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THE BASIN-WIDE TWO-DIMENSIONAL MODEL OF SEDIMENT PRODUCTION AND TRANSPORTATION FOR ESTUARY SEDIMENT SIMULATION

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Abstract: Researches and observation in Japan shows that seashore profile change around an estuary is apparently related to the volume of river's sediment input, and a model to generate this sediment input becomes necessary for estuary sediment transportation simulation. In this research, the physics-based, two-dimensional model for non-uniform sediment production is presented. In this model, the governing equations of diffusive wave model are employed to route the surface water flow. Meanwhile, sediment is produced from each grid relating to rainfall intensity, velocity, steepest slope, land use, etc. After that, the concentration continuity equation is utilized to depict the sediment transportation across the basin. Then, the sediment gradually reaches and accumulates in the channel, in which it falls into and is computed in two transportation patterns: bed load and suspended load, according to the flow capacity. One-dimensional equations are adopted to simulate the sediment movements in the river and riverbed change, and finally output the sediment volume and hydrograph that can be utilized as input or boundary conditions for estuary simulation. The model is verified in a miniature test basin and a trial run is carried out in a real watershed.

Key words: Estuary, Sediment, Sediment control

1. INTRODUCTION AND LITERATURE REVIEW

In Japan, there are plenty of studies and observations that related seashore profile change and erosion around the estuary to sediment input of the river. An estuary, as the terminal of river sediment transportation, is the important source of beach sediment transportation (Yoshida, 2003). Reservoir construction boomed during 1960s in Japan, and this resulted in abrupt cut of sediment supply to seashores around the estuary and in turn caused beach erosion (Sato and Aita, 1975). Kajimura, et al. (2001) and Sato (2003) had undertaken separately long-term investigations in the beach change of the Nakoso Coast, located at Fukushima Prefecture alongside the Pacific Ocean, from 1960 to 2000. In this period, two dams were constructed, in 1962 and 1984 respectively, on the Samekawa River flowing into the Ocean along the beach. There were data shown that, after the second dam's construction, annual average deposition before the two dams is $1.3\times10^5 m^3$/year, which is roughly equal to the decrease of seashore sediment transportation volume, $1.0\times10^5 m^3$/year. This correlation reveals that beach profile change around the estuary depends largely on the sediment supply from the river. Another research shows that drainage channels also affect beach profiles (Iwaya, 1998). A survey of the world's seashores points out that this phenomenon (river's sediment supply change accounts for part of the beach profile variation) is not unique on Japan's seashores (Marine Construction Technological Committee, 2001).

In order to reach accurate model output of beach profile change simulation around an estuary, it is apparent that data of sediment input from the river are necessary. This research presents a physics-based, two-dimensional model for producing sediment time series (sediment discharge hydrograph) during a rain event and/or a period without rain, applying to rivers with and without dams.

In the late of 20th century, the deposition issues in reservoirs became more and more severe and began to bother Japanese Engineers and researches. Among these issues, the most difficult one is determination of sediment volume produced on the slopes of the basin. In that age, distributed hydrological models were not so popular as later years just before the dawning of the 21st century when more powerful PCs have been developed. Many lumped models for sediment production from a basin had been developed in Japan, as well as in the other parts of the world. Takebayashi, et al. (1992) gave a summary to these models applied in Japan, and a report by Deposition Flushing Division of Dam Technology Committee (2001) also included two models employed in the United States.

All the above models developed linear and/or non-linear relations of sediment production with all or some of the following factors: watershed area; slope; area of landslide; land use; precipitation; flood runoff; reservoir storage; etc. However, dots of observation data and model outputs in correlation charts scattered up and suggest very weak correlation between them (Takabayashi, 1992). This phenomenon may be caused by the complexity of a real basin. Realizing this point, researchers began to turn to the distributed models, which decompose a large basin into smaller grids and therefore reduced the complexity of each grid.

In recent years, some distributed models were available in Japan. However, many these models routed the overland flow with kinematic wave model equations and sediment transport dose not involve the continuity equation. These models are not physics-based distributed models, but just lumped models applied to grids.

Johnson et al. (2000) developed a physics-based, two-dimensional upland erosion model (CASC2D-SED) and Julien and Rojas (2002) improved the same model by introducing sediment transportation in the channel. In this model, the overland flow is routed with diffusive wave model equations, and an empirical function is employed to account slope sediment production or upland erosion as the authors' terming. In the function, sediment discharge is related to water flow discharge, slope, soil and vegetation properties, and conservation practices. However, the sediment discharges in x and y directions are directly related to those water flow components and the concentration continuity equation is not involved. One merit of this model is that sediment is split into three classes (sand, silt and clay), and can be taken as a non-uniform sediment model. And in the channel, sediment deposition is possible but erosion is not allowed.

