ANALYTICAL ESTIMATION OF SEDIMENT TRANSPORT IN RIVER INTO A NEARSHORE ZONE – A LIFE OF SEDIMENT IN AN AQUATIC ZONE

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ABSTRACT: To achieve sustainable development of coastal zone, overview of sediment budget and especially the estimation of sediment supply from a river into nearshore zone through a river mouth are important. However, quantitative estimations of sediment production and transport in land, river mouth and nearshore zone have not been synthesized yet. Therefore, a general analytical scheme for sediment budget originating from inland leading to nearshore zone is necessary to get an insight into the characteristics of transportation and deposition rates on a regional long term scale and time. Moreover, regional sediment analysis should be made simple for stakeholders who may have insufficient mathematical and numerical background but have good experience in management of sediment (sand) in order to allow handling and application of the model with ease and convenience first. Then if necessary, each sub model for different sub-region can be developed more in detail based on up to date knowledge, and assembled in the main program. Thus, macroscopic civil engineering approaches such as sediment transport in river and coastal regions, and the advection-diffusion process at the river mouth are partially applied to develop the synthetic regional sediment model. The proposed model covers a hydraulic region starting from the mountain area to the nearshore zone through the river channel and river mouth.

KEYWORDS: regional sediment budget, synthesized model, topographic change in nearshore zone.

1. Introduction

Sediment on a sandy beach is generally supplied from two major sources; i.e. (i) riverine sediment and (ii) erosion of coastal cliff. The other sources are (iii) carbonate material especially in tropical and sub-tropical regions, (iv) volcanic debris and (v) beach nourishment. In recent years, it is widely recognized that sediment production in a catchment area has become a crucial problem in coastal management. Sediment production generates most of the physical changes in the river bed and nearshore topography as shown in Photo 1. The sediment transport along the river and coastal area can be explained by a scheme of sand budget.

Nishi (2008), Rosati (2005), Dean (1986), Chapman (1981) have attempted to assess the impact of quantitative estimations of sediment production and transport in river to nearshore zone, even though this problem has not been fully established yet. In this study, the problems associated with a regional sediment transport have been addressed by a simple analytical scheme that describes upstream-downstream transport which starts from the mountain to the sabo dam passing through a river (hydraulic dam), then discharging at the river mouth, and finally distributing into the nearshore zone. Macroscopic civil engineering approaches such as control box and continuity equation approach have been applied for each sub-region. In this case, each control box is connected one by one, in other words, each continuity equation should be solved one by one to downstream direction. Thus, shoreline retreat or profile erosion can be estimated in the last part of the program.

Photo 1. Example of beach erosion by decrease in sediment supply from a river

Photo 2. Example of sabo dam which controls the size of debris and stones

2. Schematization of regional sediment transport system

Schematic diagram of regional sediment transport system is shown in Fig. 1. The origin of the sediments is reckoned with respect to the mountain area considered as the initial point. The sediment transport path is described by its flow through a river directed toward the river mouth and discharged into the nearshore zone. Occurrence of a heavy rainfall causes an erosion of ground surface, may land slide, and sediment torrents in the mountain catchment. Combinations of debris flow, damming of rivers, floods and dam breaching bring huge volumes of sediment to nearshore area.

Erosion control structure such as a sabo dam is designed to prevent disasters due to debris flow. Sabo dams built in the upstream areas of mountain streams accumulate sediment and suppress production and flow of sediment. The dam such as shown in Photo 2 allows sediment to flow downstream. When a large scale debris flow occurs, sediment is captured and temporarily held to prevent disasters in downstream.

Sediment may undergo 3 paths during a movement period from mountain to nearshore area through various mechanisms in this idealized approach;

1) Production path in mountain (collapse, landslide, erosion, etc.)
2) Run-off path (bed load transport, suspended load transport, wash load transport, dredging in a river, etc.)
3) Distribution path (river mouth, nearshore zone, and offshore zone).

