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ESTIMATION OF SOIL EROSION AND SEDIMENT TRANSPORT IN THE MEKONG RIVER BASIN USING GLOBAL MAPPING DATA

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Abstract

The soil erosion process was simulated in the Nam Kam river basin, the tributary of the Mekong, by using the global mapping data, such as topography, land use, soil type etc., that were produced by Geographical Survey Institute of Japan. The soil erosion model developed in this study is an extension of the "RUSLE" model (Renard et al., 1997) to 2-dimensional domain. The model includes simple surface soil transport process as well as soil transport due to river. The observation data of the daily flow rate and sediment concentration at two observatories along the river were used for the verification of the model. The model simulations were performed for two years of 1983 and 1993, where the observed daily precipitations were used as an input. The simulation well reproduced the annual temporal variations of the sediment flux at the observation sites in the two years. Sensitivity analysis was also done, by modifying the erosion parameter for each land use. The results showed that the erosion from the agricultural area, located on the edge of hills largely contributated to the sediment flux, thus suggesting that the change of the land use for agriculture in the hillsides largely increases the risk of the soil erosion.

KEYWORDS; *GIS, Global mapping data, RUSLE, Soil erosion, model integration*

1. Introduction

Many developing countries in South-east Asia are often being forced to drastically change their land use for production of commercial agricultural products and for construction of various infrastructures to support explosively increasing population. Usually, the sustainable development of the region has not been considered in the land use change. Thus, for example, the exhaustive deforestation with characteristic monsoon climate has often disabled people from sustainable agriculture; soil erosion associated with heavy rainfall in rainy season prohibits effective use of fertilizers.

The purpose of this study is to develop a model of soil transport for the prediction of soil movement, in time and 2-dimensional space, which was caused by land use change. The target area is

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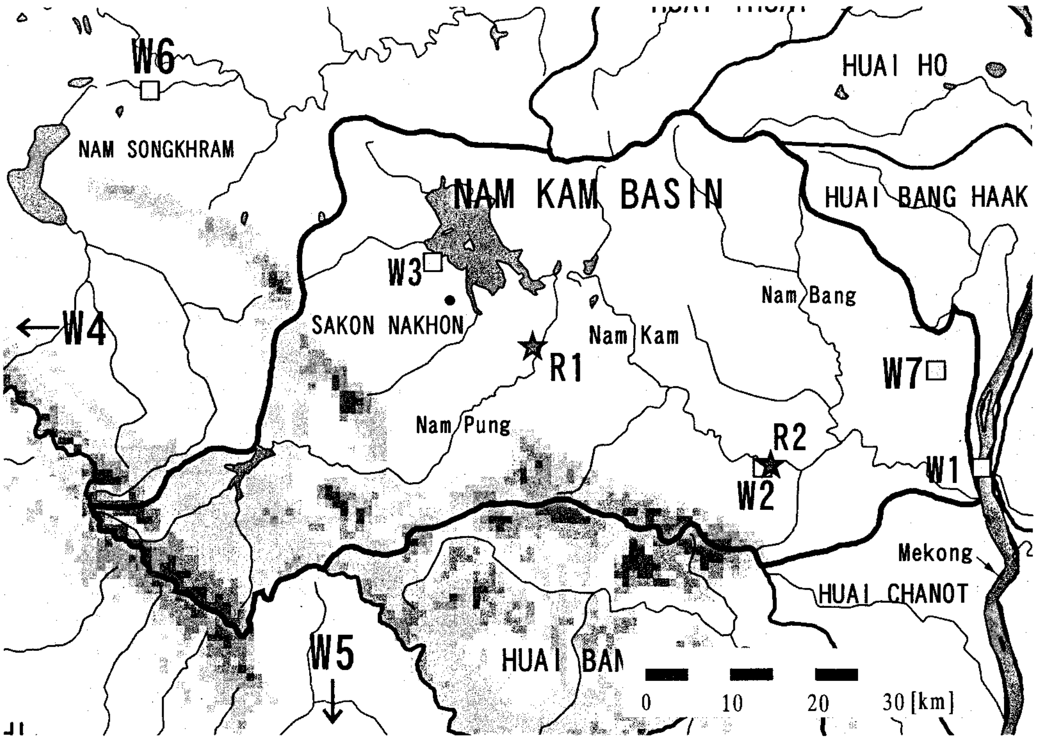


Figure 1. The watershed of Nam Kam River Basin and observation station for weather and river (W1~W7 for weather and R1 and R2 for river)

the basin of a tributary of the Mekong. The Mekong is the typical international river whose basin extends over China, Laos, Myanmar, Thailand, Cambodia and Vietnam. Drainage area is 795,000km^2 and the overall length is 4,425km. In this study, the Nam Kam river basin of the northeastern district of Thailand was chosen as the model area. Figure 1 shows a watershed of the Nam Kam river basin; its drainage area is 3,440km^2. In the study, first, the quantity of the soil erosion was estimated by using RUSLE model with the global mapping data; secondly, a simple model of both surface soil and river sediment transports was developed and used to estimate the sediment flux in the river. In these calculations, the data of land elevation, land use, soil type etc. were provided by the global mapping project (e.g. Hara et al., 1998, Oketani et al., 1998). The global mapping project is an international one, which the Geographical Survey Institute of Japan serves as its Japanese center. The goal of this project is to make datasets on global geographic information, such as land use, elevation, vegetation, drainage system, transportation etc., at a scale of 1:1,000,000 or with a ground resolution of about one-kilometer.