In this research, a fully physics-based, two-dimensional watershed sediment production and transportation model is developed. In the model, two-dimensional diffusive wave model equations are employed to simulate the water flows (both overland flow and channel flow) in the watershed, concentration continuity equation is adopted to govern the sediment transportation on the overland grids while two new lateral terms are introduce to the equation to account sediment production on the slope. In the channel, both bed load and suspended load are computed and the suspended load is accounted with the concentration continuity equation. In addition, this model is a fully multi-particle-size model and sediment can be simulated in a particle distribution at will. Finally, this model not only can produce long-term and/or short-term sediment discharge hydrograph at the basin outlet or any spot along the stream system, but also can simulate riverbed change due to deposition and/or erosion, in channels with or without dams.

2. AN INTRODUCTION TO LUO-TAMAI MODEL FOR SURFACE WATER FLOW

The LUO-TAMI model (Luo, 2000) has been developed for water balance simulation in large-scale complex watersheds (LCW), which include not only mountainous areas but also a large fraction of flatland. It has also a complex stream system with reservoirs, lakes, conjunctions, divergences, loop channels, sources, etc, as well as human impacts. The main features of this model are: 1) both overland grids and channel grids are placed in the same physical frame and governed by the same set of equations; 2) channel grids are not the boundary conditions of the overland grids but grids with the same properties as the overland grids, and therefore, there are not only mass exchanges but also momentum exchanges between them; 3) it resolves easily the difficulties in the routing of surface flows in a flat basin, in channels with conjunctions, divergences, loop channels, lakes and reservoirs. Together, this model runs with the evapotranspiration model, infiltration model and groundwater models (Luo, et al., 2000). The model can output discharge hydrograph at any point on the stream system, and of course the outlet of the watershed. In this section, the LUO-TAMAI model is introduced briefly.

The two-dimensional diffusive wave model Saint Venant equations are utilized as the governing differential equations, which can be derived from the two-dimensional free surface flow equations after some simplifications. They are written as below:

$$\begin{cases} \dfrac{\partial(uh)}{\partial x} + \dfrac{\partial(vh)}{\partial y} + \dfrac{\partial h}{\partial t} = q \\ \dfrac{\partial z}{\partial x} + S_{fx} = 0 \\ \dfrac{\partial z}{\partial y} + S_{fy} = 0 \end{cases} \tag{1}$$

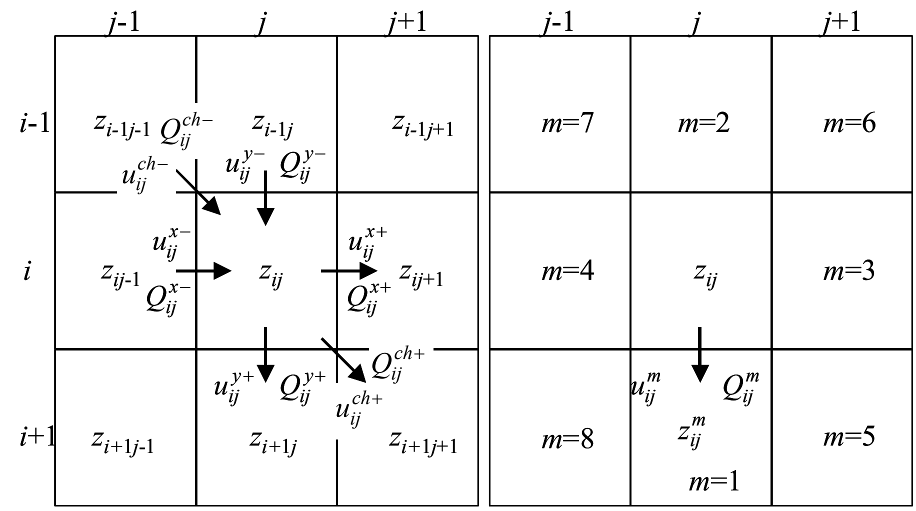
where u and v are the x and y components of velocity respectively, h is the water depth, z is the elevation of the water surface and $z = h + z_0$, z_0 is the land surface elevation, q is the lateral flow in the vertical dimension, S_{fx} and S_{fy} is the friction slopes in x and y directions respectively, which can be obtained from the following Manning equations:

$$\begin{cases} S_{fx} = \left(n_x^2 u|u|\right)/\left(h^{4/3}\right) \\ S_{fy} = \left(n_y^2 v|v|\right)/\left(h^{4/3}\right) \end{cases} \tag{2}$$

in which n_x and n_y are the Manning coefficients in x and y directions respectively. From equation (2), one can see that the friction slope S_{fx} and S_{fy} have the same directions with the velocities of u and v respectively.

