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ECOSYSTEM SERVICE ASSESSMENT IN AGRICULTURAL WATERSHED BY USING TOPMODEL

Kosuke MUKAE[1], Koji MIWA[2], Hiromu OKAZAWA[3*], Tomonori FUJIKAWA[3]

[1]Graduate School of Agriculture, Tokyo University of Agriculture, Japan
[2]Institute of Environmental Rehabilitation and Conservation, Japan
[3]Faculty of Regional Environment Science, Tokyo University of Agriculture, Japan
*Corresponding author: h1okazaw@nodai.ac.jp

ABSTRACT

In Millennium Ecosystem Assessment established by the United Nations, the ecosystem services (ES) provide benefits for human life as well as the environment. There is “regulating services” among all the supporting services. As a regulatory service, forests alleviate the flood risk after heavy rain by storing rainfall temporarily into forestlands and prevent the sudden increase in river discharge. The purpose of this research is to develop a hydrological modelling to assess this service in a watershed where consists of not only forestland but also grassland. TOPMODEL is applied for the quantification. This model was invented to forecast river discharge in watersheds where the land use is uniform. However, the model has not been applied to a watershed where agricultural and forest area are mixed in Japan. This research aimed to develop TOPMODEL to apply to such complexed land use. Because the targeted watershed is consisted of two land-use types, TOPMODEL was applied in each grassland and forestland. It predicted the river discharge by combining the predicted discharge from the different types of land calculated by TOPMODEL. The result confirmed that by developing the model, it was able to assess the water discharge from the both grassland and forestland in a watershed. The developed model also showed the better reproducibility of river-discharge prediction than the conventional TOPMODEL. In addition, it clarified that the forestland stores more water than grassland into the ground. Therefore, the effect of flood control which is the regulatory service of ES was assessable through the developed model.

Keywords: *hydrological modelling, river discharge, agricultural watershed, land use.*

INTRODUCTION

The ecosystem nurtured by coexisting with a human activity, agriculture brings various services to our life. Millennium Ecosystem Assessment (MA) established by the United Nations, put ecosystem services into three groups: “provisioning”, "regulating" and "cultural" services. Regulating services includes the effect of flooding and landslide control, such as water retention function by forests, flood control by riparian forests and soil erosion control by vegetation cover. However, despite this well-known function of the ecosystem, there has been no previous case that quantitatively assessed such regulating services in Japan with a hydrological modelling.

This research aims to develop a hydrological modelling to assess the flood control effect by an ecosystem service in a watershed of agricultural area. Hydrological modelling is the model that enables us to predict the amount of river flow affected by rainfall. The research applies a hydrological modelling, "TOPMODEL". TOPMODEL is a conceptual model widely used for assessment of river discharge amount. This model takes up water flow in the size of a watershed for analysis. It is a distribution model that divides a watershed into grids and calculates the surface flow generated from each grid. However, it regards the groundwater flow as a lumped model by considering the flow as one group in a watershed. Therefore, TOPMODEL is called a semi-distributed model.

This model has been applied to watersheds where land use is uniform and, in most of cases, only forestland. There have been a few studies which applied the model to a complex land use where forestland and grassland are combined. For these reasons, this research aims to develop TOPMODEL, and to assess its applicability for prediction of water flow in a complex agricultural basin consisting of forestland and grassland in Hokkaido, Japan.

Study site

As seen in **Fig. 1**, the objective watershed is Igarashi River watershed which is a tributary of Shubuto River, located in southwestern Hokkaido, Japan. The watershed area is 6.9 km^2 and the river length is 7.3 km. It is consisted of 2.7km^2 of grassland and 4.2 km^2 of forestland, which covers 31 per cent and 69 per cent respectively. This grassland is mainly used for pasture for livestock. In a part of the upstream of the water shed, there is cropland.

