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MODELING SIMULATION OF SEDIMENT ANALYSIS FOR MALAPRABHA RIVER IN KARNATAKA STATE, INDIA

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Abstract: Transport, settling and quantity of solutes in rivers, streams, lakes and reservoirs are the important aspects in water-quality modeling. This has been the major concern for the researchers, scientists and engineers for the last 50 years who actively involved in water quality modeling. Consequently, characterization of hydrodynamics and water budgets has been an essential component in the water–quality modeling. This paper presents on the simulation model for sediment transport, solids budget, bottom sediment as a distributed system under steady-state condition, and resuspension of solids due to currents etc. The solids considered for the study was mainly allochthonous as these are inorganic in nature and the rate of decomposition is negligible. The data collected refers to the part of the research work on Malaprabha River, near Belgaum – a district headquarters in the State of Karnataka, India. This river is a non-perennial one, and the flow is very less during the pre-monsoon period, which is favorable for application of these sediment models. The results obtained for the resuspension and burial velocities showed marked variations during the different seasons of the year. Resuspension velocities predominated during the monsoon period resulting in the non-settlement of the solids and the burial velocity during the non-monsoon period. As the river receives raw sewage from an adjoining town – Khanapur, and also the agricultural discharges, it is worth to quantify the sediment deposition in the stream.

Keywords: Allochthonous; resuspension velocity; burial velocity; transects porosity.

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INTRODUCTION

This analytical model for sediment transport, solids budget and bottom sediments is applied to a natural stream as part of the ongoing research work. The stream, Malaprabha River, takes its birth at Kankumbi, near Khanapur town of Belgaum District. The study stretch selected runs for 24 km, starting from its birth place. The river receives much non-point and point effluent discharges in this range, and only point discharges are predominant during the pre-monsoon period. The river channel alignment is fairly straight, and variations occur in widths and depths. It becomes a shallow river during summer, depths varying between 1 to 2 m with muddy bottom. The location of the river is as shown in **Fig. 1**.

MATERIALS AND METHODS

The stream water quality and sewage characteristics were analyzed during the period 2004–2005. The method of sediment sample collection, transport to the laboratory, preservation and analyses – were all carried out as per the standard methods and procedures (APHA, 1985). Besides, other aspects, such as stream hydro-geometry, flow analysis, depth and velocity measurements – were all done as per the standard procedures. The in-stream monitoring, including sediment sampling, were done at 3 to 4 lateral points at each transect. The transects selected for the study are as shown in **Fig. 2**. The sampling locations for sediment analysis, taken transversely, are shown in **Fig. 3**, which exhibit both lateral and longitudinal variations

Fig. 1 Location map for Malaprabha River

in the sediment deposits (JCE Mysore, 1988). The deposition appeared to be more near the sewage outfall and gradually reduced towards the opposite bank. The other stations showed relatively uniform sediment deposits. Note that ordinate indicates the percent of sediment deposit.

The average flow of the stream during summer was 1.68 m^3/s and the sewage recorded a flow of 0.35 m^3/s. The area of the river considered for sediment collection is the average width and the distance up to the study length, i.e. 24 km. Concentration of suspended solids in the stream water and the sewage were determined, and expressed on a dry-weight basis, i.e. dry weight of solids per volume of water. Details of solids, stream hydro-geometry, flow, depth and velocity for the study area are presented in **Table 1**.

Generally, the sediment at the upper portion of the stream is mostly as liquid phase, but this state of the sediment changes as it moves down. Near the bottom a significant fraction of the sediment volume is solid. Such systems are referred to as porous media. Porosity refers to the volume of the sediment that is in the liquid phase, and is interconnected. Strictly speaking, this excludes isolated pore-space that is considered as part of the solid phase. However, such isolated pores are rarely found in fine-grained sediments, the porosity ϕ is defined as the fraction of the total volume that is in the liquid phase (Chapra, 1997; Gruber *et al.*, 2005):

$$\phi = \frac{V_L}{V_2} \qquad (1)$$

where V_L is the volume of the liquid part of the sediment layer (m^3) and V_2 is the total volume of the sediment layer (m^3).

