Title:

MODELING SIMULATION OF SEDIMENT ANALYSIS FOR MALAPRABHA RIVER IN KARNATAKA STATE, INDIA – A Case Study.

Authors: Shri. V. K. Naik and Dr. S. Manjappa*

Addresses:

1) Shri. V. K. Naik,
Assistant Professor,
Civil Engineering Department,
KLS Gogte Institute of Technology,
Udyambag, **BELAGAUM.**
Karnataka State (India)
Pin: 590 008
e-mail: vknaik3@yahoo.com.

2) Dr. S. Manjappa*,
Professor and Head,
Department of Environmental
Science and Technology Study Centre,
Bapuji Institute of Engineering & Technology,
DAVANAGERE.
Karnataka State (India)
e-mail: drsmdvg@yahoo.co.in
drsmdvg@hotmail.com

Details of contact person:

PERMANENT ADDRESS	PRESENT ADDRESS
Shri.V. K. Naik, Assistant Professor, Civil Engineering Department, KLS Gogte Institute of Technology, Udyambag, **BELAGAUM.** Karnataka State (India) **Pin: 590 008** e-mail: vknaik3@yahoo.com Tel: +91-831-2443616	Shri.V. K. Naik, Sr. Lecturer, Department of Built & Natural Environment, Caledonian College of Engineering, P.O.Box 2322, SEEB 111 Muscat. **Sultanate of Oman.** e-mail: vknaik3@yahoo.com Tel: +968- 92562357

ABSTRACT:

One of the important aspects in water-quality modeling is the transport, settling and quantity of solutes in rivers, streams, lakes and reservoirs. 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 have been an essential component in the water–quality modeling[1] This paper presents on the simulation model for sediment transport, solids budget, bottom sediment as a distributed system under steady-state condition, and re-suspension 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 re-suspension and burial velocities showed marked variations during the different seasons of the year. Re-suspension 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, re-suspension velocity, burial velocity, transects porosity.

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 kms., starting from its birth place. The river receives many non-point and point 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.

