Research article

Application of TOPMODELs for Assessment of Ecosystem Services: Regulating Service in Agricultural and Forest Watershed

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Abstract According to Millennium Ecosystem Assessment, ecosystem services are divided into four services. Among them, regulating services include water regulation and natural hazard regulation which regulate water-discharge to rivers and mitigate flood risk by forest ecosystem. This research investigated characteristics of river flow changes at the time of rainfall runoff in two different land-use types, i.e.,1) watershed forest in Soebethu river watershed in Hokkaido and 2) intermixed watershed forest and pastureland in Igarashi river watershed in Hokkaido. A semi-distributed hydrological model, TOPMODEL was applied to simulate the amount of water discharge to the rivers. The conventional TOPMODEL was applied to the watershed forest, and the developed version of TOPMODEL to the intermixed watershed and pastureland. Monte Carlo simulation was used to identify unknown parameters required for the simulation. By comparing the identified parameters in the two different watersheds, flood control effect was evaluated in both land-use watersheds and each watershed and pastureland separately in the intermixed land-use. As the results of comparing the unknown parameters between the different land-use in the intermixed watershed and pastureland, the model showed that watershed forest has higher regulating service than pastureland. In addition, the research found that the difference of the type of surface soil influenced the amount of water discharge, that is, flood control effect. As the consequence, TOPMODEL was applicable for quantitative assessment of water regulation: the regulating service of the forest ecosystems.

Keywords TOPMODEL, ecosystem services, hydrological model, watershed, land-use

INTRODUCTION

Ecosystem services that prosper by the coexistence with agriculture provide various benefits to human life. According to Millennium Ecosystem Assessment (MEA) initiated by the United Nations, ecosystem services are categorized into four services, ‘Provisioning’, ‘Regulating’, ‘Cultural’ and ‘Supporting’ services. Regulating services that this paper focuses on, contain the flood risk alleviation by water storing function of forests such as riparian forest, and risk reduction of flood and sediment disasters by vegetation cover. In general, valuing ecosystem services can be done by monetary valuation such as hedonic approach and travel cost (Smith, 1993). However, such monetary valuation is considered an incomplete method to evaluate ecosystem services (Kate et al., 2007). Although there is also qualitative method to evaluate environmental value except for monetary valuation, there is no previous study which evaluated the regulating service in Japan.

This research applied a hydrological model, TOPMODEL to evaluate the flood control effect of forestland and pastureland. The target areas are two watersheds which differ in land-use from one another. One is a simplex land-use formed by only forestland, and another is the complex land-use by forestland and pastureland. TOPMODEL is a semi-distributed model, to predict water-runoff within a watershed scale (Beyen et al., 1979), and a conceptual model where has been confirmed its applicability in many parts of the world (David, 1993; Tada et al., 2002; Ali et al., 2015; Gao et al., 2015). TOPMODEL is a distribution model that divides a watershed into grids and calculates the surface flow generated in 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. For this reason, the conventional TOPMODEL was applied to a simplex land-use watershed, and a developed TOPMODEL was developed to enable the prediction in a complex land-use (Mukae et al., 2017). TOPMODEL is mainly applied to a watershed consisted of a simple land-use, for example a watershed only consisting of forest (Tada et al., 2002). On the other hand, there are few studies which applied to an agricultural watershed which both of forest and agriculture lands are mixed.

OBJECTIVE

This research applied the conventional TOPMODEL to a simplex land-use watershed and a developed TOPMODEL to a complex land-use watershed. It aimed to evaluate the applicability of both models for the prediction of water-runoff and the flood control effect in the different land-use types of the watersheds. Unknown parameters between the conventional and the developed models were compared to evaluate them.