Fig.1 Igarashi River Watershed

This research took data of the river discharge and precipitation daily recorded from June 1, 1998 to October 31, 1998 by Okazawa, et al. (2002). With these data, the applicability of the improved version of TOPMODEL is analyzed. Penman-monteith method (Allen, 1998) is applied for calculation of daily evapotranspiration. Daily data of temperature, wind speed and hours of sunshine which are required to calculate daily evapotranspiration, are obtained from AMeDAS in Kuromatsunai managed by Japan Meteorological Agency.

TOPMODEL

TOPMODEL is a semi-distributed model suggested by Beven et al. (1979). This model divides soil layer into root zone, unsaturated zone and saturated zone. The semi-distributed model calculates the upper layer which contains root and unsaturated zones by each grid as a distribution type. For the lower layer, which is saturated zone, it is calculated as concentration type, thus every grid has the same value. TOPMODEL has a character that calculates the status of drying state of surface layer of basin from the topographical index (TI) induced from digital elevation model (DEM) and spatially evaluates the amount of the surface-flow.

1) Fundamental Equation of TOPMODEL

In TOPMODEL, the groundwater flow is calculated in the following equation:

$$q_i = T_0 \tan \beta_i \cdot e^{-S_i/m} \qquad (1)$$

$$T = T_0 \cdot e^{-S_i/m} \qquad (2)$$

Here, q_i is the downslope saturated subsurface flow rate at any grid *i* on a hillslope $[L^2T^{-1}]$. T_0 is the downslope transmissivity when the soil is just saturated $[L^2T^{-1}]$. The $\tan\beta_i$ is the surface ground gradient of grid *i*. S_i is the local storage deficit until the saturation [L]. *m* is a model parameter [L].

It is assuming that the groundwater is lateral with the ground surface gradient in **Eq. (1)** and that transmissivity has an exponential relationship with storage deficit. The following equation is assuming the groundwater flow if a steady state is established in each time step:

$$q_i = r_i \cdot a_i \qquad (3)$$

a_i is the area of the hillslope per unit contour length (m^2) [L]. r_i is a spatially homogenous recharge rate $[LT^{-1}]$. r_i is the effective recharge rate that permeates soil and flows into the groundwater. Thus, from **Eq. (1)** and **(3)**, the following equation is generated:

$$S_i = -m \ln\left(\frac{r_i \cdot a_i}{T_0 \tan \beta_i}\right) \qquad (4)$$

An expression for the watershed mean storage deficit, $\overline{S_i}$ is calculated by seeking the average of all the grids within the watershed.

$$\overline{S_i} = \frac{1}{A_T}\sum_i - m \ln\left(\frac{r_i \cdot a_i}{T_0 \tan \beta_i}\right) \qquad (5)$$

Here, A_T is the total of the entire area of the watershed. The above equation assumes to be completed in a flooding state ($S_i < 0$).

It hypothesized that *r* is spatially homogenous within a watershed. Then the following **Eq. (6)** is obtained by removing *r* through **Eq. (4)** and **(5)**. It is a prerequisite of TOPMODEL that the following equations are completed.

$$\overline{S_i} = S_i - m\left(\gamma - \ln \frac{a_i}{T_0 \tan\beta_i}\right) \qquad (6)$$

$$\gamma = \frac{1}{A_T}\sum_i \ln \frac{a}{T_0 \tan\beta_i} \qquad (7)$$

$\ln(a_i/T_0 \cdot \tan\beta_i)$ is the soil-topographic index. γ is the mean value of the index over the watershed area. A grid which has the same value between soil and the soil-topographic index, has the same character in hydrology. Then it is called hydrological similarity. The spatial mean value of T_0 , T_e is given by the following equation:

$$\ln T_e = \frac{1}{A_T}\sum_i \ln T_0 \qquad (8)$$

With this equation, Eq.(6) is organized as follow:

$$\frac{\overline{S_i} - S_i}{m} = \left(\ln \frac{a_i}{\tan\beta_i} - \lambda\right) - \left(\ln T_0 - \ln T_e\right) \qquad (9)$$