2. Soil Erosion Model

RUSLE (Revised Universal Soil Loss Equation) of the UNEP/GRID Research (Renald et al., 1997) was used as a soil erosion model. This model consists of empirical formula that predicts the quantity of the soil erosion due to water erosion; the model was derived by statistically processing the observed data over 10,000 samples. In the model, the annual soil erosion is expressed with the multiplication of five factors. These factors of R, K, C, P and LS represent the nature of the rainfall that causes the water erosion, the erosivity of soil, the type of land covering, the method of land maintenance, and the angle and length of slope, respectively.

2.1. Evaluation of potential soil erosion

RUSLE calculates potential annual soil erosion from a unit area, A[ton·km^{-2}·yr^{-1}], using the following equation.

$$A = R \cdot K \cdot C \cdot P \cdot LS \tag{1}$$

where R [kJ·mm·km^{-2}·yr^{-1}·hr^{-1}] stands for the rainfall factor, K [(ton·km^{2}·hr)·(km^{2}·kJ·mm)$^{-1}$] the soil erosivity factor, C [-] the land use factor, P [-] the erosion inhibition factor, and LS [-] the factor of the angle and length of the slope. In this study, Eq.(1) was modified so that it calculates daily soil erosion, by applying the daily R factor.

2.2. Determination of each factor

(A) R factor

R factor represents effect of the precipitation on soil erosion. It is expressed with the multiplication of daily rainfall energy and rainfall intensity as follows:

$$R = EI_{0.5} \tag{2}$$

where E [kJ·km^{-2}·hr^{-1}] stands for rainfall energy, and $I_{0.5}$ [mm·hr^{-1}] for maximum 30-min rainfall intensity. E can be evaluated as:

$$E = 2.9 \times \left(1 - 0.72\exp\left(-0.05 I_{0.5}\right)\right)N \tag{3}$$

where N [mm·d^{-1}] is daily rainfall, and $I_{0.5}$ can be evaluated using the following relation (e.g. Takase, 1978).

$$I_T = \frac{N}{24}\left(\frac{24}{T}\right)^{\frac{2}{3}} \tag{4}$$

where T is duration of rainfall in hours.

If the daily rainfall data is obtained, the R factor is calculated by Eqs.(2) to (4).

(B) K factor

K factor denotes the erosivity of soil, and it was originally derived by taking into account the structure of the soil and content of organic matter (Schwertmann et al., 1987). However, it is also known that K factor can be determined roughly by the soil texture (Standard Handbook of Env. Eng., 1990) and age of the soil (Kappas et al., 1996). Thus, in this study, the K value was determined from the age of the soil by using the soil texture information of the target area. These are shown in Table 1.

(C) C and P factors

The factor C depends on the type of land cover and its value ranges from 0.001 for "evergreen forest" to 1.0 for "drainage/water" and "buildup area" (Mckendry et al, 1992, see Table 2). This

Table 1. K factor and the nature of soil

Geological Era		Soil Texture Class *	K Factor § ($ton \cdot km^2 \cdot hr/km^2 \cdot MJ \cdot mm$)
Quaternary	Holocene	Sandy loam	0.0316
	Pleistocene	Sandy loam	
Mesozoic	Cretaceous	Loamy Sand	0.0132
	Jurassic	Sand	0.00395
	Triassic	Silty Clay	0.0303

* From the geological layer information of lower Mekong area (Ministry of Construction, Japan, 1997).

§ (Standard Handbook of Environmental Engineering, 1990). Organic matter content was assumed as 1%

Table 2. C and P factors and the classification of landuse

Land cover	C factor‡	P factor‡
Drainage/Water	1.00	1.0
Built up Area	1.00	1.0
Barren Area	0.28	1.0
Forest	0.10 §	1.0
Agricultural Area (crop field)	0.65	0.5
Paddy Field	0.10	0.5
Grassland/Shrub	0.15	0.5
Wetland	0.56	1.0
Mixture	0.40	0.5

‡ Mckendry et al, 1992. § assumed from 0.001 for "Evergreen forest" and 0.24 for "Dry Dipterocarps Forest".

factor represents resistance of the ground surface to the transport of water-soil mixture. The large value for "built-up" area (Table 2) reflects large percentage of smooth paved surface. This means that once eroded soil would be available in "built-up" area because of, for example, soil inflow from rural area with a flood event, the soil could be drained quickly from the "built-up" area.

The factor P (see Table 2) stands for erosion inhibition effect, and reflects partly people's effort not to allow soil erosion. For example, the relatively small value of 0.5 is assigned to "paddy field" (Table 2), and this is due to maintenance of rice paddy field, e.g. construction of footpath between rice paddies, so that the soil in the paddy field will not be transported away. C and P factors in Table 2 were those estimated for Mae Klang watershed, northwestern district of Thailand (by Mckendry et al., 1992).