METHODOLOGY

Research Site

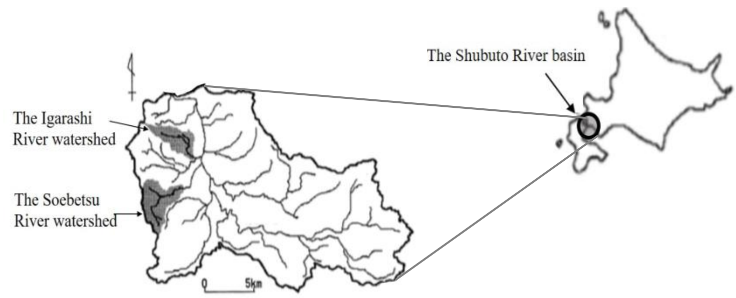

Fig. 1 The Shubuto River Basin, Hokkaido, Japan

The objective sites of this research are watersheds of the Igarashi River and the Soebetsu River. Both of them, in fact, are the size of stream rather than river and tributaries of the Shubuto River, located in southwestern Hokkaido, Japan (Fig. 1 and 2). The Igarashi River watershed has the area of 6.9 km^2 and the river length is 7.3 km. This watershed consists of a complex land-use with 2.7 km^2 of pastureland in the downstream basin and 4.2 km^2 of forestland in the upper and middle basin, which covers 31% and 69% of the watershed respectively. This pastureland is mainly used for livestock and there is cropland land in a part of the upper basin. Therefore, this watershed contains the land-use of agricultural and forest lands. On the other hand, the watershed area of the Soebetsu is 11.5 km^2, and the river length is 11.1 km. It is a simplex land-use only consisted of forestland. Since these watersheds are close to each other, the meteo-hydrological data such as precipitation amount and evapotranspiration for the both areas are similar.

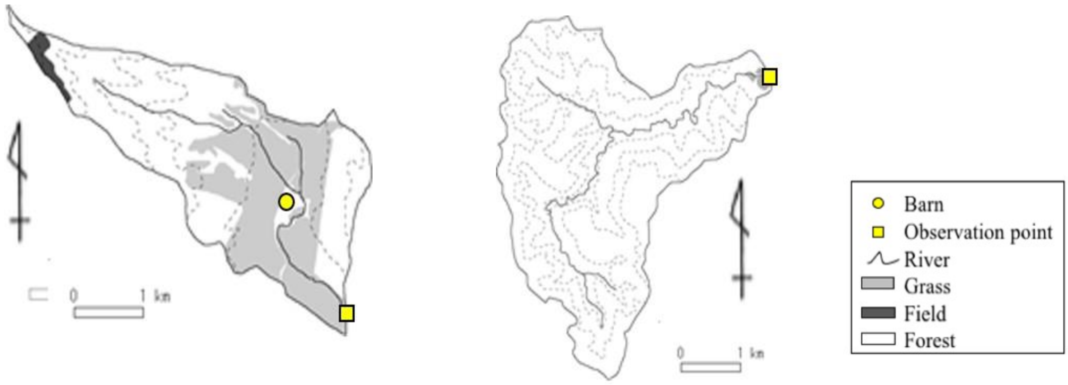

Fig. 2 Land-use of Igarashi River Watershed (Left) and Soebetsu River Watershed (Right)

This research used data of the daily record of river discharge and precipitation from June 1, 1998 to October 31, 1998 observed by Okazawa, et al. (2002). With these data, the applicability of the developed version of TOPMODEL is analyzed. Penman-monteith method (Allen, 1998) is applied for calculation of daily evapotranspiration. The daily data of temperature, wind speed and hours of sunshine which are required to calculate daily evapotranspiration, are obtained from AMeDAS in Kuromatsunai Town 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. TI is calculated from flow accumulation area and slope of each grid. If TI's value is large, the grid can be storage more water. But, If TI's value is small, the grid can be storage little water. So, Unsaturated zone is distribution model because it is calculated using Topographic Index. So, Soebethu river watershed can be storage little water than Igarashi river watershed.

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 as described below.