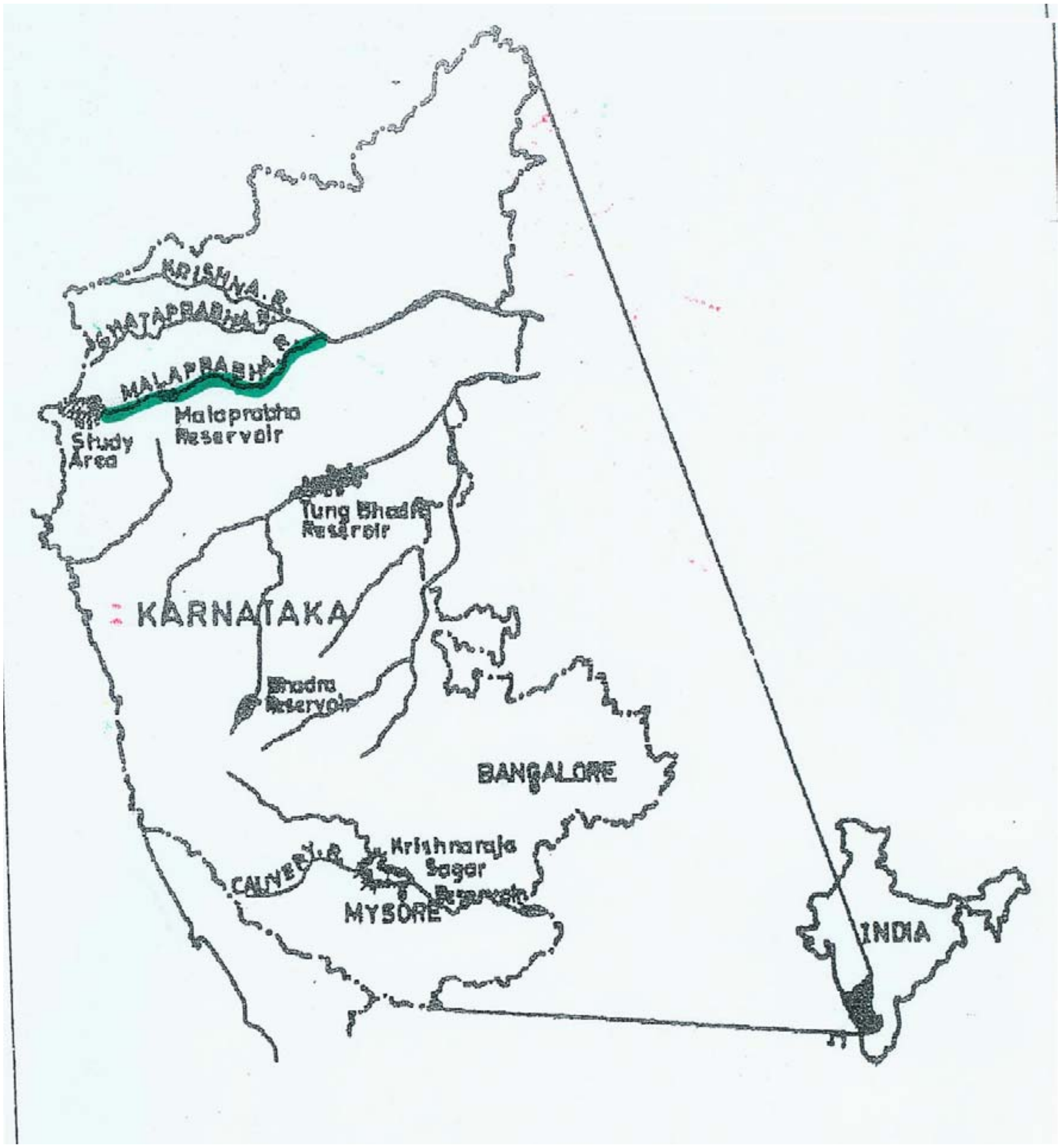


Fig.1. Location Map for Malaprabha River

MATERIALS & METHODS:

The stream water quality and sewage characteristics were analyzed during the period 2006–07. The method of sediment sample collection, transport to the laboratory, preservation and analyses – were all carried out as per the methods and procedures laid in the Standard Methods for the Examination of Water and Wastewater Analysis, APHA publications[4] 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 is 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 in the sediment deposits[2]. 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.

The average flow of the stream during summer was 1.68 m^3/ sec. and the sewage recorded a flow of 0.35 m^3/ sec. The area of the river considered for sediment collection is the average width and the distance up to the study length, i.e. 24 kms. 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 Ø is defined as the fraction of the total volume that is in the liquid phase[5],

$$\phi = \frac{V_L}{V_2} \qquad \ldots\ldots..[1]$$

$$where, \quad V_L = Volume\ of\ the\ liquid\ part\ of\ the\ sediment\ layer, m^3$$
$$V_2 = Total\ volume\ of\ the\ sediment\ layer, m^3$$

