

Investigation of rainfall–runoff mechanisms in sedimentary rock mountains focusing on bedrock properties

Jun Inaoka

2025

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CHAPTER 1

Introduction

1.1. General introduction

Sediment disasters have increased in recent years due to the effects of climate change (Cabinet Office, 2023; Haque *et al.*, 2019). In Japan, sediment disasters are commonly referred to as landslips, debris flows, and landslides. Landslips can be further subdivided into slope failures, shallow landslides, and deep-seated landslides. Debris flows and deep-seated landslides are particularly significant for disaster prevention, as they often cause large-scale damage. A debris flow occurs when sediments move downhill with water, typically triggered by heavy rainfall or other factors. The most notable examples include Hiroshima landslides of 2014 (Kaibori *et al.*, 2014), the western Hiroshima Prefecture case during the 2018 Japan floods (Kaibori *et al.*, 2018), and the 2021 Atami landslide in Izusan, Atami, Shizuoka Prefecture (Imaizumi *et al.*, 2022a, b). Although it is impossible to predict when such debris flows will occur, the mechanisms behind their occurrence have been partially clarified. Much of their behavior can be explained by the slope gradient and the amount of movable sediment and water flowing downhill. For this reason, in disaster prevention measures, the headwaters of steep catchments and areas downstream with slope gradients of two degrees or more are designated as (special) sediment disaster warning areas, and hazard maps for sediment disasters are made publicly available (Takanashi, 2004).

However, there is limited knowledge about deep-seated landslides. The *Revised Glossary of Erosion Control Terms* (Japan Society of Erosion Control Engineering, 2004) defines deep-seated landslides as relatively large landslips where the slip surface occurs at a greater depth than in shallow landslides and not only the surface soil layer but also the deeper layers of bedrock become collapsed soil mass. Significant deep-seated landslides occurred during the 2008 Iwate-Miyagi Nairiku earthquake (Irasawa *et al.*, 2008) and the 2011 Typhoon Talas in the Kii Peninsula, central Japan (Matsumura *et al.*, 2012). These events led to large-scale river channel blockages, posing severe flood and debris flow risks to communities and infrastructure both upstream and downstream. In response, the Ministry of Land, Infrastructure, Transport, and Tourism initiated countermeasures to mitigate these hazards. However, they only developed a “deep-seated landslide estimation frequency map” (Ministry of Land, Infrastructure, Transport and Tourism, 2010), which compiles past cases and

statistically analyzes that the relationship between topography and geological conditions. Additionally, they created a “deep-seated landslide stream hazard level assessment map” (Ministry of Land, Infrastructure, Transport, and Tourism, 2012), which indicates the relative risk levels by focusing on areas with identical geological and topographical conditions. However, This information is not yet objective enough to provide the public with the necessary information for evacuation during emergencies. Furthermore, unlike debris flows or slope failures, no designated (special) sediment disaster warning areas have been established for deep-seated landslides.

At the research level, from a geological and geomorphological perspective, studies have found that (1) geologically, deep-seated landslides are more likely to occur in sedimentary and volcanic rock mountains (Suzuki *et al.*, 2007) and rare in granite mountains, (2) there are many cases occur on slopes where gravitational slope deformation and internal buckling of the bedrock have taken place, which can be detected using high-resolution laser surveys as small scarps or linear depressions before disaster strikes (Chigira *et al.*, 2013), and (3) collapses frequently occur along slope discontinuities, such as faults (Chigira *et al.*, 2013).

On the other hand, the occurrence of deep-seated landslides has also been linked to groundwater (Okunishi & Nakagawa, 1977) and has been studied within the field of hydrology. Jitousono and Shimokawa (1998) found that in a deep-seated landslide in the Harihara River catchment in Izumi City, Kagoshima Prefecture, western Japan, a groundwater discharge pathway that could not be explained by the ground surface catchment boundary and revealed that groundwater converged on the failure slope. Subsequently, direct observations of the groundwater table using boreholes by Gabrielli *et al.* (2018) and Kosugi *et al.* (2011) revealed that groundwater percolates into the bedrock and is retained in large quantities as bedrock groundwater. The presence of bedrock groundwater creates what is known as green dams, where water continues to sustain and does not dry up in many streams even in the absence of rainfall. However, the exact relationship between these large volumes of groundwater and deep-seated landslides remains unclear. Meanwhile, some clues have been found in granite mountains, where Masaoka *et al.* (2021) showed that the behavior of bedrock groundwater is regulated by the topography of the bedrock surface, which serves as a hydrological basement. Direct observations of the groundwater table using boreholes revealed that bedrock groundwater flows along the bedrock surface topography and can extend beyond the catchment boundaries defined by the surface topography. In short, if a similar phenomenon is observed in sedimentary or volcanic rock mountains, it could significantly impact the mechanisms of deep-seated landslides.

Thus, deep-seated landslides have been studied from various perspectives, including hydrology, geology, and geomorphology. Recently, research in the field of hydrology has advanced by incorporating findings from geology. Kinoshita *et al.* (2021) found that in the Kuridaira area of Totsukawa Village, Nara Prefecture, where a deep-seated landslide occurred by Typhoon Talas in 2011, groundwater behavior was disrupted by fault gouge, resulting in groundwater convergence. The discontinuous surface of the fault also influenced the deep-seated landslide.

Regarding the relationship between geology or geological structure and groundwater, Jefferson *et al.* (2006) and Sakai *et al.* (2009) stated that groundwater behavior is regulated by the bedding structure of the bedrock in volcanic and sedimentary rock mountains. This is believed to result from variations in the hydraulic conductivity and other characteristics of each bedrock layer, as well as the hydraulic anisotropy of the bedrock. However, despite the potential of such studies to elucidate the mechanisms of deep-seated landslides, few studies have focused on this phenomenon in mountain headwaters, and even fewer have been based on long-term observations.

1.2. Objectives and the structure of this thesis

This study proceeds from the background described in Section 1.1, focusing on hydrological and geological/geomorphological aspects. In other words, the convergence of bedrock groundwater, which is influenced by geological structures rather than surface topography, is important for understanding the mechanisms behind deep-seated landslides. This is the objective of this study. The findings will not only help to elucidate the mechanisms of deep-seated landslides in the future but also contribute to the development of hydrology-based disaster prevention strategies against deep-seated landslides, similar to those used for debris flows.

The structure of this study is outlined in Figure 1.1. Chapter 2 provides an overview of the Shigaraki Experimental Forest (S site) in Koka City, Shiga Prefecture, central Japan, where field observations were conducted. Chapter 3 describes the results of the runoff observations at site S, including the rainfall–runoff characteristics and an analysis of the estimated mechanisms at site S. Chapter 4 describes the applicability of the short-term data from Chapter 3 over the long term by comparing it with data from granite catchments. Finally, Chapter 5 focuses on optimizing the parameters of the improved Hydrologic CYcle (HYCY) model based on observations at the S site, and discusses the influence of the geological structure in terms of the model parameters. This discussion is also based on a comparison with the granite catchments. Overall, Chapter 3 is the main focus of this study, while the other sections involve a long-term validation of its universality.

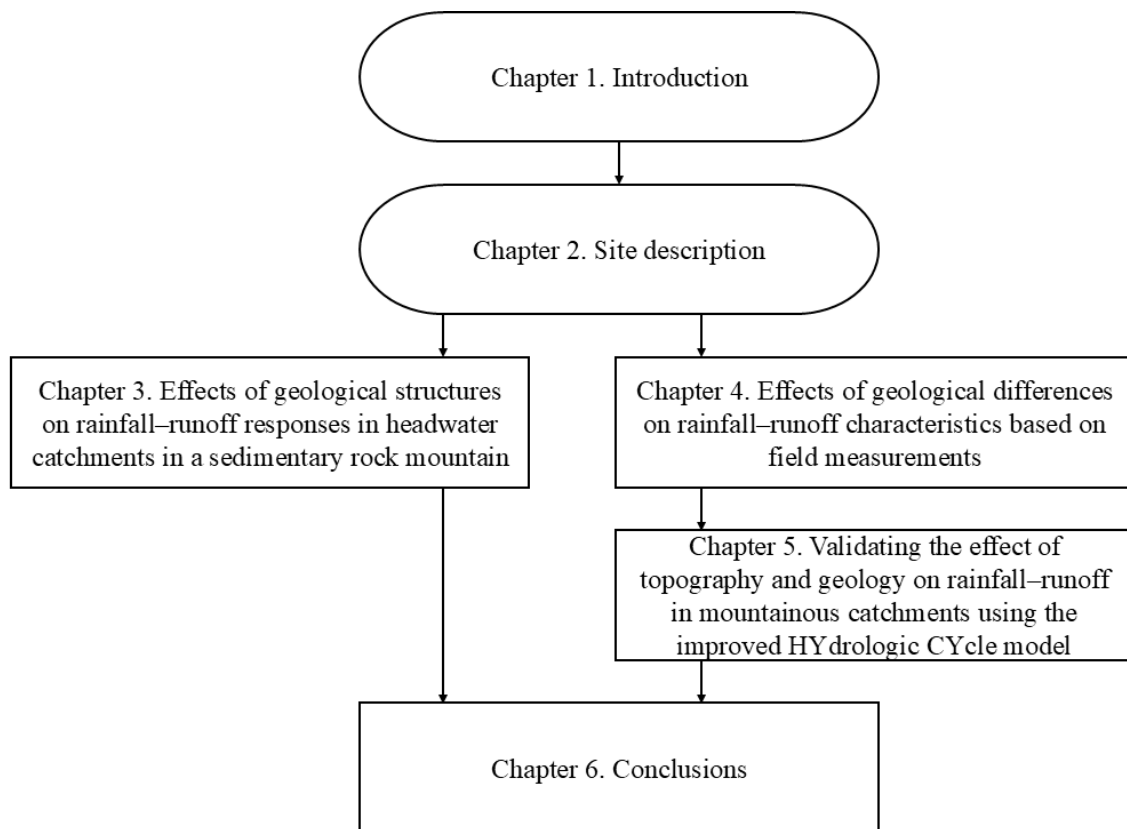


Fig.1.1. Thesis structure.