and

$$\lambda = \frac{1}{A_T}\sum_i \ln \frac{a_i}{\tan\beta_i}. \qquad (10)$$

$\ln(a_i/\tan\beta_i)$ is called Topographic Index (TI). λ is the mean Topographic Index in the watershed. TI is the index that expresses the topographic character of the catchment. It divides the watershed into the voluntary size and the watershed area that each grid has in the upper stream, (a)[L^2] and the ground surface gradient of grid, $\tan\beta_i$ are obtained from the following equation:

$$TI = \ln \frac{a}{\tan\beta_i} \qquad (11)$$

After obtaining TI in every grid in the watershed, a histogram of TI is formed (**Fig. 2**).

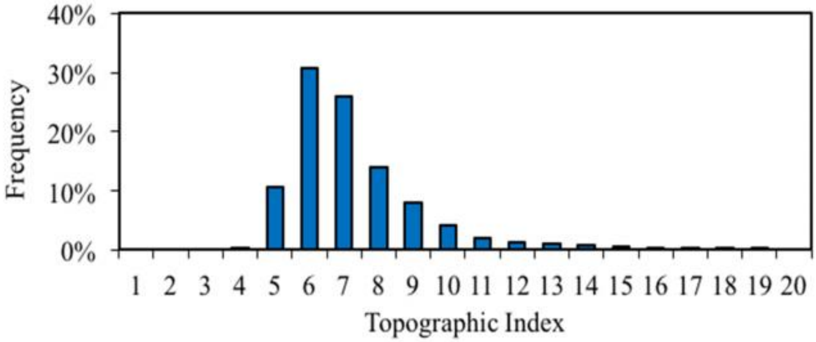

Fig. 2 Histogram of Topographic Index

2) Computational Procedure of TOPMODEL

TOPMODEL considers three storage parts, root zone, saturated zone and unsaturated zone as seen in **Fig. 3**, and calculates in each grid in the watershed.

a) Water balance equation of root zone

In root zone, the amount of water that can be stored within the root zone is calculated from the water balance of rainfall (R)[L], actual evapotranspiration amount (ET_a)[L], water available amount within root zone (SR_{max})[L] and storage deficit in root zone (SRZ)[L]. When redundant water, (EX_i)[L] is caused in root zone (SRZ<0), the redundant water is supplied to unsaturated zone and added to storage water (SUZ_i)[L]in that zone. Potential evapotranspiration (ET_0) is calculated by Penman-Monteith (PM) method, and ET_a is treated as the function of ET_0, SR_{max} and SRZ.

$$E_A = ET_0\left(1 - \frac{SRZ_t}{SR_{MAX}}\right) \qquad (12)$$

b) Water balance equation of saturated zone

The base-flow, Q_{sub}[LT^{-1}] from the whole watershed is treated as the concentrated amount per watershed. Base-flow is calculated by the following equation using the mean value of downslope transmissivity when the soil is just saturated, (T_e)[L^{2}T^{-1}], the mean topographic index of watershed, (λ) [-], the mean storage deficit in watershed, ($\overline{S_t}$) [L] and model parameter, (m):

$$Q_{sub} = T_e \exp(-\lambda)\exp\left(-\frac{\overline{S_i}}{m}\right) \qquad (13)$$

c) Water balance equation of unsaturated zone

Unsaturated zone is a temporary water storage zone that connects between root zone and saturated zone. It is calculated as a distribution model. The mean storage deficit amount in the watershed at the starting point of calculation, $\overline{S_t}$ is obtained from **Eq. (13)**, assuming that the initial discharge at the start is Q_0[LT^{-1}].

$$\overline{S_i} = -m \cdot \ln\frac{Q_0}{T_e \exp(-\lambda)} \qquad (14)$$

S_i in **Fig. 3** expresses the storage deficit of each grid, [L], and obtained from **Eq. (6)** and **(14)**. UZ_i is the amount of water supply from unsaturated zone to saturated zone [L], i is the number of grid. However, because a grid which has the same value as TI is regarded as hydrological similarity, a grid is calculated in each status class of TI rather than that the water amount is calculated in each grid (**Fig. 3**).

