Preliminary Analysis of Effects of Evapotranspiration Distribution on Streamflow Generation in a Steep Headwater Catchment

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Original Article

Preliminary Analysis of Effects of Evapotranspiration Distribution on Streamflow Generation in a Steep Headwater Catchment*

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Abstract

We analyzed effects of evapotranspiration distribution on streamflow in a forested catchment using a lumping model. The model was developed to understand the interrelation between components of water budget in two zones, source zone and hillslope zone. In this study, hydrological observations of precipitation, stream discharge, and soil moisture were conducted in a granitic steep headwater catchment in Etajima experimental forests, Hiroshima, Japan. We found a significant correlation between baseflow and saturation of source area. We analyzed effects of evapotranspiration on stand conditions on baseflow by changing the transpiration rate of each zone in the model. The results showed that (i) the annual trend of baseflow was strongly affected by evapotranspiration of the upper hillslope and (ii) the effects of evapotranspiration of source zone on baseflow appeared only during the dry period. We conclude that it is important to estimate each stand type of evapotranspiration and its distribution for understanding baseflow generation in the steep forested catchments.

Key words: evapotranspiration, baseflow, soil moisture, steep headwater catchment, saturation of source area, hillslope

1. Introduction

Forest vegetation is a major factor in the hydrological cycle (Waring and Running, 1998; Neilson, 1995). A considerable number of studies have been conducted on the effects of forests on reduction of flood peak and alleviation of water shortage (e.g. Bosch and Hewlett, 1982; Harr, 1981; Berris and Harr, 1987; Jones and Grant, 1996; Takimoto *et al.*, 1994; Shimizu, 1994). Especially, it is important for water resources management to clarify the relationships between the forest vegetation condition and baseflow of headwater catchments. However, it is very difficult to evaluate hydrological characteristics quantitatively in mountain regions because of complex terrain, relief, geology of catchments (Freeze, 1972; Kubota and Sivapalan, 1995), heterogeneity of subsurface flow such as pipe flow in soils (Uchida *et al.*, 1999 ; Sidle *et al.*,

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* 急傾斜源頭部流域の流出形成に及ぼす蒸発散分布の影響に関する予備的解析

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1995), groundwater flow in bedrocks (Hirose *et al.*, 1994; Komatsu and Onda, 1996 ; Uchida *et al.*, 2001), and spatial and temporal variability of evapotranspiration (Ohta and Kido, 1986; Miura *et al.*, 1981; Band, 1993).

To understand the roles of forest in hydrologic cycle, paired catchment approaches, comparative experiment of hydrological response between vegetation-converted catchment and control catchment, have taken place in many parts of the world in the last half-century. However, the paired catchment approaches tend to include the 'noise', which results from variability in storm characteristics and antecedent conditions. The model approaches have been also used to analyze the roles of forest in hydrological processes. If model error is small enough, the model approaches offer the potential for greater trend detect-ability than does the paired catchment approaches (Bowling *et al.* 2000). The distributed models such as TOPMODEL (Beven and Kirby, 1979), DHSVM (Wigmosta *et al.*, 1994), TOPLATS (Famiglietti and Wood, 1994), RHESSys (Band *et al.*, 1993) are useful to evaluate the effects of partial conversion of forest condition, for example clear cut or patch cut logging and load construction, because the distributed models are able to calculate the variability of soil moisture and evapotranspiration. These models also emphasize the importance of runoff from the source area for the stream discharge (Hewlett, 1961; Betson, 1964; Sivapalan *et al.*, 1987; Ohta, 1990). This means that the runoff generation depends on the recharge to the saturated zone, which is controlled by precipitation, evapotranspiration, and water storage in soil.

