than or greater than one. In SDAR model this equation is first solved using standard step method for backwater computations as introduced by Chow [5]. Flow rate is constant during computational time step but it may vary spatially along the river reach.

Based on information from backwater computations the second group of equations is

processed to quantify S-2D characteristics of channel flow. For this purpose flow is initially distributed equally among stream tubes according to Eq. 3. Afterwards, stream tube geometry, transversial velocity distribution, and other pertinent hydraulic elements of S-2D flow are determined in a manner that the value of K_{st} obtained from equations 4 and 5 equals together within the prescribed error range. At this stage the models function in processing flow hydraulics is completed.

Prediction and simulation of river bed evolution is attributed to the third group of equations. These equations play principal role in sediment routing and updating river bed variations. For this purpose the differential equation of sediment continuity (Eq. 7) is discretized and solved using sediment transport capacity simulator (Eq. 8) and information supplied by hydraulic computations. The details of overal model behaviour is schematically illustrated in Fig.1. According to the figure branch connections and withdrawal points are manipulcted by SDAR model as an integrated part of water and sediment routing system. Such notions are better described in the following section.

Remarks: In Fig1. Q(I & O) = inflow and outflow of water discharge; QS(I) = inflowing sediment rate; QS(O) = outflowing sediment rate; QSI (S.T.) = inflowing sediment into stream tube; Q(S.T.) = water discharge in stream tube; QMC= water discharge entering the main channel; QB1= inflowing water discharge at branch 1; QSB1= inflowing sediment rate at branch 1; QSB2 = sediment extracted at point 2; QSMC = sediment entering main channel; JST = number of stream tubes; QI = outgoing discharge rate; QSI = outgoing sediment rate.

3. STRUCTURE OF NUMERICAL COMPUTATIONS IN "SDAR" MODEL

In order to evaluate impacts of flow on river bed variation and to predict ultimate longitudinal profile configuration, hydraulic and sediment transport modules in SDAR model should be activated. Flow parameters such as energy grade slope, depth and width, arrangement of stream tubes, location of flood plains and their specifications along with other relevant factors are deduced using hydraulic module. Upon completion of hydraulic computations, sediment transport module is activated and bed profile variation is appraised. The flowchart of model's structural pattern is illustrated in Fig 2. The model language is Quick Basic and it works with Metric and English unit systems. Several input files support the main program.

According to Fig. 2 in order to activate the model it is necessary to introduce initial and boundary conditions. For downstream boundary stage discharge curve is sufficient and for the upstream inflowing sediment rate and its gradation must be known. Internal boundaries and control points such as weirs, specified water level or diversion units should also be recognized.

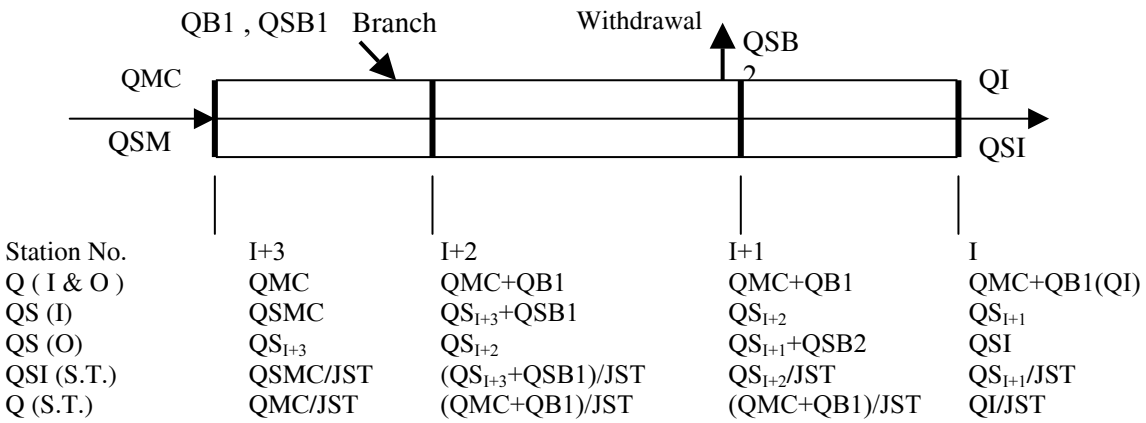

Fig. 1. Schematic plan view of river course configuration in SDAR model and illustration of routing mechanism at various reaches and stream tubes.