If S_i is 0 or negative, that class is regarded as saturation. Therefore, the excessive water inflow from root zone is return surface-flow (EX_i). If S_i is positive, the excessive water inflow is temporarily added to SUZ_i. UZ_i is

$$UZ_i = \frac{SUZ_i}{S_i \cdot t_d} \qquad (15)$$

where t_d is a parameter that expresses the period of retention, [LT^{-1}].

These are the concept of TOPMODEL. Operation of the model requires to determine five unknown parameters,"m", "T_e", "t_d", "SR_{max}", and "SRZ_0". This research determined the optimal value of five parameters by Monte Carlo method. Monte Carlo method is the generic term of a numerical simulation that uses random numbers.

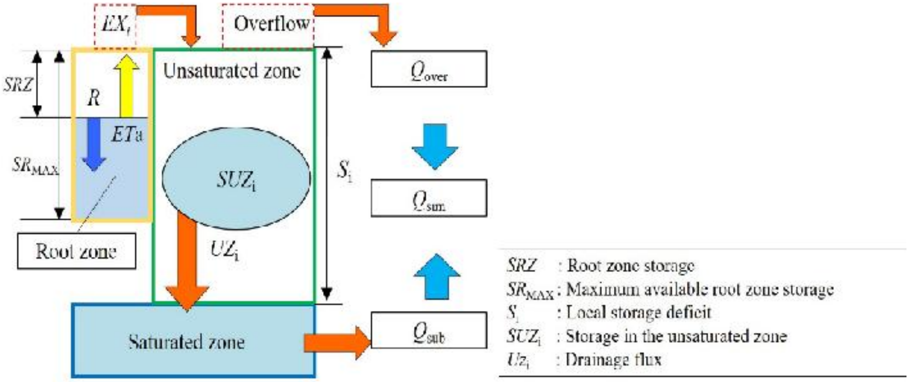

Fig. 3 Concept of TOPMODEL

TOPMODEL for Combined Forestland and Grassland

In general, TOPMODEL is applied to a simple land use at forest watershed. However, this study discusses the applicability of an improved TOPMODEL which considers the different land use of forestland and grassland, that is, a watershed with a complex land use (**Fig. 4**). The followings explain how this research calculated the complex land use.

1) Land use division

The area of forestland and grassland in the Igarashi river watershed is obtained from the 100 m mesh data of Land classification in National Land Numerical Information provided by the Ministry of Land, Infrastructure, Transport and Tourism of Japan. The ratio of land use for each forestland and grassland was 61% and 39 % respectively. From this, the mean topographic index of forestland, (λ_1) and grassland (λ_2) is calculated.

2) Computational Procedure

a) Water balance equation of saturated zone

From **Eq. (2)**, the base-flow of the whole forestland, Q_{sub1}[LT^{-1}] and the base-flow of the whole grassland, Q_{sub2}[LT^{-1}] are calculated. Then, the summation of the both values is regarded as the base-flow from the whole watershed.

$$Q_{sub} = Q_{sub1} + Q_{sub2} \quad (16)$$

b) Water balance equation of unsaturated zone

It is necessary to gain the initial river discharge (Q_{01}, Q_{02})[LT^{-1}] from forestland and grassland to gain the storage shortage (S_{i1}, S_{i2}) of each grid of forestland and grassland. Here it assumed that the ratio of flow amount from the both of forestland and grassland is always constant, and obtained the initial value of the river discharge in the following equation.

$$Q_0 = KQ_0 + (1-K)Q_0 \quad (17)$$

Here, it assumed that the ratio of water outflow from the forestland to the whole watershed is $K(0<K<1)$, the ratio of grassland is $(1-K)$, and K is an unknown parameter.

c) Other calculation

When it calculates root zone, UZ_i, it divides the watershed into forestland and grassland. From this, it determines the eleven unknown parameters "m_1", "T_{e1}", "t_{d1}", "SR_{max1}", "SRZ_{01}", "m_2", "T_{e2}", "t_{d2}", "SR_{max2}", "SRZ_{02}" and "K" for the improved TOPMODEL.

