

Predicting the dependencies of rainfall-runoff responses on human forest disturbances with soil loss based on the runoff mechanisms in granite and sedimentary rock mountains

Makoto Tani,^{1*} Masamitsu Fujimoto,¹ Masanori Katsuyama,¹ Nagahiro Kojima,² Ikuhiro Hosoda,³ Ken'ichirou Kosugi,¹ Yoshiko Kosugi¹ and Sho Nakamura⁴

¹ Graduate School of Agriculture, Kitashirakawa-oiwakecho, Sakyo, Kyoto 606-8502, Japan

² Shiga Forest Research Center, 978-95 Kitazakura, Yasu, Shiga, 520-2321, Japan

³ Kansai Research Center, Forestry and Forest Products Research Institute, 68 Nagaikyutaroh, Momoyama, Fushimi, Kyoto 612-0855, Japan

⁴ Strategic Resource Management Division, Oji Paper Co., Ltd., 4-7-5 Ginza, Chuo-ku, Tokyo 104-0061, Japan

Abstract:

Understanding the effects of severe human induced forest disturbances with soil loss on rainfall-runoff responses is important for future forest management. However, few studies have addressed this issue, which is methodologically difficult compared with the hydrological assessments of the effects of logging. In this study, several small catchments in Japan with different soil and geological conditions were compared using the runoff model HYCYMODEL to reveal their runoff characteristics. The results were then examined on the basis of runoff mechanisms to demonstrate the possible ranges of the effects derived from human disturbances for each geological type. For granite mountains, bare land can be considered the severest case of disturbances leading to high stormflow peaks, although a large baseflow remains because of the water storage fluctuation in weathered bedrock. For sedimentary rock mountains, the severest case may be a forest on the clayey soil without brown forest soil producing flashy runoff characteristics including a large stormflow volume with a sensitive response to the antecedent dryness and a low baseflow rate. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS forest disturbances; hillslope hydrology; HYCYMODEL; rainfall-runoff responses; runoff prediction

Received 20 September 2009; Accepted 25 June 2010

INTRODUCTION

Although a general belief holds that forests can mitigate flood and drought, scientists have disputed over the effects of forests on moderating a fluctuation in rainfall-runoff responses (e.g. Calder, 1999; Calder *et al.*, 2007). For example, Bradshaw *et al.* (2007) used statistical analysis to detect the influence of forests on flood frequency and suggested that the frequency was negatively correlated with the amount of remaining natural forest and positively correlated with the area of natural forest loss. However, van Dijk *et al.* (2009) reanalysed the data used by Bradshaw *et al.* and concluded that population density alone, more than forest cover or deforestation, explained most of the variation in the flood occurrences. Laurance (2007) raised the question of how forests affect floods driven by extreme events such as cyclones and typhoons. According to a report by the Food Agriculture Organization–Center for the International Forestry Research, the mechanism of forest soil, which acts as a sponge, seems to be negligible for extreme events (FAO-CIFOR, 2005).

These debates may derive from the assumption that the soil condition under a forest is not directly influenced by forest changes. That is, such studies seem to propose that the effects of land degradation are strictly distinguished from

those of deforestation, as described by van Dijk *et al.* (2009). However, throughout human history, our use of forests has often caused soil erosion (Totman, 1989), and deforestation has occurred at continental-sized scales in places such as Amazonia (Nepstad *et al.*, 1999). As the demand for forest resources continues to increase, we face limitations on forest resources (Brooks, 1997). Forest resources worldwide should be carefully managed to fill the demand, and even trees on steep hillslopes should be harvested to meet increased demands. However, if the forest management is unsuccessful, destructive deforestation, including soil erosion, may bring severe hydrological risks. Predictions of hydrological cycles in response to possible scenarios of land use are critical to avoid risks to human life and property (Oki and Kanae, 2006). Thus, more emphasis should be placed on evaluating the effects of human disturbances on the total forest system, including the underground component, to establish strategies for near-future land management. Assessments of the effects of only aboveground changes in the forest vegetation system may be of a lower priority.

Several meteorological studies have been conducted to predict the effect of continental-scale deforestation on climate (e.g. Nepstad *et al.*, 1999; Makarieva and Gorshkov, 2007; Takata *et al.*, 2009). However, very few studies have been able to detect evidence for a deforestation effect on the climate from meteorological data (Kanae *et al.*, 2001). Meanwhile, many field studies on forest hydrology have examined forest-clearing effects on runoff

*Correspondence to: Makoto Tani, Forest Hydrology Laboratory, Graduate School of Agriculture, Kitashirakawa-oiwakecho, Sakyo, Koto 606-8502, Japan. E-mail: tani@kais.kyoto-u.ac.jp

in small catchments (e.g. Bosch and Hewlett, 1982; Abe and Tani, 1985; Komatsu *et al.*, 2007), but runoff modelling to predict the effects of severe forest disturbances, including the effect of soil erosion on river runoff, is lacking. Forest hydrologists have generally focussed on the immediate effects of changes in aboveground vegetation, and a large gap remains between the field evidence and the model predictions necessary for understanding the effects of severe and/or long-term forest disturbances with soil losses. The lack of study and uncertainty among the results may contribute to the ongoing debate on the effects of forests on runoff responses.

An alternative methodology may be needed to detect the effects of human disturbances with soil loss. A good site for collecting evidence of such effects is the widespread bare land in the granite mountains of Japan that was created because of long-term human disturbances (Kadomura, 1980). Throughout Japan's long history, forests have continuously been used to provide basic resources for human activities. In central Japan, large timbers have been frequently harvested since the 7th century to build temples, shrines and palaces, and forest litter on hillslopes was traditionally collected by villagers as fertilizers and fuels (Totman, 1989). The amounts of timber and litter used increased with economic activities, becoming large during the Tokugawa period (1603–1867). Surface forest soil was gradually lost by surface erosion and landslides, as litter was removed and the root systems declined. Low-paid nighttime work by villagers contributed to deforestation, as pine roots were used as lighting materials (Chiba, 1973). Although the severe human impact commonly occurred in hilly forests surrounding villages, the results are thought to differ according to the geological condition. The most devastated result was created in the weathered granite mountains including our study field, the granite Tanakami Mountains of central Japan. These areas have little soil because rainstorms readily erode the soil particles produced from the weathered rock as described later for our bare land study catchment. Therefore, such a case can be used to scale the maximum range of the effects of human disturbances in the granite mountains. Fortunately, hydrological data are available from several study catchments with different land cover conditions in the Tanakami Mountains. A comparison of the runoff responses has provided useful information on the effects of various land cover conditions on runoff responses and water chemistry (Fukushima, 1987, 2006; Asano *et al.*, 2002). In this study, we reanalysed the data to quantitatively assess the dependencies of runoff responses on human disturbances with soil losses.

The runoff responses are much different in each geology as described in the next section, suggesting that the effect of human disturbances on them may depend on the hillslope runoff mechanisms derived from each geology. In this article, therefore, the runoff mechanisms of hillslopes, not only in granite mountains but also in sedimentary rock mountains, were reanalysed under the assistance of our preceding studies there. Understanding the runoff mechanisms must be particularly critical if you would predict these

effects in a catchment without a hydrometrical monitoring system. Hence, this study can contribute to the prediction of human impacts in IAHS-PUB (Sivapalan *et al.*, 2003).

METHODOLOGICAL CONSIDERATIONS

Predominance of geology identified from statistical analysis of rainfall-runoff responses

Because our concern here is the rainfall-runoff response, the most basic task is to classify catchments on the basis of their runoff regimes. A statistical analysis approximately 30 years ago provided an important answer, namely, mountainous catchments in Japan can be clearly classified by geology. Shimizu (1980) examined the rainfall-runoff characteristics of 70 river basins (area, 22.2–471.0 km²) in Japan and found that runoff was relatively flashy in sedimentary rock basins but was stable in igneous rock basins (see Figure 1). In Shimizu's analysis, other properties such as landform and vegetation had almost no influence on the runoff regime. Similar results were obtained from another data set in Japan by Musiaki *et al.* (1975) and from rivers in the United Kingdom by Holmes *et al.* (2002). These results strongly demonstrate that geology is a main controller of runoff, and other properties do not play significant roles in classification. Recent studies on runoff mechanisms have also demonstrated the large effect of geology (e.g. Kuraji, 1996; Onda *et al.*, 2006; Katsuyama *et al.*, 2008). However, this is not to say that the effects of properties other than geology are negligible. Rather, a new methodology may be needed to detect their

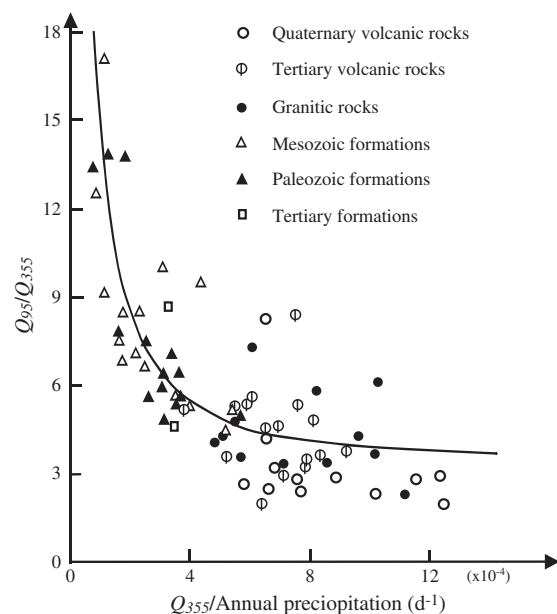


Figure 1. Classification of the runoff regime by geology derived from flow duration curves (FDCs) for mountainous rivers in Japan (after Shimizu, 1980). Q_{95} and Q_{355} represent the 95th and 355th runoff rates (specific discharge in mm day⁻¹) in an FDC. Because Q_{95} and Q_{355} may reflect runoff rates in high-water seasons and in long rainless periods, the abscissa (Q_{355} /annual rainfall amount) and ordinate (Q_{95}/Q_{355}) represent an index of drought runoff in consideration of the catchment rainfall condition and an index of runoff flashiness, respectively. See Appendix of Katsuyama *et al.* (2008) for a difference in FDC between used in this figure and in countries out of Japan

effects. Assuming that most sampled catchments have experienced long-term disturbances as have occurred in central Japan (Shidei, 1973), the effects of such disturbances on the runoff would generally emerge in all samples and may be difficult to detect. Numerous studies have compared the runoff in a newly forest-cutting catchment with the runoff in an adjacent catchment with no vegetation change. This methodology may identify a clear result of evapotranspiration (ET) decrease (Bosch and Hewlett, 1982) but give little information on the effects of long-term forest disturbances that are generally imposed on the mountainous area as a whole.