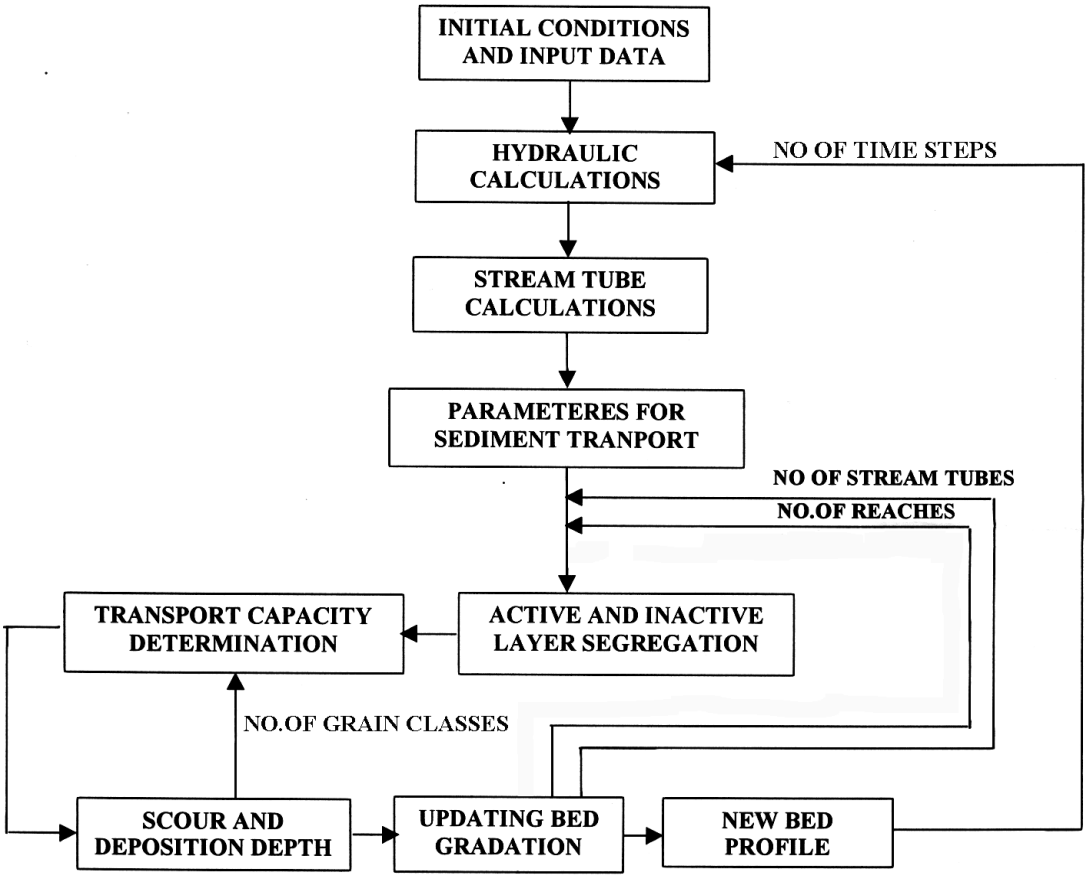

Fig. 2. Flowchart of Computational Steps in SDAR Model

Geometric information of cross sections comprise the basic input data file through which river plan form, left and right side extensions of flood plain and location of main channel can be detected by the model. Besides, gradation of bed material, thickness of bed sediment reservoir, reach lengths, Manning's roughness values, and span of movable bed are some part of required input data.

Flood hydrographs are introduced to SDAR model in discretized form so that the condition of quasi steady flow during each time step could be preseved. Water and sediment discharge from branches or sediment extraction locations need to be loaded down from the input files.

Numerical structure for hydraulic calculations in the model is derived using equations 1 and 2. These equations are converted to the following computational form, with some manipulations:

$$H_s(I+1) = H_s(I) + \Delta x(I+1) * (\overline{SF}(I+1) - S_o(I+1)) \quad (9)$$

In which H_s (I+1) and H_s (I) = Specific energy at stations I+1 and I respectively; Δx (I+1) = the reach length; $\overline{SF}$ (I+1) = the average friction slope; S_0 (I+1) = the channel slope. In the course of computations the value obtained for H_s (I+1) is compared with the theroretical specific energy determined by the following relationship:

$$H_{st}(I+1) = Y(I+1) + \propto V^2(I+1)/2g \quad (10)$$

In which H_{st} (I+1) = theoretical specific energy; Y(I+1) = the water depth.

For assumed value of water level at station I+1 the magnitudes of H_s(I+1) and H_{st}(I+1) are determined and compared with each other. If the difference is within the accepted error limit the computation terminates otherwise another water level is assumed. After completion of hydraulic calculations, marching for stream tube calculations starts, preferably from downstream. At each cross section, using equations 3 to 6 and for selected JST, flow area, transversal velocity, representative depth, tube boundaries, and other parameters at each stream tube are determined.

For bed variation forecasting sediment module is activated. In sediment routing, concepts of ***active***

and inactive layers, ***transport capacity***, and ***bed gradation*** are of major concern. Computation starts from upstream and proceeds in the direction of flow to downstream. According to sediment transport mechanism, at any time step only a portion of bed layer interacts with the flow. This layer is designated as ***active layer*** after Bennet and Nordin [3]. The remaining portion of bed sediment is not influenced by the flow and so it is referred to as ***inactive layer***. Thickness of active layer (Ta) is determined using the following equations extracted from the notions raised by Boreh et al. [4] and other contributors including the authors:

$$T_a = 100\, D_c / P_c (1 \quad \theta) \qquad (11)$$

$$q = \frac{1}{n} H_e^{5/3} S_f^{1/2} \qquad (13)$$

$$He = [4.495\, n\, q / D_c^{1/2}]^{6/7} \qquad (14)$$

$$DHE = H_e - H_a \qquad (15)$$

In which D_c= the grain size at threshold condition; P_c=percent of bed material coarser than D_c; θ = bed layer porosity; q = discharge per unit width , He = the equilibrium depth at which transport capacity for grains equal to or greater than D_c is zero ; Ha = the actual water depth.

Eq.14 is derived from Eqs. 12 & 13. They represent Shields and Manning's formulas respectively. In order to determine D_c a trial computational scheme should be implemented. Accordingly, D_{90} (grain size finer than %90 by weight) is first introduced to Eq.14 as D_c and H_e is determined. If H_e satisfies Eq.15, D_{90} is representative of D_c and T_a is then calculated from Eq.11. Otherwise, some smaller value is selected from the gradation curve and computational cycle repeats untile D_c and the relevant P_c values are established to determine T_a. Obviously, the magnitude of T_a is a function of Q and for high flows its value is greater than those of low flows.

Active layer is linked with channel bed variations through sediment transport capacity equation. Generally speaking, the validity of river models are closely related to appropriate selection of sediment transport equation under prevailing river conditions. Existing equations have frequenty been tested by investigators and their range of applicability and constraints notified. Recently Yang has also demonstrated validity tests on transport formulas and their rank of coincidence with field data notified [6]. Five of such equations with higher ranks have been included in SDAR model. These formulas are, Yang's sand and gravel formula; Laursen; Akers and white; Engeland and Hansen; and Mayer Peter and Muller equations. Using such formulas transport capacity is determined for each grain size class as if that size comprises the whole channel bed. In SDAR model bed material is divided into ten size classes with grain sizes ranging from 0.0625 to 64 millimeters. This is according to HEC-6 scheme, though it may be revised according to the user's attitude in the data input file.