Over the last few decades, although the area of saturated zone is remarkably limited in steep forested headwater catchments such as mountain regions in Japan, it has been recognized that the saturated zone near the channel is important for runoff generation (Ohta, 1990). Ohta and Kido (1986) showed that the evapotranspiration from the forest stand located at lower hillslope influenced the baseflow generation using a numerical simulation based on the two-dimensional Richards' equation. Kubota *et al.* (1983) found that the baseflow was closely related to the saturation near the channel, i.e., power function relationship, in a steep headwater catchment. Therefore, the model representing the soil moisture condition of the saturated zone near the channel is effective in predicting the baseflow in steep headwater catchments in Japan.

The objective of this study is to make a preliminary analysis of effects of evapotranspiration distribution on streamflow towards developing a distributed model in the Etajima experimental forests, Japan. We evaluate the effects of evapotranspiration of two zones (the saturated zone near the channel and upper hillslope zone) on baseflow generation using a field observation of soil moisture dynamics and a tank model, which can simulate the moisture condition of saturated zone. The Etajima experimental forests except for the stands near the channel were destroyed by terrible fire in 1978 (23 years ago). The paired catchment approach has been conducted since then to analyze the hydrological response and its long-term trend with the forest vegetation recovering. However, there is no established theory to explain the effects of forests on baseflow generation. Therefore, the model approach is necessary in the Etajima experimental forests.

2. Field observation

2.1. Site description

The experimental forests locate in Etajima Island, the Seto Inland Sea, Hiroshima prefecture, Japan (Fig. 1). The annual precipitation is 1490mm and the annual mean air temperature is 15oC in this area, which belong to the Setouchi climate province characterized by relatively scarce precipitation in Japan. This area consists of weathered granitic rock and steep slopes with shallow soils. Etajima Island lost most of the forest vegetation by terrible fire occurred on June 1978. Hiroshima Prefecture has selected three small catchments (A, B and C) for hydrological and ecological study and observed rainfall and stream discharge for more than 20 years after the fire. Catchment A (10.7ha) happened to escape from the fire and was decided as the control. On the other hand, the forest vegetation in catchment B (19.2ha) and C (17.4ha) was burned down except for the stands near the channel. The vegetation of these catchments was similar before the fire.

In this paper, to examine the results produced by the model simulation, we focus on the relationship between rainfall, runoff and soil moisture in catchment C because the soil moisture has been measured intensively at a steep hillslope since March 2000. In catchment C, the mean slope angle and mean slope aspect are 37° and N35°E, respectively (Fig. 1). The seed dispersal by aircrafts (1978～1980) and the hillside planting works (1978～1988) were conducted, and the

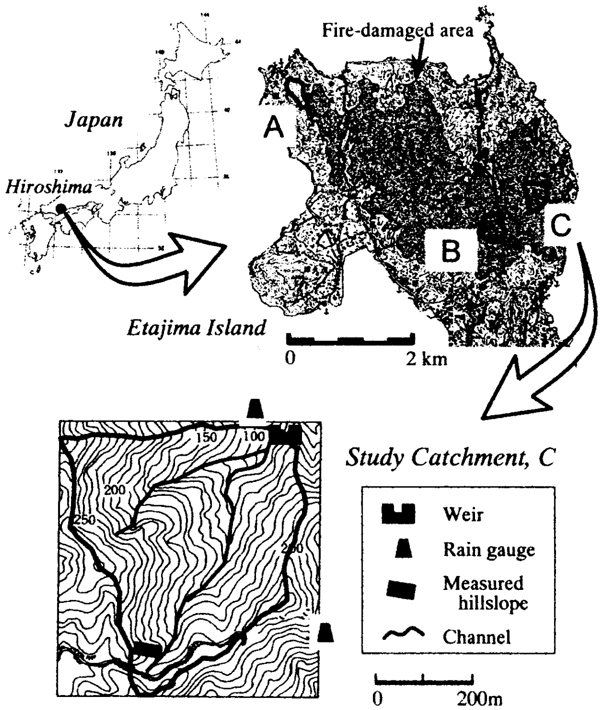

Fig. 1 Study site.

land surfaces have already covered by tree canopies. The overstories in most part of the catchment are dominated by *Pinus densiflora* Sieb. et Zucc. and *Quercus serrata* Thunb., while in the stand near the channel are *Castanopsis cuspidata* Thunb. Schottky var. *sieboldii* Makino Nakai and *Camellia japonica* L.. The understories are dominated by *Rhododendron mucronulatum* Turcz. var. *cilliatum* Nakai and *Eurya japonica* Thunb.