We can conclude that the statistical analyses of runoff responses in mountainous catchments can detect only the effect of geology and that catchment studies of the effects of forest-cutting can demonstrate an ET decrease. However, we should apply an alternative method to detect the effects of severe long-term human disturbances on runoff characteristics.

Data suitable for detecting soil effects on runoff responses

Fukushima (1987, 2006) has applied a unique methodology for elucidating the effects of soil on runoff in the granite Tanakami Mountains. He first developed a runoff model and obtained its parameters by simulating the hydrographs for small catchments with different revegetation histories: one catchment was covered with bare land where no revegetation work was carried out, and the other four catchments differed by that time since hillside work consisting of terrace making and soil mounding on the terrace for planting seedlings was completed. The parameters for the runoff model, HYCYMODEL (described later in Figure 2), were optimised by simulating the hydrograph responses obtained from the rainfall-runoff measurements in these catchments. Large differences in the storm hydrographs were shown between the bare land catchment and the others, and a gradual change was detected among the catchments with different revegetation histories. Differences in the hydrographs for these catchments were assumed to be mainly controlled by soil conditions because catchments share a common geology. We can say that a delicate difference may be only detected from comparisons between a favourable data set as used in this study. According to this study experience and the predominance of geology (last section), the effects of human disturbances with soil loss should be studied in each of the geological types by a careful data selection. In this article, we attempt to estimate the quantitative ranges of the effects of the disturbances in two geological types (granite and sedimentary rock) that widely cover mountain areas of Japan. The runoff mechanisms in each geology were taken into consideration in the estimation because the appearance of effects might be strongly dependent on them.

The gap between the model and the mechanisms

A runoff model offers a good method to compare the characteristics of rainfall-runoff responses between catchments because the characteristics can be extracted by

parameter values even when the climate conditions differ among catchments. A parameter set optimised for each catchment may reflect characteristics of the runoff responses in that catchment, and it is desirable that an individual parameter value represent a physical property included in the runoff processes. However, model simulations using parameter values obtained from measured data sets of runoff processes by an *a priori* estimation procedure do not often give satisfactory results (Duan *et al.*, 2006). This unexpected model performance may be due to the uncertain relationships between model parameters and catchment properties with heterogeneous distributions. For example, although a modelling study using TOPMODEL assumed that the saturation excess overland flow yielded a storm runoff response and parameterised the effects of a catchment's topographical properties on that response (Beven and Kirkby, 1979), many field observations have demonstrated that preferential pathways such as natural pipes through the soil-bedrock interface control the response (Mosley, 1982; McDonnell, 1990; Tani, 1997; Uchida *et al.*, 1999). A discrepancy between the simplicity of a model structure and the complexity of the runoff processes often makes it difficult to predict the runoff responses in an ungauged basin (Sivapalan, 2003; Kling and Gupta, 2009). For example, various models may produce a similar rainfall-runoff response assuming different runoff mechanisms, and thus the successful agreement between simulated and observed runoff response does not necessarily endorse the validity of the runoff mechanism assumed in a given model (Dunn and Lilly, 2001; Kling and Gupta, 2009).

This gap between runoff model structures and runoff mechanisms forces us to make sharp distinctions between selecting a runoff model to compare the catchment runoff responses and identifying the mechanism causing the runoff responses although a final integration should follow both analyses. A good model for such comparison should have the following features: (i) it should produce excellent simulation results against the observed hydrographs, (ii) it should simply reflect a basic nature included in the runoff responses involved in most of the catchments and (iii) it should be as free as possible from assumptions about the runoff mechanism. Although achieving features 2 and 3 is not easy, for feature 2, runoff in a recession stage can often be approximated by the drainage from a tank considering its functional relationship to tank storage, and rainfall-runoff responses can be well simulated by a system composed of plural tanks. Sugawara's successful achievements in tank modelling have clearly demonstrated this capacity (Shamir, 1993; Sugawara, 1995). In this respect, such a storage model is preferable; however, Sugawara's Tank model itself has too many parameters. This may be acceptable for simulation purposes but presents difficulty when comparing the parameter values between catchments because the best set of parameter values is not fixed, as many parameter sets give good simulation results. A simpler model with fewer parameters is better for comparison. Feature 3 is also important because it is preferable to avoid the influence of model assumptions in

the discussions of the runoff mechanisms. On the basis of these considerations, the HCYMODEL (Fukushima and Suzuki, 1986; Fukushima, 1988) was selected for analysis in this study.

METHODS

Runoff model

Our study selects the HCYMODEL for the comparison of catchment rainfall-runoff responses. Details of the HCYMODEL have been previously described by Fukushima (1988). Therefore, in this section, we only explain its summary with some minor modifications. Here, the ET procedure is very simply operated using the averaged monthly values estimated from the short-term water budget method (Linsley *et al.*, 1958). The same monthly ET is given to the catchment every year. The observations for 33 years in one of the small catchments, the Kiryu Experimental Watershed (KI), showed a very small variability in the annual ET (Kosugi and Katsuyama, 2007). This result supports our assumption that the same monthly ET is given every year. In addition, no reduction of ET is considered because the study area is relatively moist. The method for how to give monthly ET values to each catchment in the simulations is described later in the section Calculation preparation.

The short-term water budget method follows an algorithm developed by Suzuki (1985), using the following main equation (for details, see Kosugi and Katsuyama, 2007):

$$E = P - Q = \int_{t_1}^{t_2} r(t)dt - \int_{t_1}^{t_2} q(t)dt \quad (1)$$

where E is the ET amount (mm), P is the precipitation amount (mm), Q is the runoff amount (mm), $r(t)$ is the

precipitation intensity (mm day^{-1}) and $q(t)$ is the runoff rate (mm day^{-1}). This method is based on an assumption that when the runoff rates at the recession stages from t_1 to t_2 are the same, the catchment water storage values are also the same. Kosugi and Katsuyama (2007) demonstrated that the seasonal variation of ET estimated from the short-term water budget method in KI agreed with that calculated by the eddy covariance method using meteorological observations from a tower in the catchment (Kosugi *et al.*, 2007).

Figure 2 shows the procedure for the runoff component in the HCYMODEL. The model's four tanks are briefly described as follows. Tank 1 produces stormflow (q_1) from a channel system, and rainwater (with intensity r) falling onto the channel is given as its input. The channel system occupies a constant area of the entire catchment, the ratio of which is represented as C . The rest of the catchment ($1 - C$) is a hillslope system represented by three tanks. Runoff discharges from tanks 3 and 4 contribute to the stormflow (q_3) and baseflow (q_4). The functional relationship of storage to runoff discharge and the water budgets of tanks 1, 3 and 4 are expressed as follows:

$$S_1 = k_1 q_1^{p_1} \quad (2)$$

$$\frac{dS_1}{dt} = r - q_1 \quad (3)$$

$$S_3 = k_3 q_3^{p_3} \quad (4)$$

$$\frac{dS_3}{dt} = r_e - q_3 \quad (5)$$

$$S_4 = k_4 q_4^{p_4} \quad (6)$$

$$\frac{dS_4}{dt} = q_{in} - q_4 \quad (7)$$

where S is the water storage in each tank, p and k are the parameters and the suffixes coincide with the tank number. Tank 2 plays a role in allocating the rainwater to stormflow, baseflow and ET components. The percolation from tank 2 to tank 4 (q_{in}) and the ratio (m) of effective rainfall (r_e) to given rainfall (r) are both controlled by the storage of tank 2. The water budget and the allocations of rainwater are written as follows:

$$\frac{dS_2}{dt} = (1 - m)r - e - q_{in} \quad (8)$$

$$m = Q \left[\frac{1}{\sigma} \ln \left(\frac{S_2}{D_M} \right) \right] \quad \text{and} \quad S_2 = k_2 q_{in}^{p_2} \text{ for } S_2 > 0 \quad (9)$$

$$m = 0 \text{ and } q_{in} = 0 \text{ for } 0 \geq S_2 > D_L \quad (10)$$

$$m = 0 \text{ and } q_{in} = -e \text{ for } S_2 = D_L \quad (11)$$

where D_M and σ are the median and the standard deviation of the log-normal distribution controlling a shape of the functional relationship of m to S_2 in Equation 9, D_L is zero or a negative value for the minimum limitation of S_2 , the absolute value of which represents the maximum storage deficit, and Q is defined by

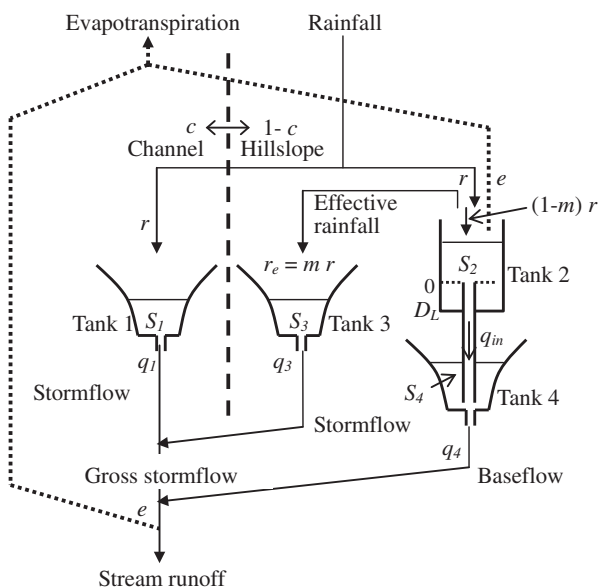


Figure 2. A schematic view of a simplified version of HCYMODEL

$$Q(\xi) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\xi} \exp\left(\frac{-u^2}{2}\right) du \quad (12)$$

When the storage in tank 2 is positive in Equation 8, the portion of a given rainfall allocated to tank 3 is calculated by Equation 9. For a dry condition, where water is not drained by gravity, we assume that ET continuously occurs from small pores within the soil. This process is reflected by the storage range described in Equation 10. For the driest condition, a recent study shows that transpiration from evergreen trees tends to continue without reduction due to the effects of the long roots (Tanaka *et al.*, 2004). Considering this tendency, we tentatively removed the reduction procedure of the ET included in the original model (Fukushima, 1988) in our calculation, although the protocol for the ET reduction requires further study (e.g. Schymanski *et al.*, 2008). Equation 11 reflects this process.