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CHAPTER 2

Site description

2.1. Study site

In this study, runoff observations were carried out in a mountainous headwater catchment with sedimentary rock as the bedrock. The observations were carried out at the Shigaraki Experimental Forest in Koka City, Shiga Prefecture, central Japan. There were two main reasons for conducting the study at the S site: first, there are 12 catchments at the S site, which are generally located in one mountain body and within a relatively small area, making it convenient to observe multiple catchments in the same mountain at the same time. The second is that the site is where boreholes were drilled at a high density, which is rare in the world, by previous research (Kosugi, 2017), and data on groundwater as well as runoff data are available. Due to these favorable conditions, most of the research was conducted at the S site, as it was considered relatively easy to model runoff in sedimentary rock mountains by combining various observations and analyses at the S site. In contrast, the Fudoji Experimental Forest (G site), located in Otsu City, Shiga Prefecture, central Japan, is composed of granite catchments. They are 4.5 km north of the S site and were used to verify geological differences.

Especially in Chapter 4 and 5, we compare sites G and S catchments to clarify effects of geological settings and structures on rainfall–runoff characteristics in headwater catchments. Table 2.1 shows that site G catchments have half or smaller size than site S catchments. Some previous studies have shown the effects of catchment areas on rainfall–runoff characteristics (e.g. Laudon *et al.*, 2007) and some readers may consider that the difference revealed by this study would also be affected by catchment scales. However, I regard the effect as small for the following two reasons. Firstly, differences in drainage density between granitic and sedimentary rock catchments have been shown in many studies (e.g. Onda *et al.*, 2004). Therefore, when we try to compare headwater catchments in these different geological settings, catchment scale would inevitably be different. Secondly, in addition, comparison of large catchments show that granitic catchments have gentler hydrograph recessions while sedimentary rock catchments have steeper hydrograph recessions (Musiak *et al.*, 1981; Shimizu, 1980). This is the same as our results (Figure 4.2), and we thought that effect of catchment scale is at least smaller than the effect caused by geological differences, which enables us to discuss the effect of geological settings and structures. The following sections provide overviews of the S and G sites.

Table 2.1. Catchment areas, average slope gradients, and V-notch angles for the 19 studied catchments.

Catchment	Area [ha]	Average Slope [°]	V-notch angle [°]
S01	1.53	32.2	90
S02	0.696	35.1	60
S03	1.37	35.4	90
S04	3.08	39.4	90
S05	1.63	40.6	90
S06	2.15	40.2	90
S07	2.01	39.2	90
S08	1.83	34.0	90
S09	2.13	35.1	90
S10	1.44	37.8	60
S11	1.47	38.1	90
S12	2.19	37.6	90
G0	2.34	33.8	90
G1	0.293	36.9	45
G2	0.465	31.0	60
G3	0.106	34.5	30
G4	0.206	32.2	60
G5	0.116	33.5	30
G6	0.472	34.6	60

2.1.1. Shigaraki Experimental Forest

Shigaraki Experimental Forest locates in the Southern Shiga Prefecture, central Japan (Figure 2.1a). During the study, rainwater discharges from 12 catchments that extend radially from the peak of Mt. Kanayama, which is located at the center of the experimental forest, and is 565.2 m above sea level, were investigated (Figure 2.1b). Between 1991 and 2020, the mean annual precipitation and mean annual temperature measured at the Shigaraki Station of the Japan Meteorological Agency, which is located 9.8 km northeast of the study site, were 1534.6 mm and 12.6°C, respectively (Japan Meteorological Agency, 2024). Around S site, there is almost no snow or ice. As shown in Figure 2.2, the geology of the study area is a mélange matrix of mudstone and sandstone, partially containing chert, accreted in the Jurassic period (Wakita *et al.*, 2013). In sedimentary rock mountains, the strata

have slope and direction called dips and strikes (Figure 2.3). Based on Figure 2.2, which shows the results of a study conducted by Wakita *et al.* (2013), and our survey, the strikes in this study area have direction in the range N 48° E to N 139.5° E, with a mean of N 101.6° E, while the dips have direction in the range 25° N to 85° N, with a mean of 55° N (Table 2.2). The vegetation of the study area is a planted forest, primarily consisting of *Chamaecyparis obtusa* (Japanese cypress) and *Cryptomeria japonica* (Japanese cedar), which were both planted in the 1950s (Tani *et al.*, 2012). Every catchment in this study area is covered with brown forest soil (Tani *et al.*, 2012), which is typical of low relief mountains in Japan.

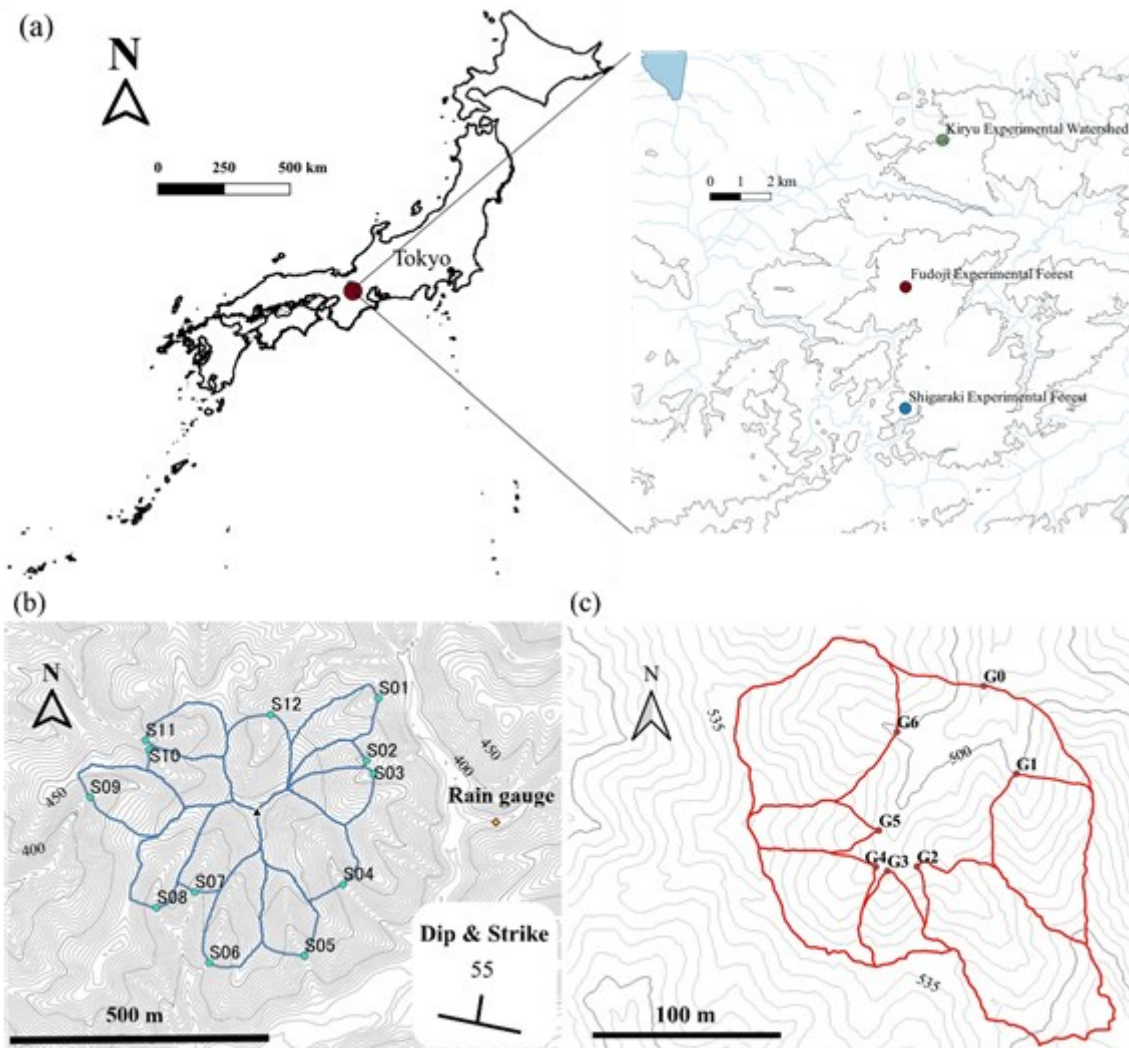


Figure 2.1. (a) Location of the study sites. Topographic map of (b) Shigaraki Experimental Forest (S site) and (c) Fudoji Experimental Forest (G site). The gray contours are located at 5-m intervals, whereas the black contours are located at 50-m intervals in both the topographic maps. The dip and strike of S are displayed at the bottom of (b).