Actual transported sediment usually differs from potential capacity determined by transport functions. This may be due to insufficient sediment storage at the channel bed or active layer to which the term ***availability limited*** is applied. In the presence of sufficient bed material however, the overall influence of various grain sizes, already existed in the moving sediment mixture, controls entrainment rate and the so called ***capacity limited*** case prevails. To formulate these processes the concept of ***residual transport capacity*** introduced by Boreh and et al. has been introduced in the model. According to this concept the actual amount of sediment transported out of a reach, for a specific size fraction, is influenced by inflowing sediment concentration of all existing size fractions already in motion. This expression can be generalized to any size fraction, Dj, as follows:

$$QSR_j = QS_j (1 - \sum_{j=1}^{N} \Sigma (QSI_j / QS_j)) = \Omega\, QS_j \qquad (15)$$

$$QSI_j = QSIN_j + QSL_j \qquad (16)$$

In which QSR_j = residual transport capacity or actual rate of outflowing sediment for size fraction j; QS_j = potential transport capacity of size fraction j : QSI_j= total inflowing sedimenst rate for size fraction j ;$QSIN_j$= the inflowing sediment rate from upper reach; QSL_j= lateral sediment rate entering the reach or extracted: N= the total number of size fractions; Ω = the remaining fraction of QS_j for transporting additional material of size D_j.

Depending on hydraulic conditions and inflowing sediment specifications the coefficient

Ω may take three distinct values. When $\Omega > 0$ the channel bed is in eroding condition and any size fraction available for entrainment in the active layer is removed and added to the inflowing sediment of the same size already in transport. Similarly when $\Omega < 0$ aggradation occurs on the bed since the flow carries sediment load in excess of its transport capacity. In case $\Omega = 0$ equilibrium condition prevails and there exist no net change in sediment load entering and leaving the reach. In order to account for eroded and deposited sediment for each size fraction ***the sediment accounting procedure*** proposed by Boreh and et al. has been applied in the model. The details of Boreh's analysis concering the structure of entrainment frequency materix, distributing weight of active layer among the matrix elements, and the time history of armor layer development may be traced in the paper presented by Boreh and his coworkers [4].

The integrated effects of various sediment transport feature on river bed variations are summerized in Eq.7 which is a sediment mass balance of partial differential form. To quantify aggradation – degradation magnitude, this equation is discretized according to following numerical computational scheme:

$$\Delta QS_j / \Delta x + B(1-\Theta)\Delta Z_j / \Delta TS = 0 \qquad (17)$$

$$\Delta QS_j = QSO_j - QSI_j \qquad (18)$$

By rearrenging Eq.17 bed variation for each size fraction and the resultant total elevation change of the river bed could be evaluated. Considering that ΔQS_j in Eq.17 is actually the same as QSR_j it follows:

$$\Delta Z_j = (\Delta TS / B(1-\theta)\Delta x)(QSR_j) \qquad (19)$$

$$\Delta Z = \sum_{j=1}^{N} \Delta Z_j \qquad (20)$$

$$QSO_j \le (QSI_j + QSR_j) \qquad (21)$$

$$\Delta TS = \Delta X / V \qquad (22)$$

In which QSO_j= total outflowing sediment rate from the reach; ΔQS_j = the difference of sediment rate entering and leaving the reach; QSI_j= total inflowing sediment rate to the reach ; QSR_j= net sediment rate leaving the reach or deposited at the bed; ΔZ_j = bed variation caused by size fraction j; ΔZ_j = total bed variation caused by all size fractions; ΔTS = sediment routing time step; V= the average velocity within the reach; j = size fraction index.

At this stage it is necessary to notify some considerations related to the structural configuration of the model in processing bed variation forcasting:

Firstly sediment transport rate is sensitive to bed gradation changes and it is clearly logical to repeat routing cycle during each computational time step, ΔT, adopted for hydraulic calculations. The number of gradation recalculation, ITS, is determined as follows:

$$ITS = DT / \Delta TS \qquad (23)$$

Details of discussion on this subject and the limit of ITS could be followed in the literature such as [2] and [8].

Secondly it is recognized that the bed material load is transported in equilibrium mode, so that at any instant and location sediment load discharge is equal to the sediment transport capacity of the flow. There are some circumstances, however, that the spatial delay and / or time delay effects are important and non-equilibrium condition should be considered. Some models use the method introduced by Han for concentration evaluation under non–equilibriam transport condition[7]. In SDAR model for scouring case the following procedure has been applied [8]:

$$ER = \Delta X / 30 * h \qquad (24)$$

$$EC = 1.368 - e^{-ER} \qquad (25)$$

$$QSN_j = EC * QSE_j \qquad (26)$$

In which ER = entrainment ratio; ΔX = the reach lergth; h = the flow depth; EC = entrairnment coefficient with maximum limit of 1; QSE_j = equilibrium transport capacity rate for size fraction j; QSN_j= nonequilibrium transport capacity rate for size fraction j.

When deposition condition prevails the actual deposition rate also is determined using trap efficiency (TE) of the reach as introduced by Jahnson and et al. [9].

$$TE_j = 1 - e^{-DEC} \qquad (27)$$

$$DEC = (2\Delta X\ W_j) / hV \qquad (28)$$

$$QSD_j = QSDE_j * TE_j \qquad (29)$$

In which TE_j = trap efficiency for each size class j with maximum limit of 1; DEC = power of the exponential function; ΔX = the reach length; W = the fall velocity for each grain size class j; h = the flow depth; V= the average flow

volocity; $QSDE_j$ = the inflowing sediment rate for size class j; QSD_j = the actual rate of sediment deposition for size class j.