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

$$(1-\phi) = \frac{V_p}{V_2} \qquad \ldots\ldots..[2]$$

TABLE – 1

AVERAGE VALUES OF HYDROGEOMETIC PROPERTIES AND SEDIMENT

Sl.No.	Month/ Yr	Depth (m)	Top width meter.	Q (m^3/yr.) $Q_R + Q_S$	S. Solids mg/lt.	Solids loading gm/yr.	Surface Area m^2	Volume m^3	Solids Settling m/yr.
1	Jun,2006	2.350	66.6	165.88 X 10^6	20.0	3.86 X 10^6	1.59 X 10^6	3.76 X 10^6	401.50
2	Jul, 2006	2.750	66.6	1.95 X 10^9	230.0	6.12 X10^{10}	1.59 X 10^6	4.39 X 10^6	839.50
3	Aug,2006	3.130	66.6	2.51 X 10^9	260.0	41.1 X 10^9	1.59 X 10^6	5.0 X 10^6	292.00
4	Sep,2006	2.600	66.6	1.13 X 10^9	120.0	22.4 X 10^9	1.59 X 10^6	4.16 X 10^6	511.00
5	Oct,2006	2.100	66.6	1.83 X 10^8	20.0	6.8 X 10^9	1.59 X 10^6	3.36 X 10^6	803.00
6	Nov,2006		13.8	1.19 X 10^8	12.0	4.2 X 10^9	3.31 X 10^5	2.32 X 10^5	693.50
7	Dec,2006	0.640	12.3	5.65 X 10^7	5.0	4.9 X 10^8	2.94 X 10^5	1.89 X 10^5	912.50
8	Jan,2004	0.520	8.6	3.91 X 10^7	3.0	2.1 X 10^8	2.07 X 10^5	1.08 X 10^5	985.50
9	Feb,2007	0.440	5.8	3.28 X 10^7	3.0	1.38 X 10^8	1.39 X 10^5	0.61 X 10^5	1022.00
10	Mar,2007	0.320	4.3	2.7 X 10^7	2.0	0.68 X 10^8	1.03 X 10^5	3.31 X 10^4	584.00
11	Apr,2007	0.180	2.7	1.79 X 10^7	2.0	0.42 X 10^8	6.46 X 10^4	1.16 X 10^4	511.00
12	May,2007	1.820	20.7	138.12 X 10^6	8.0	1.4 X 10^9	4.96 X 10^5	9.02 X 10^5	401.50

Note: S. Solids = Suspended Solids.

$where, \qquad V_p = Volume\ of\ the\ solid\ or\ particulate\ phase\ of\ the\ sediment, m^3.$

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

$$\rho = \frac{M_2}{V_p} \qquad \ldots\ldots\ldots..[3]$$

where, ρ = Density, g per m^3

and M_2 = Mass of the solid phase in the sediments, gms.

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:

$$m_2 = \frac{M_2}{V_p} \qquad \ldots\ldots\ldots..[4]$$

where, m_2 = Suspended solids concentration in sediments, gms. per ltr.

Eqn. [3] can be solved for:

$$M_2 = \rho \times V_p \qquad \ldots\ldots\ldots.[5]$$

Eqn. [2] can be solved for:

$$V_2 = \frac{V_p}{(1-\phi)} \qquad \ldots\ldots\ldots\ldots..[6]$$

Eqns. [5] and (6) may be substituted in Eqn. (4) to get:

$$m_2 = (1-\phi) \times \rho \qquad \ldots\ldots\ldots[7]$$

Thus we have re-expressed the sediment solids concentration in terms of parameters that are conventionally used to measure porous media. We now use this expression to develop a solids budget for a sediment-water system. In the following discussions, it will be useful to recognize that the term (1- Ø) ρ represents the “suspended solids” concentration of the bottom sediment.

Simple Solids Budget[5]:

Now that we know something about suspend and bottom sediments, we can develop a solids model. 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 re-suspension.

For the first case, following mass balance can be written for the water:

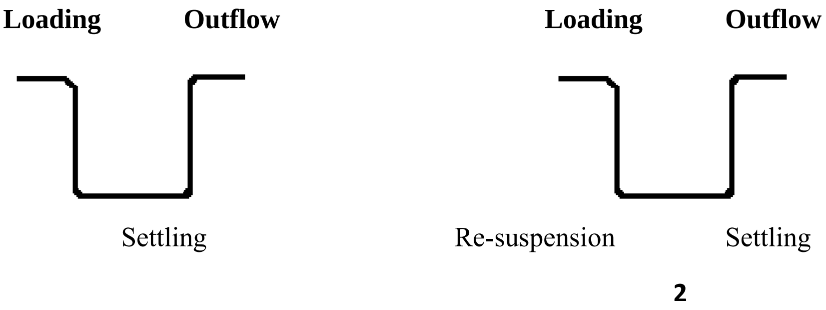
$$V\left(\frac{dm}{dt}\right) = Q.m_{in} - Q.m - v_s.A_s.m \qquad \dots\dots\dots\dots[8]$$