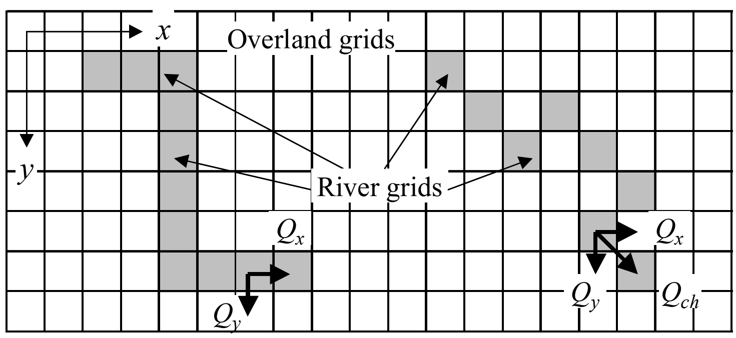
In order to route the basin's flat areas correctly, the staggered scheme (Fig. 1) is adopted to discretize the governing equations. Once a direction is assigned to the flow (positive for flowing out of the grid, and negative for in flow), flows in Fig. 1 (a) can be denoted in a simplified way as Fig. 1 (b). Considering the possible flow direction of diagonal for channel grids (Fig. 2), the governing equations become:

$$\begin{cases} \dfrac{1}{\Delta x \Delta y} \sum\limits_{m=1}^{9} u_m \overline{A}_m + \dfrac{\Delta h}{\Delta t} \dfrac{A_g}{\Delta x \Delta y} = q \\ u_m \overline{A}_m = \dfrac{\overline{A}_m \overline{R}_m^{\,2/3}}{\overline{n}_m \sqrt{L|\Delta z_m|}} \Delta z_m = \overline{A}_m B_m \Delta z_m , \quad (m = 1,2,...,9) \end{cases} \tag{3}$$



(a) The staggered grid (b) Simplified denotation

Fig. 1 The staggered grid scheme in this research



(a) (b)

Fig. 2 Possible river flow directions and discharges

in which all subscripts of ij are omitted, and:

$$\begin{cases} \Delta z_m = z_{ij} - z_{ij}^m \\ B_m = \overline{R}_m{}^{2/3} \Big/ \left(\overline{n}_m \sqrt{L|\Delta z_m|} \right) \end{cases} \tag{4}$$

For a more effective convergence of numerical solutions, the SIMPLE algorithm is adopted to solve equations (3).

3. SEDIMENT PRODUCTION AND TRANSPORTATION ON OVERLAND GRIDS

On overland grids, the modified two-dimensional concentration continuity equation is employed to govern the sediment transportation of sediment:

$$\frac{\partial(\overline{c}_l h)}{\partial t} + \frac{\partial(\overline{c}_l uh)}{\partial x} + \frac{\partial(\overline{c}_l vh)}{\partial y} = q_{Issl} - w_{fl}\overline{c}_l \tag{5}$$

where $\overline{c}_l$ is the average concentration of a kind of particles, and subscript l is the index of particles with the representative diameter d_l; q_{Issl} is the sediment production term, which is the volume of sediment of unit area and unit time, eroded from the grid, and has the velocity dimension: (m/s); and w_{fl} (m/s) is the falling velocity for particles of index l. Together, the right-hand term: $(q_{Issl} - w_{fl}\overline{c})$ serves as the source term accounting for the sediment exchange between the flow and the land surface.

After intensive investigation into world's large watersheds, Morris and Fan (1998) attributed basin sediment yield to the combination of the following factors: geology, slope, climate, drainage density, and patterns of human disturbance. And, they also find that land use and precipitation are two dominant factors. Based on these findings and those from the study of references in the Introduction section and the researches of the authors, the sediment production term in equation (5) is written as:

$$q_{Issl} = \gamma_l s_0 P' \sqrt{u^2 + v^2} \tag{6}$$

in which, γ_l is the sediment production coefficient, a dimensionless coefficient (different for different particle index l) relating to land use, geological properties of soil, and human impact and other factors, and it is subject to calibration; s_0 is the steepest slope of the grid; and, P' is the normalized precipitation with no unit.

The falling velocity is given by the following function:

$$w_{fl} = \sqrt{\frac{2}{3}\left(\frac{\rho_s}{\rho} - 1\right) g d_l + \frac{36\nu^2}{d_l^2}} - \frac{6\nu}{d_l} \tag{7}$$

where ρ_s is the density of sand; ρ is the density of water; g is the gravitational acceleration (=9.8 m/s^2); d_l is the representative diameter of particles of index l; and, ν is the kinematic viscosity of water.

Equation (5) is discretized according to the staggered scheme and solved iteratively with the implicit method.

4. SEDIMENT TRANSPORTATION IN A CHANNEL

Sediment transporting in a channel or bed material comprises two parts according to their different flow properties. One is suspended load and the other bed load. These two parts of sediment transportation are computed separately and then unified in the riverbed change simulation.