The total stormflow q_d is calculated as

$$q_d = C_{q1} + (1 - C)q_3 \quad (13)$$

and the baseflow q_b is calculated in the following equation by withdrawing evaporation from the channel

$$q_b = (1 - C)q_4 - Ce \quad (14)$$

The stream runoff q_c is the total of the stormflow and baseflow:

$$q_c = q_d + q_b \quad (15)$$

In Fukushima's original model, the estimation of effective runoff in Equation 9 assumed a log-normal distribution of hillslope topsoil on the basis of an observation by Kubota *et al.* (1983). Physically, this means that the saturation excess overland flow is generated where the water storage in the topsoil exceeds the depth with a log-normal distribution. This appears to result from the physical properties in a given catchment. However, it is generally difficult to verify the topsoil distribution by field investigation; an estimation can be obtained through an optimisation procedure. Unlike TOPMODEL, in which the ratio of effective rainfall to rainfall is controlled by the distribution of catchment topography (Beven and Kirkby, 1979), the ratio is not based on a clear physical structure, but is controlled by D_M and σ in Equation 9 obtained through an optimisation of parameter values. This is one of the reasons for using the HYCYMODEL to purely compare runoff characteristics, that is, it is preferable that the model be as free as possible from any model assumptions concerning runoff mechanisms as mentioned in the previous chapter. This flexible characteristic of the HYCYMODEL was applied to a recent study on the development of hydro-biogeochemical model (Katsuyama *et al.*, 2009b).

The parameter optimisation of the HYCYMODEL was conducted with shuffled complex evolution method developed at The University of Arizona (SCE-UA) developed by Duan *et al.* (1992) using a programme by

Tada (2008). The following mean absolute error (J) was selected for the objective function of our optimisation because the simulation target was placed not only on the long-term trend but also on transient storm-hydrograph responses:

$$J = \frac{1}{n} \sum_{i=1}^n |q_{ci} - q_{oi}| \quad (16)$$

where q_{ci} and q_{oi} are the calculated and the observed runoff rates, respectively, during the i th time interval (h), and n is the number of time intervals.

Study catchments

For our one hour records of comparison of rainfall-runoff responses, we selected four small headwater catchments in a mountainous area (consisting of granite) and three catchments in two sedimentary rock mountain areas (Figure 3). With the exception of one of the sedimentary rock mountains, all of the other catchments are located in southern Shiga Prefecture in central Japan. Geologically, the mountains consist of sedimentary rocks created as a Jurassic accretionary complex and granite rocks that intruded in the Cretaceous period (Matsuda and Isozaki, 1991). Four catchments are located in the northern granite area, the Tanakami Mountains, and two are in the adjacent southern part, the Shigaraki Mountains (Figure 3). Both of these mountain ranges have experienced similar tectonic and sedimentary processes, and the present geomorphology, with a relatively lower relief, was developed from peneplains during the Quaternary (Yokota *et al.*, 1978). However, the weathering process started much earlier than this recent landform process, creating a thick and strongly weathered layer in the granite mountains. The development of such a strongly weathered condition of granite bedrock requires more than 6×10^6 years (Kimiya, 1981). The lower resistance to erosional forces would have contributed to the distinctive topography of the high valley density, with short slopes in the granite mountains compared with the more resistant sedimentary rock mountains (Ikeda, 1998).

The six study sites were the KI (34°965'N, 135°994'E), the Jakujo catchment (JA; 34°929'N, 135°972'E), a second-order catchment of the Fudoji Experimental Watershed (F2; 34°918'N, 135°982'E), the Rachidani catchment (RC; 34°930'N, 135°972'E) in the Tanakami Mountains (conducted by Kyoto University) the Shigaraki B catchment (SB; 34°871'N, 135°979'E) and the C catchment (SC; 34°877'N, 135°985'E) in the Shigaraki Mountains (by Shiga Forest Research Center) (Figure 4). To detect the dependencies of the runoff responses on different soil conditions due to human disturbances for sedimentary rock, we added another catchment to our analysis: the Kitatani catchment in the Tatsunokuchi-yama Experimental Forest (KT; 34°708'N, 133°963'E) (by Forestry and Forest Products Research Institute). This catchment is located in the Okayama Prefecture, approximately 180 km west-southwest from the other catchments. Table I summarises the catchment characteristics. All of the catchments have a warm-temperate climate. Rainfall occurs throughout the year, with a peak in the summer, and little snow falls in winter. However,

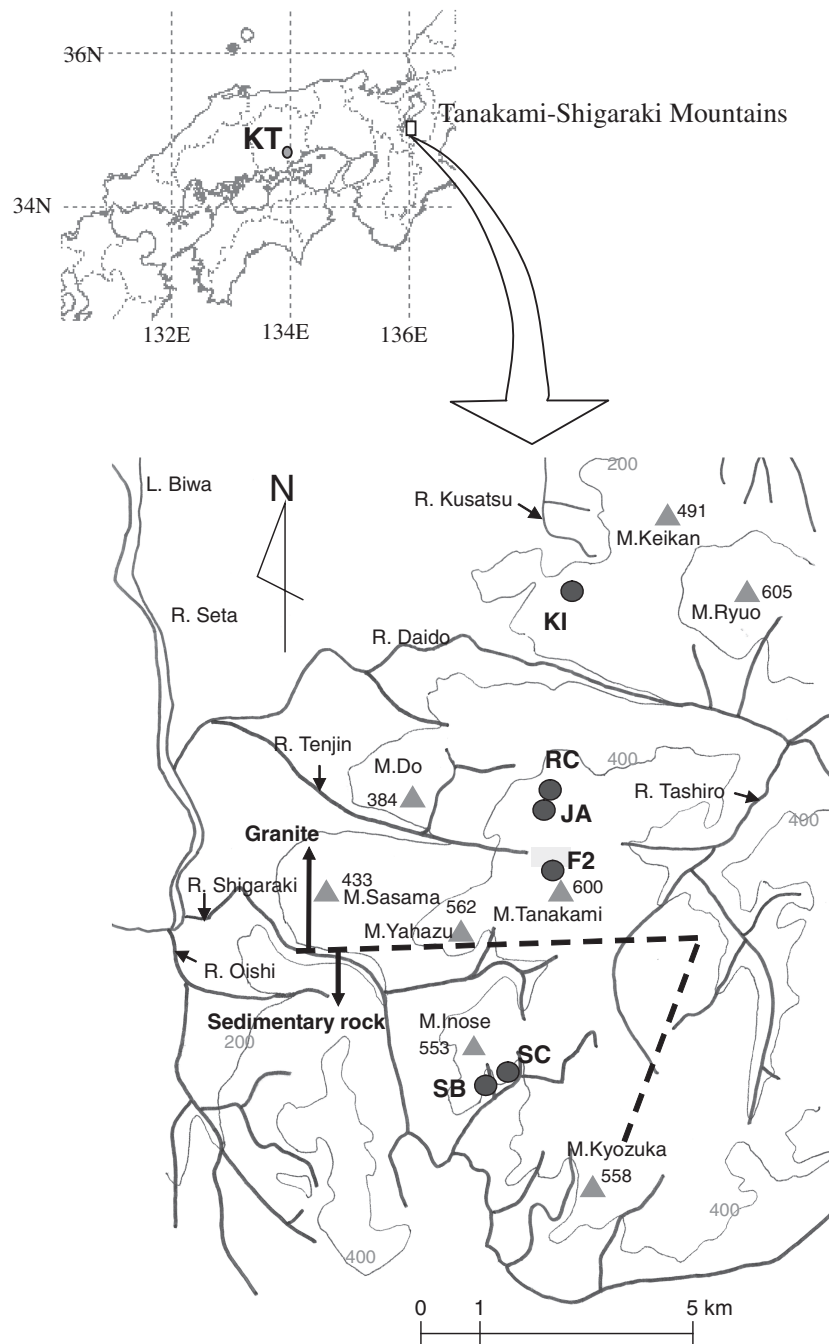


Figure 3. Location map of the study catchments

compared with the other catchments, KT receives less rainfall and is drier in the summer.

Next, we describe the detailed properties of each catchment. Catchments KI, JA and RC in the Tanakami Mountains had bare land cover in the 19th century. For KI, where many hydrological and biogeochemical studies have been reported (e.g. Ohte *et al.*, 2003; Kosugi *et al.*, 2006; Kosugi and Katsuyama, 2007; Katsuyama *et al.*, 2009a), hillside work with a *Pinus thunbergii* (Japanese black pine) plantation was carried out in 1897 and 1916 (Fukushima *et al.*, 1972). The slopes are comparatively gentle, and reforestation was generally successful. Most of the area is now covered with semi-mature forest consisting of mixed stands of *Chamaecyparis obtusa* (Japanese cypress), *Pinus densiflora* (Japanese red pine) and several deciduous

species. Similar plantation work was applied to JA later in 1935–1936, but because of unsatisfactory growing conditions, additional fertilizer was applied in 1976–1977 (Fukushima, 1987). Currently, pines and broad-leaved trees cover the area, but the forest condition is still poorer than that at KI. The generally steeper slopes of JA may contribute to the low vegetation condition at JA. RC is located just north of JA, and the surface has been left bare to exhibit the importance of hillside work. Although a layer of deposited soil with short *P. thunbergii* and *C. obtusa* trees covers a small area at the hollow bottom and minimal soil depositions occur in gentle slope areas such as just above core stones, all other slope areas have a very thin soil layer less than 10 cm with no vegetation (Asano *et al.*, 2004; Figure 5A). Every year, the thin soil layer is