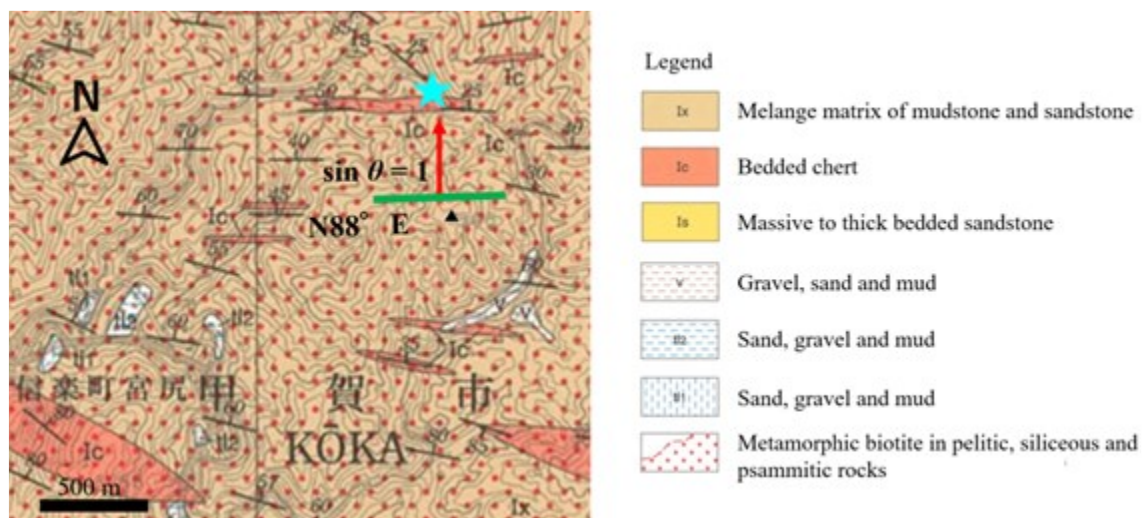


Figure 2.2. Geological map of the study area, including the $N88^\circ E$ line and the arrow perpendicular to the $N88^\circ E$ line shown in Figure 3.6. The light blue star indicates the location of the slope shown in Figure 2.3. The green line, red arrow, light blue star, summit mark, scale bar, compass mark, and North mark were added to the geological map produced by Wakita *et al.* (2013).



Figure 2.3. Dips and strikes in the study area. This picture was taken at the place indicated by the light blue star in Figure 2.2. In this picture, the strike is $N83^\circ E$ and the dip is $65^\circ N$.

Table 2.2. Average dip value and strike direction in the vicinity of the study site.

Source	Points	Dip	Strike
Wakita <i>et al.</i> (2013)	8	39° N	N100.7° E
Our research	35	59° N	N101.8° E
Average	43	55° N	N101.6° E

2.1.2. Fudoji Experimental Forest

Fudoji Experimental Forest has seven headwater catchments (Figure 2.1c; Table 2.1). The geological setting consists of granite that formed during the Late Cretaceous (Tanakami Granite; Wakita *et al.*, 2013). The bedrock has numerous joints and fissures, and strike-slip shear cracks predominate along the straight valley (Yokota, 1974; Figure 2.4). Groundwater often gushes from these cracks, and the mountain streams of catchments G3 and G5 emanate from these springs. Catchment G3 is located at the extension of the channel of catchment G0 and is perpendicular to that of catchment G5. Vegetation at site G is *Chamaecyparis obtusa* (i.e., Japanese cypress) and several deciduous species (Masaoka *et al.*, 2021). This forest also has brown forest soil (Asano *et al.*, 2004), i.e. the same as that at site S.

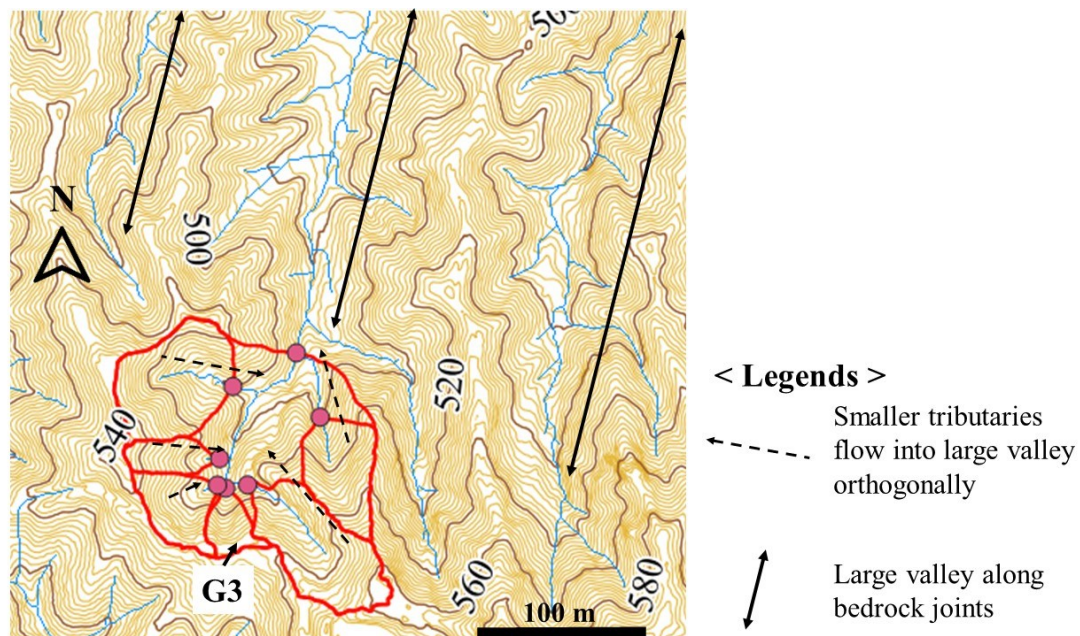


Figure 2.4. Distribution of channels around site G. Site G catchments are shown in red. Blue lines are channels drawn by QGIS.

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CHAPTER 3

Effects of geological structures on rainfall–runoff responses in headwater catchments in a sedimentary rock mountain

3.1. Introduction

Japan has been subject to several disasters (Okada *et al.*, 2011; Ushiyama, *et al.*, 2019), including slope failures, debris flows, and landslides (Marutani *et al.*, 2017; Miyagi *et al.*, 2011), and adequate preparation for these hazards is still a major challenge. To accurately predict sediment disasters, an understanding of rainfall–runoff responses in mountainous areas is important (Corominas *et al.*, 2005; Kosugi *et al.*, 2011). Additionally, rainfall–runoff responses do not only affect sediment disasters, they also affect flood prediction (Fujimoto *et al.*, 2008), water resource management (Hughes, 1995), and chemical as well as ecological material transport (Sakai *et al.*, 2009). Thus, studying on rainfall–runoff responses is enormously beneficial to the society.

In previous studies, the effects of vegetation and land use on rainfall–runoff responses have been reported (Kirkby *et al.*, 2002; Tani *et al.*, 2012). Additionally, it has been reported that topography and geology affect rainfall–runoff responses (Iwashita *et al.*, 1994; Kato *et al.*, 2000; Tani *et al.*, 2012), and that the effect of topography is very significant (Beven & Kirkby, 1979; Hernandez *et al.*, 2003; Zevenbergen & Throne, 1987), i.e., large catchment areas tend to develop overland saturated flow; thus, they significantly result in an increase in runoff. Gentle topographic slopes also tend to develop overland saturated flow given that groundwater movements become slower. Furthermore, the steep channel gradient contributes to rapid runoff. Based on these topographical effects, Beven and Kirkby (1979) developed TOPMODEL, and it is one of the most widely used hydrological models today. However, many previous studies in which the effects of topography on rainfall–runoff responses were investigated did not consider the effects of geological structures.

Studies on the effects of geological structures on rainfall–runoff responses have been primarily conducted in crystalline mountains (*e.g.*, Fujimoto *et al.*, 2008; Han *et al.*, 2012; Miyata *et al.*, 2003; Séguis *et al.*, 2011). However, in some previous studies, the focus was on catchments in sedimentary rock mountains (Komatsu, 2008; López-Tarazón *et al.*, 2010; Uchida *et al.*, 1999). Moreover, Kato *et al.* (2000) and Tani *et al.* (2012) compared catchments in crystalline and

sedimentary rock mountains. However, the exact effects of dips and strikes, which are typical of sedimentary rock mountains, on rainfall–runoff responses have not yet been evaluated.