4.1 SUSPENDED LOAD

Suspended load is depicted with the similar equation to that for sediment transportation in the overland flow:

$$\frac{\partial(\bar{c}_l h)}{\partial t} + \frac{\partial(\bar{c}_l u h)}{\partial x} + \frac{\partial(\bar{c}_l v h)}{\partial y} = q_{sul} - w_{fl} c_{bl} \tag{8}$$

in which, q_{sul} is sediment pick-up rate from the riverbed, with the dimension of velocity; and c_{bl} is the concentration near the riverbed. According to Hydraulics Committee (2000), q_{sul} is a function of applied sheer stress (τ_{*l}) or friction velocity (u_*), and falling velocity; and c_{bl} is related to the average concentration $\bar{c}_l$, and therefore, equation (8) becomes:

$$\frac{\partial(\bar{c}_l h)}{\partial t} + \frac{\partial(\bar{c}_l u h)}{\partial x} + \frac{\partial(\bar{c}_l v h)}{\partial y} = q_{sul}(u_*, w_{fl}) - \omega_l(u_*, w_{fl})\bar{c}_l \tag{9}$$

Equation (9) has only one variable ($\bar{c}_l$) and therefore can be solved. In this research, a stream is taken as a one-dimensional domain. However, the two-dimensional equation is employed and the excessive dimension is utilized as the linkage with overland grids to obtain source input of sediment from them.

4.2 BED LOAD

The dimensionless bed load for sediment of non-uniform particles is calculated with Ashida and Michiue formulas (Hydraulics Committee, 1999). These formulas related the dimensionless bed load to Reynold's Number (R_*), applied sheer stress (τ_{*l}) and critical sheer stress (τ_{*cl}), representative diameters (d_l) and the average diameter (d_M) of particles, and some empirical coefficients. In the calculation of dimensionless bed load for non-uniform sediment, the critical sheer stress for each particle index l is adopted. It can be obtained from the average critical sheer stress after some rectification.

The volume of bed load of unit width can be obtained by multiplying the dimensionless bed load by the normalization factor, shown as below:

$$q_{bl} = \sqrt{(\rho_s/\rho - 1)gd_l^3} \cdot q_{*bl} \tag{10}$$

in which q_{*bl} is the dimensionless bed load, and q_{bl} is bed load volume of unit width (m^2/s).

4.3 RIVERBED CHANGE SIMULATION

When sediment transports along with water flow in a channel, it deposits onto the riverbed and erodes the riverbed as well. This phenomenon must be simulated, otherwise the model will give incorrect sediment yield at the basin outlet or estuary. Riverbed change includes variations of both elevation and particle size distribution (Hydraulics Committee, 2000). The equation for elevation variation is given as below:

$$(1-\lambda)\frac{\partial z_b}{\partial t} + \frac{1}{B}\frac{\partial\left(B\sum_l q_{bl}\right)}{\partial x} = \sum_l \left(w_{fl}c_{bl} - q_{sul}\right) \tag{11}$$

in which, λ is the porosity of the riverbed soil, z_b is riverbed elevation, and, B is river width. Riverbed sediment particle distribution change is accounted with the following equations:

$$\begin{cases} \delta(1-\lambda)\dfrac{\partial p_l}{\partial t} + p_l^*(1-\lambda)\dfrac{\partial z_b}{\partial t} + \dfrac{1}{B}\dfrac{\partial(q_{bl}B)}{\partial x} = w_{fl}c_{bl} - q_{sul} \\ \sum_l p_l = 1 \end{cases} \tag{12}$$

where δ is the thickness of riverbed sediment exchange layer, p_l is the present percentage of particles of index l, p_l^* is the percentage of riverbed sediment given by the following equations:

$$p_l^* = \begin{cases} p_l, & if\ \partial z_b/\partial t \geq 0 \\ p_{0l}, & if\ \partial z_b/\partial t < 0 \end{cases} \tag{13}$$

in which p_{0l} is the percentage of original distribution of the riverbed particles. The riverbed sediment exchange layer is a thin layer with a constant thickness δ but variable upper and lower boundaries changing with time (Sediment Control Association, 2000). Equations (11) and (12) can be solved explicitly.

5. MODEL CALIBRATION AND VALIDATION IN A TEST BASIN

Sediment gauging in the river flow is very difficult and there exist very few measured data. However, Santos et al. (1998) provided a miniature basin (100m×100m, grid size=2m, max elevation difference=10m, two streams), and relatively detailed data of precipitation, discharges and sediment quantities during several rainfall events.

Rainfall event 4 is used to calibrate the model. First of all, the water flow discharge is calibrated. The precipitation data are applied evenly over all grids of the miniature basin and the model outputs water flow discharge hydrograph (Fig. 3). Then, sediment yield is calibrated. No sediment discharge hydrograph but the total amount of sediment yield is available, and the sediment yield in rainfall event 4 is 1,200kg. The calibrated model gives a sediment yield of 1,113kg with the proper sediment production coefficient γ_l.