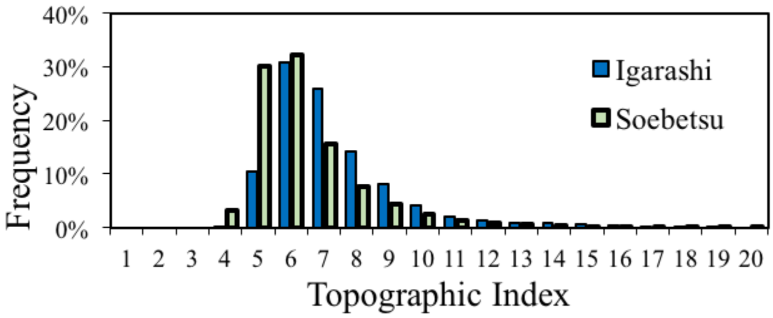

Fig. 3 Histogram of Topographic Index

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*.

$$ET_a = ET_0\left(1-\frac{SRZ_t}{SR_{MAX}}\right) \tag{1}$$

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, ($\overline{S_i}$) [L] and model parameter (m):

$$Q_{sub} = T_e \exp(-\lambda)\exp\left(-\frac{\overline{S_i}}{m}\right) \tag{2}$$

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, $\overline{S_i}$ is obtained from Eq. (3), assuming that the initial discharge at the start is Q_0 [LT^{-1}].

$$\overline{S_i} = -m \cdot \ln\frac{Q_0}{T_e \exp(-\lambda)} \tag{3}$$

S_i in Fig. 4 expresses the storage deficit of each grid [L] and obtained from Mukae et al. (2017). 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. 4).

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

$$UZ_i = \frac{SUZ_i}{S_i \cdot t_d} \tag{4}$$

where t_d is a parameter that expresses the period of retention.

These [LT^{-1}] 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.

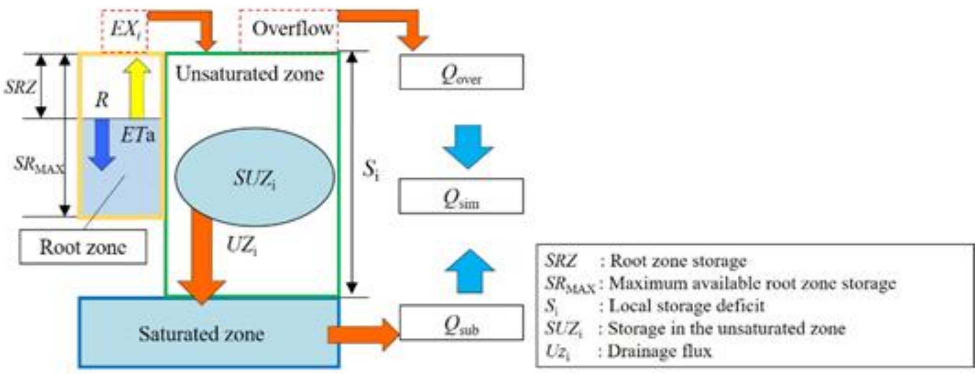

Fig. 4 Concept of TOPMODEL

TOPMODEL for Combined Forestland and Pastureland

In general, TOPMODEL is applied to a simple land-use at forest watershed. However, this study discusses the applicability of the developed TOPMODEL which considers the difference of land-use between forestland and pastureland, that is, a watershed with a complex land-use (see Fig. 5). The followings explain how this research calculated the complex land-use.

1) Land-Use Division

The area of forestland and pastureland in the Igarashi's 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 pastureland was 61% and 39 % respectively. From this, the mean topographic index of forestland, (λ_1) and pastureland (λ_2) is calculated.

2) Computational Procedure

a) Water balance equation of saturated zone: From Eq. (5), the base-flow of the whole forestland, Q_{sub1}[LT^{-1}] and the base-flow of the whole pastureland, Q_{sub2}[LT^{-1}] are calculated. Then, the summation of the both values is regarded as the base-flow from the whole watershed.

$$Q_{sub} = Q_{sub1} + Q_{sub2} \tag{5}$$

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 pastureland to gain the storage shortage (S_{i1}, S_{i2}) of each grid of forestland and pastureland. Here it assumed that the ratio of flow amount from the both of forestland and pastureland is always constant, and obtained the initial value of the river discharge in the following equation.

$$Q_0 = KQ_0 + (1-K)Q_0 \tag{6}$$

Here, it assumed that the ratio of water outflow from the forestland to the whole watershed is K($0<K<1$), the ratio of pastureland 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 pastureland. 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 developed TOPMODEL.