Dips and strikes, which are not characteristic of crystalline rocks that are formed from the solidification of magma, are features that develop during the formation of sedimentary rocks. Therefore, to study rainfall–runoff responses in sedimentary rock mountains, the results obtained for crystalline rock mountains cannot be applied. Additionally, it is necessary to evaluate the effects of geological structures that are characterized by dips and strikes on rainfall–runoff responses. Actually, Kato *et al.* (2000) observed multiple type of rainfall–runoff responses in sedimentary rock catchments unlike in crystalline catchments.

In sedimentary rocks, different rock layers share a bedding plane creating hydraulic anisotropy (Singhal & Gupta, 2010). Thus, it has been reported that, in sedimentary rocks, a greater amount of water tends to infiltrate parallel to the bedding plane than in the orthogonal direction (Suenaga *et al.*, 2002). Such an effect of hydraulic anisotropy can be found in other geological settings. For example, Jefferson *et al.* (2006) discussed the hydraulic anisotropy caused by lava flow geometry through the volcanic history. They studied discharges, temperatures, and water chemistries of seven springs located in the west of the Oregon High Cascades, which showed the effects of geological stratigraphy on runoff. Thus, the groundwater system can significantly be affected by the hydraulic anisotropy originating from geological stratigraphy.

In sedimentary rock mountains, previous studies suggested convergence of groundwater flows in the direction of strikes. For example, Sakai *et al.* (2009) monitored the spatial distribution of baseflow discharge from catchments with an area of a few km² located in the Plio-Pleistocene Kazusa Group in Boso Peninsula, Japan. They also revealed that catchments that have average flow direction oriented toward the strike (*i.e.*, strike-oriented catchments) tended to have large baseflows. Strike-oriented groundwater movements are also reported in the results of a study conducted in pre-glacial Canadian Rocky Mountains (Ford, 1983). However, in these previous studies, the effects of dips and strikes on rainfall–runoff responses in headwater catchments, which are the most important source regions for runoff generation, were not investigated, and none of these previous studies focused on the effects of geological structures on storm runoff responses. Additionally, the runoff properties of catchments that have their average flow direction oriented toward the dip direction (*i.e.*, dip-oriented catchments) and toward the opposite dip direction (*i.e.*, opposite dip-oriented catchments), have not yet been clarified.

Therefore, the objective of this study was to evaluate the effects of geological structures on

rainfall–runoff responses in headwater catchments in sedimentary rock mountains. Based on the simultaneous observation of 12 catchments that lie radially from a single, isolated mountain peak, this study aims to clarify the effects of dips and strikes, which characterize sedimentary rock mountains, on water discharge.

3.2. Methods

3.2.1. Observation methods

Runoff was observed at the outlets of the 12 catchments in Shigaraki Experimental Forest shown in Figure 2.1(b). The 12 catchments were numbered based on their clockwise locations (*i.e.*, catchments S01–S12), and the areas of the 12 catchments as well as their average slopes are summarized in Table 2.1. A V-notch weir made of stainless steel and a water level sensor was installed in the outlet of each catchment, and water level was recorded using a data-logger (HIOKI LR5042) at five-minute intervals. The angle of the V-notch weir is 90° for every catchment, except for the S02 and S10 catchments. For the S02 and S10 catchments, a V-notch weir with an angle of 60° was used. Precipitation was observed at an open space close to catchment S04 using a tipping-bucket rain gauge with a resolution of 0.5 mm (Figure 2.1b).

3.2.2. Storm events

In this study, 2 storm events, both of which resulted in total rainfall of ~ 60 mm, were analyzed (Table 3.1). Prior to each of these events, there was a long no-precipitation period. Moreover, both events had relatively simple hyetographs. As shown in Table 3.1, event 1 had a greater peak intensity than event 2.

Table 3.1. Characteristics of rainfall events.

Event	Date	Total rainfall [mm]	Peak intensity [mm/10min.] ([mm/h])	No-precipitation period before event
1	September 24, 2014, 22:20 - September 25, 2014, 5:40	57.5	6.5 (21.5)	13 days 7 hours 10 minutes
2	October 5, 2014, 13:20 - October 6, 2014, 13:20	62.5	3.5 (14.5)	10 days 7 hours 50 minutes

3.2.3. Analysis of hydrographs

For calculating direct runoff, we used the same method employed by Hewlett and Hibbert (1967), which allows the separation of the hydrograph into direct runoff and baseflow using a straight line unique to watershed. To separate the hydrographs of all the catchments, a line with a constant slope value of 2.4×10^{-5} mm/h/h was assumed.

For analyzing storm runoff timing, we computed D_1 and D_2 values. Here, D_1 represents the direct runoff amount during the period from the start to the end of precipitation, and D_2 represents the direct runoff amount 24 h just after the precipitation ceased. The ratio of D_2 to D_1 represents the timing of storm runoff occurrence.

3.2.4. Calculation of the area-proportional discharge ratio and the observed discharge ratio

To evaluate the characteristics of the hydrographs observed in detail, the following method, which allows the comparison of the area-proportional discharge ratio and the observed discharge ratio for each catchment, was used.

Primarily, the total discharge from the mountain, Q_{all} [L^3T^{-1}], was defined as:

$$Q_{\text{all}} \equiv \sum Q_i \quad (3.1)$$

where Q_i represents the discharge from each catchment, i , and the summation involved all 12 catchments. Additionally, the total catchment area of the mountain, A_{all} [L^2] was defined as:

$$A_{\text{all}} \equiv \sum A_i \quad (3.2)$$

where A_i represents the area of each catchment, i . Thus, the total specific discharge, q_{all} [LT^{-1}], from

the mountain was calculated as:

$$q_{\text{all}} = Q_{\text{all}}/A_{\text{all}} \quad (3.3)$$

In contrast, the specific discharge from each catchment, i , denoted q_i , was calculated as:

$$q_i = Q_i/A_i \quad (3.4)$$

On the other hand, the area-proportional discharge, Q_i^* (*i.e.*, the discharge expected from each catchment based on its area) was then calculated according to Equation (3.5) below.

$$Q_i^* = Q_{\text{all}}A_i/A_{\text{all}} \quad (3.5)$$

where Q_i^* represents the area-proportional discharge from each catchment, i . Equation (3.5) indicates that the ratio of the area-proportional discharge from each catchment, i , to the total discharge from the mountain (*i.e.*, the area-proportional discharge ratio for catchment i) is the same as the ratio of the area of catchment i to the total catchment area of the mountain, A_i^* , *i.e.*,

$$Q_i^*/Q_{\text{all}} = A_i/A_{\text{all}} \equiv A_i^* \quad (3.6)$$

In contrast, the ratio of the observed discharge from catchment i to the total discharge from the mountain (*i.e.*, the observed discharge ratio for catchment i), Q_i^* , was calculated as:

$$Q_i^* = Q_i/Q_{\text{all}} \quad (3.7)$$

Substituting Equations (3.3) and (3.4) into Equation (3.7) gave:

$$Q_i^* = A_i^* q_i/q_{\text{all}} \quad (3.8)$$

By comparing the area-proportional discharge ratio, A_i^* , and the observed discharge ratio, Q_i^* , it was possible to evaluate the contribution of each catchment to the total discharge from the mountain, *i.e.*, when Q_i^* was greater than A_i^* , it implied that the discharge yield of the catchment, i , was greater than the discharge expected from the catchment area, and when Q_i^* was less than A_i^* , it implied that the yield discharge of the catchment, i , was lower than expected value. Equation (3.8) shows that Q_i^* is greater than A_i^* when q_i is greater than q_{all} . If the q_i hydrograph is the same as the q_{all} hydrograph, then Q_i^* will always be equal to the constant, A_i^* .

3.2.5. Terrain analysis

To evaluate the topography of each catchment, the distribution of the topographic wetness index (TWI) introduced by Beven and Kirkby (1979) was determined. TWI is a fundamental variable

in TOPMODEL, which was developed by Beven and Kirkby (1979), and it is indicative of the development of saturation-excess overland flow. When a catchment is cut into grids, the TWI value of each grid can be calculated based on the ratio of the upslope area to the tangent of the topographical slope of the grid. In this study, we used SAGA plugins from QGIS (ver. 3.4.12) (QGIS Development Team, 2019) to calculate TWI values using the one-meter mesh digital elevation model (DEM) developed by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan.