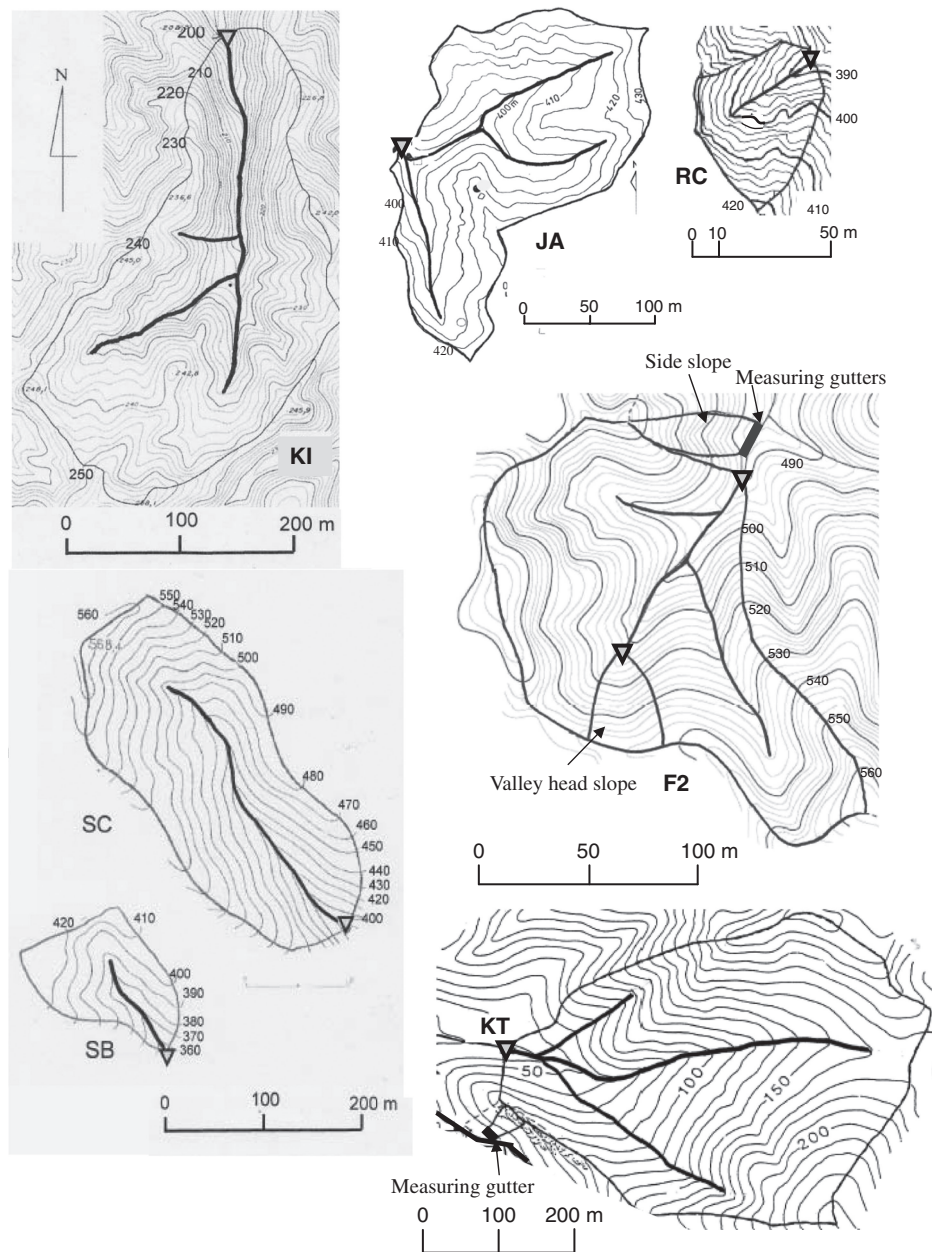


Figure 4. Topographic map of the study catchments. Reverse triangle is the measuring weir with a triangle notch

recreated when soil particles are exfoliated from the weathered rock by the freezing–melting processes in the early spring and the soil erodes during the following rainy season (Takei *et al.*, 1981; Suzuki and Fukushima, 1985, Kimoto *et al.*, 2003). Therefore, the vegetation never recovers naturally because the seeds are washed out with the soil particles every year.

In contrast to these catchments, F2 lies in one of the only areas that was protected from human disturbances, namely, a summit where a temple was established in the 9th century. The catchment is covered by a mature forest, consisting of a mixed stand of *C. obtusa* and deciduous and evergreen oaks such as *Quercus serrata*, *Quercus acuta* and *Quercus salicina*. The soils are predominantly brown forest soil and have developed on the slope for several thousands of years (Asano *et al.*, 2004). Previous studies have been conducted in the area. For example, Uchida *et al.*

(2006) compared the hydrometric characteristics of the zero-order F2 watershed, located at a headwater of the F2 catchment, with those of Maimai, New Zealand. Fujimoto *et al.* (2008) studied the effects of slope topography on the hydrological responses by comparing the observations at a valley-head slope (called a zero-order watershed in Uchida *et al.*, 2006) with those at a side slope located just downstream of F2 catchment (Figure 4). At this study side slope, the runoff rate was collected using three gutters fixed on the surface of a 17-m-long exposed bedrock (Figure 5B). The water collected by each gutter was measured by a tipping bucket, and the data of the centre (5 m long) were used for our discussion in this article.

In the Shigaraki Mountains, composed of sedimentary rock, the SB and the SC catchments are covered by semi-mature forest consisting of a mix stand of *C. obtusa* and *Cryptomeria japonica* (Japanese cedar). They were planted

Table I. Profile of the study catchments

Catchment	Annual temperature (°C)	Annual precipitation (mm)	Catchment area (ha)	Altitude (m)	Mean slope angle	Mean slope length (m)	Geology	Vegetation
KI	13.6 ^a	1645 ^a	5.99	190-258	21° ^b	62 ^b	Granite	Coniferous forest ^a
JA	10.9 ^d	1712 ^c	2.89	390-430	24° ^e	34	Granite	Mixed secondary forest ^e
F2	10.9 ^d	1712 ^c	1.9	500-530	37° ^c	43	Granite	Mature forest ^c
RC	10.9 ^d	1712 ^d	0.18	385-420	34° ^d	47	Granite	No vegetation ^d
SB	12.2 ^f	1513 ^f	1.06	355-425	27°	54	Sedimentary	Coniferous forest
SC	12.2 ^f	1513 ^f	4.71	398-558	41°	64	Sedimentary	Coniferous forest
KT	14.3 ^g	1229 ^g	17.2	38-243	28.4° ^g	123 ^g	Sedimentary	Mixed secondary forest ^g

^a Kosugi *et al.* (2007).

^b Fukushima (1988).

^c Uchida *et al.* (2003).

^d Asano *et al.* (2002).

^e Fukushima and Takei (1981).

^f Estimated from climate records for Shigaraki measured by the Japan Meteorological Agency.

^g Tani (1997).

in 1955–1956 (SB) and 1961–1964 (SC), and thinned in 1990 and 2007 (SB) and 1990 and 2002 (SC), respectively. Brown forest soil covers the slopes. Before the planting, however, the mountains were categorised by a type of

secondary forest called *satoyama* in Japanese (Shidei, 1973; Kobori and Primack, 2003), where villagers traditionally collected fertilizer and fuel. The other sedimentary rock catchment, KT, is located in a drier

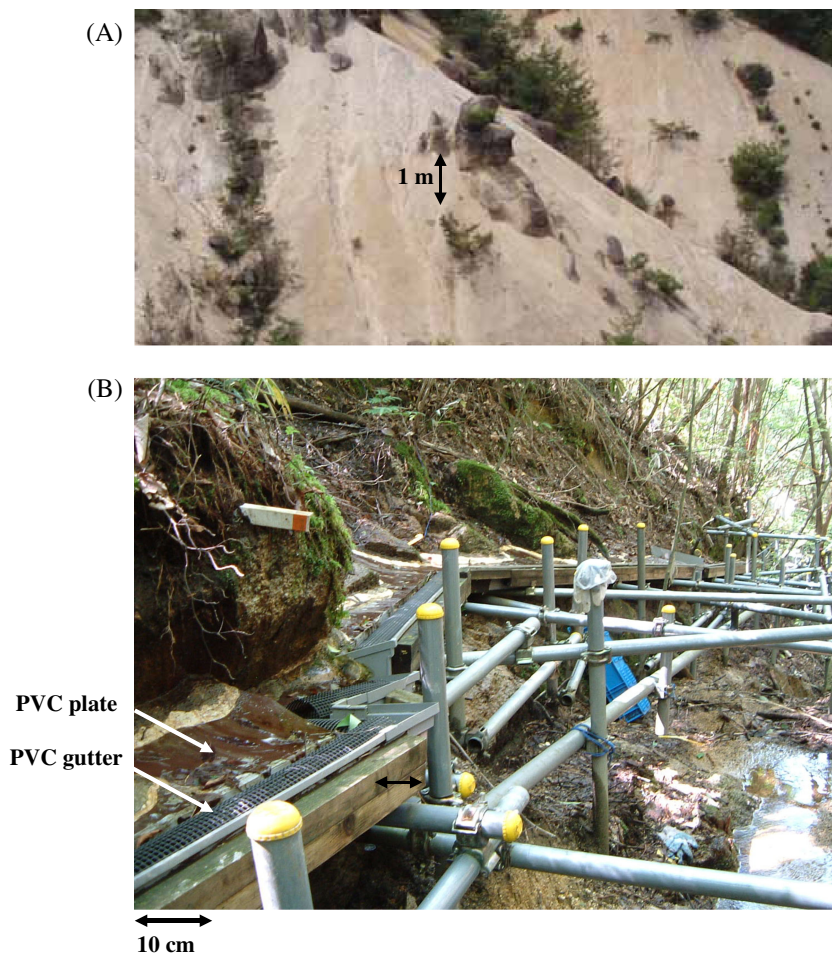


Figure 5. (A) Photo of a bare land at RC catchment. (B) Photo of a measuring gutter fixed to the surface of exposed bedrock at the bottom of the study side slope adjacent to F2 catchment

region than the other study catchments. The bedrock in the main part was created as a Permian accretionary complex. The catchment area was covered with forest, consisting of *P. densiflora*, when hydrological observation first began in 1937 (Takeda, 1942). Following the forest clearing in 1945, no other forest operations were conducted at KT. A natural secondary forest, consisting of *Q. serrata* and other deciduous and evergreen trees, has been growing since that time (Goto *et al.*, 2006). The key property of this catchment is a soil condition characterised by only a few centimetres of brown forest soil overlaid by a thick soil layer of clay loam with a low hydraulic conductivity ($<10^{-3} \text{ cm s}^{-1}$) (Tani, 1997). It is difficult to separate causes between the disturbance caused by humans and the natural background, but the past use of forest litter by villagers may have partly contributed to the decrease in surface forest soil. In addition, frequent forest fires due to the dry condition of the area must have increased the soil erosion in periods of less vegetation following the fires. A forest fire occurred over the area of an adjacent study catchment (Minamitani) in 1959 and influenced runoff responses (Fujieda *et al.*, 1979). Therefore, the runoff responses for KT are considered to represent one of the typical runoff characteristics in a sedimentary rock mountain catchment where the forest soil effects are scarce.

Calculation preparation

Here, we describe the process of estimating the monthly ET values by using the short-term water budget method. For KI and KT, the monthly ET values were obtained from the previously published data, using 10-year averages from 1995 to 2004 from Kosugi *et al.* (2007) and from 1967 to 1976 from Suzuki (1985). For other catchments, the averages were newly estimated by this study using data from 1981 to 1985 for JA and from 2004 to 2006 for F2. For SB and SC, we used the KI values because these catchments all had a similar coniferous forest cover. For RC, the monthly ET values were calculated by multiplying those of the adjacent catchment JA by a constant E_r value of 0.554 because a very large sediment discharge often disturbed the runoff measurements at RC. The constant value E_r was obtained from a comparison of annual water budgets after a careful estimation of missing runoff data at RC.