Thirdly bed armoring is traced by the model during each sediment computational cycle, because it directly influences the scour depth in the model. River bed is assumed to be armored when material within the active layer can not be transported by the flow. As time passes, grains finer than the critical diameter (D_c) are removed and the remaining coarser ones develope an armor layer which resists against the erosive force of flow and the bed degradation stops. When armor layer developes the inflowing load is transported through the reach straight downstream. The armor layer may break down, however, as flow condition changes. The stability of armor layer is checked by the model using the Gessler's method [10]. In this method BSF (Bed Stability Factor) is the controlling parameter. BSF is determined using the following equation:

$$BSF = \sum_{j=1}^{N} P_{aj}^2 \ . \ PF_j \ . \ D_j \ / \sum_{j=1}^{N} P_{aj} \ . \ PF_j \ . \ D_j \qquad (30)$$

In which P_{aj} = probability that grains will stay at the bed, from Gessler's curve, for each size class; PF_j = fraction of bed composed of size class j; D_j = mean grain diameter for each size class j ; j = size class index ; N = Total number of size classes.

If BSF is equal or greater than 0.65 the armor layer is stable, otherwise the bed is destroyed and a new active layer is computed.

Sedimet transport module in SDAR model embodies the above mentioned criteria. At the end of transport calculation bed elevation is adjusted and both longitudinal and transversal profiles are updated. The computational cycle repeats untile the final time step is implemented.

According to Fig. 3 it should also be emphesized that transport calaulations, profile adjusments, bed sorting and armoring are limited to the main channel course designated by the movable bed boundary.

4. MODEL CALIBRATION AND RESULTS

In the course of model development SDAR was thoroughly tested for its two principal modules of hydraulics and sediment transport, using conseptual and real case data. Outcomes of simulations were also compared with results from HEC-6 , GSTARS-2 and FLUVIAL-12 recognized as the reference models, [8], [2], [11]. Table1 summerizes basic features of test channels applied for model calibration and performance simulation

According to Table 1 model calibration covers various schemes of bed gradations, flow hydrographs, and channel configuration systems. Mississippi belongs to the group of rivers flowing mostly on plain areas and having smooth flood hydrographs with extended time bases.

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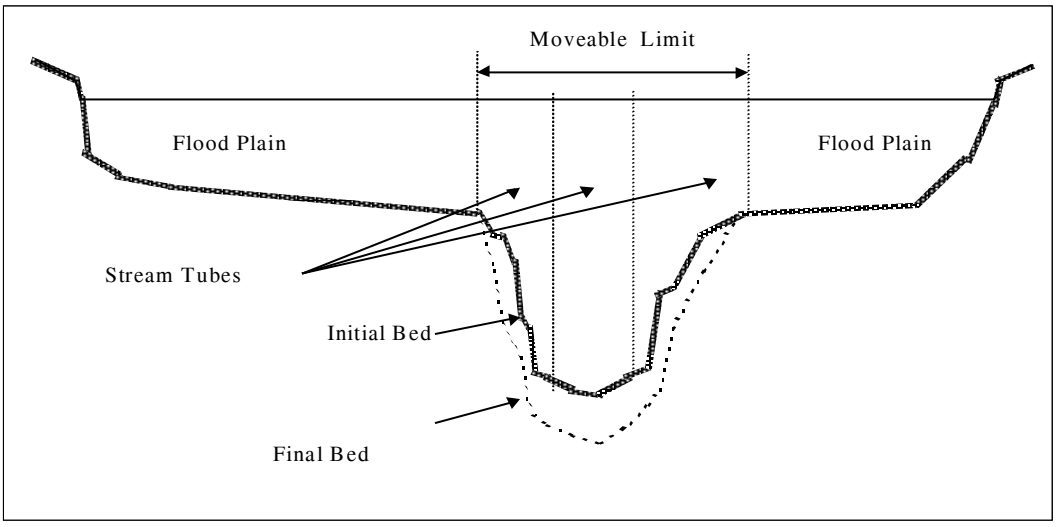

Fig. 3. Specifications of cross section span of moveable bed in SDAR model for river bed elevation determination.

Table 1. General characteristics of Test Channels Applied in SDAR model Calibration

Channel Name		Zumbro River	Mississippi River	Upper San Diego River	Lab. Flume
Initial Bed material Gradation (mm)	D_{50}	0.8	0.56	0.57	1.7
	D_{max}	50	10	8	10
	D_{min}	0.15	0.065	0.065	0.1
Average Bed Slope (m/m)		$1.2*10^{-3}$	$1.1*10^{-4}$	$3.4*10^{-3}$	$4*10^{-3}$
Channel Length (m)		8000	10000	1625	20
Average Reach Length(m)		800	417	160	0.5
Number of Branches		3	-	-	-
No. of cross Sections		11	24	11	41
Peak Flow (Q_{max})-CMS*		284	9800	908	0.0341
Base Flow (Q_{min})-CMS		14	1400	34	0.0341
Total Flow Duration (day)		54	120	0.83	0.041
Computational Time Step (Sec)		86400	86400	720	12
Reference Model		HEC-6	GSTARS-2	FLUVIAL-12	GSTARS-2
Type of Model		1-D	S2-D	1-D	S2-D
References		[8], [12], [15]	[2]	[11]	[13], [7]

* Cubic Meter Per Second

Upper San Diego and Zumbro rivers run on relatively steep slopes and produce comparatively sharp crested hydrographs having shorter time bases. Flumes customarily are applied for physical model studies and the performance of mathematical models are also examined using experimental data from direct flume observation runs. The process of validity tests for SDAR model in predicting channel bed evolution was accomplished at both solid and moveable bed domain. The results of test runs are described and presented below.

4.1. Simulating Hydraulic Behaviour Under Solid Bed Condition

River processes are directly affected by flow hydraulics. This implies that precise functioning of hydraulic algorithm is a prerequisite in moveable bed model developement. The first step in fulfillment of such requirement is to examine model reaction under solid bed condition. For this purpose outcomes from SDAR model runs were compared with those of HEC-6 results. HEC-6 is a 1-D model and its sound background and widespread engineering applications pursue that to consider its output as a kind of yardstick in model ability testing. Figure 2 illustrates the case of comparison for Zumbro river [8]. In a reach of 8 Kilometer this river recieves inflowing discharge from mainstream and three lateral banches.