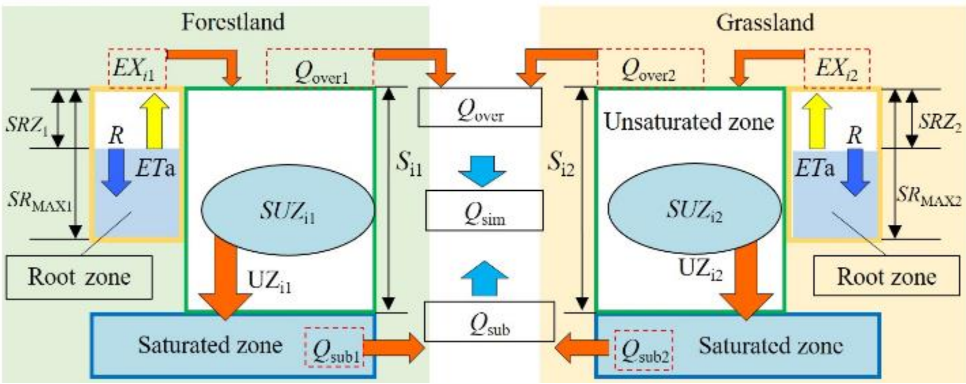

Fig. 5 Concept of Developed Version of TOPMODEL

Method of Identification and Comparison of Unknown Parameter

This research determined the optimal values of the 11 unknown parameters for the developed TOPMODEL by using Monte Carlo method. Through the method, generating random numbers for each 11 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.

RESULTS AND DISCUSSION

The actual value of rainfall and river discharge and the predicted values generated by both conventional TOPMODEL and developed TOPMODEL are shown in Fig. 6 for the Igarashi and Fig. 7 for the Soebetsu. Both models estimated changes of river discharge according to the changes of rainfall accurately. In addition, the developed TOPMODEL showed the closer value to the actual value than the conventional one when the river discharge decreases after it reached the peak point.

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). Regarding the accuracy of prediction in the function value, the conventional TOPMODEL showed 0.823 for NS and 1.069 for RMSE. On the other hand, the developed TOPMODEL showed 0.853 for NS and 0.973 for RMSE. From these values, it confirms that the developed TOPMODEL has the higher accuracy of prediction of river flow changes by rainfall than the conventional one throughout the target period.

The optimal value of unknown parameters of the conventional TOPMODEL and the developed TOPMODEL were determined by the Monte Carlo method as seen in Table 1. The developed model showed the higher value in T_e and t_d than the conventional one. Besides that, the developed model showed that these two values are higher in forestland than those in pastureland. As T_e expresses the downslope transmissivity when the soil is just saturated, forestland has better transmissivity than pastureland. 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 pastureland 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 pastureland.

A parameter, t_d expresses the delayed time caused by when water moves from unsaturated to saturated zone. That is, it shows that water flows more slowly from unsaturated to saturated zone in the developed model than the conventional one.

Comparting the unknown parameters between the forest watersheds in the Igarashi and the Soebetsu, the values except coefficient of saturated hydraulic conductivity showed the almost same values. The reason for the same value is that forest watersheds in the Igarashi and the Soebetsu are adjacent to the watershed, both of which are considered to have forestland. On the other hand, the cause of the gap in the coefficient of saturated hydraulic conductivity is probably attributed to the surface soil. The surface soil is composed by conglomerate and sandstone in the Igarashi watershed, and by mudstone in the Soebetsu watershed. Since transmissivity is lower in mudstone than conglomerate and sandstone (Ogata et al., 1992), it is considered that coefficient of saturated hydraulic conductivity in the Soebetsu watershed is lower. From these, it confirms that in case that watersheds have the same water system and land-use, the unknown parameters except coefficient of saturated hydraulic conductivity can be the same values and the difference of the coefficient is caused by the surface soil.