Before the parameter optimisation for the HYCYMODEL, some of the parameter values were fixed on the basis

of basic rainfall-runoff response characteristics. Although it would be possible to optimise many parameter values, the *a priori* fixing was chosen because numerous parameters might be difficult to compare among catchments, as mentioned previously. The values of the exponent parameters follow those reported by Fukushima (1988), namely, p_1 of 0.6, p_2 of 1.0, p_3 of 0.6 and p_4 of 0.1. The ratio of the channel area to the entire catchment area (C) can be measured by field investigation, but it is not easy to estimate the widths of small stream channels in headwater catchments. Therefore, we used Fukushima's fixed value of 0.035 for all the catchments. In addition, a good simulation result with the absolute error in Equation 16 of $J < 0.03 \text{ mm h}^{-1}$ for each catchment was obtained by a fixed value of zero for the minimum limitation of storage in tank 2, D_L , although its value for RC was inevitably larger than 0.03 mm h^{-1} because of observational disturbances caused by much soil discharge from the bare land (Takei *et al.*, 1981). As a result, the parameters for our optimisation procedure were k_1 , k_2 , k_3 , k_4 , D_M and σ . For catchment KT only, we added D_L to the optimisation process because the fixed value of zero produced a drastically larger simulated hydrographs for small storm runoff responses only following dry conditions in summer.

RESULTS

Basic comparison of runoff responses

Optimised parameter values for the HYCYMODEL simulation for each catchment and the mean absolute error are listed in Table II. Figure 6 presents a comparison of examples for the simulated and observed annual hydrographs. Considering the relationship between stormflow and baseflow, the calculated baseflow rate (q_b in Equation 14) is also plotted for each of the results. The simulation results are generally good. Although the runoff characteristics of each catchment in response to the same rainfall and ET conditions are strictly compared later in the next sections, three main differences can be detected even from rough comparisons of the observed hydrographs with different periods: first, the storm runoff for RC is characterised by high peaks and rapid recession limbs, whereas the other three catchments in the granite group (KI, JA and F2) have similar gentle storm hydrographs. This character of RC is represented by its smaller values for

Table II. Optimised parameter values for HYCYMODEL

Catchment	k_1 $\text{mm}^{0.4}\text{h}^{0.6}$	k_2 h	k_3 $\text{mm}^{0.4}\text{h}^{0.6}$	k_4 $\text{mm}^{0.9}\text{h}^{0.1}$	D_M mm	σ	D_L mm	J mm h^{-1}
KI	4.74	50.40	15.30	1010	88.6	1.80	0	0.013
JA	5.50	43.90	18.20	901	94.8	1.64	0	0.018
F2	4.23	50.40	16.30	826	79.2	1.62	0	0.019
RC	2.23	42.60	4.82	810	62.8	2.31	0	0.034
SB	13.30	114.00	30.70	2620	26.0	0.76	0	0.027
SC	16.60	147.00	38.40	3657	28.6	0.73	0	0.024
TK	8.91	49.40	15.30	4320	5.8	0.96	-47.2	0.020

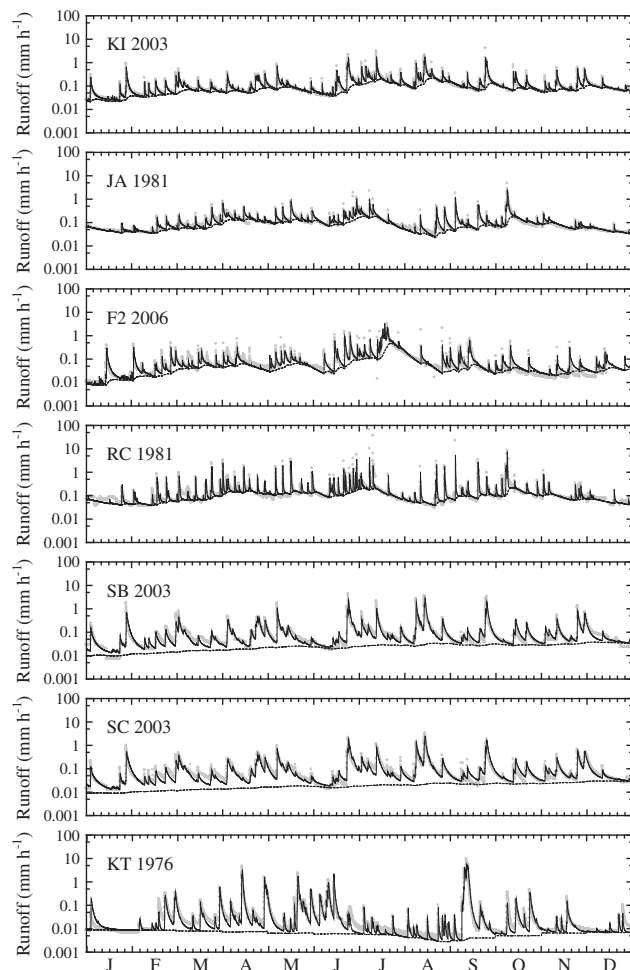


Figure 6. Comparison of simulated annual hydrographs by HYCYMODEL with those observed for each of the seven catchments. Grey, observed; solid, simulated; broken, simulated baseflow as drainage from tank 4 of HYCYMODEL

k_1 and k_3 yielding stormflow components in the HYCYMODEL (Table II). Second, among the three sedimentary rock catchments, KT has a particularly lower baseflow. A very low value of D_M in Table II represents this characteristic in the HYCYMODEL although it may be also influenced by the dry climate with a smaller annual rainfall amount. The negative D_L value for the KT, the optimisation of which was not necessary for the other six catchments, reflects the small storm hydrographs after a severe dry condition around August in Figure 6. Unique runoff-response characteristics are suggested for KT.

As for the third remarkable differences shown in Figure 6, the baseflow rates in long non-rain durations for the granite catchments (KI, JA, F2 and RC) seemed to be higher than those for the sedimentary rock catchments (SB, SC and KT). Interestingly, the bare land catchment, RC, was also included with the granite group. This tendency is clearly represented by the large differences in the calculated baseflow rate, q_b , between two geological types. To compare the detailed relationships of the stormflow and baseflow between these two types, the short-term hydrographs for the KI and SC are displayed in Figure 7. The recession curves for both catchments were much different although the rainfall was similar. The

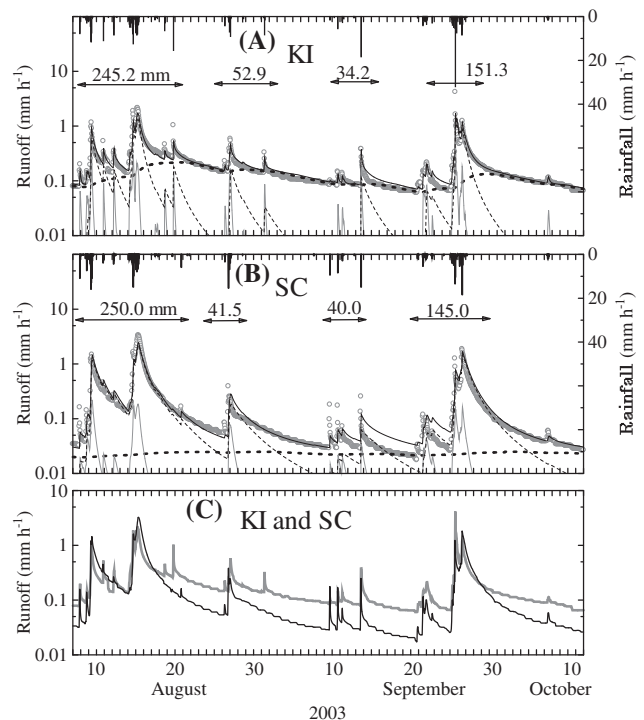


Figure 7. Simulated and observed hydrographs for KI and SC to compare their recession stages for large storm events. (A) Hydrographs for KI. Grey circle, observed; black solid, simulated; grey solid, discharge from tank 1; thin broken, discharge from tank 3; thick broken, discharge from tank 4. (B) Hydrographs for SC. The symbols are the same as in panel A. (C) Observed hydrographs for KI (grey) and SC (black)

recession curves longer than 10 days from big storm events around August 20 and September 30 were mainly shared by the stormflow, q_d , mainly produced from tank 3 for SC, whereas the runoff components were earlier switched from q_d to q_b for KI (Figure 7). The long and smooth recession curves, without any turning point as shown in the observed hydrograph of SC, strongly suggest a continuous flow from a single runoff system (the bottom panel of Figure 7). In the HYCYMODEL parameter values in Table II, this difference is produced by the large D_M value for the granite group, which leads to a small allocation of rainwater to the stormflow. Although the k_1 value of the channel system (tank 1) is also different between these two groups, the effect reflects minor stormflow peaks (grey solid lines in Figures 7A and 7B) compared with the effect of parameters of the hillslope system (tank 3) (thin broken lines). The difference in the D_M value strongly suggests the existence of a runoff component, producing high baseflow rates in granite mountains that correlate with the findings obtained from comparisons of runoff responses in large catchments (Musiatek *et al.*, 1975; Shimizu, 1980). We suggest that this difference in the baseflow production component is the most important property for both geologies.

Comparison of flow duration curves under the same climate condition

To compare the long-term runoff characteristics among the seven catchments in response to the same rainfall and ET conditions, we conducted simulations using the seven optimised HYCYMODEL parameters listed in Table II. A rainfall data of KI from 2001 to 2004 and ET estimated for KI

were used for the comparison without the influences of input differences. Because the ET for the RC was much lower than the others because of the bare land condition, two simulations were conducted for E_r of 0.554 and 1. The former reflects the actual condition, but the latter estimates the character of the runoff process independent of ET influences.

To compare the runoff responses, we produced flow duration curves (FDCs) by sorting the simulated hourly runoff rates from largest to smallest. Figure 8 shows the results. The right-hand figure represents an enlarged part of the 0.4% range of the left-hand figure for a comparison of the runoff rates near the largest range. Each of the granite catchments except RC has a similar FDC, with lower stormflow and higher baseflow than the sedimentary rock group. The FDCs of RC and KT differ largely from the FDCs for the other catchments. The FDC of the RC with $E_r=0.554$ is larger than that of any other catchment over the runoff range, except in the largest runoff range, where KT has the highest rate (the right-hand figure of Figure 8). The FDC of the RC with $E_r=1$ is only slightly lower than that with $E_r=0.554$ in the largest runoff range, but it becomes very low from the medium to small ranges. This demonstrates that the comparatively large baseflow in the observed hydrograph of RC in Figure 6 is attributable to the small ET from the bare land, suggesting that the runoff rate from the RC may turn into having a very flashy runoff character accompanied not only by high stormflow but also by low baseflow when the net input (the difference between rainfall and ET) is the same as that in a forested catchment. In addition, this effect of ET almost disappears in a large storm range because both of the simulation results by $E_r=0.554$ and 1 have similar high runoff rates in this range (the right-hand figure of Figure 8). KT is characterised by a low FDC from the medium to small runoff ranges but has the highest runoff rates in the largest range. This indicates that the runoff system in the KT produces the flashiest runoff responses and the highest stormflow of our catchments, including the bare land RC catchment.