In Fig. 4 water surface profiles belonging to low, medium and high flows for both models demonestrate approximately the same trends with only little detectable differences at low flow condition, implying an overall sound hydraulic performance of newly developed SDAR model program.

4.2. Simulating hydraulic Behaviour Under Moveable Bed Condition

Hydraulic computations under solid bed assumption, in quasi steady flow, is not sensitive to the selected time step (ΔT). On the contrary, in moveable bed domain, deposition and scouring of sediment influences river bed geometry and the chain of hydraulic computations become more sensitive to the introduced ΔT value. In other words, for loose boundary condition, if ΔT is not appropriately selected, computations may diverge from the real solution, or otherwise unrealistic results should be expected. Accordingly, in SDAR model hydraulic behaviour under moveable bed condition was tested for variety of flows and channel configuration schemes and systematic program adjustments were implemented for the sake of better functioning and realistic outcome achievements. These studies clarify that to avoid abnormalities and for insurance of numerical persistancy and stability, selection of appropriate time step is a necessity. In order to guarantee such requirements, it is plausible to conduct several preliminary test runs, using major peak flows, before the complete progrm run is fulfilled. Based on such introductry tests, a reasonable ΔT value then could be selected

which assures consistency between hydraulics and sediment transport modules. This also may be interpreted as the establishment of the ***Courant condition*** under which numerical computation advances smoothly toward the expected final solution [2]. The discussion may best be documented by resorting to Table 1. According to the Table, ΔT values range from 12 to 86400 seconds, within the calibration test examples. Obviously from the range of adapted time steps it should be interpreted that, ΔT shows more sensitivity to channel size, since its value is noteciably larger for rivers as compared with small one attributed to the test flume.

It should be emphesized that, river models are also sensitive to the selected reach length (ΔX). A review of Table 1 partialy refelects the role of ΔX in simulation studies. In the Table average reach length varies from small value of 0.5 m for the flume up to relatively longer strech of 800 m for river system. This clarifies that models become more sensitive to the seleted ΔX as the channel size and length diminish.

In Figure 5 the result of hydraulic response for moveable boundary condition is illustrated as a sample from a series of test trials. Initial and final profiles of both bed and water elevations for Upper San Diego river, predicted by SDAR and FLUVIAL-12 models, during passage of 100 yr flood wave are concurrently demonestrated in the figure. It could be postulated from Fig.5 that the water surface profile simulated by SDAR fairly follows the path of FLUVIAL-12 outcome with some tolrable minor differences.

4.3. Simulation and Prediction of River Bed Variation

The ability of SDAR model in predicting bed elevation variation was studied using data from several example river systems and experimental investigation information as notified in Table 1. Refering to Table 1 for Zumbro and Upper San Diego reaches 1-D scheme and for Mississipi river S2-D model were applied. Results of SDAR model application along with HEC-6, FLUVIAL-12 and GSTARS-2 outcomes are plotted in Figures 6, 7 and 8 respectively. For Mississippi river observed bed variation data are also availble within the study reach as reported at the reference [2].

In Fig.6, for Zumbro river, initial bed and its response after complete model run for a 54 day lasting hydrograph with discharge ranging from 14 to 70 CMS are sketched. It is evident from the figure that the general trend of longitadinal profile evolution for SDAR model nearly follows that of HEC-6, considering the fact that at some localities the depth of scour or deposition is some how different for two models.

Figure 7 is another illustrative example of bed variation forcasting in Upper San Diego river. In this case the reaction of river bed for a passage of 100 yr flood hydrograph with a relatively short time duration and in a shorter reach of about 1600 m was detected.

Initial flow rate amounts to 34 CMS and it increases to the peak value of 908 CMS within 20 hours. From Fig. 7, it can be claimed that, for most part of the study reach the predicted profile by SDAR model keeps close resemblence to FLUVIAL-12 plotting.

At the lower reach, however, SDAR prediction diverges from FLUVIAL outcome rather sharply. Special attention should also be paid to the ***contracted section*** in which the mode of sudden drops for both models fit eachother fairly.

Tests for river bed variation simulation using S2-D schemes were carried out by applying data from Mississippi river reaches [2]. The influence of flow hydrograph upon river bed elevation changes was studied and illustrated in Figure 8. For 120 day flow duration, applied for simulation purposes, the discharge varies from a minimum of 1400 to the maximum of 9200 CMS.

In Fig. 8 two profiles from SDAR and GSTARS-2 model go along with the observed final profile at the project site of Mississippi river. According to the Figure, simulated curves try to follow the observed elevation variation line though sporadically. For GSTARS-2 the general trend of simulated curve stands somehow higher than the monitored thalweg line, and SDAR simulation, while following the observed general trend, is more depressed at the ***contracted section*** and demonstrates occassional deviations from the recorded final profile. For quantitative appraisal of the model's ability in predicting bed profile variation and in order to represent a relatively clear perspective of simulation endeavor devolted to model structuring set up and its foundation establishment, the magnitude of scour

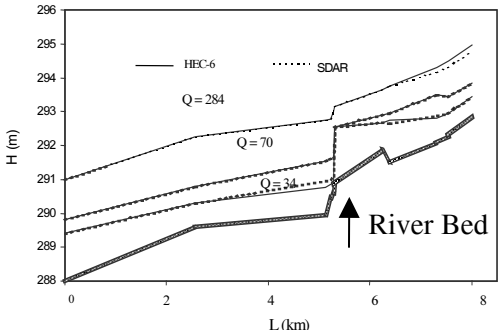

Fig. 4. Comparison of water surface profiles simulated by SDAR and HEC-6 models under solid bed condition (Zumbro River).