For the first case, following mass balance can be written for the water:

$where,$ $v_s = settling\ velocity, m/yr.$
$A_s = area\ of\ the\ sediment - water\ interface, m^2$

At steady-state condition, Eqn. [6] can be solved for:

$$m = \frac{Q.m_{in}}{(Q + v_s.A_s)} \qquad \dots\dots\dots..[9]$$



a) No sediment-water Interaction

b) Sediment-water interaction

Fig.4

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:

$$V_1\frac{dm_1}{dt} = Qm_{in} - Qm_1 - v_s.A_s.m_1 + v_r.A_s.m_2 \qquad \dots\dots\dots.[10]$$

$$V_2\frac{dm_2}{dt} = v_s.A_s.m_1 - v_r.A_s.m_2 - v_b.A_s.m_2 \qquad \dots\dots\dots.[11]$$

$where,$ $v_r = resuspension\ velocity,\ m/yr.$
$v_b = burial\ velocity,\ m/yr.$

Eqn. [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:

$$0 = Q.m_{in} - Q.m - v_s.A_s.m + v_r.A_s.(1-\phi).\rho \qquad \text{.......[12]}$$

$$v_s.A_s.m - v_r.A_s.(1-\phi).\rho - v_b.A_s.(1-\phi).\rho \qquad \text{........[13]}$$

Then, Eqn. [9] may be solved for

$$(1-\phi).\rho = \frac{v_s.m}{(v_r + v_b)} \qquad \ldots\ldots\ldots [14]$$

which can be substituted in Eqn. [8], and the result solved for:

$$m = \frac{Q.m_{in}}{[v_s.A_s.(1-F_r)]} \qquad \ldots\ldots..[15]$$

where, F_r is the re-suspension factor that is defined as:

$$F_r = \frac{v_r}{(v_r + v_b)} \qquad \ldots\ldots\ldots\ldots[16]$$

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 re-suspension. Thus, if burial dominates re-suspension, i.e. $v_b \gg v_r$, the re-suspension factor $F_r \sim 0$, and Eqn. [11] reduces to a well-mixed model with no sediments. On the other hand, if re-suspension dominates burial, i.e. $v_r \gg v_b$, Fr ~ 1, and Eqn. [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 $\rho,\ \phi,\ m, m_{in}, Q,\ A_s, v_s, v_r$ and v_b. For the steady state case Eqns. [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 ρ and ϕ are known. Typical values of ρ and ϕ for fine-grained sediments are $2.4\ to\ 2.7 \times 10^6\ \ gms/m^3$ 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 re-suspension 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 Eqns. [8] and [9] may be added to give:

$$0 = Q.m_{in} - Qm - v_b.A_s(1-\phi).\rho \qquad \ldots\ldots\ldots[17]$$

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

$$v_b = \frac{Q.(m_{min} - m)}{[A_s.(1-\phi).\rho]} \qquad \ldots\ldots\ldots[18]$$

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 re-suspension velocity can then be estimated by solving the steady state version of Eqn.[9] as:

$$v_r = \left\{\frac{v_s.m}{[(1-\phi).\rho]}\right\} - v_b \qquad \ldots\ldots..[19]$$

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 these models represent a simplified form of the dynamics of solids in such systems. Rather, it is found that the sediment re-suspension 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, and such lumped models are useful in areas such as toxicant modeling. 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. The Fig.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 lastly, 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 interface is static and the sediments advecting downward.

In case of a dissolved contaminant the three mechanisms can be combined into the following mass balance as shown in Fig.5:

$$\frac{\delta c}{\delta t} = -v_b\left(\frac{\delta c}{\delta z}\right) + \phi . D . \left(\frac{\delta^2 c}{\delta z^2}\right) - kc \qquad \text{- - - - - [20]}$$

where, c = concentration of a dissolved contaminant, mg/ lt.