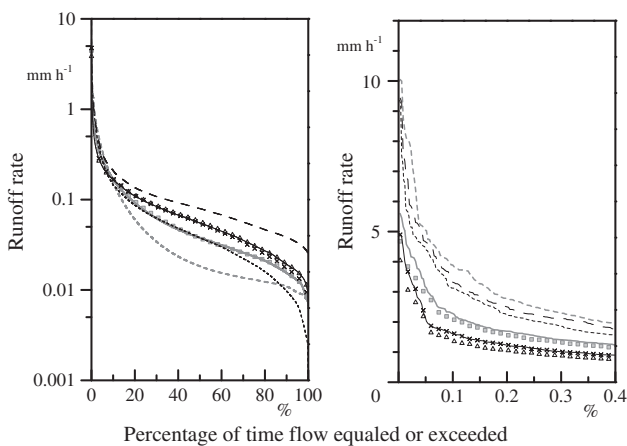


Figure 8. Flow-duration curves produced from the simulated hydrographs for the study catchments. The right-hand figure is an enlarged part of the 0.4% highest-runoff range of the left-hand figure. Black solid, KI; black triangle, JA; black cross, F2; black broken, RC with the ET rate of 0.554; black dotted, RC with the ET rate of unity; grey solid, SB; grey rectangular, SC; grey broken, KT

Comparison of stormflow responses

Stormflow responses can be basically characterised by the rainwater allocation to the storm-runoff system and the quickness of the stormflow responses. In the framework of the HYCYMDEL, the latter can be simply represented by the values of k_1 in tank 1 and k_3 in tank 3 listed in Table II. The parameters k_1 and k_3 control the relationship of the drainage, from the tank to the storage, quantifying the runoff-buffering potential of the runoff system (Tani, 2008). Figures 9A and 9B show the recession curves of drainage from tank 1 to tank 3, respectively, calculated at the initial rate of 20 mm h^{-1} without ET using the model parameters of each catchment to compare the quickness of the stormflow responses. The response for tank 1, reflecting a stream channel system, is quicker than that for tank 3, which reflects a hillslope system in each catchment, and the quickest responses for both Figures 9A and 9B are found in the RC with bare land. The sedimentary rock group tends to produce less quick responses than the granite group, but responses for the KT are relatively quicker than those of

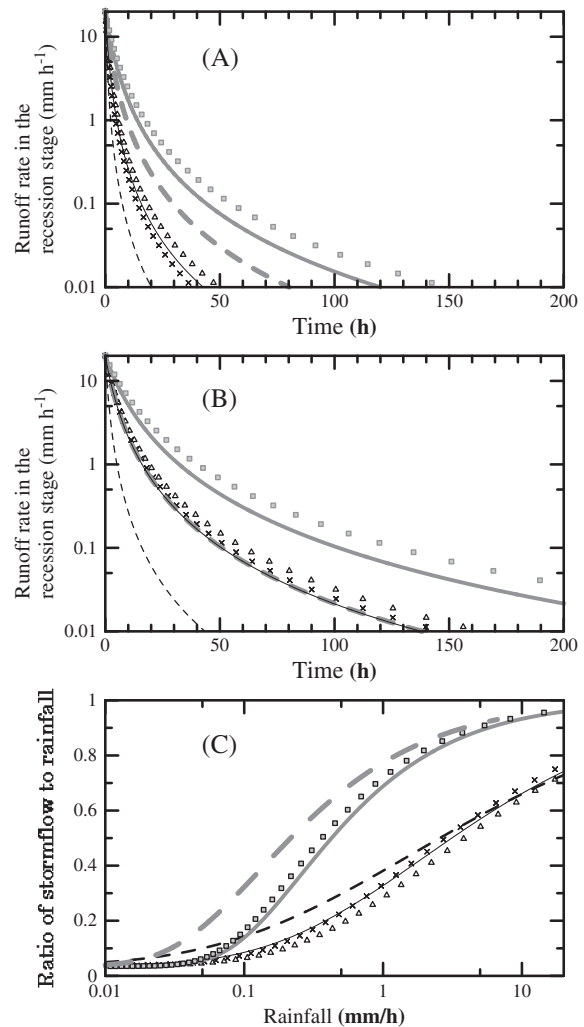


Figure 9. Intercomparison of the stormflow characteristics of each catchment by the parameters of HYCYMODEL. (A) Stormflow recession curve produced from tank 1 representing the channel system. (B) Stormflow recession curve produced from tank 3 representing the hillslope system. (C) Ratio of the stormflow rate to a given rainfall rate in a steady state. The symbols are the same as in Figure 8, but RC with an ET rate of unity was removed

the other two sedimentary rock catchments. This suggests that the lack of a forest soil layer causes quick stormflow responses.

The rainwater allocation to the storm runoff system is represented by a complex procedure for tank 2 in the HYCYMODEL involving parameters k_2 , D_M , σ and D_L . To show the character of each catchment in the allocation, we compared the ratio of stormflow to a given constant rainfall in the steady state without ET in Figure 9C. Such a steady state was thought to be achievable only in sprinkling experiments in small catchments (Tsuboyama *et al.*, 1994; Anderson *et al.*, 1997) but actually occurred during a large typhoon rainstorm in September 1976 in KT. Figure 10 is an enlarged plot of Figure 6 showing the detailed hydrograph for 12 September 1976. As shown in the figure, the mean observed runoff rate of 5.4 mm h^{-1} was produced in response to a mean rainfall intensity of 5.7 mm h^{-1} for 7 h from 06:00 to 13:00 h in the wettest condition after a large amount of cumulative rainfall. The simulated runoff rate of 4.8 mm h^{-1} was slightly lower but approximately followed this steady-state response. The ratio of 0.84, calculated from the simulated runoff and observed rainfall rates in Figure 10, actually coincides with the allocation ratio in response to the rainfall rate of 5.7 mm h^{-1} in Figure 9C regardless of the different ET conditions between both calculations. Therefore, the steady-state relationship in Figure 9C provides an actual index of the rainwater allocation property independent of the quickness of the stormflow responses. The ratio of stormflow increases with a given rainfall intensity for every catchment, but the ratios for the granite group are limited, still low for high rainfall intensities, whereas those for the sedimentary rock group approximate unity as the intensity increases. For the comparison within the same geology group, however, the allocation tends to be larger for the RC and KT than for the other catchments in each group, suggesting that the lack of a forest soil layer contributes to a large allocation of rainwater to storm runoff as well as to a quick stormflow responses (Figures 9A and 9B). Note that for the granite group, the characteristics of rainwater

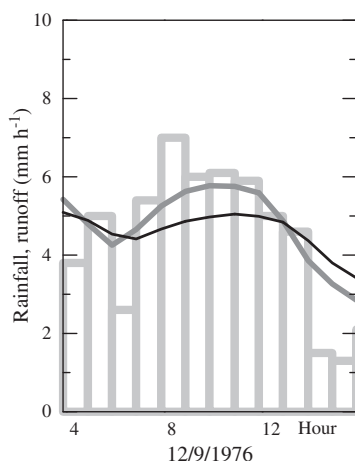


Figure 10. Observed hyetograph (bar) and hydrographs observed (grey) and simulated (solid) by HYCYMODEL for KT during a large typhoon-induced rainfall event in September 1976

allocation and the quickness of the runoff responses does not differ between the catchments reforested from a bare land condition (KI and JA) and the catchment with a mature forest but without a bare land history (F2), although different characteristics are shown for the bare land catchment (RC).

The HYCYMODEL simulations for our seven catchments demonstrate a flashy runoff character with low baseflow and high stormflow for the sedimentary rock group compared with the granite group. This finding is mainly derived from a larger allocation of rainwater to stormflow in the sedimentary rock group. Regarding the effects of forest soil, they may decrease both the allocation of rainwater to stormflow and the quickness of the stormflow response for our two geological groups.

DISCUSSION

We have examined the runoff characteristics in response to the same rainfall conditions among catchments with different soil conditions in granite and sedimentary rock mountains. These results may be caused by their runoff mechanisms. The discussion in this chapter was made from this point of view.

Runoff mechanisms and dependencies on forest disturbances in granite catchments

The notable characteristic of the small granite catchments in the Tanakami Mountains is a stable FDC with high baseflow. Numerous studies have shown that this characteristic is due to the large storage capacity of deeply weathered granite bedrock, the depth of which is more than 10 m in the middle of hillslope (Katsura *et al.*, 2008). For example, Kosugi *et al.* (2006) conducted hydrometrical observations at subcatchments within the KI, where they demonstrated that the saturated and unsaturated infiltration from soil to bedrock is a dominant hydrological process at the soil–bedrock interface and that the annual bedrock infiltration ranged from 35% to 55% of the annual precipitation. A dominant contribution of bedrock water has also been confirmed by end-member analysis using SiO_2 and H_2SO_4 at KI (Katsuyama *et al.*, 2005) and by the water pressure and temperature measurements at F2 (Uchida *et al.*, 2003). Recently, Katsura *et al.* (2008) directly measured the temporal variations of bedrock groundwater and found that the baseline of the annual runoff variation was controlled by that of the bedrock groundwater on the hillslope. Because of the high weight of bedrock infiltration, stormflow is produced by water escaping from the infiltration in a granite hillslope. Except for at the RC, the weathered bedrock is covered with soil, and the water that does not enter the bedrock runs downslope along the bedrock surface under the ground. This process was found within subcatchments of the KI (Katsuyama *et al.*, 2005), but the mechanism of downslope flow may differ in the slope topography. Uchida *et al.* (2003) investigated the stormflow generation in a valley-head slope within F2 (Figure 4) and concluded that the

transient groundwater in the upper part of the hollow flowed via lateral preferential flowpaths. On the other hand, the role of preferential flowpaths was small for a side slope with a planar topography as found by the following analysis.