3.3. Results

3.3.1. Observed hydrographs

The results obtained after monitoring the runoff and precipitation events are shown in Figure 3.1, which reveal that even though all the catchments are located in the same mountain, their runoff characteristics were significantly different. For example, the peak runoff of catchment S06 was very high, while that of catchment S01 was relatively lower, and catchments S03 and S09 had very high baseflows. Additionally, these observations were similar for both storm events. For event 1, which showed a high first precipitation peak and low second precipitation peak (Figure 3.1), all the catchments, excluding catchments S10 and S11, had a peak runoff corresponding to the first precipitation peak. On the other hand, catchments S10 and S11 had peak runoffs corresponding to the second precipitation peak. For event 2, the hydrograph of catchment S12 clearly showed a delayed second peak after the precipitation event ceased.

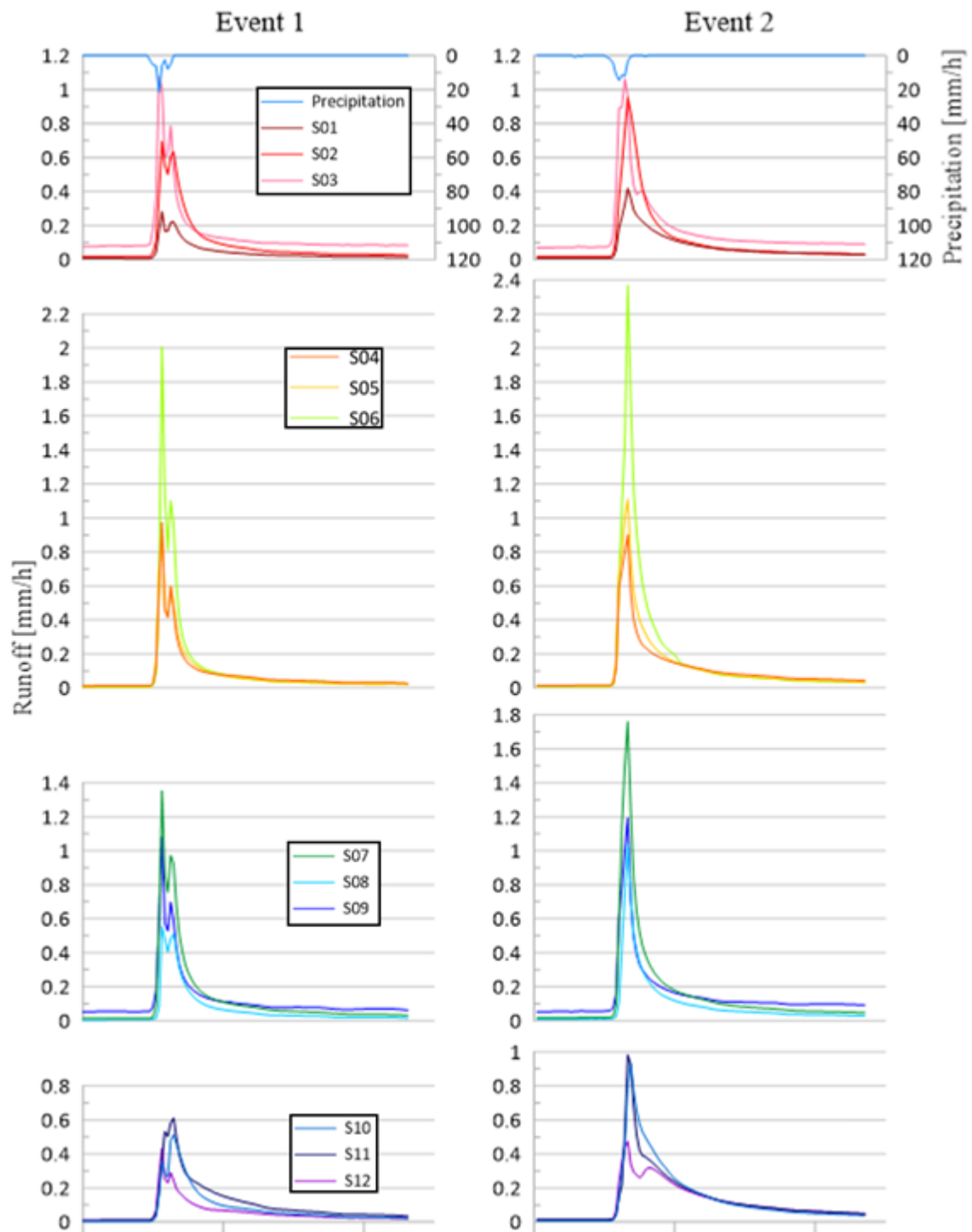


Figure 3.1. Observed hyetographs and hydrographs for the events 1 and 2.

3.3.2. Characteristics of hydrographs

Figure 3.2(a) shows a comparison of the runoff for a duration of one hour prior to the start

of each event for the different catchments. These runoff data can be regarded as baseflows, since there was a long no-rainfall period preceding each event (Table 3.1). From this figure, it is evident that catchments S03 and S09, which are located eastward and westward of the mountain summit respectively, had remarkably high baseflow runoffs before both storm events. Among the other catchments, catchments S02 and S07 showed relatively high baseflow runoffs, while the baseflow runoff of catchment S10 was the lowest.

In Figure 3.2(b), the storm peak flow rates (*i.e.*, the maximal one-hour runoff for each event) of the different catchments are compared. The southern catchments, S06 and S07, showed high storm peak flow rates, while the northern catchments, S12 and S01, showed lower values.

Figure 3.2(c) shows that the trends observed in the direct runoff distribution were similar to those in the storm peak flow distribution shown in Figure 3.2(b), *i.e.*, catchments S06 and S07 had high direct runoffs, while the direct runoffs of catchments S01 and S12 were generally lower. However, the differences in direct runoffs of all the catchments were less distinct than the differences in their peak flow rates. Particularly, in catchment S12, the direct runoff for event 2 was much higher than that for event 1, and this was attributed to be the occurrence of the second peak in catchment S12 as shown in Figure 3.1.

The observation that event 2 resulted in a much greater direct runoff than event 1 was also true for catchment S10. For the other catchments, the direct runoff for event 2 was also higher than for event 1. Figure 3.2(a) indicates that the baseflow rate before event 2 was higher than that before event 1 for most of the catchments, and as shown in Table 3.1, event 2 had a shorter antecedent no-precipitation period than event 1. Additionally, Suzuki (1980) suggested that the non-rainfall period before event 2 (*i.e.*, early October) showed a lower potential evapotranspiration than that before event 1 (*i.e.*, mid-September). These observations suggest a wetter antecedent condition for event 2 than for event 1, which probably resulted in the higher direct runoff for event 2.

Figure 3.2(d) compares the ratio D_2 to D_1 , which represents the timing of storm runoff occurrence. A high D_2 to D_1 ratio implied a delayed occurrence of the storm runoff. For event 1, the ratio was high for catchments S10 and S11, and for event 2, it was high for catchments S10, S11, S12, and S01, indicating that catchments located northwestward, northward, and northeastward to the mountain summit tended to show delayed storm runoff timings.

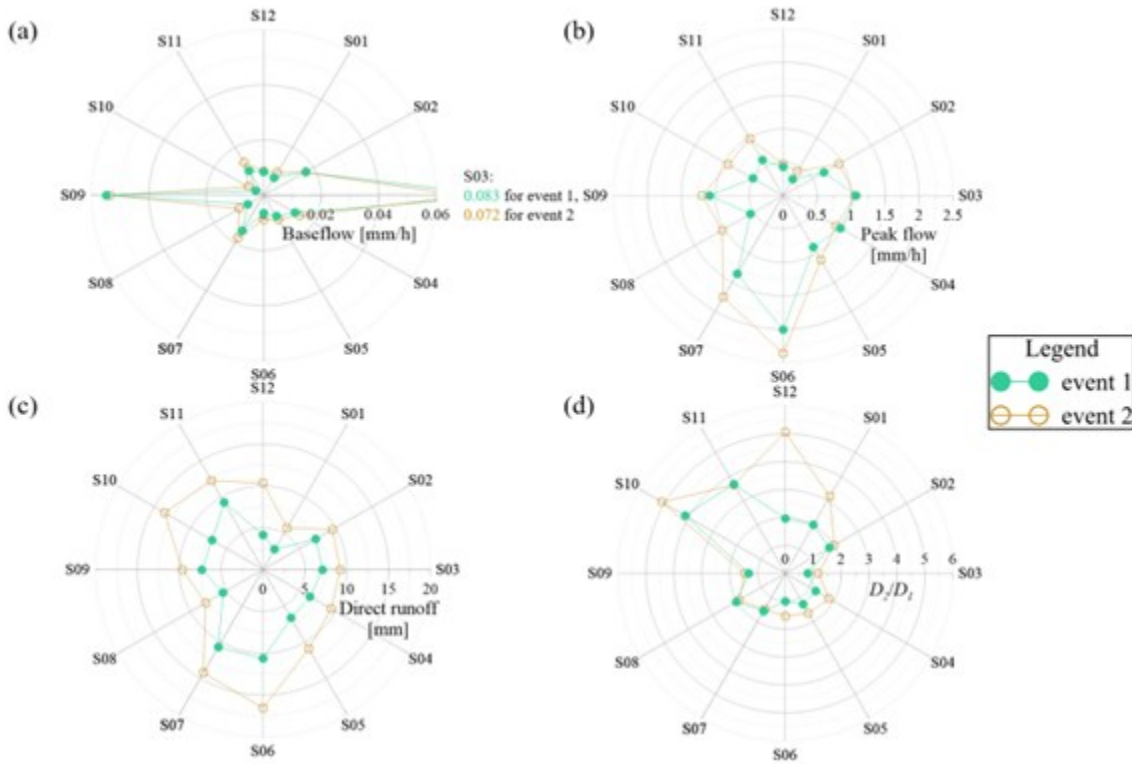


Figure 3.2. Characteristics of the studied two storm events showing (a) baseflow rate just before each event, (b) peak flow rate, (c) amount of direct runoff, and (d) ratio of D_2 to D_1 where D_1 represents direct runoff amount during the period from the start to the end of precipitation, and D_2 represents the direct runoff amount for 24 hours just after precipitation ceased.