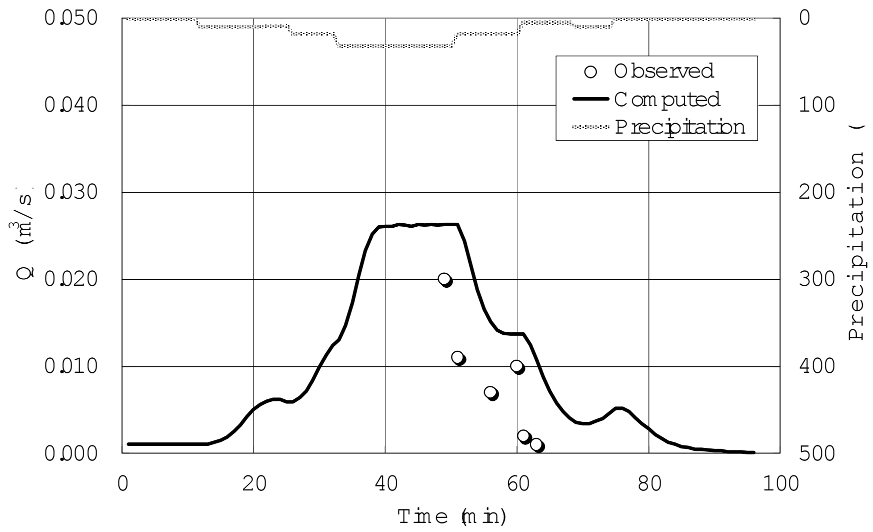


Fig. 3 Hydrographs for calibration (rainfall event 4)

Rainfall event 13 is utilized to validate the model with the calibrated γ_l. A comparison of water flow hydrograph is shown in Fig. 4. The observed sediment yield is 4,000kg and the simulated sediment yield is 4,110kg. These results can be taken as good agreements.

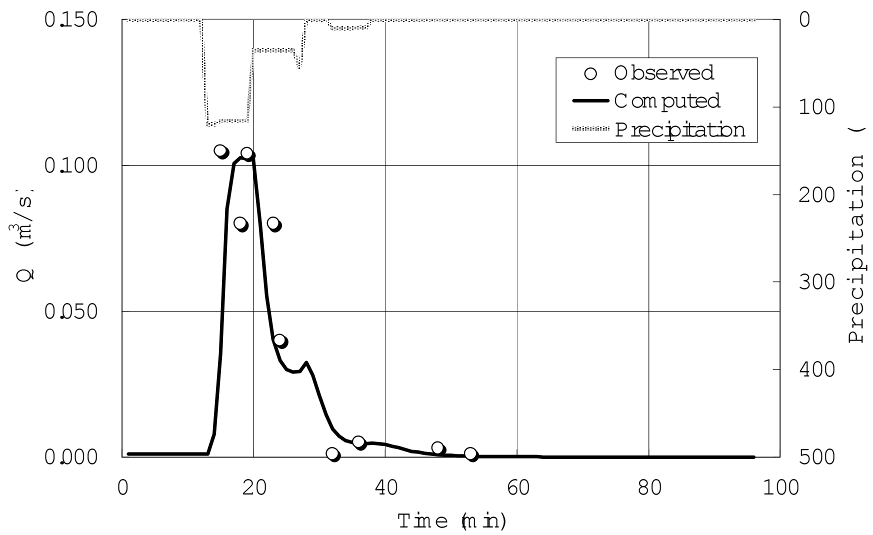
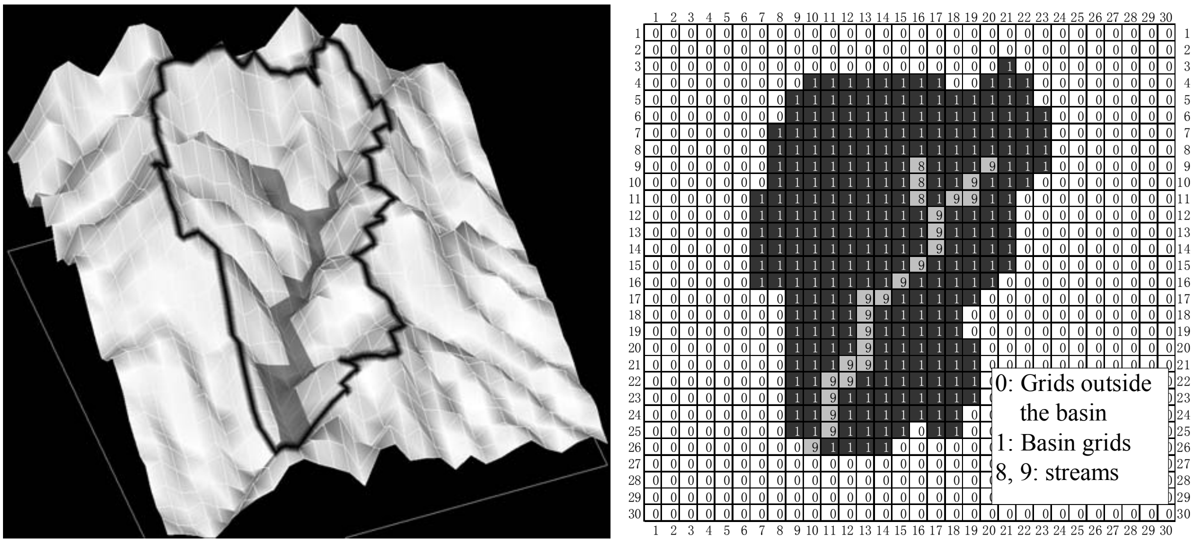