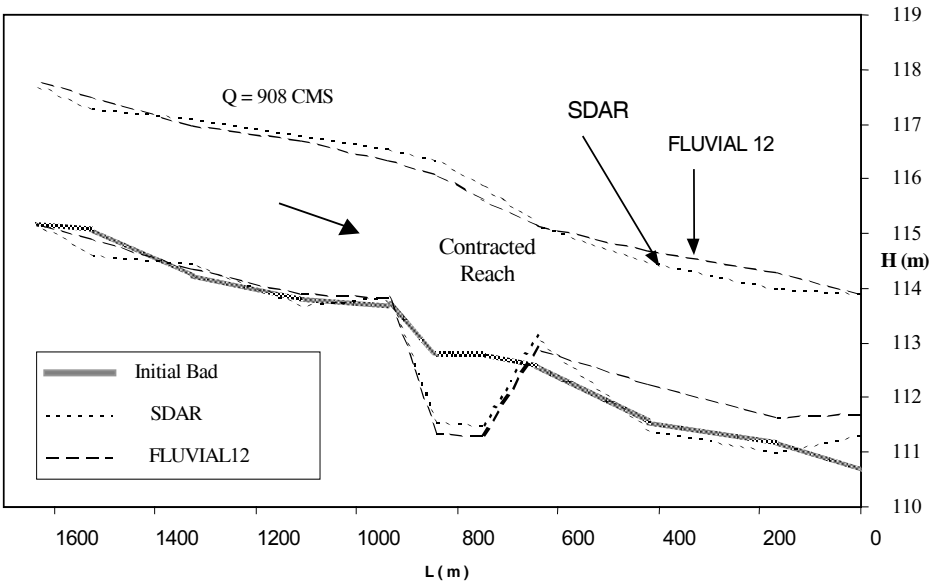

Fig. 5. Traces of water surface profiles simulated by SDAR and FLUVIAL-12 models under moveable bed condition (Upper San Diego River – 100 yr Flood).

Table 2. Precent Differences in Predicted Scour and Deposition by SDAR model as Compared with Reference Models

River Name	Reference Model	Percent: Difference		Duration of Flow Hydrograph (day)	Demonestrated Test Reach Length (m)
		Deposition	Scour		
Zumbro	HEC-6	-40	57	54	2750
Upper San Diego	FLUVIAL-12	21	39	0.83	1625
Mississippi	GSTARS-2	-	77	120	800
Mississippi	Observed Values	-	36	120	800

and deposition predicted by SDAR model was compared with the achievements from the reference models. Results of this comparison are summerized in Table 2. According to the table, for specified test runs the amount of difference or error for predicted scour and deposition vary between 36 to 71 and – 41 to 21 percent respectively. These ranges are not abnormal

values in the field of transport modelling, as several uncertainities could affect results of model applications according to many paper discussions including [9] and [14]. Specially the 36 percent difference between observed scour magnitude in Mississippi river case and calulated by SDAR is encouraging and confirms the model's promising functioning in facing with real case simulations.

4.4. Simulating Cross Sectional Changes

Longitudinal profile variation presentation reveals only some features of morphplogcal behaviour induced by transport phenomena. Manipulating of lateral profile evolution or cross sectional changes is equally important in morphological investigations and model validity tests. Several factors influence transversal variation of river bed elevation such as nonhomogenity of bed material accross the river, lateral velocity distribution variation, span of moveable bed and bank fauilure mechanism among many others.

In SDAR model lateral bed variation is limited to the main channel as designated by moveable boundary span (See Fig. 3). Figures 9 and 10 are two counterpart examples of lateral bed variation simulation linked with longitudinal profile predictions at test reaches Mississippi and Upper San Diego rivers as described at the previous sections.

In Fig. 9 the synthesized cross section of Mississippi river predicted by SDAR is compared with the observed final bed stretch. Outcome from GSTARS model also is illustrated on this figure. According to Fig. 9 the trend of simulation by SDAR closely follows the observed path with only some dismatchings at the right bank side. GSTARS prcdiction rather deviates from the observed trend as it shows more deposition at righter side of the cross section while, scouring is meager and mainly limited to the central part of the river.

Figure 10 is another indication of cross sctional evolution, synthesized by SDAR and FLUVIAL-12 models.

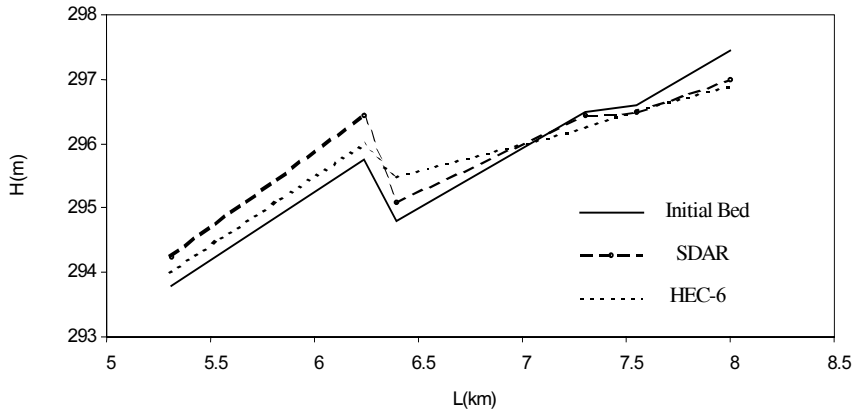

Fig. 6. Comparison of bed elevation variations predicted by SDAR and HEC-6 models (Zumbro River).

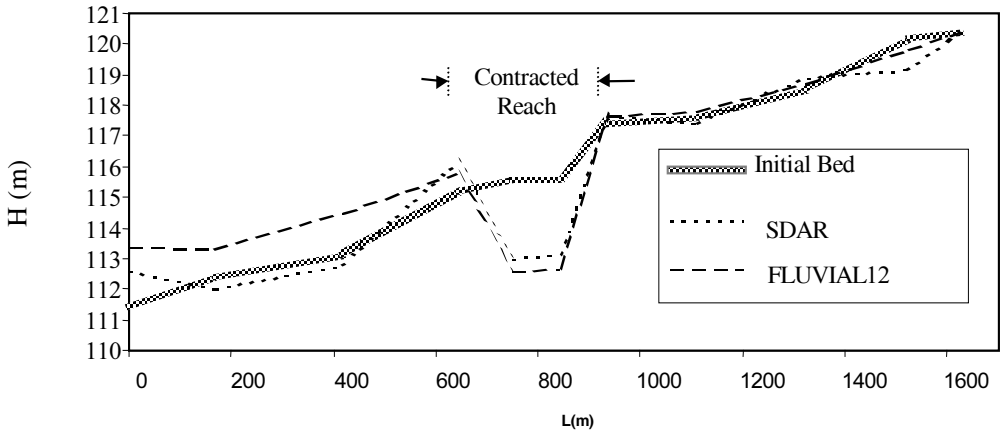

Fig. 7. Comparison of bed elevation variations predicted by SDAR and FLUVIAL-12 models (Upper San Diego River).