3.3.3. Catchment classification based on the observed discharge ratio

The specific discharges that were used to compute the observed discharge ratio are summarized in Figure 3.3(a), and Figure 3.3(b) shows the area-proportional discharge ratio, A_i^* , and the observed discharge ratio, Q_i^* , for catchments S03, S06, and S12 during event 2. These catchments exhibited distinctive Q_i^* hydrographs.

As shown in Figure 3.3(b), catchment S03 showed a very high Q_{S03}^* compared to A_{S03}^* before precipitation, i.e., the observed baseflow for catchment S03 was much larger than the value expected from the catchment area. During precipitation, Q_{S03}^* quickly decreases, and became approximately the same as A_{S03}^* , meaning that the storm runoff rate of catchment S03 is consistent with the explanation of the rate based on its area. After precipitation ceased, Q_{S03}^* gradually increased.

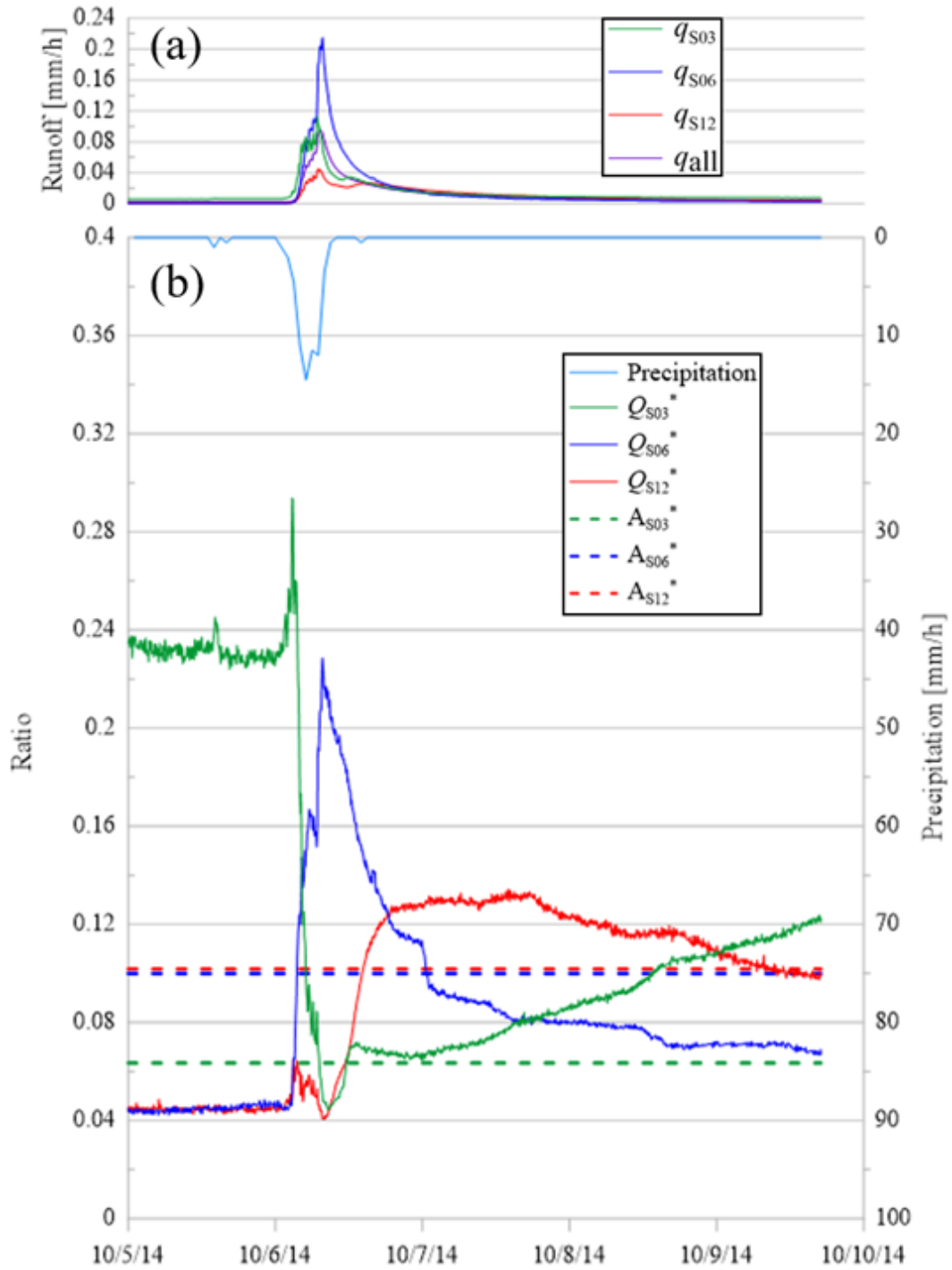


Figure 3.3. (a) Specific discharge q_i , and (b) Area-proportional discharge ratio, A_i^* , and the observed discharge ratio, Q_i^* , for catchments S03, S06, and S12 (event 2). In Figure 3.3(a), the total specific discharge from the mountain, q_{all} , is included. In Figure 3.3(b), the hourly precipitation is included. Note that A_{S06}^* and A_{S12}^* are about the same value.

For catchment S06, the value of Q_{S06}^* was less than A_{S06}^* before precipitation, i.e., catchment S06 has smaller baseflow than expected from its area. During precipitation, Q_{S06}^* increased significantly, and formed a sharp peak at approximately the same time as the precipitation peak, at which it was more than two-fold as high as A_{S06}^* . After precipitation, it decreased immediately and became lower than A_{S06}^* . Thus, the storm flow from catchment S06 responded quickly to precipitation input, compared with the total storm flow response of the mountain.

Like Q_{S06}^* , the value of Q_{S12}^* was less than A_{S12}^* before precipitation, indicating the small baseflow of catchment S12 for its area. During precipitation, there was no significant increase in Q_{S12}^* , suggesting that the runoff from catchment S12 remained below the expected value. However, close to the end of precipitation, Q_{S12}^* began to increase, and after precipitation, it formed a dull peak that lasted for a day, and thereafter declined gradually. In the vicinity of the peak, Q_{S12}^* became higher than A_{S12}^* , suggesting the occurrence of a discharge that was greater than the expected value. In summary, relative to the total storm flow from the mountain, the generation of storm flow in catchment S12 was delayed.

Figure 3.4, which shows A_i^* and Q_i^* values for event 2 for all the catchments, clearly reveals that Q_{S09}^* was very similar to Q_{S03}^* ; and that Q_{S09}^* had high values before the storm event, which decreased during precipitation and gradually increased again after the storm event. Thus, catchments S03 and S09 could be classified under the same group, characterized by a large baseflow (LBF). Figure 3.4 also shows that with the exception of catchments S03 and S09, all the other catchments had Q_i^* values that were smaller than their corresponding A_i^* values before the storm event, which means that they have smaller baseflow than LBF catchments.

The time series of both Q_{S05}^* and Q_{S07}^* were similar to that of Q_{S06}^* , i.e., they exhibit sharp peaks corresponding to the precipitation peak. Therefore, catchments S05, S06, and S07 could be classified under the same group, i.e., catchments characterized by relatively quick storm flow (QSF) occurrences. Moreover, even though Q_{S04}^* gradually increased after precipitation, it showed a sharp peak that corresponded to the precipitation peak, and even though the peak of Q_{S08}^* was relatively dull and small, it appeared at approximately the same time as the precipitation peak. Thus, it was reasonable to classify both S04 and S08 catchments into the quasi-QSF group.

The values of Q_{S11}^* and Q_{S10}^* shown in Figure 3.4 were similar to that of Q_{S12}^* . Given that catchments S10 and S11 both showed dull peaks after precipitation ceased, together with catchments S12, they were classified into the same group, i.e., catchments characterized by relatively delayed storm flow (DSF) occurrences. Moreover, even though Q_{S01}^* and Q_{S02}^* varied slightly during

precipitation, they were each characterized by a dull peak after the precipitation peak. Therefore, catchments S01 and S02 were classified under the quasi-DSF group.