(D) LS factor

The LS factor is determined by the length and angle of the slope of the ground. The value used here was taken from the table in Renard et al. (1997), which relates land use classification to the

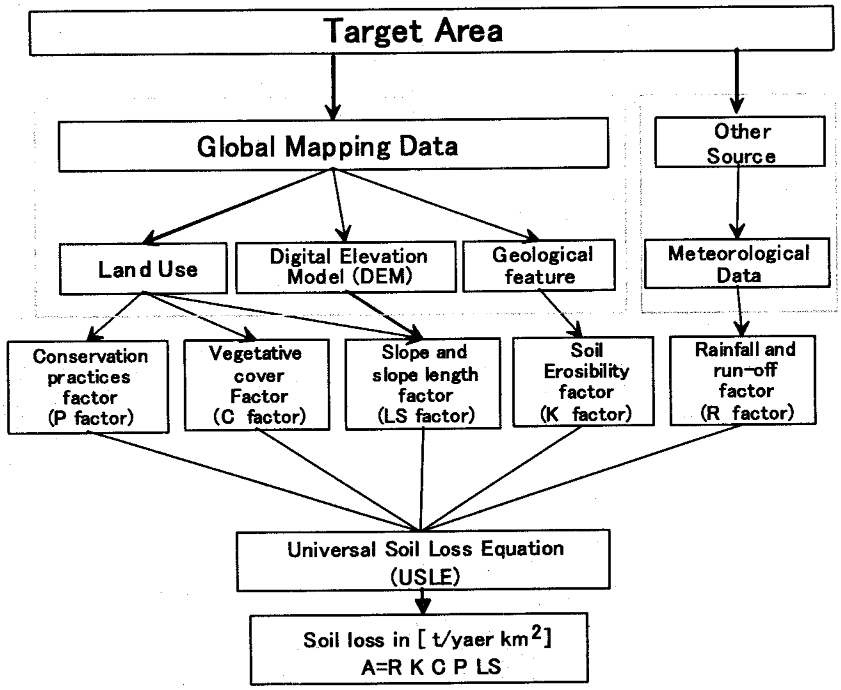


Figure 2. Calculation Scheme of Soil erosion using the global mapping data and RUSLE model.

angle and length of slope.

The quantity of the soil erosion was calculated by overlaying these factors on GIS. Figure 2 shows how the data of the global map and daily precipitation in the target area are used for RUSLE.

3. Soil Transport Model

The soil transport from a grid cell to the lower river was calculated by two kinds of models. The first model deals with the sediment movement among grid cells until the sediment reaches rivers. The second model calculates sediment transport in the rivers.

3.1 Transport model of sediment among grid cells

In the model, the sediment, which calculated by soil erosion model on each grid cell, is assumed to be transported in the steepest down-gradient direction of the elevation. The transport calculation is carried out every one hour. The soil moved to the next grid cell in unit time, Q[ton/hr], was estimated with the following equation.

$$Q = \alpha \times S \times D \times \beta \tag{5}$$

where α is the coefficient representing the conditions of drainage system and surface roughness, and was assumed to be 1.0. S stands for the total sediment quantity in a grid cell [ton], D for gradient to the next grid cell [m/km], and β for the switching parameter (0 or 1) relying on the presence of the surface water run-off.

For hydrological process, two layers tank model (surface layer and under-ground layer) was adopted (e.g. Hino, M. et al, 1985). The sediment transport over land was allowed to occur only when run-off takes place. The capacity of the under-ground layer is 50mm and the daily evaporation quantity was assumed at 5mm.

3.2. River channel run-off model

The soil that reached the grid cell where river channel exists is assumed to immediately flow into the river channel. The river channel within the basin was divided to 21 segments. The transport of the sediment between segments was calculated by taking into account the delay time that was related to the length and slope of each segment. The delay time was assumed to be 1 hour for 1km at the normal gradient (1m/km) in the Nam Kam River Basin.

The time constant of the river runoff on this basin scale is shorter than a day. Rather the discharge operation from the reservoir dominates river flux. However the data of the discharge from the dam and reservoir could not be obtained. Then the daily discharge was assumed to be proportional to the observed flux at the water observatory in downstream area.

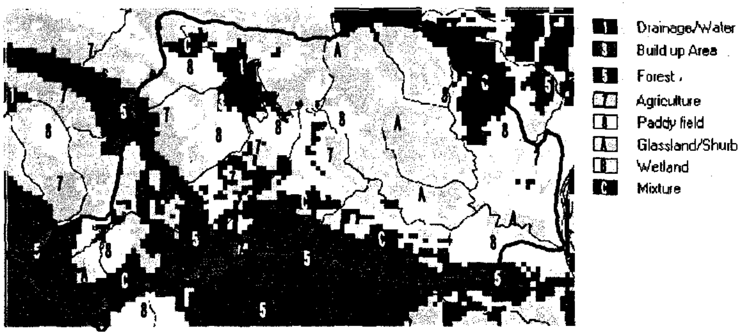
4. Target Area and Input Data

The target area locates from 103.78° to 104.84°E and from 16.79° to 17.33°N, covering all the Nam Kam river basin. The simulation used the data of land use, nature of soil, slope and daily precipitation. The calculations were performed for 1983 and 1993, because there were much quantity of information comparatively on these two years. The daily precipitation amount in 1983 and 1993 were used in the calculation. (Mekong River Commission, 1985 and 1994) The nature of soil and slope of topography were assumed to be same for both years.