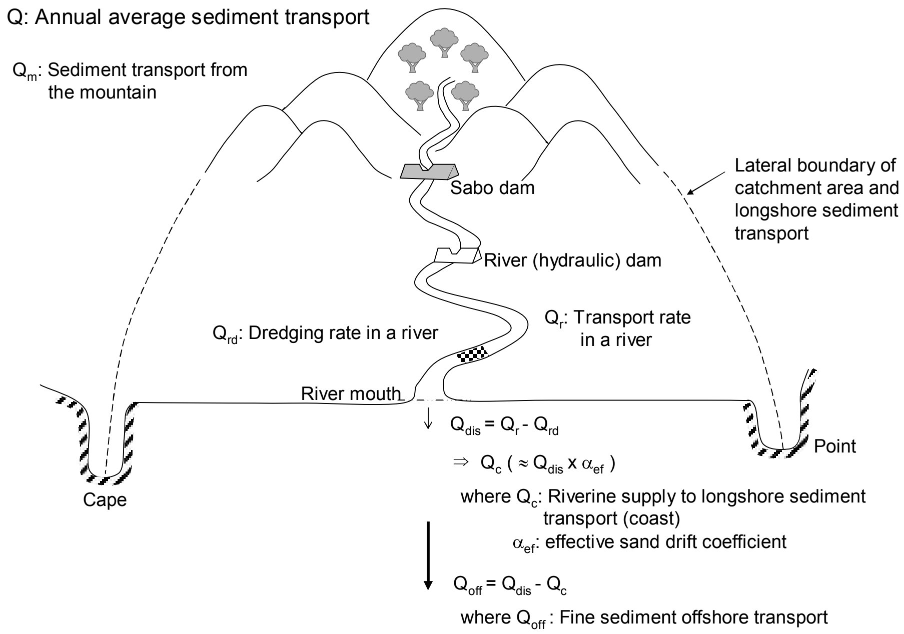


Figure 1. Schematic transport path from inland to the nearshore zone

In order to describe regional sediment transport system, the path of inland sediments originating from the mountains which are transported by the river passing through boundary control structures i.e. sabo dam, and river dam, and discharged at the river mouth distributing into coastal zone is an essential parameter for analysis. Figure 1 shows the transport path and the intervention structures involved. Each path shows the scheme to predict characteristic changes of transportation and deposition sediment rates in space and time.

Figure 2 shows the connection of sub-regions and continuity relationships of sediment transport originated from inland. The sediment transport system in Fig. 2 is a sort of basic version, therefore, any sub-regions, sediment transport mechanism or control boxes can be added for user's application. Thus, change in sediment volume in certain control box can then be quantified.

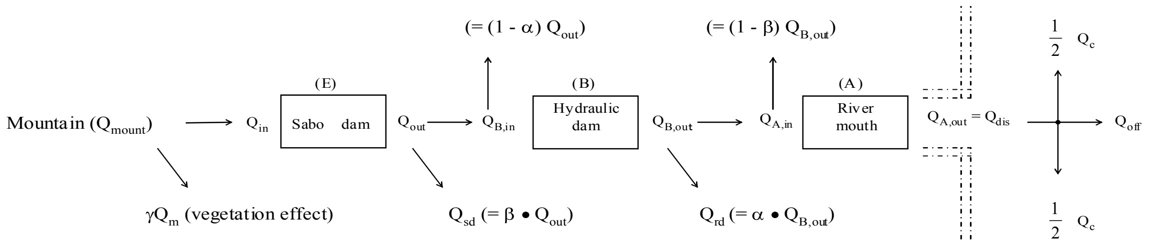
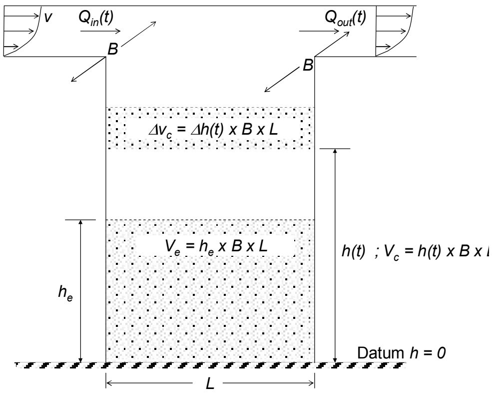