Figure 3.5 shows the variation of the computed Q_i^* during event 1 for all catchments. The trends shown in this figure are approximately the same as those shown in Figure 3.4 for event 2, indicating that the classification of catchments based on runoff characteristics is consistent for both storm events. Thus, in the vicinity of Mt. Kanayama, the 12 catchments were classified into the 3 groups: catchments with large baseflow (LBF: S03, S09), catchments with relatively quick storm flow (QSF: S05, S06, S07, and quasi-QSF: S04, S08), and catchments with relatively delayed storm flow (DSF: S10, S11, S12, and quasi-DSF: S01, S02).

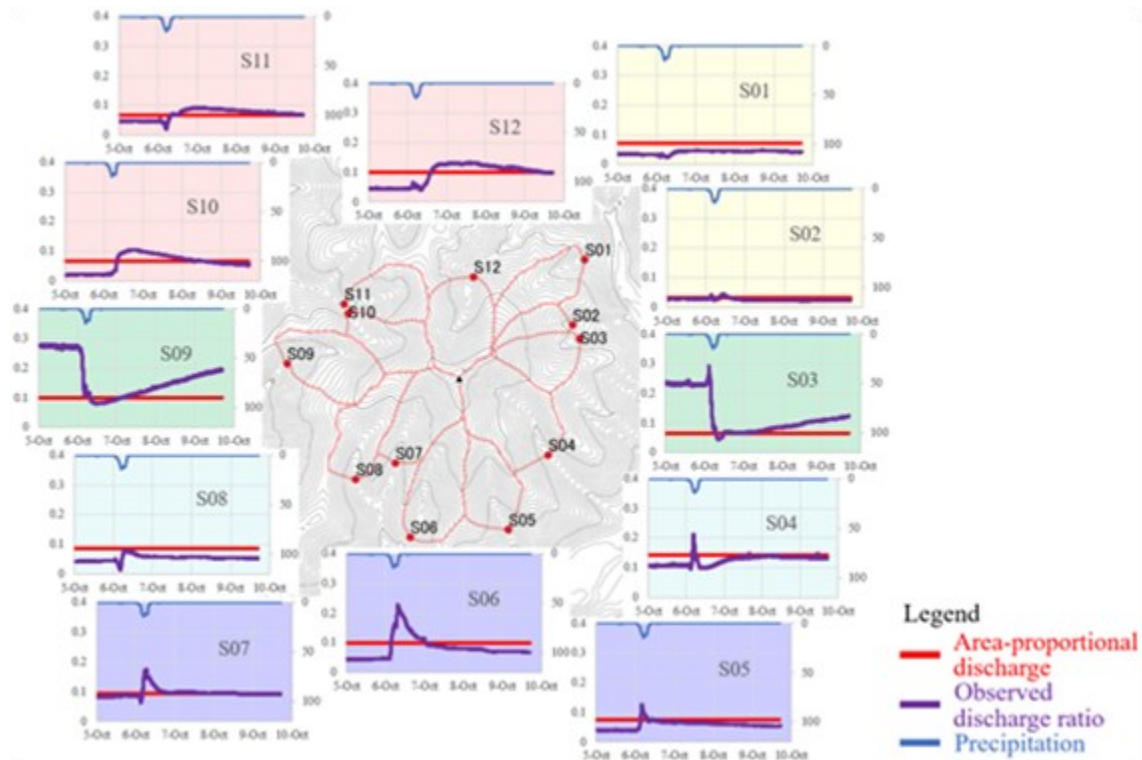


Figure 3.4. Variation of A_i^* and Q_i^* for the event 2. In each panel, the left axis represents the discharge ratio, and the right axis represents precipitation [mm/h].

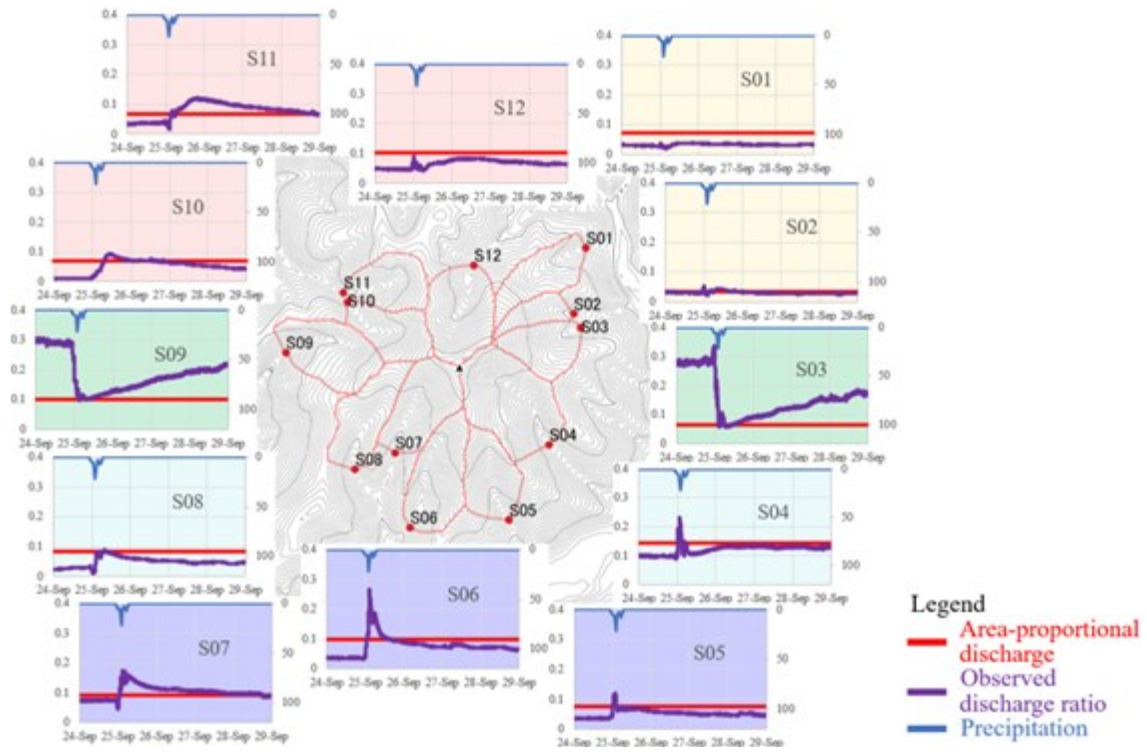


Figure 3.5. Variation of A_i^* and Q_i^* for event 1. The axes are as defined in Figure 3.4.

3.4. Discussion

3.4.1. Relation between geological characteristics and runoff characteristics

As shown in Figures 3.4 and 3.5, catchment classification based on runoff characteristics seems greatly related with catchment direction from the summit of Mt. Kanayama, suggesting that rainfall–runoff responses might be controlled by the flow directions of the catchments. To confirm this suggestion, the flow directions of each of the 12 catchments were computed using the method proposed by Sakai *et al.* (2009), who defined flow direction as the direction from the highest to the lowest point (*i.e.*, the outlet) of the catchment. The resulting flow directions for catchments S03 and S09, both of which were categorized as LBF catchments (Figures 3.4 and 3.5), were N80° E and N84° W, respectively, and both of them were oriented northward by 8° from the N88° E line (Figure 3.6). Based on this N88° E line, the flow direction was defined by an angle, θ , as shown in Figure 3.6, and the $\sin \theta$ values for all the catchments were compared. For example, given the flow direction of catchment S12 (N8° E) as shown in Figure 3.6, its computed θ was 80°, and the resulting $\sin \theta$ was 0.98.

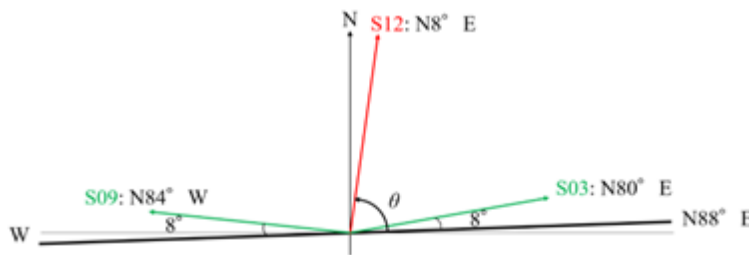


Figure 3.6. Flow directions for catchments S03, S09, and S12, along with the defined θ . The flow directions for catchments S03 and S09, both of which were categorized as LBF catchments, are oriented northward by 8° from the $N88^\circ$ E line. The flow direction of S12 is shown as an example for $\sin \theta$ calculation.