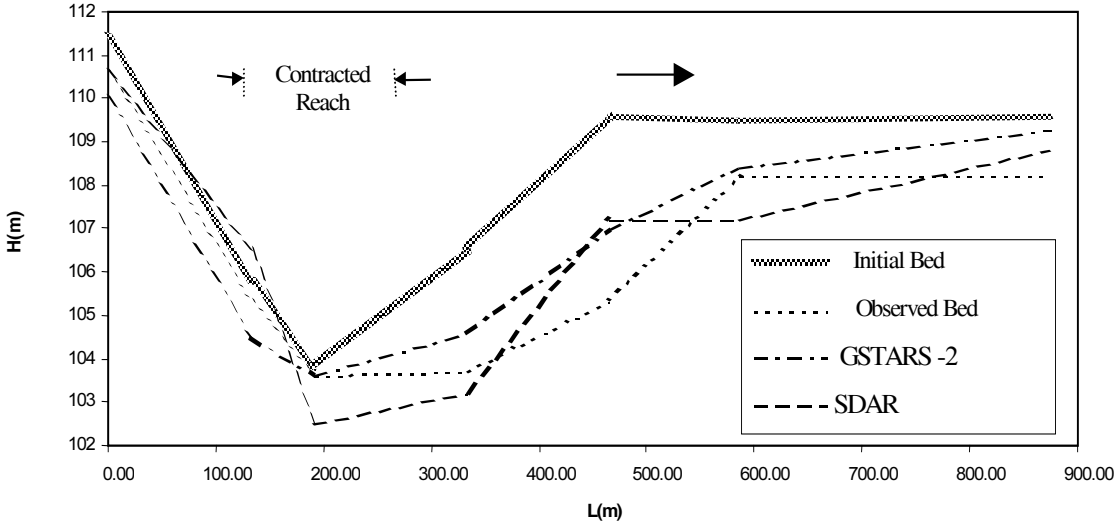

Fig. 8. Comparison of bed variations predicted by SDAR and GSTARS-2 models with observed final bed (Mississippi River).

The section belongs to Upper San Diego river and reflects impacts of a 100 yr flood passage within a simulation time of 20 hours (for more details concerning flow characteristres see previous sections). From the Figure, predicted shapes of cross section by two models are fairly similar, considering the fact that more deposition is predicted by FLUVIAL-12 than the SDAR model. It is also evident from Fig. 10 that a prevailing deposition phase is experienced by the river at this locality.

4.5. Simulating armor layer developement at the bed

The ability of river models in simulating armor layer development is a sign of reliable model performences and its better functioning under various field conditions. As previously mentioned, for specified hydraulic condition, developement of armor layer reduces scouring and it may even completely cease if the layer covers the whole exposed bed surface area. In order to test SDAR model's ability in predicting armor layer developement the case of laboratory study by Ashida and Michiue was selected [13] (see also Table 1). In this experiment a flume with 20 m length and 0.8 m width was mounted to investigate armor layer development process, downstream of a reservoir dam. Clear water was introduced at the upstream, having constant discharge equal to 34 lit/sec, and bed gradation variation was traced untile the armor layer developement was completed. In Figure 11, initial bed gradation curve, size distribution of observed armor layer along with SDAR and GSTARS model runs are shown. From this figure armor layer gradation obtained by SDAR model closely follows the observed experimental distribntion curve. In this figure also GSTARS outcome plotting for armor layer prediction is illustrated as a comparison of SDAR model behaviour with a well documented general purpose model. From the Figure, both experimental and simulated curves resemble to each other and is an obvious indication of SDAR model ability in processing armor layer developement mechanism.

4.6. Limitations of "SDAR" Model

The complex nature of river environment processes, makes it unlikely to introduce a comprehensive universal model by which all flow and sediment transport behaviours could be simulated. Therefore any river model at most, encompasses only specified domain of simulation catagory in the vast field of engineering applications. Likely in SDAR model, sediment routing and bed variation is limited to the main channel and no entrainment occurs at the flood plain. Besides, river bed layer is assumed homogeneous at any reach and stratification is not considered in the model. Of course, grain size may vary at different sections. Presently, for sediment routing three stream tubes is allocated while for hydraulic routing up to ten stream tubes can be specified. Fifty cross

sections and ten branches could also be processed by the model. Obviously all the above mentioned constraints are subject to alterations in the course of future model refinement. It should also be emphasized that cohesive sediments are not mainipulated by SDAR model.

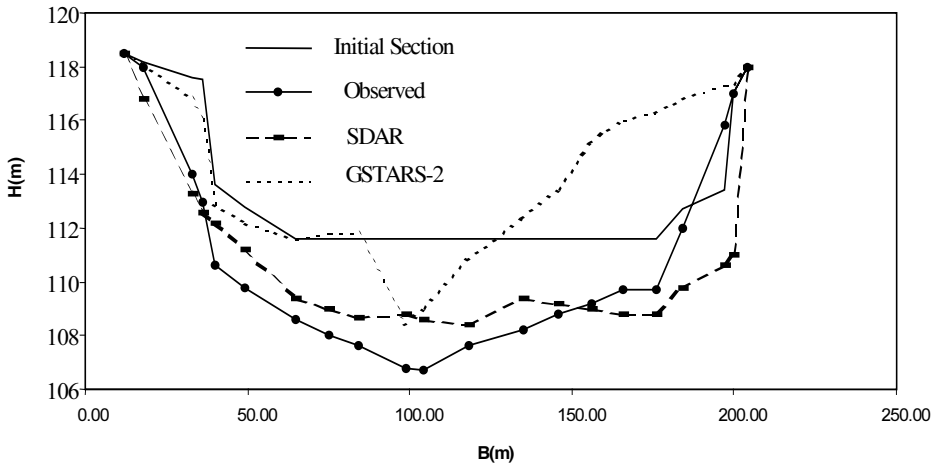

Fig. 9. Comparison of simulated cross sections by SDAR and GSTARS-2 models with observed cross section (Mississippi River).