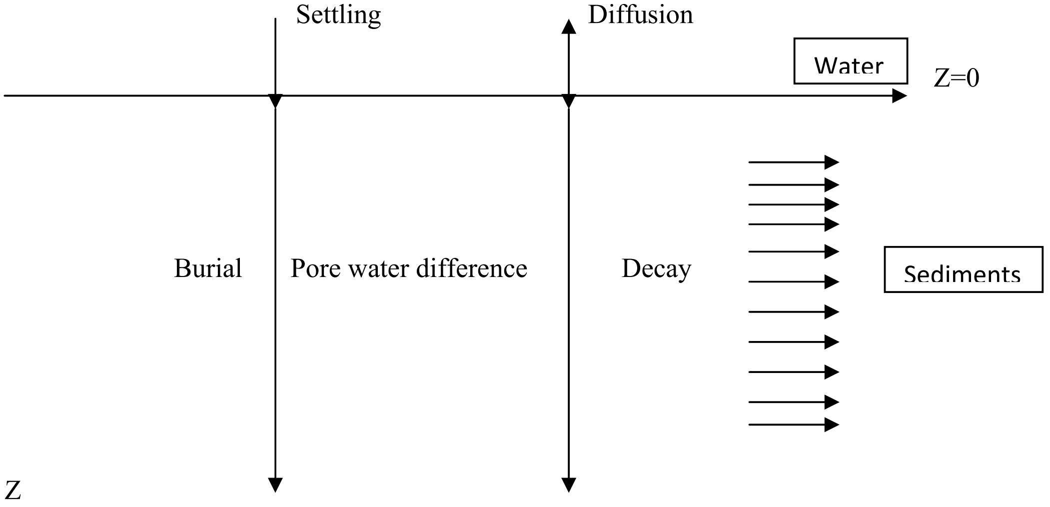


Fig. 5. Schematic of a sediment viewed as a vertical distributed system

where,

$v_b = Burial\ velocity, m/yr.$

$c = concntration\ of\ a\ dissolved\ contaminant, mg/lt.$

$D = An\ effective\ diffusion\ coefficient\ through\ the\ sediment\ pore\ waters, m^2/yr.$

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 Eqn.[16] becomes:

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

with boundary conditions,

$$c\,(0,t) = c_0$$
$$c\,(\infty,t) = 0$$

Then, the solution for the equation is given by:

$$c = c_0 . e^{zl} \qquad \text{- - - - - - [22]}$$

Where,

$$l = \left(\frac{v_b}{2\phi . D}\right) \times \left\{1 - \left[\sqrt{1 + \frac{4\phi . D}{v_b^2}}\right]\right\} \qquad \text{- - - - - [23]}$$

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 re-suspension 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/ lt., during July, 2006, 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/ lt. which is during April, 2007. This value again increased during the period of May, 2007 which can be attributed to the pre-monsoon showers.

Marked variations were also found in burial and re-suspension velocities at different months of the year. The maximum value of v_b was estimated during November, 2006, when naturally, the re-suspension velocity, i.e. v_r was minimum i.e. – 0.00023 m/ yr. 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, 2006, i.e. – 1.602 $m/yr.$, and naturally the re-suspension velocity, v_r was at its peak during this period. This clearly indicates that velocity generated during this period was all re-suspension, and there was hardly any settling of particles. This may be due to the high currents that generally develop during rainy season. The values of re-suspension 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.