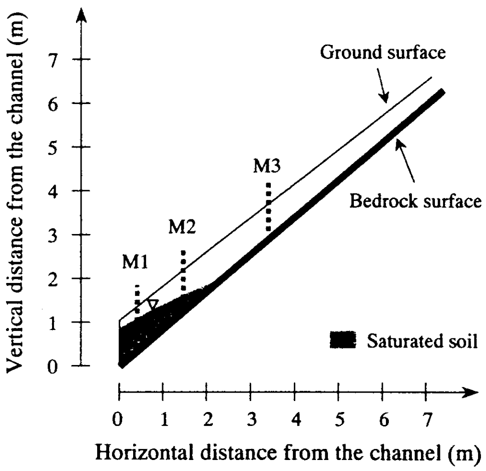

Fig. 2 Illustration of the lower part of measured hillslope. The horizontal distance of whole measured hillslope is about 50m. M1, M2, and M3 are the location of soil moisture sensors. The upper boundary of subsurface saturated soil is usually between M2 and M3.

2.2. Observation

Since 1980, stream stage has been recorded continuously by a chart recorder at the outlet of the catchment and converted into discharge, and precipitation has been measured using tipping buckets at two open sites (Fig. 1).

A hillslope in catchment C was selected for detecting the soil moisture dynamics (Fig. 1). The soil thickness at the observation hillslope ranged 0.3 to 1.0m judging from the result of excavations. The soil moisture sensors were installed at the lower hillslope (Fig. 2). The bottom of soil near the channel is saturated throughout the year. This area corresponds to the source zone. The vertical profile of soil moisture was measured using CS615 water content reflectometers (Campbell Scientific) and tensiometers (Daiki Rika Kogyo). The two types of sensors complemented each other. The measurement depths were 0.1, 0.3, and 0.5m at the hillslope zone and 0.2, 0.3, 0.6m at the source zone. The soil depths of the measurement points are 0.6m. An additional set of CS615 was installed vertically to measure the average water content within the topsoil (0～0.3m) in each point. All sensors were monitored each minute and the 10-minute means were stored on a CR10X data logger (Campbell Scientific).

The soil core sample of each depth was examined in the laboratory to know the soil properties. The saturated volumetric water content (θ_S) was 0.468m^{3}m^{-3}. The volumetric water content at pF 1.8 and pF 2.7 ($\theta_{pF1.8}$ and $\theta_{pF2.7}$, respectively) were 0.327 and 0.119m^{3}m^{-3}, respectively.

3. Model structure

The catchment is conceptually assumed to consist of two soil zones or tanks as shown in Fig. 3. When gross rainfall, P (m) falls onto canopy, the evaporations from interception water of hillslope and source zone take values I_{SL} (m) and I_{SAT} (m), respectively. For the sake of simplicity, I_{SL} and I_{SAT} are assumed to be constantly 15% of the rainfall base on Suzuki *et al.* (1979). The net rainfalls upon the soil of hillslope and source zone are Px_{SL} and Px_{SAT}, respectively, which are $0.85P$. The water flow in bedrocks is not considered in the model because the contribution of the flow in bedrocks on the streamflow is small at the granite catchment (e.g. Onda *et al.*, 1999).