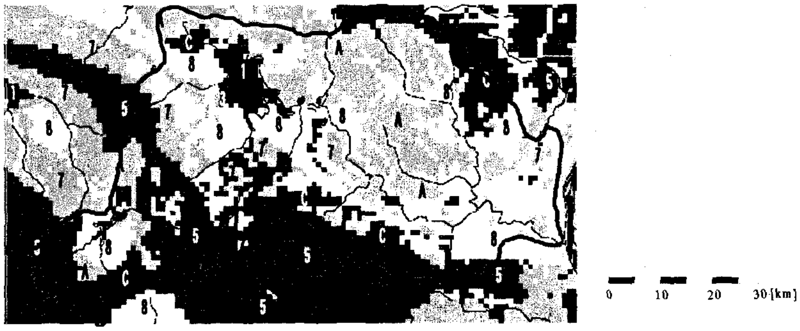
The land use data was produced from the Landsat TM image of 1988 and 1995. These are shown in Figs. 3(a)(b). The percentage of each land use type is 50, 10, and 40% for paddy field, forest (mainly dry dipterocarpaceae forest) and others, respectively. The "mixture" area was assigned when two or more land use coexists in a single grid cell, without any dominant land use type. A field survey suggests that mixture area consist of "paddy field and crop field" or "crop field and shrub". In this study, according to the later component, the mean values of these land use were assumed for C, P, LS factors. In the target area, most of the plain is already used as a paddy field or crop field completely, and the remaining forest in the hill is protected as a national park. Therefore, there are few changes of the landuse from 1988 to 1995. However, the paddy field increased in a lower basin, and also a little forest reduced in the hill.

The daily precipitation at each grid cell was estimated by interpolating observed data at the nearest weather observatories: four and six weather stations were available for 1983 and 1993, respectively. The daily precipitation at each observatory is shown in Fig 4. In general, the annual precipitation is less at the southwestern part of the basin than the northeastern part. There was not enough data of the flooding in the target area. Thus no flooding was supposed.

The measured values of the river flow rate and sediment concentration were used for the verification of the simulation result. The flow rate was measured every day at two observatories, and the sediment concentration was measured several times a month at same observatories. The sediment fluxes were computed from the flow rate and the sediment concentration at two observatories.

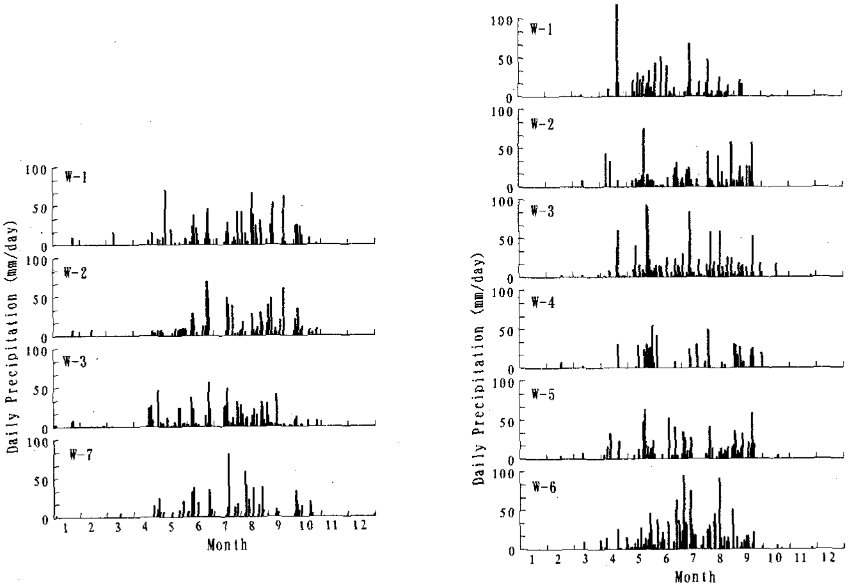


(a) 1988



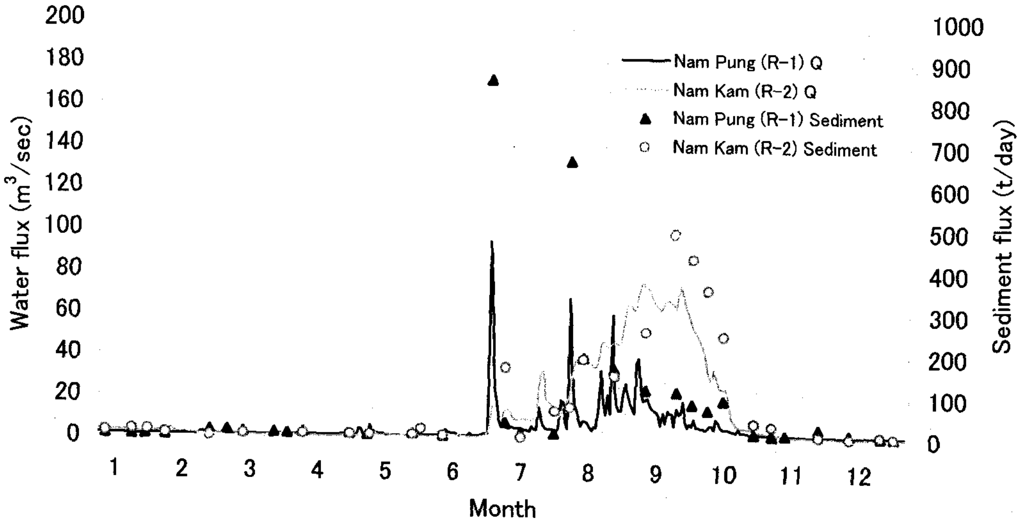
(b) 1995

Figure 3. The landuse of the target area in 1988 and 1995.