TABLE - 2
RESUSPENSION VELOCITIES

Sl.No.	Month/ year	m_{in} mg/lt.	Burial vel. (m/yr.) v_b	Re-suspension vel. (m/yr) v_r
1	June, 2006	23.50	0.001520	0.03190
2	July, 2006	31.50	-0.001010	0.80600
3	August, 2006	16.50	-1.602000	1.91800
4	September, 2006	19.80	-0.296700	0.55300
5	October, 2006	37.20	0.008250	0.05870
6	November, 2006	35.30	0.034900	-0.00023
7	December, 2006	8.70	0.002960	0.01605
8	January, 2007	5.40	0.001890	0.01040
9	February, 20067	4.21	0.000012	0.01280
10	March, 2007	2.50	0.000546	0.00432
11	April, 2007	2.35	0.000405	0.00385
12	May, 2007	10.00	0.002320	0.01110

A comparative graphical representation is presented in Fig.6, which clearly shows the difference between the two velocities depicting the fact that when one is at its maximum, the other is minimum.

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 re-suspension velocity predominates the burial velocity. A minimum settling velocity of $292 m/yr.$, was observed during August, 2006 and the maximum of $1022 m/yr.$, during February, 2007. Quiescent conditions which prevail during pre-monsoon period, favored the settling of solids.

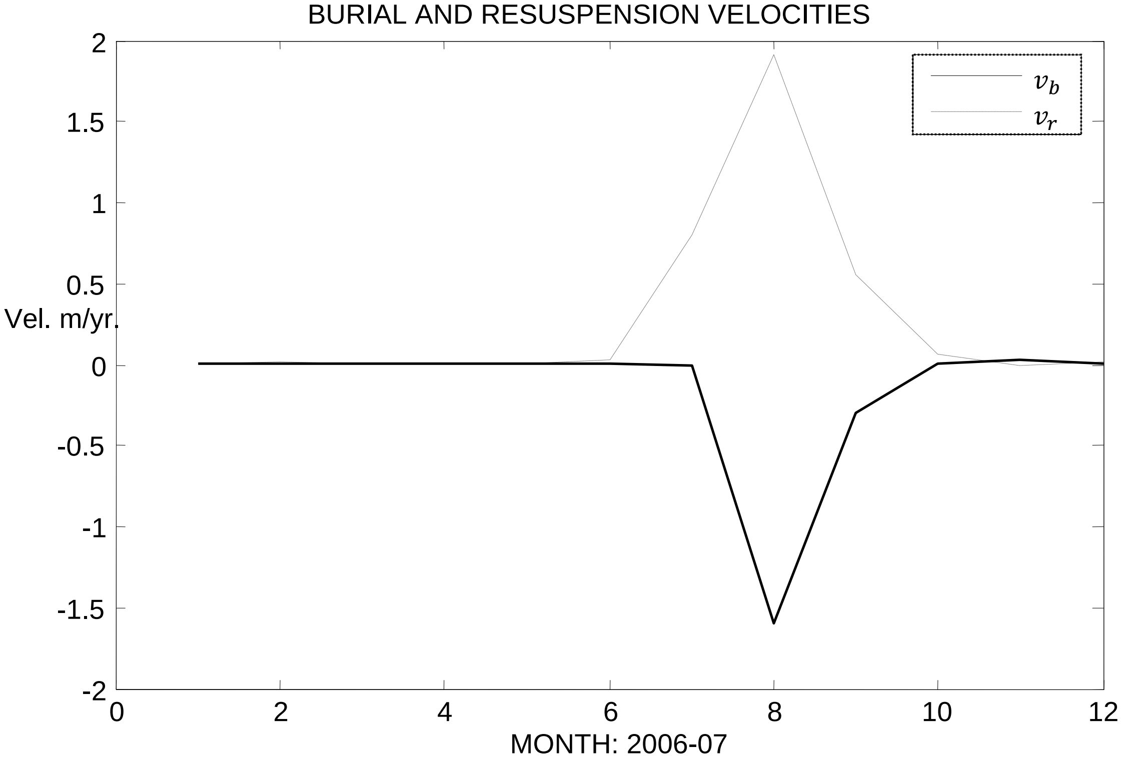


Fig. 6. Burial and Re-suspension velocities.

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