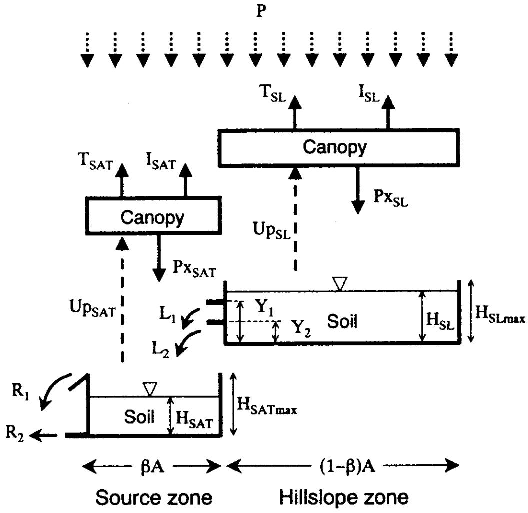

Fig. 3 Model structure. Subsurface zone is divided into two zones, and represented as two reservoirs. The runoff is generated from the saturated zone near the channel, i.e., source zone.

The water budget equations of hillslope and source zone for a time step (1day) are

$$\Delta H_{SL} = Px_{SL} - \frac{L_1 + L_2}{(1\text{-}\beta)A} - Up_{SL}, \qquad (1)$$

and

$$\Delta H_{SAT} = Px_{SAT} - \frac{L_1 + L_2 - R_1 - R_2}{\beta A} - Up_{SAT}, \qquad (2)$$

respectively, where H_{SL} and H_{SAT} are water storage of hillslope and source zone (m), A is catchment area (m^2), β is area ratio of source zone to whole hillslope, L_1 and L_2 are subsurface lateral flow components from hillslope zone to source zone (m^3), R_1 and R_2 are runoff (streamflow) components (m^3), and Up_{SL} and Up_{SAT} are root water uptakes (i.e. transpiration losses, T_{SL} and T_{SAT}) of hillslope and source zone (m), respectively.

The subsurface lateral flow is determined by the water storage of hillslope zone:

if $Y_1 < H_{SL}$,

$$\begin{aligned} L_1 &= \alpha_1 \times (H_{SL} - Y_1) \\ L_2 &= \alpha_2 \times (H_{SL} - Y_2) \end{aligned}, \qquad (3)$$

if $Y_2 < H_{SL} \leqq Y_1$,

$$\begin{aligned} L_1 &= 0 \\ L_2 &= \alpha_2 \times (H_{SL} - Y_2) \end{aligned}, \qquad (4)$$

if $H_{SL} \leqq Y_2$,

$$\begin{aligned} L_1 &= 0 \\ L_2 &= 0 \end{aligned}, \qquad (5)$$

where α_1 and α_2 are coefficients, Y_1 and Y_2 are represented as follows:

$$Y_1 = D_{SL} \times \theta_{pF\,1.8}$$
$$Y_2 = D_{SL} \times \theta_{pF\,2.7} \quad (6)$$

where D_{SL} is soil depth of hillslope zone (m). The soil water less than pF 1.8 is gravitationally drained downward through the non-capillary pores (Tsukamoto, 1992). The pF 2.7 is the boundary between the water held in the coarse pores and in the fine pores (Takeshita, 1985; Arimitsu, 1987).

The runoff depends on the saturation of source zone:

if $H_{SATmax} < H_{SAT}$,

$$R_1 = H_{SAT} - H_{SAT\max}$$
$$R_2 = k \times S_{SAT}^{\ m} \quad , \quad (7)$$

if $H_{SAT} < H_{SATmax}$,

$$R_1 = 0$$
$$R_2 = k \times S_{SAT}^{\ m} \quad , \quad (8)$$

where H_{SATmax} is the maximum water storage of source zone (m), S_{SAT} is the saturation of source zone (=H_{SAT}/H_{SATmax}), and k and m are parameters. H_{SATmax} is represented as follows:

$$H_{SAT\max} = D_{SAT} \times \theta_S \ , \quad (9)$$

where D_{SAT} is soil depth of source zone (m).