Figure 2. The connection of major control boxes to the nearshore zone through the river mouth

Figure 3 shows the schematic diagram of volume change in a control box. Q_{in} indicates the sediment transport inflow control box and Q_{out} is sediment outflow to and from control box. The volume of sediment in an equilibrium condition; $V_e = h_e$ (equilibrium height) x B (box width) x L (box length). Temporal volume of sediment in the control box; $V(t) = h(t)$ (height sediment deposition) x B (box width) x L (box length).



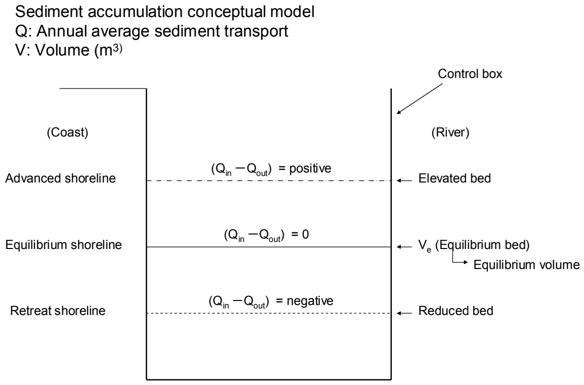


Figure 3. Schematic diagram of sediment volume change in a control box

Figure 4. Schematic diagram of river bed and shoreline change in a control box

Figure 4 shows how the net transport (or the net volume) in the control box affects the change in river bed elevation and shoreline position, schematically.

The sand budget of certain control box such as shown in Fig. 3 can be represented by;

$$\frac{\Delta V_c(t)}{\Delta t} = Q_{in} - Q_{out} \tag{1}$$

where,

Q_{in} : inflow (assuming a steady-state flow at this moment)
Q_{out} : outflow (in the control box)

In addition, the average runoff Q_{out} can be proportional to the inflow rate Q_{in}, and the ratio of temporal sand volume to equilibrium condition in general, therefore;

$$Q_{out}=\frac{V_c}{V_e}Q_{in}=\frac{Q_{in}}{V_e}V_c \tag{2}$$

Thus, the continuity equation (1) can be modified as;

$$\frac{\Delta V_c(t)}{\Delta t}=Q_{in}-\frac{V_c}{V_e}Q_{in}=Q_{in}\left(1-\frac{V_c}{V_e}\right) \tag{3}$$

The solution to Eq. (3) is defined as,

$$V_c(t)=V_e\left(1-e^{-\frac{Q_{in}}{V_e}t}\right) \tag{4}$$

The derivation of Eq. (4) from Eq. (3) will be shown in the Appendix. In the same manner, the sand volume at time *t* can be derived for each control box. Then, it is noted that each control box is connected by $Q_{out\ (upstream)} = Q_{in\ (downstream)}$ relationship.

The succeeding equations describe the amount of sediments transported from upstream to downstream and deposited due to the presence of hydraulic structures (dams) with reference to Fig. 2. Finally the change in the amount of sediment at the river mouth sub-region (A) is represented by the following,

$$\begin{aligned}\frac{\Delta V_A}{\Delta t}&=(Q_A)_{in}-(Q_A)_{out}\\&=\frac{V_E}{V_B}\frac{V_{E,e}}{V_{B,e}}Q_{in}-\frac{V_A}{V_{A,e}}\left(\frac{V_B}{V_{B,e}}.\frac{V_E}{V_{E,e}}Q_{in}\right)\\&=\frac{V_E}{V_B}\frac{V_{E,e}}{V_{B,e}}\left(1-\frac{V_A}{V_{A,e}}\right)Q_{in}\\&=\left(1-\frac{V_A}{V_{A,e}}\right)\hat{\hat{Q}}_{in}\end{aligned} \tag{5}$$