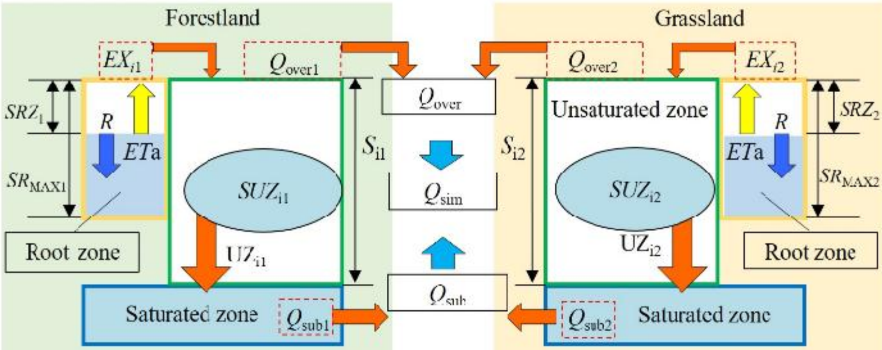

Fig. 4 Concept of Improved Version of TOPMODEL

Method of Identification and Comparison of Unknown Parameter

This research determined the optimal values of the eleven unknown parameters for the improved TOPMODEL by using Monte Carlo method. Through the method, generating random numbers for each eleven unknown parameter, "m_1", "T_{e1}", "t_{d1}", "SR_{max1}", "SRZ_{01}", "m_2", "T_{e2}", "t_{d2}", "SR_{max2}", "SRZ_{02}" and "K", 100,000 sets of combination were created. As the result of 100,000 times of calculation, it obtained the combination that accords the closest between the actual value of flow amount and the estimated value.

Evaluation Function

The compatibility of the actual value of river discharge and the estimated value is evaluated by Nash-Sutcliffe coefficient (NS value) and Root Mean Squared Error (RMSE). N stands for the total number of calculation time, $Q_{obs}(i)$ is the actual river discharge at any time step of i, $Q_{sim}(i)$ is the estimated river discharge of at any time step of i, and Q_{av} is the mean value of the actual river discharge.

NS value is calculated in **Eq. (18)**. The closer the value is to 1, the higher the accuracy of the model's estimate is.

$$NS = 1 - \frac{\sum_{i=1}^{N}[Q_{obs}(i) - Q_{sim}(i)]^2}{\sum_{i=1}^{N}[Q_{obs}(i) - Q_{av}]^2} \quad (18)$$

RMSE is calculated in the following **Eq. (19)**. The closer to 0, the higher the reproducibility of the estimated value is.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[Q_{obs}(i) - Q_{sim}(i)]^2} \quad (19)$$

RESULT AND DISCUSSION

The actual value of rainfall and river discharge in Igarashi River watershed and the predicted value generated by both of the conventional TOPMODEL and the improved TOPMODEL are shown in **Fig. 5**. Both models estimated the change of river discharge according to the change of rainfall well. However, the improved TOPMODEL showed the closer value to the actual value than the conventional one when the river dischaege decreases after it reached the peak point.