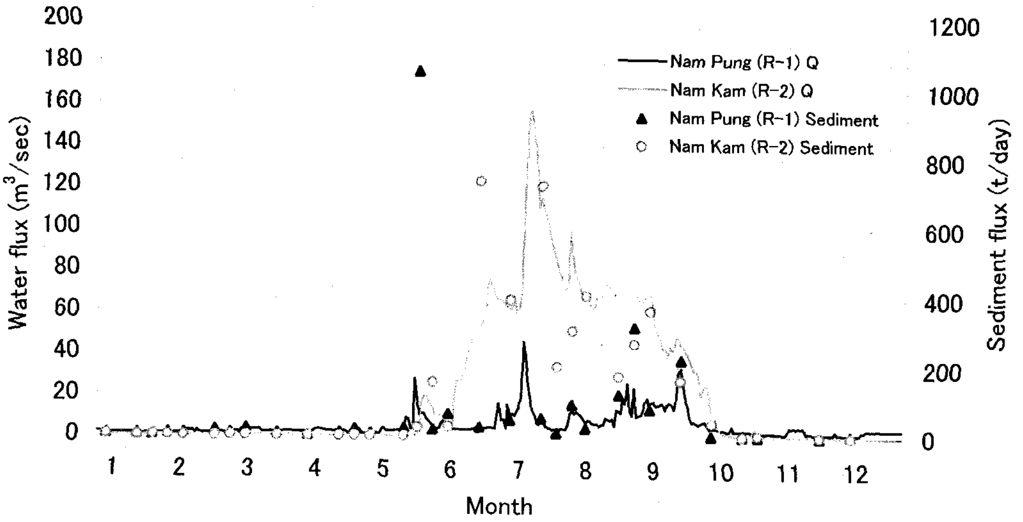


(a) 1983 (b) 1993

Figure 4. Observed daily precipitation at W1-W7 (see Fig.1) in 1983 and 1993



(a) 1983



(b) 1993

Figure 5. Observed flow rate Q, and sediment flux at two observatories (R-1, R-2 in Fig.1) in 1983 and 1993

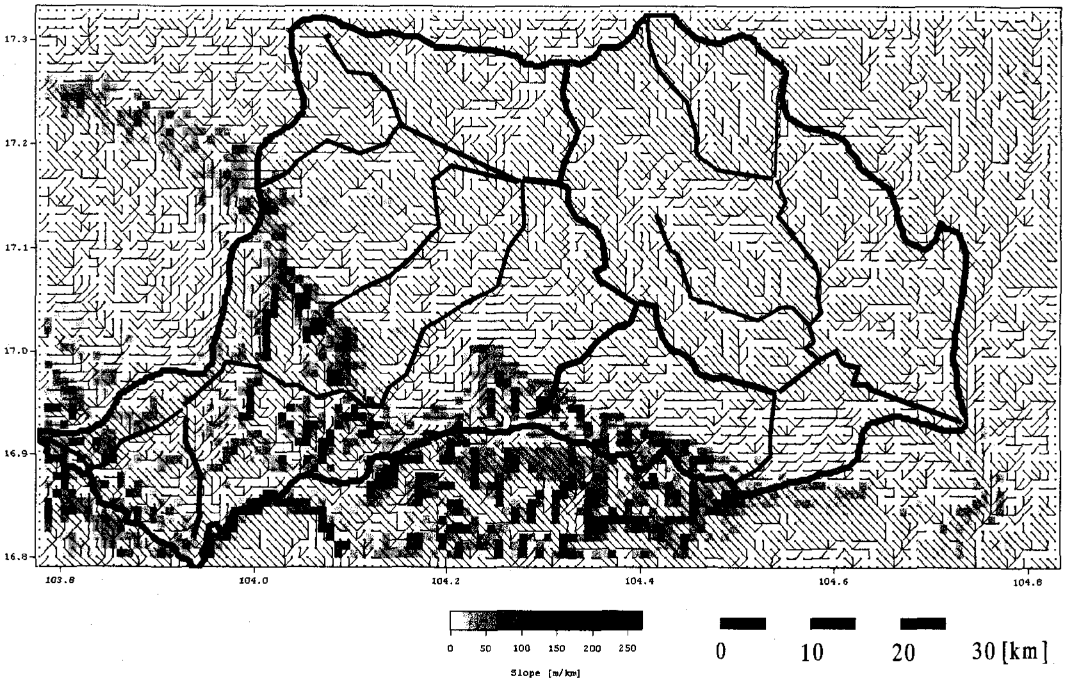


Figure 6. Slope and calculated surface run-off direction.

They are shown in Fig. 5.

The slope of target area and surface run-off direction that was calculated from Digital Elevation Model (DEM) data are shown in Fig. 6.