Fig. 4 Hydrographs for validation (rainfall event 13)

6. A TRAIL RUN IN A REAL BASIN

Since model accuracy may affected model outputs, especially in a small domain of hydrological modeling. The above miniature basin is an artificial basin, and both the spatial and temporal scales are too small to demonstrate the model's ability. A small watershed with an area of 300km^2, Kusaki, located at a tributary of the Tone River in Kanto Region of Japan, is selected to take a trail run (Fig. 5). In this test simulation, time step varies with rainfall intensity from several seconds to one hour, and time step for data output is one hour.

In the digital basin (Fig. 5 b), the black grids are basin grids, and the gray grids are stream grids. The grid size is 1km, and distributed radar precipitation data in the same grid size are available across the basin. Other data, such as DEM, land use, and outlet water discharge hydrograph during the rain event, are also available. But there are no data of sediment discharge. Fig. 6 shows water flow calibration during a rainfall event.



(a) Bird eye view of the basin (b) Digitalized basin

Fig. 5 Kusaki basin for the trial run

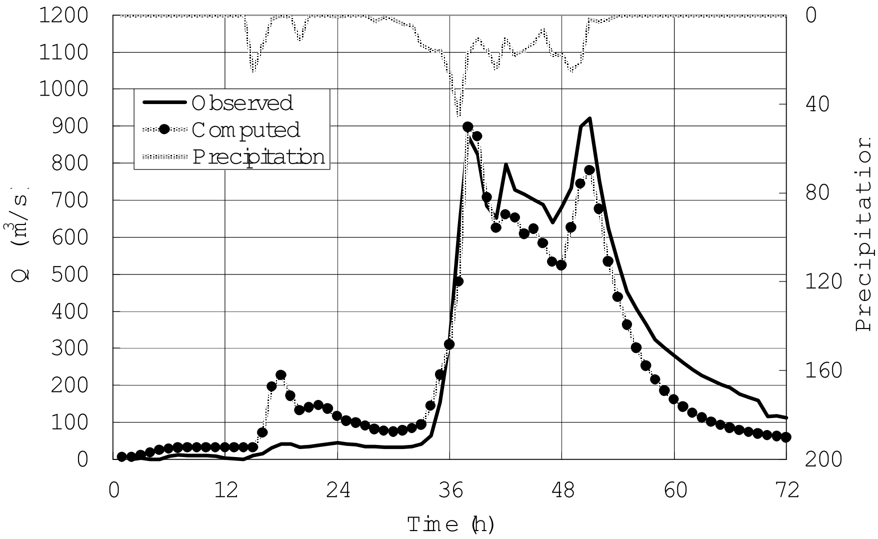


Fig. 6 Discharge comparison in a rainfall event

In this mountainous watershed, there are only two types of land use: forest and water body. For water body, there is no sediment production and $\gamma_l = 0$. For forest, six different values of γ_l are selected to test the model, and the simulated sediment discharges at the basin outlet are shown in Fig. 7. This figure demonstrates that the sediment production coefficient affected greatly sediment output at the basin outlet, or sediment output is very sensitive to the sediment production coefficient. Fig. 8 shows sediment discharge's response to water flow discharge or precipitation.

As mentioned in section 1, this model not only can produce sediment discharge hydrographs at any point of the stream system, but also can simulate riverbed changes of both elevation evolution and particle size distribution. Fig. 9 shows the riverbed change related to the original riverbed elevation in a time period of 72 hours, and Fig. 10 is the average particle size evolution in the same time periods. From this figure, one can find an interesting phenomenon that the eroded sections (with negative riverbed elevation change) have their average particle size increased, and vice versa for the sections of deposition (with positive riverbed elevation change).