The transpiration losses are expressed as follows:

$$T_{SL} = \begin{cases} c_{SL} \times Tp, & P = 0 \\ 0, & P \neq 0 \end{cases}$$
$$T_{SAT} = \begin{cases} c_{SAT} \times Tp, & P = 0 \\ 0, & P \neq 0 \end{cases} \quad , \quad (10)$$

where, Tp is the daily potential transpiration (m) and c_{SL} and c_{SAT} are the coefficients depending on the vegetation condition of hillslope and source zone, respectively. The annual trend of potential transpiration is expressed as follow:

$$Tp = 0.00275 + 0.00125 \sin\left(\frac{DOY - 123}{366} 2\pi\right) , \quad (11)$$

where DOY is the day of the year. The maximum and minimum Tp are 0.0040md^{-1} (=4.0mmd^{-1}) on August 1 and 0.0015md^{-1} (=1.5mmd^{-1}) on February 1, respectively. We regarded that the coefficient c_{SL} was equal to c_{SAT} and its value was 1.0 because the canopy closure in the saturated and the hillslope zone was apparently similar. In addition, the transpiration reduction caused by dry water condition is not considered in this model.

4. Results and discussion

4.1. Parameters and model calibration

According to the intensive field measurement by Ohta (1990), the fluctuation of the saturated area of source zone to the rainfall in steep hillslopes was much less than that of the saturated volume. Therefore, we regarded the area ratio β as constant throughout the year in the model. The distance from the lowest point to the ridge of the measured hillslope is 50m. Since the boundary between source zone and hillslope zone is between M2 and M3 in most cases (Fig. 2), we assume that the distance from the lowest point to the boundary is 3m. Thus, the value β is 0.06 (=3/50).

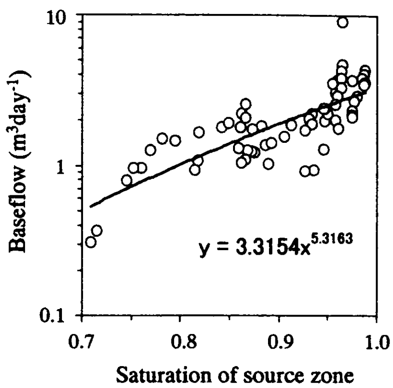

Fig. 4 Relationship between baseflow and saturation of source zone. The regression line is fitted ($y=3.3154x^{5.3163}$, n=66, r=0.79).

Figure 4 shows the relationship between the baseflow and the saturation of the source zone. The baseflow data used in this analysis were daily data during the recession periods, i.e., the fifth day after a rainfall event to the next event. We found the power function relationship between the baseflow and S_{SAT}, which expressed in equation (7) and (8), and then the parameter k and m were determined as 3.3154 and 5.3163, respectively.

The optimum values of coefficient α_1 and α_2 were determined as 0.1479 and 0.0109, respectively, by iteration of calculation so as to minimize the average relative error ($Er1$) when the average water budget error ($Er2$) is less than 0.05:

$$Er1 = \frac{1}{N} \sum_{t=1}^{N} \frac{|Q_{ob}(t) - Q_{cal}(t)|}{Q_{ob}(t)} , \tag{12}$$

and

$$Er2 = \frac{\left| \sum_{t=1}^{N} Q_{ob}(t) - \sum_{t=1}^{N} Q_{cal}(t) \right|}{\sum_{t=1}^{N} Q_{ob}(t)} , \tag{13}$$

where N is the number of days during the calculation period, $Q_{ob}(t)$ and $Q_{cal}(t)$ were the observed and calculated streamflow at the day t, respectively. The criterion, $Er2 < 0.05$, is based on the preliminary calculation, and means that the model is rigorous on the allocation of net rainfall to the runoff component during the calculation period. Table 1 lists the model parameters.