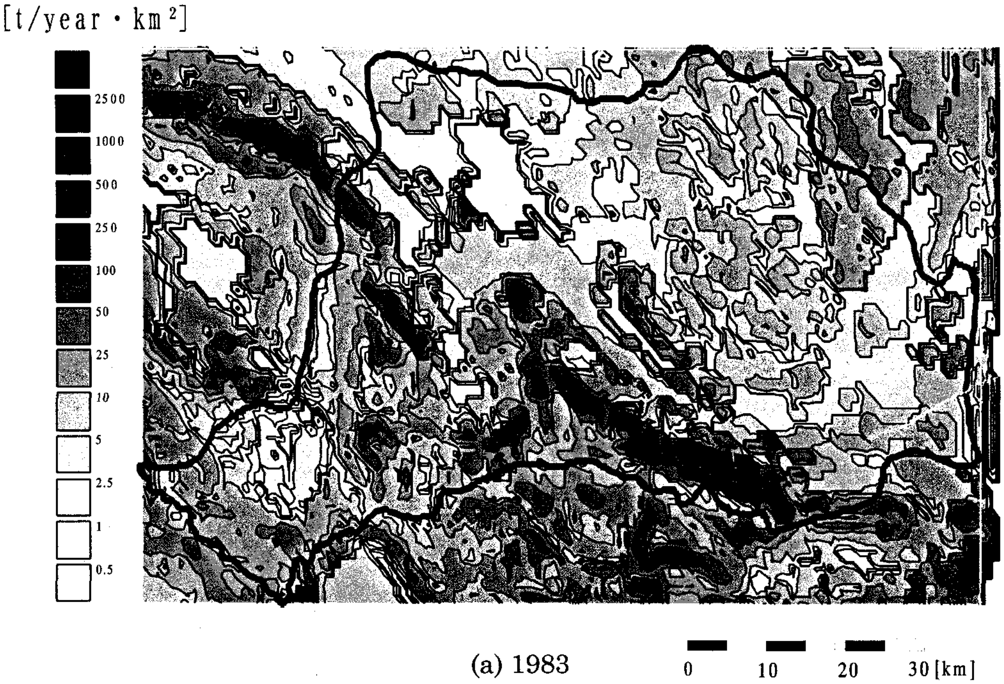
5. Result and Disccusion

5.1. Soil Erosion and its Transport

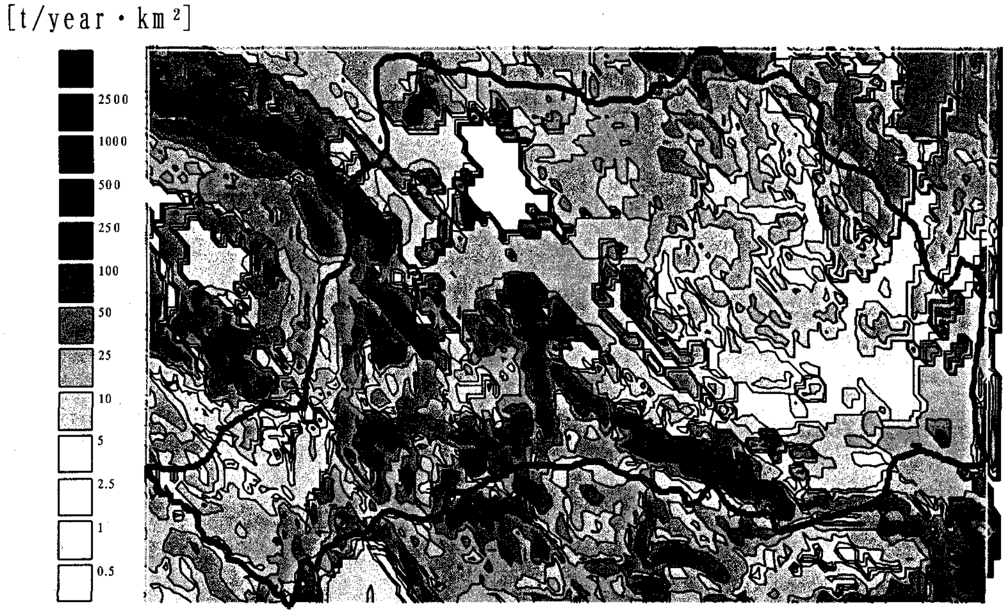
The spatial distributions of the calculated annual soil erosion in 1983 and 1993 are shown in Fig.7. It is clearly demonstrated that the soil erosion mainly depends on the land use and the slope. The estimated soil erosion for different land use is: 10–50t/year/km^2 in forest area and grassland/shrub area, and 50–100t/year/km^2 in agricultural area. Especially large value of 500–3000t/year/km^2 was predicted for the mixture and also the agricultural areas where were on the edge of hills with relatively steep slope.

Figure 8 shows both calculated and observed sediment fluxes at the two river observatories in 1983. The sediment flux was not seen at observatory R-1 until end of June. The significant sediment flux occurred after the continuous rainfall commenced in July. The trend is qualitatively reproduced in the calculation at R-1.