Then, the fraction of the sediment that is in the solid phase is given by:

$$1 - \phi = \frac{V_p}{V_2} \qquad (2)$$

where V_p is the volume of the solid or particulate phase of the sediment (m^3).

Another quantity that is used in modeling porous media is the density, which can be represented as follows:

$$\rho = \frac{M_2}{V_p} \qquad (3)$$

where ρ is the density (g/m^3) and M_2 is the mass of the solid phase in the sediments (g).

Above quantities can now be used to define a number of parameters that are needed to model sediment – water interactions. As the suspended solids concentration form the critical metric of the solids content of the water, suspended solids concentration in the sediments can be expressed as:

$$m_2 = \frac{M_2}{V_2} \qquad (4)$$

Table 1. Average values of hydro geometric properties and sediment

Sl. No.	Date	Depth (m)	Top width (m)	Q (m^3/year) $Q_R + Q_S$	Suspended Solids (mg/L)	Solids loading (gm/year)	Surface Area (m^2)	Volume (m^3)	Solids Settling (m/year)
1	Jun, 2004	2.350	66.6	165.88×10^6	20.0	3.86×10^6	1.59×10^6	3.76×10^6	401.50
2	Jul, 2004	2.750	66.6	1.95×10^9	230.0	6.12×10^{10}	1.59×10^6	4.39×10^6	839.50
3	Aug, 2004	3.130	66.6	2.51×10^9	260.0	41.1×10^9	1.59×10^6	5.0×10^6	292.00
4	Sep, 2004	2.600	66.6	1.13×10^9	120.0	22.4×10^9	1.59×10^6	4.16×10^6	511.00
5	Oct, 2004	2.100	66.6	1.83×10^8	20.0	6.8×10^9	1.59×10^6	3.36×10^6	803.00
6	Nov, 2004	0.700	13.8	1.19×10^8	12.0	4.2×10^9	3.31×10^5	2.32×10^5	693.50
7	Dec, 2004	0.640	12.3	5.65×10^7	5.0	4.9×10^8	2.94×10^5	1.89×10^5	912.50
8	Jan, 2005	0.520	8.6	3.91×10^7	3.0	2.1×10^8	2.07×10^5	1.08×10^5	985.50
9	Feb, 2005	0.440	5.8	3.28×10^7	3.0	1.38×10^8	1.39×10^5	0.61×10^5	1022.00
10	Mar, 2005	0.320	4.3	2.7×10^7	2.0	0.68×10^8	1.03×10^5	3.31×10^4	584.00
11	Apr, 2005	0.180	2.7	1.79×10^7	2.0	0.42×10^8	6.46×10^4	1.16×10^4	511.00
12	May, 2005	1.820	20.7	138.12×10^6	8.0	1.4×10^9	4.96×10^5	9.02×10^5	401.50

where m_2 is the suspended solids concentration in sediments (g/L).

Eq. (3) can be solved for:

$$M_2 = \rho V_p \tag{5}$$

Eq. (2) can be solved for:

$$V_2 = \frac{V_p}{(1-\phi)} \tag{6}$$

Eqs (5) and **(6)** may be substituted in **Eq. (4)** to get:

$$m_2 = (1-\phi)\rho \tag{7}$$

Thus the sediment solids concentration may be re-expressed in terms of parameters that are conventionally used to measure porous media. This expression may be used to develop solids budget for a sediment-water system. In the following discussions, it will be useful to recognize that the term $(1 - \phi)\ \rho$ represents the "suspended solids" concentration of the bottom sediment.