Table 1 Comparison of Unknown Parameters

unknown parameter		m (mm)	Te (mm/d)	td (mm/d)	SRZ_0 (mm)	SR max (mm)	K
Sobetsu (Conventional)		26.1	1.0×10^4	0.0218	0.13	0.88	
Igarashi (Conventional)		46.0	2.5×10^4	0.0104	0.52	0.62	
Igarashi (developed)	forestland	24.5	9.0×10^4	0.0206	0.42	0.85	0.43
	grassland	81.6	6.5×10^4	0.0198	0.43	0.49	

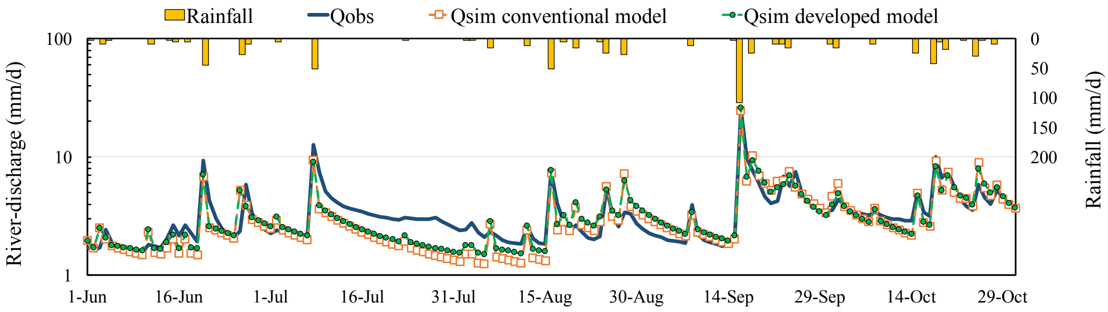

Fig. 6 Comparison between the conventional and the developed TOPMODEL

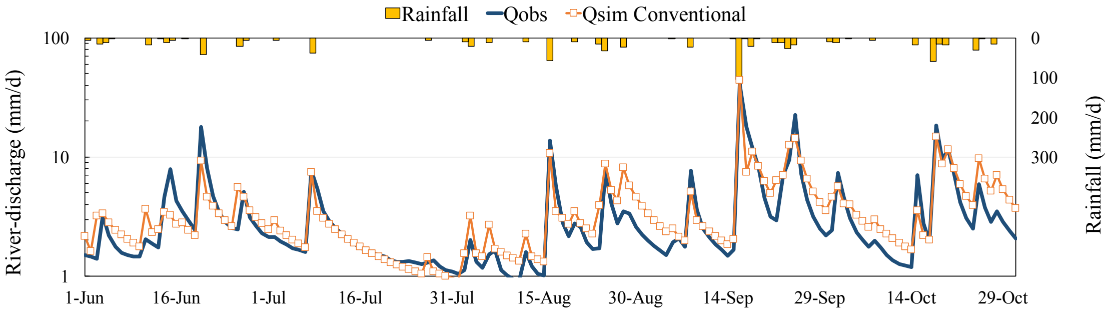

Fig. 7 Comparison between the conventional TOPMODEL

CONCLUSION

By comparing the unknown parameters between a simplex land-use and a complex land-use with application of the conventional TOPMODEL and developed TOPMODEL, it showed the result that forest watershed has higher flood control effect than pasture watershed. Besides that, it is expected that the value of coefficient of saturated hydraulic conductivity is related to the type of surface soil. For these reasons, this research clarified if the water system and land-use are the same, the unknown parameters except coefficient of saturated hydraulic conductivity in TOPMODEL gain the close values, and coefficient of saturated hydraulic conductivity is influenced by surface soil. Therefore, flood control effect as a regulation service which one of the ecosystem services is evaluated by the application of the conventional TOPMODEL and developed one.

For future study, this research result should apply to other agricultural and forest watersheds and different water system by using the same method to evaluate the ecosystem service more accurately.

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