The predicted sediment flux at R-2 did not necessarily agree with the observed. This is probably because of uncertainty of the discharge program from the big reservoir in the upstream area of the Nam Kam river (see Fig. 1). The flow rates of the Nam Kam river below the water reservoir are



(a) 1983



(b) 1993

Figure 7. Simulation result of the annual soil erosion in 1983 and 1993

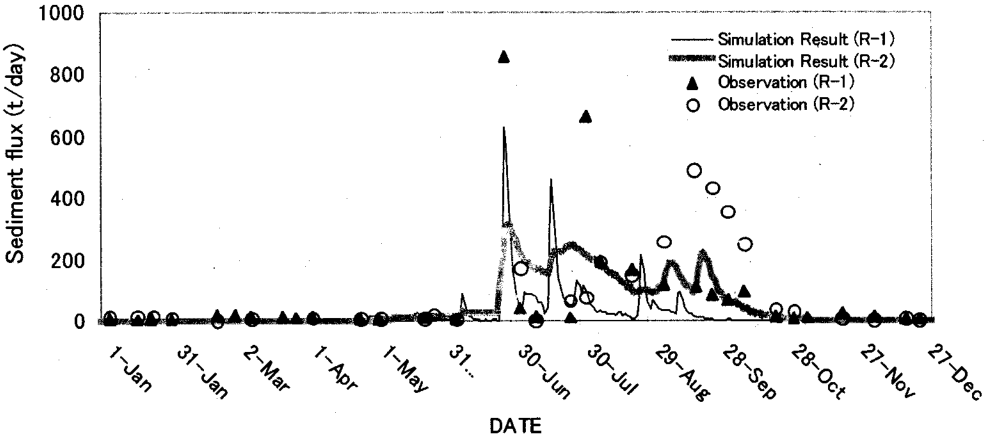


Figure 8. Simulated sediment flux and observation at the each river observatories in 1983

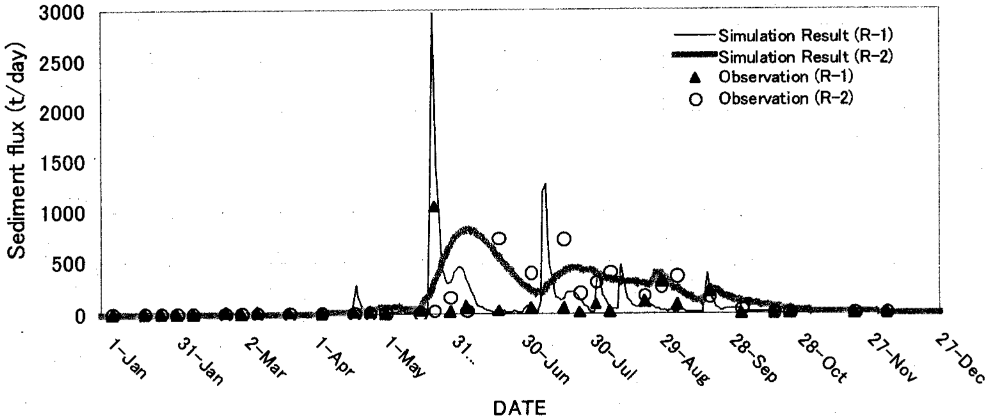


Figure 9. Simulated sediment flux and observation at the each river observatories in 1993

largely controlled by its discharge, and the record of the discharge was not maintained. Thus, in the simulation, the water released from the reservoir was assumed to be proportional to the flow rate at R-2, and probably this assumption was not adequate. The disagreement between the observed and the simulated sediment fluxes at R-2 should be improved once data of the water discharge are available.

Figure 9 shows the calculated and the observed sediment fluxes at R-1 and R-2 in 1993. In this year, there were large precipitation events in May and early July (Fig. 4b). Thus the simulation predicted large sediment fluxes at R-1 in the middle of May and early July as shown in Fig. 9. The calculated fluxes at R-1 qualitatively agree with the observation, but tend to overpredict. Those at R-2 follow quite well to the observed flux. The site R-1 covers much small watershed compared with the site R-2. The characteristic of smooth (R-2) vs. rough (R-1) temporal variation in the observation in Fig.9 was partly caused by the difference in the area of watershed, and the simulation well captures this feature.

The simulation-derived total soil erosion in the river basin covering the site R-1 (2,360km^2) was