where subscripts A, B, E denote sub-region river mouth, hydraulic dam and sabo dam respectively;

$$\hat{\hat{Q}}_{in}=\frac{V_E}{V_{E,e}}\frac{V_B}{V_{B,e}}Q_{in}$$

In Fig. 2, the change in the volume of sediment transported due to the presence of sabo dam (E) is defined as,

$$\frac{\Delta V_E}{\Delta t}=Q_{in}-Q_{out}=Q_{in}-\frac{V_E}{V_{E,e}}Q_{in}$$

$$= \left(1 - \frac{V_E}{V_{E,e}}\right) Q_{in} \tag{6}$$

In the region where the river dam (B) is situated, the sediment balance is described as,

$$\begin{aligned}
\frac{\Delta V_B}{\Delta t} &= (Q_B)_{in} - (Q_B)_{out} \\
&= \frac{V_E}{V_{E,e}} Q_{in} - \frac{V_B}{V_{B,e}} (Q_B)_{in} \\
&= \frac{V_E}{V_{E,e}} Q_{in} - \frac{V_B}{V_{B,e}} \cdot \frac{V_E}{V_{E,e}} Q_{in} \\
&= \frac{V_E}{V_{E,e}} \left(1 - \frac{V_B}{V_{B,e}}\right) Q_{in} \\
&= \frac{V_E}{V_{E,e}} \left(1 - \frac{V_B}{V_{B,e}}\right) Q_{in}
\end{aligned} \tag{7}$$

where

$$(Q_B)_{in} = Q_{out}$$

$$Q_{out} = \frac{V_E}{V_{E,e}} Q_{in} \tag{8}$$

Q_{in} in this equation is represented by $\hat{Q}$ which results to,

$$\frac{\Delta V_B}{\Delta t} = \left(1 - \frac{V_B}{V_{B,e}}\right) \hat{Q}_{in} \tag{9}$$

where

$$\hat{Q}_{in} = \frac{V_E}{V_{E,e}} Q_{in}$$

The numerical calculation to quantify the change in volume of sediment for each region described in Fig. 2 employs for instance the Runge Kutta Method. In the region where the sabo dam is situated, the change in volume of sediment is defined as,

$$\frac{\Delta V_E}{\Delta t} = \left(1 - \frac{V_E}{V_{E,e}}\right) Q_{in} \tag{10}$$

Applying the Runge Kutta scheme, the solution is as follows,

$$\frac{\left(V_E^{\,t+1} - V_E^{\,t}\right)}{\Delta t} = \left(1 - \frac{V_E^{\,t}}{V_{E,e}}\right) Q_{in}^{\,t} \tag{11}$$

$$V_E^{\,t+1} = (\Delta t) \cdot \left(1 - \frac{V_E^{\,t}}{V_{E,e}}\right) Q_{in}^{\,t} + V_E^{\,t} \tag{12}$$

However, for the stability of the calculation, it is better to apply the implicit method. Discretization of the equation by the implicit method is presented as follows;
At the sabo dam (E) location,

$$V_E^{t+1} = \frac{\Delta t}{2\left(1+\frac{\Delta t}{2V_{E,e}}Q_{in}^{t+1}\right)} \cdot \left[Q_{in}^{t+1} + Q_{in}^{t} + \left(1-\frac{\Delta t}{2V_{E,e}}Q_{in}^{t}\right)V_E^{t}\right] \tag{13}$$

At the river dam (B),

$$V_B^{t+1} = \frac{\Delta t}{2\left(1+\frac{\Delta t}{2V_{B,e}}\hat{Q}_{in}^{t+1}\right)} \cdot \left[\hat{Q}_{in}^{t+1} + \hat{Q}_{in}^{t} + \left(1-\frac{\Delta t}{2V_{B,e}}\hat{Q}_{in}^{t}\right)V_B^{t}\right] \tag{14}$$