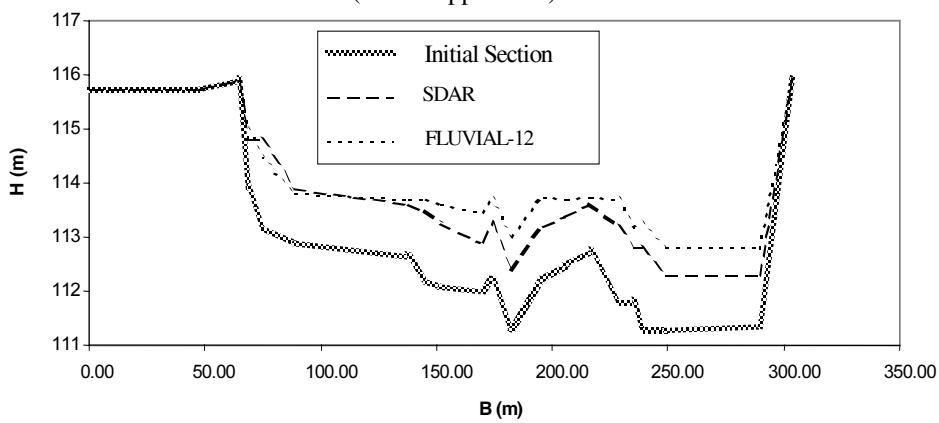

Fig. 10. Comparison of predicted cross sections by SDAR and FLUVIAL-12 models (Upper San Diego River).

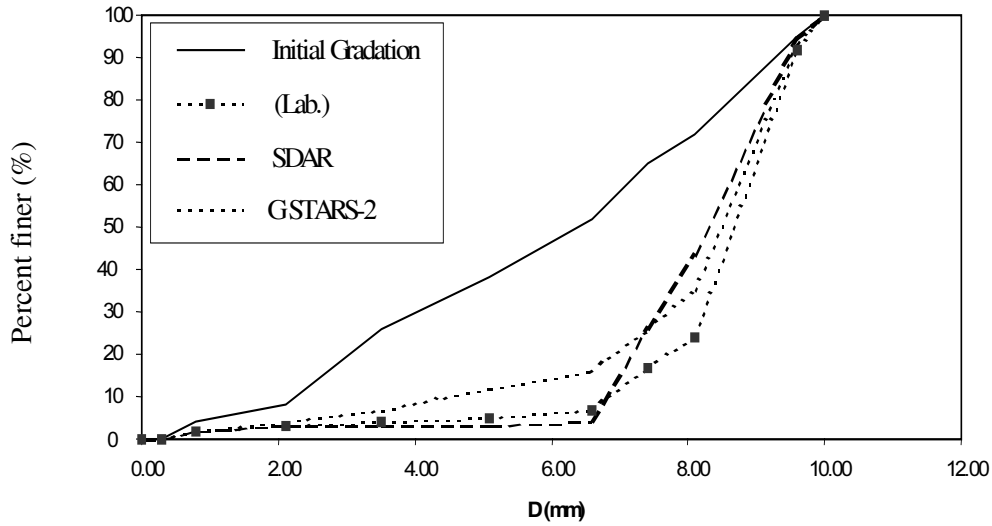

Fig. 11. Comparison of armor layer gradation distribution curves simulated by SDAR and GSTARS-2 models with the observed curve at the Lab. Flume.

5. CONCLUSIONS

In this investigation the semi-two dimensional SDAR model was developed and applied to few field cases and results are compared with several well-known models as described in the text. It was confirmed that the model is cappable of predicing bed variations in alluvial domain consisting of noncohesive sediments and subject to the specified constraints, the results of which are summrized as follows:

Regarding the characteristics of rivers and flow specifications selected for model calibration tests, it may be claimed that SDAR model can successfully be applied for variety of engineering purposes, as well as morphological behaviour investigations at alluvial rivers within the specified frame borders.

Detailed studies of SDAR functioning reveals that the model acts more satisfactorily for various simulation processes when S2-D feature is activated as compared with1-D scheme. The limited space dose not allow here to illuminate various aspects of this special problem and it certainly requires another opportunity to provide thorough discussions and analytical presentations concerning the subject.

From practical view point 1-D alternative is more adapted for general purpose studies and S2-D option is better fitted for precise and detailed river behaviour investigations concerning hydraulics and sediment transport. It should, however, be emphasized that the S-2D application requires more data and supplementary information as compared with 1-D case.

Because of unrealistically large computer capacity requirements, direct applications of pure 2-D morphological models are restricted to short distances and locally interested engineering sites. Application of S-2D model like SDAR on long river stretches clarifies that such models though less sophisticated, but functionally are very powerful in simulating 2-D behaviour of rivers without occupying abnormally huge computer capacity.

Sediment extraction or sand mining is another senario that could be manipulated by SDAR model application. Of course for the reliable functioning of the model, calibration tests should also be conducted using reliable field data and available case studies.

The applicability of SDAR model may also be enhanced by including appropriate module for cohesive bed material or fine sediments, provided that validity tests and calibration stages be thoroughly accompolished.

Simulation of bank failure and its effects on the planform variation is another important morphological feacture which may be linked with the SDAR model structure in the course of future model amendments.

ACKNOWLEDGMENTS

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