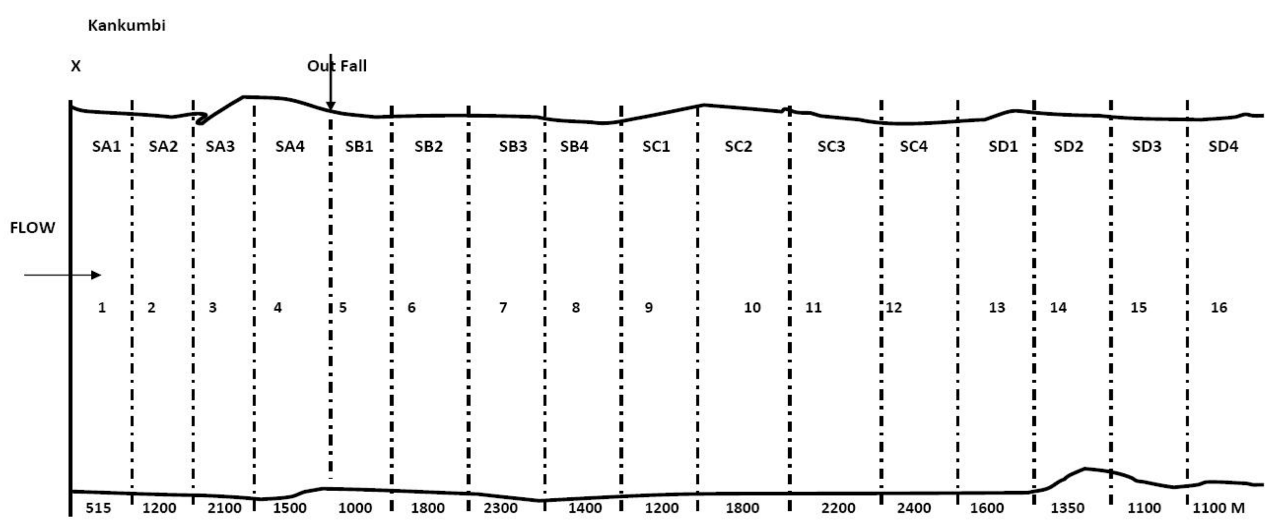
Simple Solids Budget

Now that suspend and bottom sediments are understood, a solids model can now be developed. For simplicity the model will be developed for allochthonous solids in a well-mixed lake. As in **Fig. 4**, two cases will be examined. In the first a one-way loss to the sediments is used. Then we couple the sediments and water by adding resuspension.

For the first case, following mass balance can be written for the water (Thomann & Mueller, 1987):

$$d\frac{dm}{dt} = Qm_1 - Qm - v_s A_s m \tag{8}$$

where v_s is the settling velocity, m/year and A_s is the area of sediment-water interface (m²). At steady-state condition, **Eq. (6)** can be solved for:



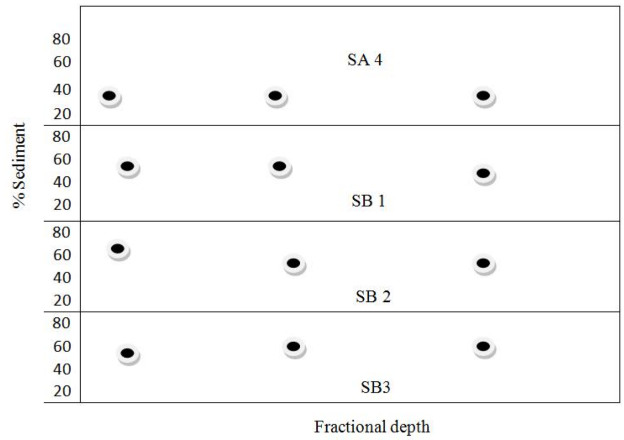


Fig. 3 Lateral variation in sediment deposit.

$$m = \frac{Qm_{1n}}{(Q + v_s A_s)} \tag{9}$$

Now, a sediment layer may be added to the model. Mass balances for the solids in the water and the sediment layer may be written as:

$$V_1\left(\frac{dm_1}{dt}\right) = Qm_{in} - Qm_1 - v_s A_s m_1 + v_r A_s m_2 \tag{10}$$

$$V_2\left(\frac{dm_2}{dt}\right) = v_s A_s m_1 - v_r A_s m_2 - v_b A_s m_2 \tag{11}$$

where v_r is the resuspension velocity (m/year) and v_b is the burial velocity (m/year).