At the river mouth (A),

$$V_A^{t+1} = \frac{\Delta t}{2\left(1+\frac{\Delta t}{2V_{A,e}}\hat{\hat{Q}}_{in}^{t+1}\right)} \cdot \left[\hat{\hat{Q}}_{in}^{t+1} + \hat{\hat{Q}}_{in}^{t} + \left(1-\frac{\Delta t}{2V_{A,e}}\hat{\hat{Q}}_{in}^{t}\right)V_A^{t}\right] \tag{15}$$

The above discretized equations quantitatively will estimate the amount of material transported at a given time from upstream to downstream with respect to the regions (hydraulic structures and river mouth) in consideration. As river flood water flows out from the river mouth to the nearshore area, finer sediments are also further transported offshore, and proper (medium, coarse) sediment transported longshore. The sediment transport mechanism can be described by means of the advection-diffusion phenomena. Photo 4 shows a visualization of the transportation of sediments from the river mouth to offshore. The amount of sediments discharged from the river mouth is dependent upon the supply from the source as a result of flooding and river overflow. Regarding coastal management and shore protection, the estimation of the longshore component of sediment discharge at river mouth is necessary because it is effective to maintain the sandy beach. The amount of the sediment transported along the shore (Q_c) is a function of $Q_{Aout} (= Q_{dis})$ multiplied by an effective sand drift coefficient (α_{ef}).

3. Diffusion and advection process

As an example, a schematic diagram of the nearshore sediment transport is shown in Fig. 5, where the y axis represents the coast, x axis for offshore, and z axis to indicate the concentration of the sediments in the nearshore described by the turbidity of the water. To determine the concentration of the material diffused in the nearshore zone, Eq. (16) can be applied as the first order approximation.

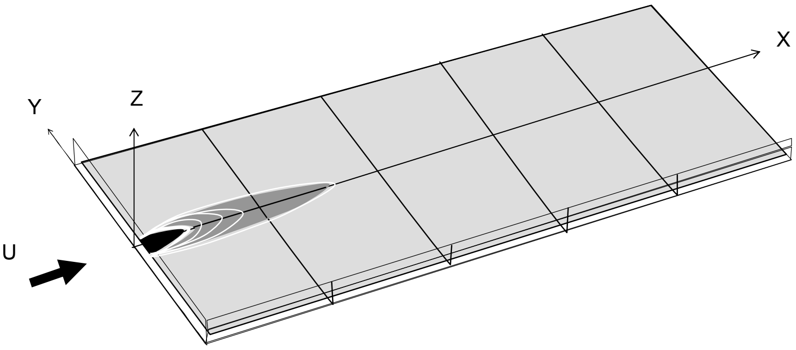


Figure 5. Schematic diagram of a coordinate system

$$C(x,y,z)=\frac{Q}{2\pi U(\sigma_y\sigma_z)}\exp\left\{-\frac{y^2}{2\sigma_y^2}\right\}\times\left[\exp\left\{-\frac{(H-z)^2}{2\sigma_2^z}\right\}+\exp\left\{-\frac{(H+z)^2}{2\sigma_2^z}\right\}\right] \quad (16)$$

where

$$\sigma_y=\sqrt{2K_y x/U}$$

$$\sigma_z=\sqrt{2K_z x/U} \quad (17)$$

σ_y, σ_z : diffusion width (m)
C : suspended sediment concentration (mg/l)
H : height from the source (m)
Q : sediment transport rate (g/sec)
K_y, K_z : turbulence diffusion coefficient (m^2/s)
U : velocity in the x direction (m/s)

4. Sediment transport in nearshore zone

Nearshore hydrodynamics such as longshore current and rip current play an important role in the diffusion of the sediments in the nearshore zone as river water transporting sediment material is discharged at the river mouth (Photo 3). Wave set-up and set-down provide the longshore head of water to drive the feeder currents and produce the rip currents. This current is responsible for the transport of sediment offshore as shown in Photo 4.