Nakamura *et al.* (2006) analysed the runoff at the centre (the length of 5 m) of the three gutters (Figures 4 and 5B) installed at the bottom of the study side slope adjacent to the F2 catchment and the pressure head values measured by tensiometers installed on the bedrock surface at two points upslope (1.2 and 1.7 m, horizontal distances) from the gutter. Assuming that the downslope flow along the bedrock surface follows Darcy’s law for groundwater, the vertical profile of saturated hydraulic conductivity K_s can be inversely estimated from the runoff rate and the water depths of the two points during the recession runoff stage. The method used here followed that proposed by Brooks *et al.* (2004). The core equation for the inverse estimation of K_s at the depth of z from the surface is described as

$$K_{s,avg(h)} = \frac{\int_h^{D_s} K_s(z) dz}{D_s - h} \quad (17)$$

where $K_{s,avg(h)}$ is the saturated hydraulic conductivity averaged over the groundwater flow for the depth (from the soil surface) of water table (h) and D_s is the depth of the hydraulically restricting layer. Using this method, we estimated the K_s values for our observational data and compared the results with those obtained from 100-ml soil samples with a constant head permeability test. The results in Figure 11 clearly demonstrate that the K_s profile based on Darcy’s law was well explained by that from the soil samples, indicating that the downstream flow followed this law and that it was not necessary to consider the effects of preferential flowpaths. Figure 12 presents the downslope flow rates calculated by pressure head data at the two points using Darcy’s law and K_s profile for comparison with the observed runoff rate at the centre section of the three gutters. The vertical profile of K_s for our calculation, plotted in Figure 11, was optimised using the data both of the inverse method and the sample permeability test:

$$K_s = 0.217 \exp(-0.095z_a) \quad (18)$$

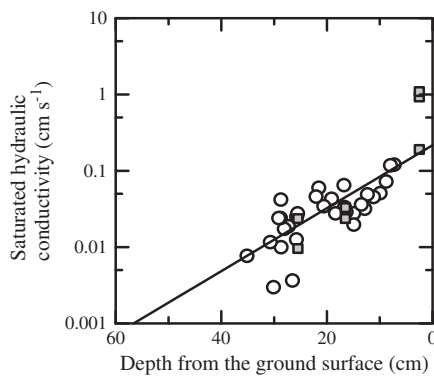


Figure 11. Vertical profile of saturated hydraulic conductivity on the study side slope adjacent to F2. Circle, inversely estimated from the groundwater table; rectangle, obtained from soil samples with a constant head permeability test

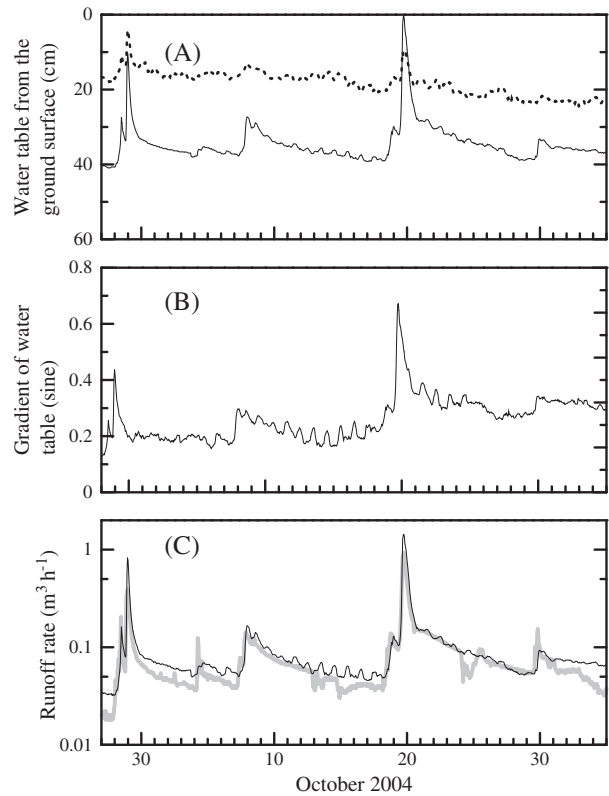


Figure 12. Results of applying Darcy’s law to downslope flow within the soil layer on the side slope adjacent to F2. (A) Observed depths of the water table from the ground surface at points 1.2 m (dotted) and 1.7 m (solid) from the slope bottom gutter. (B) Gradient of the water table calculated from the water depths at points 1.2 and 1.7 m from the gutter. (C) Comparison of the calculated hydrograph (solid) by Darcy’s law with that observed (grey)

where z_a is the averaged depth of the water table between the two points measured from the ground surface. The hydrograph calculated by the downslope matrix flow described by Darcy’s law agrees with that observation, indicating that the stormflow from this side slope can be produced through the soil matrix. Although K_s decreases with depth from the soil surface, K_s values are generally high because of the sandy soil derived from the weathered granite (Ikeda, 1998). The result, shown in Figure 12, that downslope flow can be drained smoothly through the soil matrix may be due to the relatively high soil permeability.

The mechanism of downslope flow, particularly that characterised by dominant matrix flow on a planar slope, depends greatly on the high permeability of the soil. When the water flowing downslope within the soil matrix concentrates in a concave hollow, the groundwater storage is smoothly drained through the preferential flowpaths already created along the hollow as found in the valley-head slope by Uchida *et al.* (2003). Therefore, Darcy’s law is followed at least in the early stages of downslope flow. This produces a moderate increase of the groundwater storage in response to a rainwater supply, whereas a high drainage capacity of the downslope flow within preferential flowpaths may contribute to a much less increase of the storage as demonstrated in a theoretical analysis by Tani (2008) on the runoff buffering potential in a sloping

permeable domain. In addition, before the downslope flow occurred, an increase of the water storage along vertical unsaturated flow during a storm event also depends on the soil physical properties: Kosugi (1999) showed a soil with a high permeability produced a larger increase of the water storage than that with a low permeability. Therefore, under an application of Darcy's law, both vertical and downslope flows within a high permeable soil support a moderate storage increase in response to rainwater supply.

This process sequence creates similar runoff responses at KI, JA and F2, although soil conditions are different: the soils were characterised by immature sand at KI and JA but by brown forest soil at F2. Although they have different development histories, these soils all have a high permeability. This suggests that the characteristics of runoff responses in granite mountains differ little according to the soil development, once the weathered bedrock is covered with the sandy soil produced from weathered granite.

The RC catchment with bare land was characterised by a large peak of storm runoff and a steep recession limb (Figures 6 and 9), and this is clearly due to a thin soil layer on the weathered granite bedrock. Rainwater not infiltrating into the bedrock would start to run downslope through the soil matrix, rapidly producing saturation excess overland flow that would then quickly reach the concave hollow at the centre of catchment. Frequent overland flow would erode the new thin soil layer produced by the freezing–melting process in the early spring, as mentioned earlier, resulting in a sustained bare land condition on the hillslope (Takei *et al.*, 1981). Therefore, this overland-flow process produces the high peaks of stream runoff at the RC. However, the allocation of rainwater to the stormflow and baseflow also strongly controls their characteristics. The hydrometrical observation of Kosugi *et al.* (2006) in a headwater catchment of KI revealed that the moderation of the high intensity rainfall through the infiltration within a soil layer prevented infiltration excess at the soil–bedrock interface and a thick layer allowed all the rainwater infiltrate into the weathered bedrock. The findings of Kosugi *et al.* (2006) suggest that the allocation of rainwater to stormflow must be larger for bare land than for forest. In addition to this, our application of the HYCYMODEL to the RC catchment in Figure 8 shows a smaller ET for bare land than for forest contributes to the runoff rate throughout the year. Therefore, both the reduction of infiltration into weathered bedrock due to a very thin soil cover and the decrease of ET by a lack of vegetation may contribute to much stormflow with very high peaks produced by the saturation excess overland flow, whereas the reduction of infiltration and ET decrease, playing a compensatory role in the weathered bedrock's water supply, may give a delicate balance to the baseflow rate as shown in Figures 6 and 8. For RC, however, we should note that the slope was not perfectly bared, but the soil covered a small area at the hollow bottom and some gentle portions of the slope (Figure 5A), contributing to some moderation of the stormflow. Larger stormflow amounts with high peak rates than those observed in RC may be expected for a condition in which all of the bedrock is perfectly exposed.

We can conclude that a large fluctuation of water storage in the deeply weathered granite bedrock contributes to a stable runoff character and that both the vertical unsaturated flow and the downslope groundwater flow in the highly permeable soil, either immature sandy or brown forest soil, add a further fluctuation of the water storage to that in the bedrock, supporting a moderate stormflow response. For a high-relief catchment in the Japan Alps, Onda *et al.* (2006) showed that the downslope groundwater flow along the relatively unweathered granite bedrock contributed to stormflow generation. Although this mechanism of stormflow was similar to that for our low-relief catchments, a difference occurred in the storage volume of water that can be fluctuated in the bedrock. The result from our granite catchments on the effects of human forest disturbances may be acceptable for low-relief catchments, although the effects of disturbances may be different for high-relief mountains.

Runoff mechanisms and dependencies on forest disturbances for sedimentary rock catchments

Although many hydrological findings have been reported for the granite Tanakami Mountains, only a few have been obtained in sedimentary rock mountains. Some studies of small catchments (Tani, 1997; Katsuyama *et al.*, 2008) have found that flashy runoff characteristics with high stormflow rates and low baseflow rates are similar to those reported by Shimizu (1980) for large mountainous catchments. First, one of the typical runoff mechanisms with a scarce forest soil layer is summarised here from catchment and hillslope observations (Tani and Abe, 1987; Tani, 1997). The hillslope study was conducted using a measuring gutter at the bottom of a side slope adjacent to the KT catchment (Figure 4) and showed that its runoff characteristics were similar to those of the KT although a comparatively thinner soil modified them. The stormflow generation there was estimated by a combination of vertical matrix flow through the unsaturated soil and the quick downslope flow through preferential flowpaths. Because the hillslope is covered by clayey soil with scarce brown forest soil, the slope contains a small percentage of large soil pores where water can be drained by gravity and a large percentage of small pores. Therefore, although much water was retained within the small soil pores, it can only be removed by transpiration because of the very low matrix potential. The storm runoff volume was found to be quite sensitive to the antecedent soil water content. That is, the rainwater was consumed to fill the small pores in a dry condition, but once small pores were saturated, few large pores were available for further water storage. In addition to this soil effect, a lack of weathered bedrock may contribute to the high stormflow allocation of rainwater in the wet conditions. These mechanisms, derived from soil and bedrock conditions, provide a so-called threshold behaviour, reflecting the phenomenon that stormflow suddenly increases after cumulative rainfall exceeds a certain value as illustrated in Figure 13 for the storm runoff and rainfall relationship (Tani and Abe, 1987; Tani, 1997)

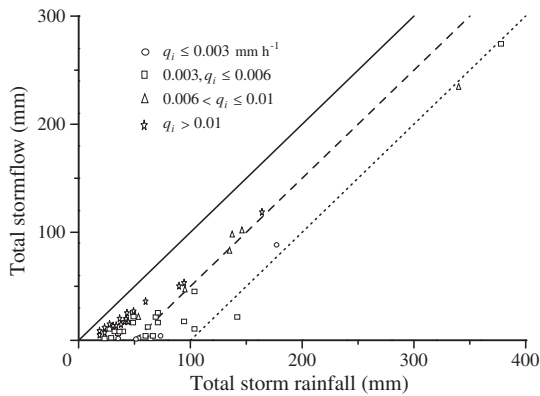


Figure 13. Relationship of the total stormflow volume (Q_d) to the total rainfall volume (R) in a storm event for KT (after Tani and Abe, 1987). The relationships are categorized by initial runoff (q_i) representing the antecedent wetness condition of the catchment. The solid, broken and dotted lines represent $Q_d = R$, $Q_d = R - 50$ mm and $Q_d = R - 100$ mm, respectively

and being of current interest (Tromp-van Meerveld and McDonnell, 2006; Zehe and Sivapalan, 2008). For stormflow responses, a quick downslope flow through developed preferential flowpaths within clayey soil was estimated to contribute to the production of high stormflow peaks. The mean slope length of 123 m at KT is much longer than our other granite and sedimentary rock catchments (Table I), but the quick responses represented by a parameter value of k_3 is similar to granite catchments (except RC) and smaller than other sedimentary rock catchments (Table II), which may reflect the high drainage capacity of highly developed preferential flowpaths. We can summarise that runoff mechanisms derived from a clayey soil without brown forest soil and a lack of weathered bedrock contribute to flashy runoff characteristics with a high sensitivity of storm runoff magnitude for the antecedent dryness in KT.