Eq. (7) may be used to express sediment suspended solids m_2 in terms of sediment porosity and density. At steady state, the resulting solid balance equations are:

$$0 = Qm_{in} - Qm - v_s A_s m + v_r A_s (1-\phi)\rho \tag{12}$$

$$0 = v_s A_s m - v_r A_s (1-\phi)\rho - v_b A_s (1-\phi)\rho \tag{13}$$

Then, **Eq. (9)** may be solved for,

$$(1-\phi)\rho = \frac{v_s m}{(v_r + v_b)} \tag{14}$$

which can be substituted in **Eq. (8)**, and the result solved for (Chapra, 1997):

$$m = \frac{Qm_i}{Q + v_s A_s (1 - F_r)} \tag{15}$$

where F_r is the resuspension factor that is defined as

$$F_r = \frac{v_r}{(v_r + v_b)} \tag{16}$$

In the above equations, the effect of adding the sediment layer is isolated in the dimensionless parameter group F_r. This group represents the balance between the resuspension rate and the total rate at which the sediment purges itself of solids, i.e. both burial and i.e. $v_b \gg v_r$, the resuspension factor $F_r \sim 0$, and **Eq. (11)** reduces to a well-mixed model with no sediments. On the other hand, if resuspension dominates burial, i.e. $v_r \gg v_b$, $F_r \sim 1$ and **Eq. (11)** reduces to $m = m_{in}$. In other words, when resuspension dominates, the water concentration approaches the inflow concentration, as everything that settles is immediately re-suspended.

The above solutions are in the simulation mode, where all the parameters are known. Although the solids model may be used in this way, it is more conventional for the model to be employed to estimate some of the parameters. This may be done as follows:

Parameter Estimation

The parameters in model are ρ, ϕ, m, m_{in}, Q, A_s, v_s, v_r and v_b. For the steady state case **Eqs (8)** and **(9)** represent a pair of simultaneous algebraic equations. Hence, seven of the parameters are known, these equations will provide us the other two values. Of the nine parameters, it is assumed that the values of are known. Typical values of ρ and ϕ for fine-grained sediments are 2.4 to 2.7 × 10^6 g/m^3 and 0.8 to 0.95, respectively. It is also possible to get the values of Q and A, i.e. the flow and the area from the field data. It is now left with five unknown parameters, i.e. m, m_{in}, v_s, v_r and v_b. Now among these, the value of resuspension velocity v_r, is extremely difficult to measure. There are two situations that generally occur:

In the first case, m and m_{in} are measured, along with the settling velocity, v_s which can be measured directly or can be estimated. Then, **Eqs (8)** and **(9)** may be added to give:

$$0 = Qm_{in} - Qm - v_b A_s (1-\phi)\rho \tag{17}$$

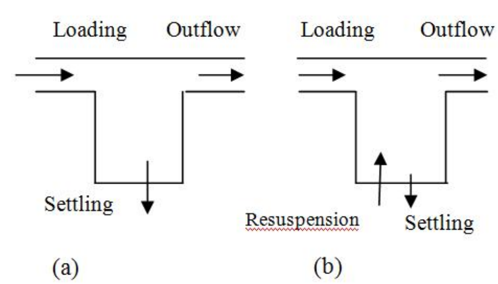


Fig. 4 Solids model (a) no sediment-water interaction and (b) sediment-water interaction.