Figure 5 shows the results of the model calculation with input data (rainfall). The model tends to underestimate the discharges at flow peaks and S_{SAT} during the dry period. The former may be caused by the large time step for calculation or the difficulty in evaluating the preferential flow such as pipeflow. Moreover, in case that we discuss the storm flow at catchment scale, it may be necessary to regard the area ratio β as variable. The latter may be improved using the transpiration model based on the meteorological data and soil moisture condition. However, the model reproduces the annual trend of S_{SAT} and baseflow. We judge that this model is helpful to

Table 1 Model parameters.

Parameter		*Value*
β	area ratio of source zone to whole hillslope	0.060
θ_S	saturated volumetric water content	0.4680
$\theta_{pF1.8}$	volumetric water content at *pF* 1.8	0.3270
$\theta_{pF2.7}$	volumetric water content at *pF* 2.7	0.1190
D_{SL} (m)	soil depth of hillslope zone	0.60
D_{SAT} (m)	soil depth of source zone	0.60
H_{SLmax} (m)	maximum water storage of hillslope zone	0.2808
H_{SATmax} (m)	maximum water storage of source zone	0.2808
Y_1 (m)	depth of upper drain of hillslope zone tank	0.1962
Y_2 (m)	depth of lower drain of hillslope zone tank	0.0714
α_1	coefficient of upper drain of hillslope zone tank	0.1479
α_2	coefficient of lower drain of hillslope zone tank	0.0109
k	coefficient related to runoff from source zone	3.3154
m	exponent related to runoff from source zone	5.3163
c_{SL}	coefficient depending on vegetation condition of hillslope zone	1.0
c_{SAT}	coefficient depending on vegetation condition of source zone	1.0

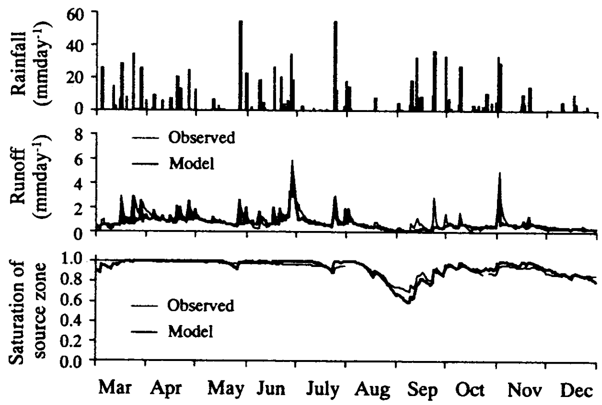

Fig. 5 Results of model calibration using observed runoff data from March to December 2000.

understand the effects of evapotranspiration of hillslope zone and source zone on S_{SAT} and the baseflow.

4.2. Simulations

S_{SAT} is a most important factor for analyzing the baseflow generation. In order to make preliminary estimates of the effects of evapotranspiration distribution on the baseflow generation, we conducted eight numerical experiments, i.e., manipulations of the transpiration of hillslope (T_{SL}) and source zone (T_{SAT}). The above-mentioned calibrated parameters and the input data (rainfall) were reference of the experiments (Case 0). In Case 1 to 4, c_{SL} was altered: 0.5, 0.8, 1.2 and 1.5, respectively (Fig. 6a). In contrast, in Case 5 to 8, c_{SAT} was altered in the same way (Fig.

6b). Then, we focused on the trend of S_{SAT}. T_{SL} critically controlled S_{SAT} throughout the year (Fig. 6a). On the other hand, T_{SAT} influenced S_{SAT} only during the dry period, when the subsurface flow to source zone could be neglected (Fig. 6b). These results imply that the subsurface lateral flow from hillslope to the source zone is important for the baseflow generation. According to Kubota and Sivapalan (1995), the area of saturated zone decreases with the hillslope angle. Therefore, in steep headwater catchments like Etajima experimental forests, the area of saturated zone would be extremely limited near the channel. In other words, the stable baseflow generation would depend on the durability of subsurface lateral flow to source zone.