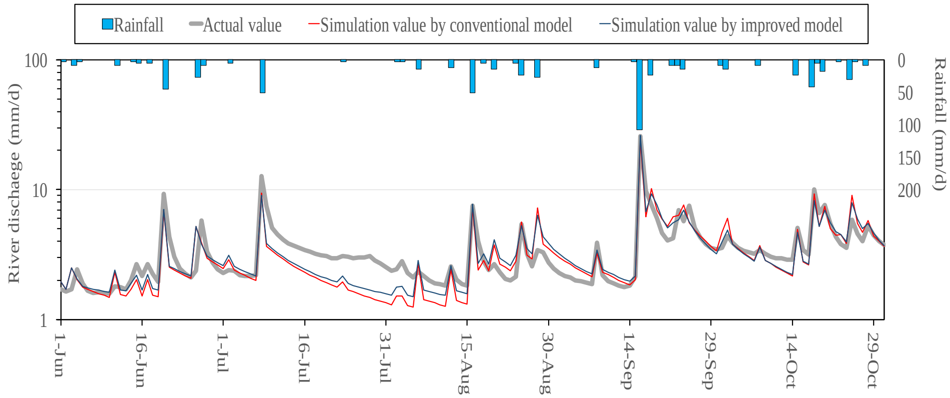

Figure 5. Comparison between the conventional and the improved TOPMODEL

The function value showed the accuracy of prediction of the both models. On one hand, the conventional TOPMODEL showed 0.823 for NS and 1.069 for RMSE. On the other hand, the improved TOPMODEL showed 0.853 for NS and 0.973 for RMSE. From these values, it confirms that the improved TOPMODEL had the higher accuracy of prediction of river flow change by rainfall than the conventional one throughout the target period.

The optimal value of unknown parameters of the conventional TOPMODEL and the improved TOPMODEL determined by the Monte Carlo method are shown in **Table 1**. The improved model showed the higher value in T_e and t_d than the conventional one. In addition, the improved model showed the two high values in forestland than grassland. As T_e expresses the downslope transmissivity when the soil is just saturated, forestland has better transmissivity than grassland. According to Ohte et al. (1989) and Ohta et al. (1989), transmissivity of forestland is generally high in Japan. This is because the transmissivity in grassland is lowered due to soils compressed by tiller machine or tractor. For this reason, it is valid that T_e is higher in forestland than grassland.

Table 1. Comparison of Unknown Parameters

Unknown parameter		m (mm)	T_e (mm/d)	t_d (mm/d)	SRZ_0 (mm)	SR_{max} (mm)	K
Conventional model		46.0	2.5×10^6	0.0104	0.52	0.62	
Improved model	Forestland	24.5	9.0×10^6	0.0206	0.42	0.85	0.43
	Grassland	81.6	6.5×10^6	0.0198	0.43	0.49	

t_d is a parameter that shows the delayed time caused when water moves from unsaturated to saturated zone. That is, this research showed that water flows slower from unsaturated to saturated zone in the improved model than the conventional one.

K showed 0.43. Although the ratio of land use for forestland is higher than grassland in the watershed, the ratio of outflow from forestland is lower than grassland. In the grassland, although the surface flow is high at the time of rainfall, the baseflow is remained within a certain limit because the ground cannot retain water regardless of the precipitation amount. On the other hand, in the forestland although the surface flow is low during rainfall because the ground stores the water, that stored water is discharged as baseflow after the rainfall. Comparing the amount of discharge per 1 km^2 for 153 days between forestland and grassland, forestland was 48.86mm and grassland 63.09mm. It means that forestland stores more water than grassland. Therefore, it clarified that forestland has the effect of flood control.

CONCLUSION

This research showed the applicability of the improved version of TOPMODEL for the case of watershed with the complex land use. Especially it has the high reproducibility when the actual river discharge is low. In addition, it showed the flood control effect in forestland by comparing with unknown parameters. In this way, the regulating service, which is one of the ecosystem services, is assessed in the complexed land-use by applying the improved TOPMODEL.

In the future study, the comparison of the improved TOPMODEL with the Soil and Water Assessment Toll (SWAT) is considered to clarify the higher accuracy of water flow prediction in the mixed land use watershed. SWAT is a model that considers the land use to evaluate the ecosystem service in watersheds consisting of agricultural land and forestland.

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