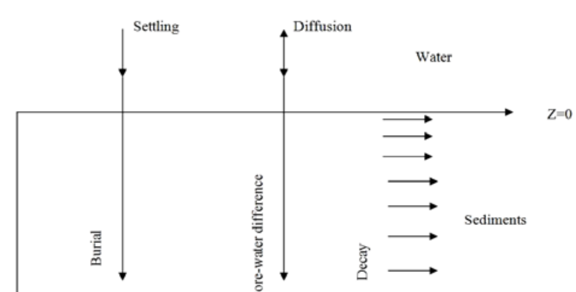


Fig. 5 Schematic of a sediment viewed as a vertical distributed

Table 2. Resuspension velocities

No.	Date	m_{min} (mg/L)	Burial velocity v_b (m/year)	Resuspension velocity v_r (m/year)
1	June, 2004	23.50	0.001 520	0.03 190
2	July, 2004	31.50	- 0.001 010	0.80 600
3	Aug, 2004	16.50	- 1.602 000	1.91 800
4	Sept, 2004	19.80	- 0.296 700	0.55 300
5	Oct, 2004	37.20	0.008 250	0.05 870
6	Nov, 2004	35.30	0.034 900	- 0.00 023
7	Dec, 2004	8.70	0.002 960	0.01 605
8	Jan, 2005	5.40	0.001 890	0.01 040
9	Feb, 2005	4.21	0.000 012	0.01 280
10	March, 2005	2.50	0.000 546	0.00 432
11	April, 2005	2.35	0.000 405	0.00 385
12	May, 2005	10.00	0.002 320	0.01 110

Eq. (13) can now be used to estimate v_b as below:

$$v_b = \frac{Q(m_{in} - m)}{A_s(1-\phi)\rho} \tag{18}$$

In the second case, the burial velocity, v_b is sometimes measured directly using sediment-dating techniques. Once v_b is measured or estimated by any technique, the resuspension velocity can then be estimated by solving the steady state version of **Eq. (9)** as

$$v_r = \frac{v_s m}{(1-\phi)\rho} - v_b \tag{19}$$

The sediment budgets described above are used in conjunction with contaminant balances to model toxic substance dynamics in lakes and rivers. However, it is found that this model represents a simplified form of the dynamics of solids in such systems. Rather, it is found that the sediment resuspension is not a steady-state process, and occurs episodically – usually due to high winds in lakes and high currents in rivers.

Bottom sediment as a distributed system

In the last section the bottom sediments are characterized as a single layer. Further, sediments can also be characterized as distributed systems. The simplest such approach depicts the bottom sediments as a one-dimensional continuum in the vertical (Chakrapani, 2005). **Figure 5** shows three processes that are involved in modeling such a distributed sediment system. The substance being modeled is subject to simple first-order decay, it is assumed that it diffuses within the pore water, and finally, as the solid matter rains down from the overlying water, substances in the sediment are buried.

As such although a layer of sediment does not move physically, its distance from the sediment-water interface increases with time as matter accumulates on the bottom, i.e. the sediment-water interface is advecting upward. However, for our modeling purpose, it is convenient to conceptualize the process as if the downward. In case of any dissolved substance, the three mechanisms can be combined into the following mass balance as shown in **Fig. 5**:

$$\frac{\partial c}{\partial t} = -v_b\left(\frac{\partial c}{\partial z}\right) + \phi D\left(\frac{\partial^2 c}{\partial z^2}\right) - kc \tag{20}$$

where c is the concentration of any dissolved substance, (mg/L) and D is an effective diffusion coefficient through the sediment pore waters (m²/year).

In modeling the sediment as a distributed system, constant parameters are assumed in the above equation. Strictly speaking this may not hold good practically, as sediments are subjected to compaction as the weight of overlying sediments presses down on deeper layers during their transport. Such a process, in simple form, means that both the velocity and the porosity vary with depth.

Steady-state distributions

The system can be considered as steady-state assuming the pore water at the sediment-water interface is held at a constant level c_0 for a sufficiently long time, and the **Eq. (20)** becomes:

$$0 = -v_b\left(\frac{dc}{dz}\right) + \phi D\left(\frac{d^2 c}{dz^2}\right) - kc \tag{21}$$

with boundary conditions, $c(0, t) = c_0$ and $c(\infty, t) = 0$, then the solution for the equation is given by:

$$c = c_0 e^{zl} \tag{22}$$

where,

$$l = \frac{v_b}{2\phi D}\left[1 - \left(1 + \frac{4\phi D}{v_b^2}\right)^{1/2}\right] \tag{23}$$

RESULTS AND DISCUSSIONS

The above equations were then applied for modeling the sediment analysis of the water in Malaprabha River. The estimated values for burial and resuspension velocities for different months in a year are presented in **Table 2**. As seen from the results, the inflow concentration of solids increased during the monsoon period. This is due to the fact that the discharges in to the stream from non-point and point sources increased considerably during this period. The inflow concentration of solids, i.e. m_{in} was 31.5 mg/L. during July, 2004, which generally is the maximum rainfall period.