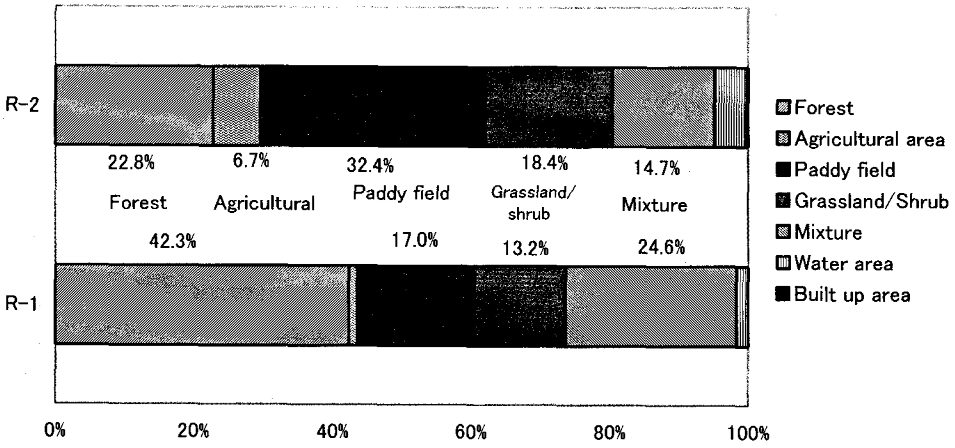


Figure 10. Proportion of the land use of each river basin

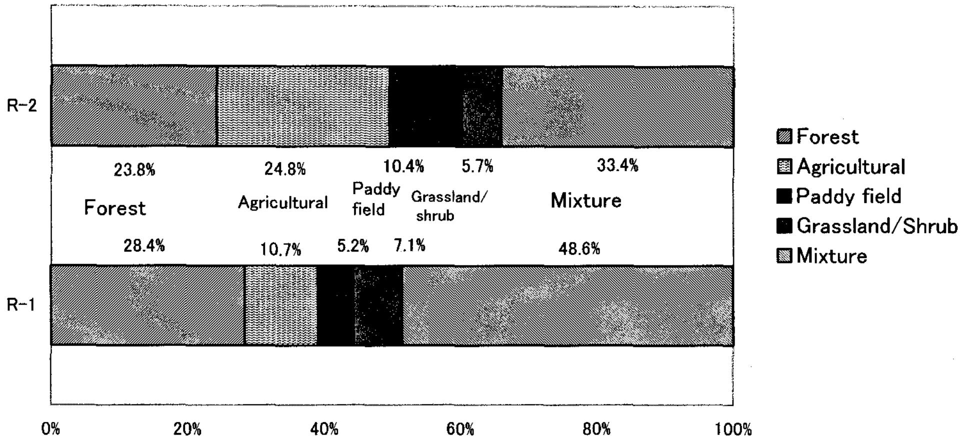


Figure 11. The contribution rate from each land use.

18,900 t/year in 1983 and was 54,400 t/year in 1993. On the other hand, observation-derived annual sediment flux at R-1 were 27,000 t/year in 1983 and 44,900 t/year in 1993. These suggest that the present model could give quite good estimation for the year-based soil erosion. The annual precipitation averaged over the target area was 963mm/year in 1983 and 1088mm/year in 1993. The estimated heaviest rainfall was 81mm/day in 1983 and 118mm/day in 1993. It is possible that the difference resulted in by three times larger soil erosion in 1993 than in 1983.

5.2. Estimation of the contribution of each landuse type to the total sediment flux

To examine the contribution of each landuse type to the total sediment flux, the change of sediment fluxes at river observatories R-1 and R-2 were compared for five cases that the RUSLE factor for forest, agricultural area, paddy field, grassland and mixture area were individually changed.

The contribution rate is expressed as the proportion of the difference to the total sediment flux. This calculation used the precipitation and land use data in 1983. The proportion of each land use of the watershed area above R-1 and R-2 are shown in Fig 10.

Contributions of each landuse to the total annual sediment flux at the two river observatories R-1 and R-2 are shown in Fig 11. Contributions of wet area and built-up area were not included in this figure, because these contributions were small. The contribution from the mixture area was the largest. This is because the erosion coefficient (C×P) at mixture area is 0.2, and much larger than those of 0.05 at paddy field and 0.075 at grassland. Also the mixture area tend to have a large LS factor, because most part of mixture area was around the edge of hill. The contribution from agricultural landuse was relatively large, in spite of its small area parentage (see Fig. 10). This is because the agricultural area has also a large erosion coefficient, 0.325 and often locates around the edge of hill.

The land around the edge of hill and hill slope is not usually used for paddy filed, since the gradient is too large and also there is not enough water for rice paddy. Thus, such an area tend to be developed as an agricultural area (crop field). According to the result of these simulations, the land use especially around the hill must be managed to avoid the soil erosion.

5.3 Integrated system for environment impact analysis of development activities in regional scale - Future plan -

Only the RUSLE model was used in the present calculation to predict the soil erosion, and only the daily precipitation data at several observatories in the target area were used for the estimation of the distribution of the daily precipitation and its hourly intensity. Therefore, the spatial interpolation of rainfall from sparse observed data and the assumption of the equation of rainfall intensity were inevitable, since rainfall amount and intensity largely affect the soil erosion. It will be useful to apply a meso-scale weather model such as PSU/NCAR MM5 (Grell et al., 1995) for the estimation of the spatial and temporal distribution of rainfall.

Also, more sophisticated hydrological circulation model such as IISDHM (Jha et al., 1997) should be used to predict sediment transport by the surface run-off and the river itself with higher accuracy.

Issues to be discussed for integration of the models may be summarized as follows.

A) The time scale and spatial scale of the input/output data of each model should be consistent.

B) The hydrological surface run-off process was not considered directly in RUSLE. If the output from the hydrological circulation model can be used, the modification of the soil erosion model to treat this process will be necessary.

C) When the surface soil spills, it may influence to the vegetation or agricultural style. The technique of the feedback to reflect these changes to the input as a hydrological model and the others will be necessary.

D) The method that regulates the difference of the required data quality in each model will be necessary.

6. Summury and Conclusions

In this study, a dynamic model to predict the soil erosion and sediment transport in two-dimensional spatial space was developed to assess the impact of the modification of land use; it consists of the models of RUSLE for soil erosion and horizontal transport for sediment, and uses the global mapping data and meteorological data. Obtained results are summarized as follows. (1) The trend of simulated annual sediment flux at observatories agreed qualitatively with the observed in spite of the insufficient input data. (2) It was suggested that the development or cultivation of the edge of the hill have a high risk of increasing the soil erosion remarkably.

The present global mapping data may be insufficient for the detailed assessment performed in the advanced countries. However, in the developing country where geographical information is not adequate in quantity and quality, the global mapping data should be valuable because of its homogeneity in quality.

Each environment model applied in this study was developed in the advanced country, where the basic data is readily available. Consequently, the model needs to be deformed to a simpler model, when applied to the environment prediction in the developing country.

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