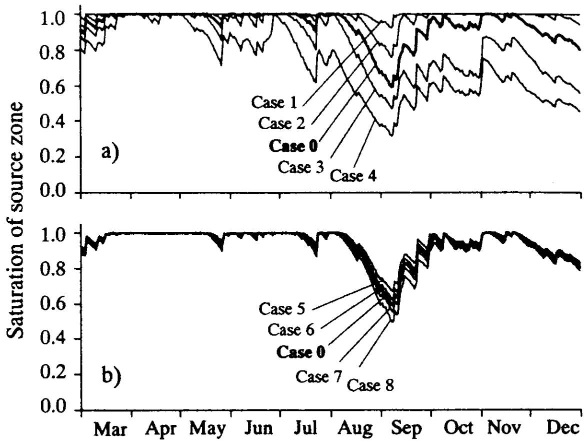

Fig. 6 Simulation results. Case 0 (c_{SL}=c_{SAT}=1.0) is reference. (a): In Case 1 to 4, c_{SL} is altered (0.5, 0.8, 1.2 and 1.5, respectively) and c_{SAT} is fixed. (b): In Case 5 to 8, c_{SL} is fixed and c_{SAT} is altered (0.5, 0.8, 1.2 and 1.5, respectively).

5. Conclusion

In this study, to analyze the relationship between transpiration and baseflow generation in a steep headwater catchment, the model representing the soil moisture condition of the saturated zone near the channel, i.e., the saturation of source zone (S_{SAT}) was developed. A good agreement between calculated and observed saturation of source zone was obtained.

The model simulation by changing the transpiration rate of hillslope and source zone led to the following results:

1) S_{SAT} sensitively responded to the transpiration of the hillslope zone.

2) The transpiration of source zone influenced S_{SAT} only during the dry period.

We conclude that it is necessary to carefully determine the distribution of transpiration and soil moisture in the catchment, in order to evaluate the effects of vegetation recovery on the long-term trend of streamflow after fire in the Etajima experimental catchment. It is also suggested that the transpiration of source zone is a key factor to understand the role of forest in the stable supply of water during the water shortage period, which is a substantial feature in the Setouchi climate province. These specific relations between the source zone and hillslope zone should be considered in developing the distributed runoff model in the Etajima catchment.

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急傾斜源頭部流域の流出形成に及ぼす蒸発散分布の影響に関する予備的解析

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要　旨

森林流域における蒸発散分布が基底流量に与える影響について流出タンクモデルを用いて予備的に解析した．このモデルでは，流域の斜面が2つの領域に概念的に区分されている．一つは，土層中に飽和帯が形成されるような流路沿いの領域（Source zone）であり，もう一つは，それよりも上部の領域（Hillslope zone）である．このモデルにより，各領域における水収支構成要素の相互関係を把握することができる．本研究では，山地源頭部の花崗岩流域である広島県江田島水文試験地において降雨，流出，土壌水分の観測がなされた．その結果，基底流量と流路沿いの土層の飽和度との間に有意な相関が見いだされ，この関係はモデルに組み込まれた．約10ヶ月間の降雨，流出データに基づいてモデルをキャリブレーションした結果，Source zoneの飽和度の変化傾向は，流路沿いの土層で観測された飽和度の変化傾向とよく一致していた．すなわち，このモデルにより，蒸発散が基底流量に与える影響を十分に説明できると判断できた．そこで，各領域の蒸散強度を変化させる数値実験を行った．その結果，(i)Hillslope zoneの蒸散は基底流量の年変化に強く影響すること，(ii)Source zoneの蒸散は渇水期にのみ基底流量に影響することがわかった．以上より，急傾斜森林流域における基底流出の形成を明らかにするためには，林分タイプ別の蒸発散とその空間的分布を評価することが極めて重要であると結論づけられた．

キーワード： 蒸発散，基底流出，土壌水分，急傾斜源頭部流域，ソースエリア飽和度，斜面