The overflow from agricultural lands contributed maximum solids during this period. This inflow of solids concentration then reduced gradually as the precipitation decreased. During the post and pre monsoon period the inflow of solids is mainly due to point sources and also due to other activities that take place on the banks of the river. Minimum solids inflow was 2.35 mg/L, which is during April, 2005. This value again increased during the period of May, 2005 which can be attributed to the pre-monsoon showers.

Marked variations were also found in burial and resuspension velocities at different months of the year. The maximum value of v_b was estimated during November, 2004, when naturally, the resuspension velocity, i.e. v_r was minimum i.e. 0.00 023 m/year. This shows that there is minimum disturbance for settling of particles, and the effect of sediment settlement due to compaction is more during this period. On the other hand, the minimum value of v_b occurred during August, 2004, i.e. -1.602 m/year, and naturally the resuspension velocity, v_r was at its peak during this period. This clearly indicates that velocity generated during this period was all resuspension, and there was hardly any settling of particle. This may be due to the high currents that generally develop during rainy season. The values of resuspension velocities then gradually decrease as the post-monsoon and the pre-monsoon season approach, i.e. as the flow in the stream reduces resulting in favorable conditions for the settling of the particles.

The aspect to be noted here is the settling velocity of the solids. It can be observed from **Table 1** that the settling velocities reduce during the period of monsoon which is the result of high currents and disturbances for settling of the particles. At this time the resuspension velocity predominate the burial velocity. A minimum settling velocity of 292 m/year was observed during August, 2004 and the maximum of 1022 m/year during February, 2005. Quiescent conditions which prevail during pre-monsoon period, favored the settling of solids.

CONCLUSIONS

Field measurements were carried out for Malaprabha River, Karnataka State, India. This work presented the characteristics of the sediment with regard to the burial and resuspension velocities during different months of the study period. Results showed that burial velocity reached its maximum during November, with maximum velocity of 0.034 900 m/yr, and the resuspension velocity was peak during August, with a value of 1.91 800 m/yr. This model application to the present research work appeared to suit to the field conditions and gave fairly good results.

The result for the burial and resuspension velocities are presented in **Fig. 6**, which clearly depicts the tendency of the sediment either to settle when the resuspension velocity is at minimum or distribution of sediment as suspended matter when the resuspension velocity is more. The model can be further extended to simulate flow-sediment transport, river bed profiles and water surface through optimization procedure, and geometric parameters by fitting the model with required additional river data and finding the best-fit values of each parameter. Optimization methods are found to be very useful when applied to sediment routeing problems in streams and river system. Such techniques were made use for optimization of some of the important parameters involving sediment routeing and bed armouring process (Santos *et al*,. 2003). Such findings and studies would go a long way in assisting the researchers, engineers and others in their approach to solve the sediment problems.

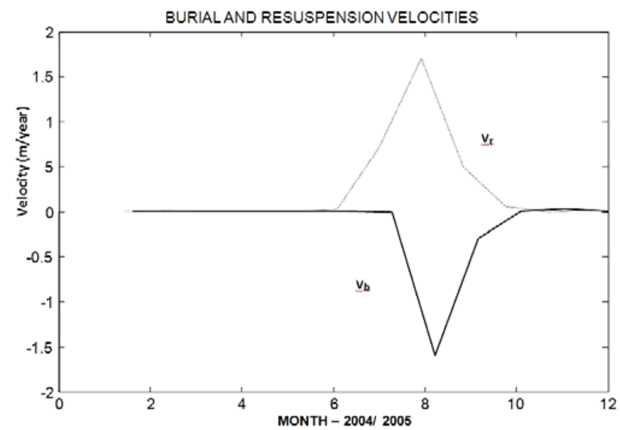


Fig. 6 Comparision of Re-suspension and Burial velocities.

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