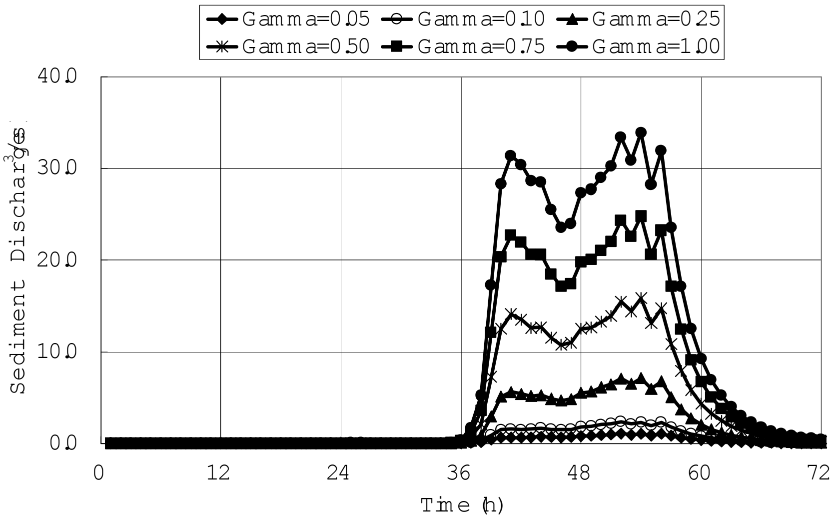


Fig.7 Sediment discharge sensibility to sediment production coefficient γ_l

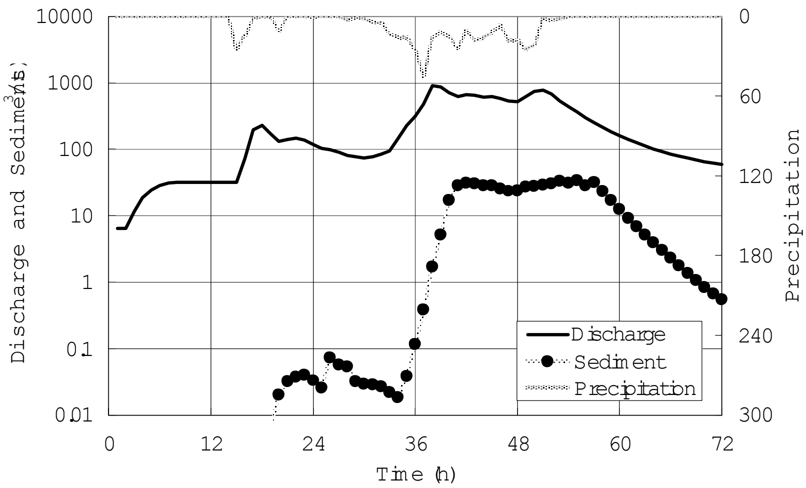


Fig. 8 Sediment discharge response to water flow discharge ($\gamma_l = 1.00$)

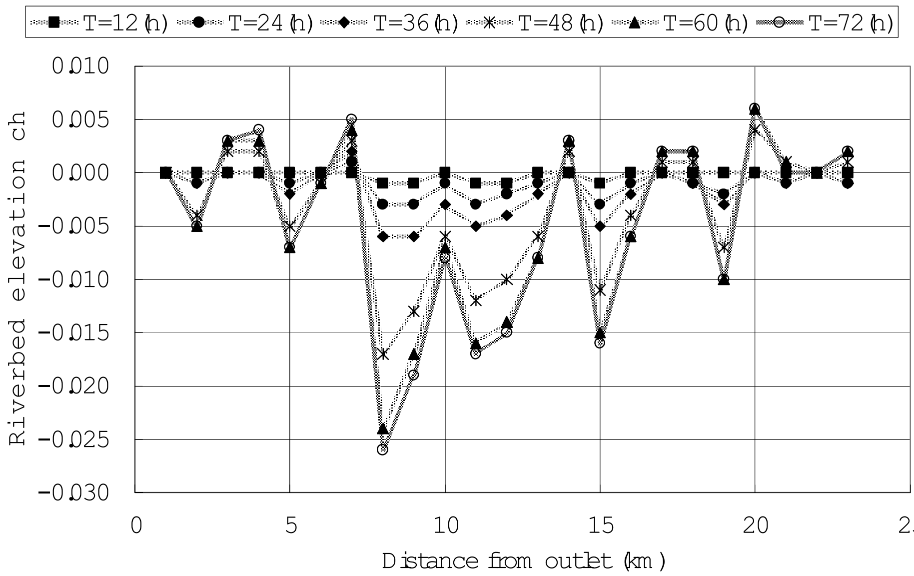


Fig. 9 Riverbed elevation change related to original riverbed elevation ($\gamma_l = 1.00$)