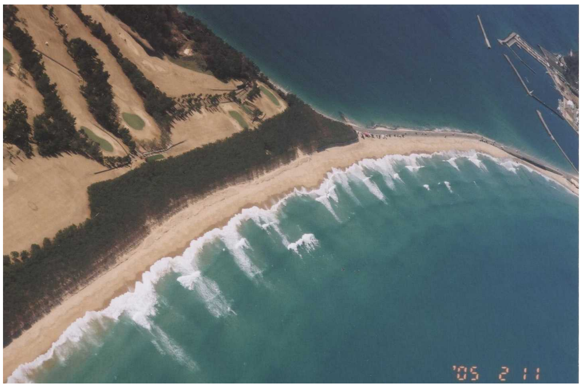


Photo 3. Series of nearshore circulations

Photo 4. Rip currents transporting sediment offshore

In general, longshore sediment transport plays major role in terms of long term shoreline change and corresponding shore protection. The equation for longshore sediment transport is defined as,

$$Q = (H^2 C_g)_b (a_1 \sin 2\theta_{bs} - a_2 \cos 2\theta_{bs} \frac{\partial H}{\partial x})_b \tag{18}$$

where H is wave heigth, C_g is group velocity, θ_{bs} is incident wave angle at breaking point and subscript b represents the breaking wave conditions.

Once the Q including the longshore component of the river discharge is estimated, change in shoreline position (or erosion and accretion rates) can be simulated by;

$$\frac{\partial y}{\partial t} + \left(\frac{\partial Q}{\partial x} - q \right) = 0 \tag{19}$$

where y is shoreline position, Q is longshore sediment transport rate, and q is additional sediment transport rate. Therefore, the change in shoreline position here as a function of sediment transport in time and space is one-dimensional. Based on this approach, the appropriate quantitative estimation of sediment transport needs to be managed.

4. Concluding remarks

A simple analytical model is developed to get the understanding of characteristics of sediment transport and deposition rates in sub-aquatic environment. The proposed model covers a hydraulic region originating from the mountain area to the nearshore zone through the river channel and river mouth. In addition, this approach can be applied to asses the impact of sea level rise on the change in shoreline and nearshore profile.

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Appendix

Prediction of a mass balance in Eq. (4) - induced the balance of the material inside in the control box,

$$\frac{\Delta V_c(t)}{\Delta t} = Q_{in} - Q_{out} = Q_{in} - \frac{V_c}{V_e} Q_{in}$$

$$= Q_{in}(1 - \frac{V_c}{V_e}) \quad \text{(A1)}$$

where the following variables are represented;

$$\Delta V_c(t) = \Delta y \quad , \quad Q_{in} = A \quad , \quad V_e = B$$

Substituting the variables to Eq. (A1) results to,

$$\frac{\Delta y}{\Delta t} = A(1 - \frac{y}{B})$$

$$= \frac{A}{B}(B - y) \quad \text{(A2)}$$

Using separation of variables and integrating both sides yields,

$$\frac{dy}{B - y} = \frac{A}{B} dt$$

$$\int \frac{1}{B - y} dy = \int \frac{A}{B} dt$$

$$-\log(B - y) = \frac{A}{B} t + C \quad \text{(A3)}$$

$$B - y = e^{-\frac{A}{B}t - c}$$

$$= e^{-\frac{A}{B}t} \cdot C$$

Thus,

$$y = B - C \cdot e^{\frac{-A}{B}t}$$

$$V_c(t) = V_e - C \cdot e^{-\frac{Q_{in}}{V_e}t} \quad \text{(A4)}$$

Applying the initial conditions at $t = 0$, $V_c(t) = 0$

$$V_c(t) = V_e - C \cdot 1 = 0$$

Thus, the integration of constant C;

$$C = V_e$$

Therefore, the solution to Eq. (A1) is,

$$V_c(t) = V_e(1 - e^{-\frac{Q_{in}}{V_e}}) \quad \text{(A5)}$$