Such characteristics have been found in other sedimentary rock mountains, although the bedrock condition is variable and the layer of brown forest soil is thicker. For baseflow characteristics, Uchida *et al.* (2006) reported that the baseflow was lower in a sedimentary rock hillslope, in Maimai, New Zealand, than that in a valley-head slope within our granite F2 catchment because of its smaller water-storage volume in the bedrock. For flowpaths within a sedimentary bedrock, Onda *et al.* (2006) reported that water was carried far to a low-elevation point through a large number of fissures in the bedrock. Nevertheless, unlike a ubiquitously weathered granite bedrock, contributing to a large fluctuation of water storage, the sedimentary bedrock may be characterised by a lower contribution, probably because the total pore volume of the fissures is much smaller than that of the weathered granite bedrock. The characteristics of stormflow generation, including both the high sensitivity of storm runoff volume to the antecedent soil water content and the contribution of almost all rainfall to stormflow in the wettest conditions, were also found in a small metamorphic-rock catchment with tropical rainforest in Malaysia (Noguchi *et al.*, 1997). Such a high sensitivity to the antecedent wetness was also

reported in a high-relief mountainous catchment in Japan (Onda *et al.*, 2006). Although the development of preferential flowpaths contributing to a rapid downslope flow estimated for the KT hillslope has to be investigated in further studies, evidence of the high drainage capacity of preferential flowpaths was obtained by a tracer-injection experiment in an Eocene unchannelled hollow with steep topography in Coos Bay, Oregon (Anderson *et al.*, 1997). These studies suggest that the observational findings detected in KT (Tani, 1997) may reflect one of the basic runoff mechanisms for sedimentary rock catchments.

When returning to the comparison of our small sedimentary rock catchments, we should note an important difference in the existence of brown forest soil between the KT and the other two catchments (SB and SC). Forest soil generally has a higher ratio of large soil pores compared with the undeveloped clayey soil, and a large storage increase within the large pores in response to a given rainwater supply decreases the stormflow peak (Hayashi *et al.*, 2006). The more moderate runoff characteristics for SB and SC compared with KT shown in Figure 8 and Table II may be caused by the forest soil at SB and SC. Katsuyama *et al.* (2008) showed that the small steep catchments in sedimentary rock mountains were characterised by flashier runoff characteristics than our granite KI catchment. Because their catchments are carefully managed by a sustainable forestry operation of *C. japonica* and covered with brown forest soil (Fukushima and Tokuchi, 2009), the milder character compared with KT, similar to our SB and SC catchments, is probably supported by a large fluctuation of the rainwater storage within brown forest soil. These suggest that a brown forest soil may be a key factor of the stable runoff characteristics for sedimentary rock catchments because a fluctuation of water storage is not supported by either immature sandy soil or ubiquitous weathered bedrock that plays an important role in the runoff moderation for granite catchments even associated with a lack of forest soil.

CONCLUSION

The final goal of our study was to evaluate the quantitative dependency of runoff characteristics on severe forest disturbances with soil loss in steep mountains in consideration of the rapidly increasing demand for forest resources worldwide. To do so, we analysed the rainfall-runoff responses and runoff mechanisms in small mountainous catchments in Japan with different histories of human disturbances. Our analysis has revealed a range of dependencies for granite and sedimentary rock mountains.

In granite mountains, severe human disturbances led to a bare land condition at the entire mountain scale, where stormflow peaks drastically increased because of widespread occurrences of overland flow. This wide and devastating bare land condition is maintained semipermanently without any terrace works (Takei *et al.*, 1981; Suzuki and Fukushima, 1985), although forest and soil have naturally recovered on bare land created by a small-scale landslide (Shimokawa, 1984). In the large bare land

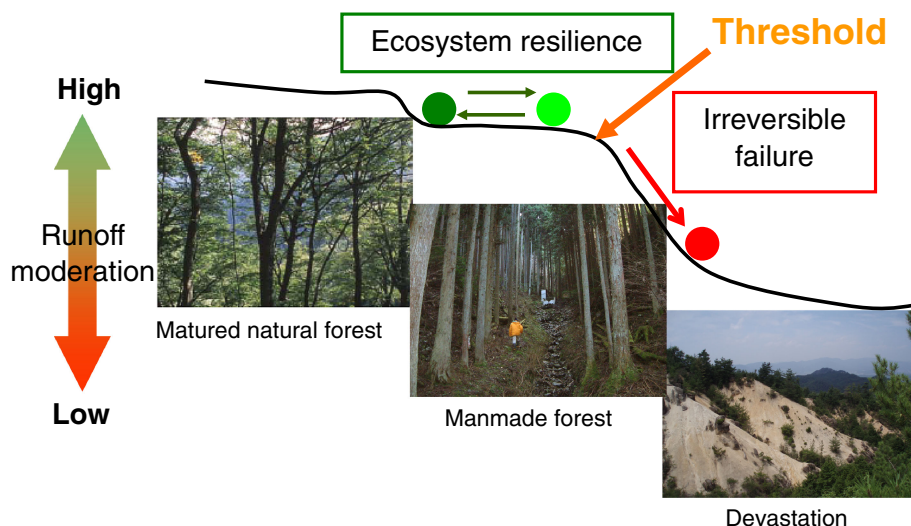


Figure 14. A schematic diagram for the reduction of runoff moderation effects due to human forest disturbances

conditions, a smooth invasion of vegetation from the surrounding forested area (Shimokawa, 1984) is not expected. To quantitatively predict changes in runoff, however, we should also consider the increasing allocation of rainwater to stormflow and the decreasing of ET as discussed in the last section. Therefore, as the severest effects of human forest disturbances occur in granite mountains, we can consider very high peak runoff rate with an increase of rainwater allocation to stormflow, although a large baseflow characteristic consistently may remain by deeply weathered bedrock.

In sedimentary rock mountains, a bare land condition is not created in response to human forest disturbances probably because the soil produced from the parent sedimentary bedrock has a greater resistance than does the sandy soil produced from granite (Tsukamoto, 2001). However, its effect on runoff moderation is generally lower because the bedrock does not contribute to a large fluctuation of water storage in it although it includes many fissures. Furthermore, although forest can continue to thrive on clayey soil, the loss of forest soil may decrease the fluctuation of water storage in soil layers, as shown at KT in Tatsunokuchi-yama. The remaining clayey soil with abundant small pores makes storm runoff responses very sensitive to the antecedent wetness. Therefore, the severest case, resulting from human disturbances of forest in sedimentary rock mountains, may be flashier runoff characteristics with a large stormflow and a low baseflow, but it should be noted that the stormflow may become small in case of a dry antecedent condition. This indicates that sufficient water resources cannot be expected from a small amount of rainfall during the dry season. The characteristics of flashy runoff and sensitivity to dryness are made milder if soil with enough large pores exists where water can be drained by gravity. This may be only achieved by the existence of brown forest soil for a sedimentary rock catchment.

Human disturbances of forests are unavoidable as forest resources have supported the development of human

society and are still needed in our daily lives. The recent continent-scale reductions in natural forest in regions such as Siberia and Amazonia mean that forests even on steep slopes must be harvested in regions with a high tectonic activity to satisfy the increasing demand. Most of these catchments are ungauged, and it is important to be able to predict future changes in river runoff characteristics in response to various types of forest use and various disturbance scenarios. This strongly demonstrates that it is crucial to continuously get long-term hydrological data in small catchments, where a reliable data set necessary for the future prediction can be guaranteed due to both a small spatial variability of rainfall and an accurate flow observation with a notch-gauging weir.

To prevent flood, erosion and landslide, we must identify strategies of forest use that do not exceed the threshold condition at which an irreversible failure occurs in rainfall-runoff responses or the disturbances do not exceed the resilience of the ecosystem (Zehe and Sivapalan, 2008). Although Figure 14 provides a schematic diagram, indicating that the reduction of runoff moderation effects due to human forest disturbances has a threshold, our study demonstrates that the reduction behaviour may be different between granite and sedimentary rock catchments. A management for land-use and forestry in regions with a high tectonic activity should take these findings into careful consideration to balance the sustainability of natural resources and the prevention of hazards.

ACKNOWLEDGEMENTS

The authors express their deep appreciation to Professor Yoshihiro Fukushima (Tottori University of Environmental Studies), Professor Masakazu Suzuki (University of Tokyo) and Associate Professor Nobuhito Ohte (University of Tokyo) for a lot of contributions to hydrological studies in the catchments analysed in the present article. They also thank Associate Professor Tsuyoshi Tada (National Defense Academy of Japan) for his kindly allowing us to

use his SCE-UA programme code, Professor Haruya Tanakamaru (Kobe University) for his advice on the optimisation procedure of model parameters, Dr Sumio Matsuura (Forestry and Forest Products Research Institute; present affiliation: Kyoto University) for kind permission to use the data from KT and Dr Toshio Shimizu (Association of International Research Initiatives for Environmental Studies) for allowing us to present his original figure. They also thank Professor Emeritus Sumiji Kobashi (Kyoto University), Professor Takahisa Mizuyama (Kyoto University), Dr Taro Uchida (Public Works Research Institute) and Dr Yuko Asano (University of Tokyo) for their fruitful comments. This research was partially supported both by a grant-in-Aid for Scientific Research (A)18201036, and by the Mitsui & Co., Ltd. Environment Fund.

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