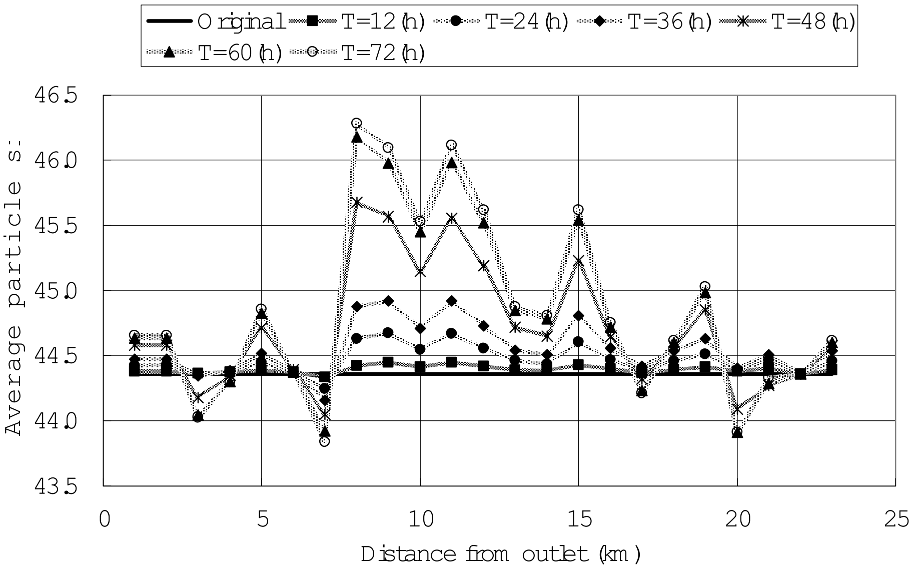


Fig. 10 Riverbed average particle size evolution ($\gamma_l = 1.00$)

7. CONCLUSIONS

This research presents a physics-based, two-dimensional model for watershed sediment production and transportation. After the above analysis and study, it can be concluded that: 1) the physics-based two-dimensional model for watershed sediment production is corrected and effective for sediment output; 2) the introduction of sediment production term and sediment production coefficient for overland grids is successful; 3) the model's capability is not limited to generation of sediment discharge hydrographs, it is also capable to simulate riverbed change.

However, due to lack of observation date of sediment in a real basin, the model still needs further calibration and validation before applied to a real basin.

REFERENCES

Deposition Flushing Division of Dam Technology Committee, 2001. Reservoir deposition flushing strategy: present situation and problems, *Oodamu (Great Dam)*, No. 176 (2001-7), pp. 1-49. (In Japanese)

Hydraulics Committee, 1999. A Collection of Hydraulic Formulas, JSCE. (In Japanese)

Hydraulics Committee, 2000. A Collection of Hydraulic Formulas in CD-ROM, JSCE. (In Japanese)

Iwaya, T., 1998. Study on the floodway in the seaside dune blockade area, *J. Hydrau., Coast. Environ. Eng., JSCE*, No. 586/II-42, pp. 61-75. (In Japanese)

Johnson, B.E., et al, 2000. The two-dimensional upland erosion model CASC2D-SED, *Journal of the American Water Resources Association*, Vol. 36, No. 1, pp. 31-42.

Julien, P., and R. Rojas, 2002. Upland erosion modeling with CASC2D-SED, *International Journal of Sediment Research*, Vol. 17, No. 4, pp. 265-274.

Kajmura, T., et al., 2001. Sand movement and long-term beach evolution in an alluvial system composed of the same river and the Nakoso coast, *J. Hydrau., Coast. Environ. Eng., JSCE*, No. 691/II-57, pp. 121-132. (In Japanese)

LUO, Qiang, 2000. A distributed water balance model in large-scale complex watersheds (LCW) and its application to the Kanto Region, Ph.D. dissertation of the University of Tokyo, Tokyo, Japan.

LUO, Qiang, et al., 2000. Non-optimization direct method of the inverse problem for groundwater modeling (NODMIP) in a large scale basin, *Journal of Japan Society of Hydrology and Water Resources*, Vol. 13, No. 2, pp. 148-155.

Marine Construction Technological Committee, 2001. Marine Construction Technologies of the World, Sankaidou Press, Tokyo, Japan. (In Japanese)

Morris, G.L., and J. Fan, 1997. Reservoir sedimentation handbook, McGraw-Hill.

Santos, C.A.G., et al., 1998. Sediment yield due to heavy rainfall from a test field in Brazil and its analysis by a runoff-erosion model, *J. Hydrau., Coast. Environ. Eng., JSCE*, No. 586/II-42, pp. 117-126.
Sato, S., 2003. Coastal conservation based on comprehensive sediment control in the fluvial system, *Kasen (River)*, No. 680, Japan River Association, pp. 15-19.
Sato, S., and Aita, 1975. Civil Engineering Handbook for Easy Understandings, Shokoku Press, Tokyo, Japan. (In Japanses)
Sediment Control Association, 2000. Numerical Simulation Methods for Riverbed Evolution in Mountainous Rivers, Sankaido. (In Japanese)
Takebayashi, S., et al., 1992. A method to estimate amount of sedimentation in dam-reservoirs sedimentation as stochastic process, *Dam Engineering*, No. 8, pp. 6-20. (In Japanese)
Yoshita, T., 2003. Relation between seacoasts and estuaries, *Kasen (River)*, No. 680, Japan River Association, pp. 6-8. (In Japanese)