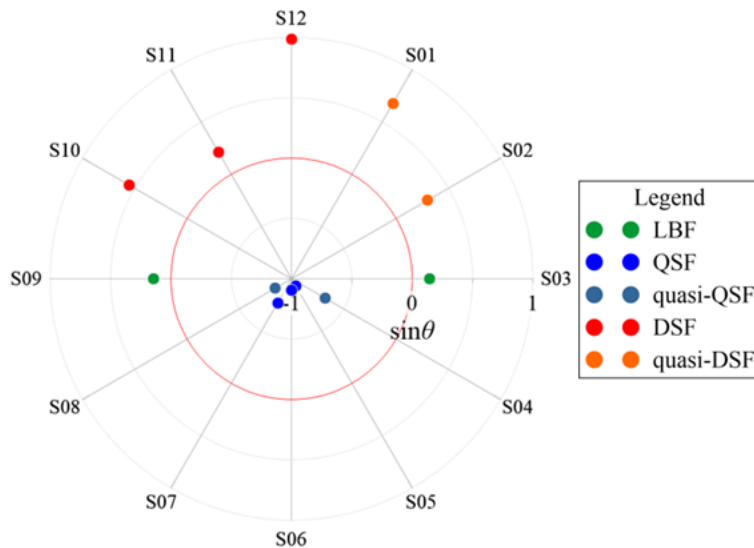


Figure 3.7. $\sin \theta$ for the different catchments. $\sin \theta$ is defined in Figure 3.6. The acronyms in the legend represent catchment classification.

strike survey conducted by Wakita *et al.* (2013) were compared in Figure 2.2. The figure revealed that the $N88^\circ$ E line was approximately the same as the strike line in the vicinity of Mt. Kanayama, and the direction with $\sin \theta = 1$ corresponded to the dip direction. Therefore, the $\sin \theta$ values shown in Figure 3.7 could be recognized as an index that can be used to evaluate the level of agreement between the flow direction of a catchment and the dip direction, i.e., when a catchment has a $\sin \theta$ value close to 1, it implies that its flow direction is oriented toward the dip direction (*i.e.*, it is a dip-oriented catchment). Conversely, when the $\sin \theta$ value of a catchment is close to zero, it implies that its flow direction is oriented toward the strike direction (*i.e.*, it is a strike-oriented catchment). Additionally, when the $\sin \theta$ value is negative and close to -1, it implies that the flow direction of the catchment is

A summary of the $\sin \theta$ values of all the catchments is shown in Figure 3.7, which clearly shows that the $\sin \theta$ values corresponded well to the classification of the catchments based on runoff characteristics. LBF catchments (*i.e.*, the S03 and S09 catchments) had a $\sin \theta$ value of 0.14, while QSF and quasi-QSF catchments had negative $\sin \theta$ values ranging from -0.93 to -0.68, and DSF and quasi-DSF catchments had large $\sin \theta$ values ranging from 0.21 to 0.98.

To evaluate the geological implication of the $N88^\circ$ E line, which was used to calculate the $\sin \theta$ values, the $N88^\circ$ E line and the direction with $\sin \theta$ value equal to 1 as well as the results of the dip and

oriented toward the opposite dip direction (*i.e.*, it is a opposite dip-oriented catchment). Therefore, the results shown in Figure 3.7 indicate that the LBF, QSF, and DSF catchments corresponded to strike-oriented, opposite dip-oriented, and dip-oriented catchments, respectively.

3.4.2. Relations between the topographic index and runoff characteristics

In some previous studies, it has been reported that topography has a significant effect on rainfall–runoff responses (Hernandez *et al.*, 2003; Zevenbergen & Throne, 1987). Figure 3.8 shows the TWI distributions obtained for the 12 catchments studied, which revealed that the TWI distributions of all the catchments were similar. To evaluate the distributions of TWI objectively, we

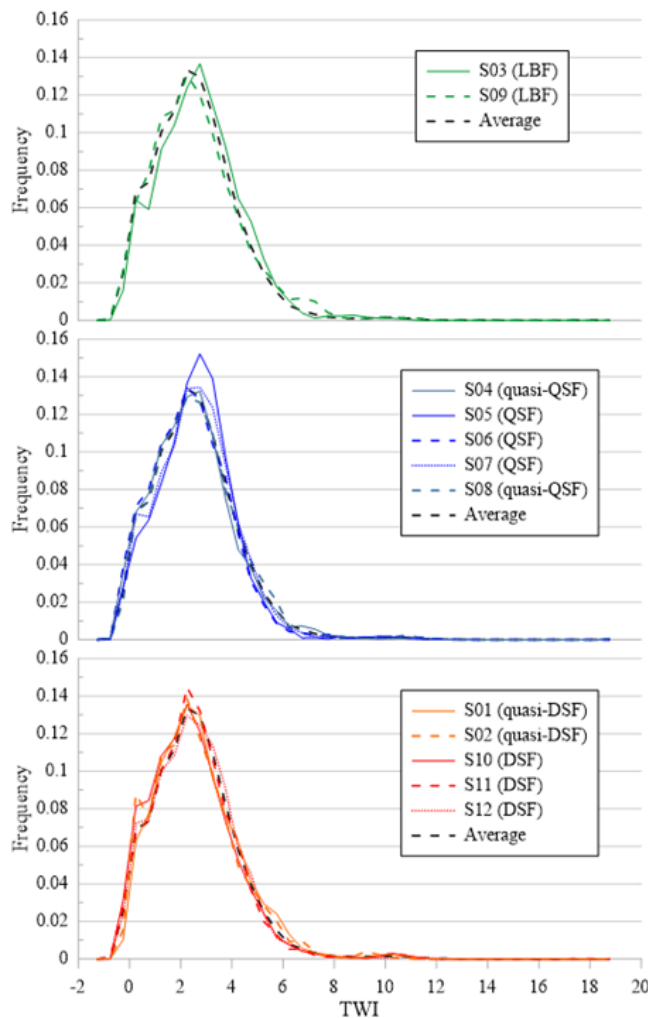


Figure 3.8. Distribution of TWI (topographic wetness index) for each catchment. The black dotted lines represent TWI distribution for all the 12 catchments. The class interval is 0.5.

conducted two-sample Kolmogorov–Smirnov tests using the Matching package for R (Sekhon, 2011). According to the test, the maximum K–S statistic value was 0.2439 and the corresponding p -value was 0.136 implying that TWI distributions do not differ significantly. Thus, the surface topography characterized by the TWI distribution could not be used to describe the differences in the rainfall–runoff responses of the 12 catchments and had little to do with the classification of the catchments as LBF, QSF, or DSF.

3.4.3. The effect of geological structures on runoff

The strike-oriented catchments, S03 and S09, showed large amounts of baseflow, and were categorized as LBF catchments. In

sedimentary rock mountains, a significant proportion of the baseflow results from the exfiltration of bedrock groundwater (Burns *et al.*, 1998). According to Bruno (1994), Singhal and Gupta (2010), and Suenaga *et al.* (2002), sedimentary rocks, which are formed by the bonding of horizontally deposited materials, and consists of layers with different hydraulic conductivities, tends to have a higher permeability in the horizontal direction than in the vertical direction, i.e., sedimentary rocks show hydraulic anisotropy, characterized by a high hydraulic conductivity in the direction parallel to the bedding plane. Therefore, in sedimentary rock mountains, groundwater is expected to flow along the bedding plane. Figure 3.9 shows cross section image of the study site. As summarized in Table 2.2, the average dip angle in the study site is 55° , which is greater than the average slope angle of the studied catchments (Table 2.1). In Figure 3.9, rainwater infiltrated into the mountain would face the low hydraulic conductivity rock at some depths, and then flows downwards along the bedding plane forming the bedrock aquifer. Because the low hydraulic conductivity rock interrupts the water flow, only some parts of the bedrock aquifer can contribute to the exfiltration in the dip-oriented catchment and in the opposite dip-oriented catchment. In most parts of the aquifer, which are surrounded by the low hydraulic conductivity rocks, the only way for the water to exfiltrate is to flow toward the strike-oriented catchments. Thus, in the strike-oriented catchments, the large contribution of the bedrock aquifer sustains the significant baseflow.

Sakai *et al.* (2009) investigated baseflow discharges from basins with areas of a few km^2 in sedimentary rock mountains located in the Boso Peninsula, which is close to Tokyo, Japan. They analyzed rainfall–runoff responses in relation to geological structures and concluded that strike-oriented catchments tend to have large baseflows. Furthermore, Ford (1983) suggested that strike-oriented groundwater flows in pre-glacial Canadian Rocky Mountains underlain by sedimentary rocks. The results of these previous studies support the idea of major groundwater flow along bedding planes in sedimentary rock mountains, which consists with our findings based on the study of the 12 headwater catchments.

In this study, opposite dip-oriented catchments were classified as QSF, and dip-oriented catchments were classified into the DSF. The TWI distributions shown in Figure 3.8 could not be used to explain these differences in runoff characteristics. According to Beven and Kirkby (1979), TWI can be used to explain the frequency of the generation of saturation-excess overland flow. The runoff properties of overland flow are primarily affected by topographical slope values, i.e., a steeper slope accelerates overland flow runoff. Table 2.1 shows that the catchments classified as QSF (*i.e.*, catchments S05, S06, and S07) had an average slope of $\sim 40^\circ$, while those classified as DSF (*i.e.*, catchments S10, S11, and S12) had an average slope of $\sim 38^\circ$.

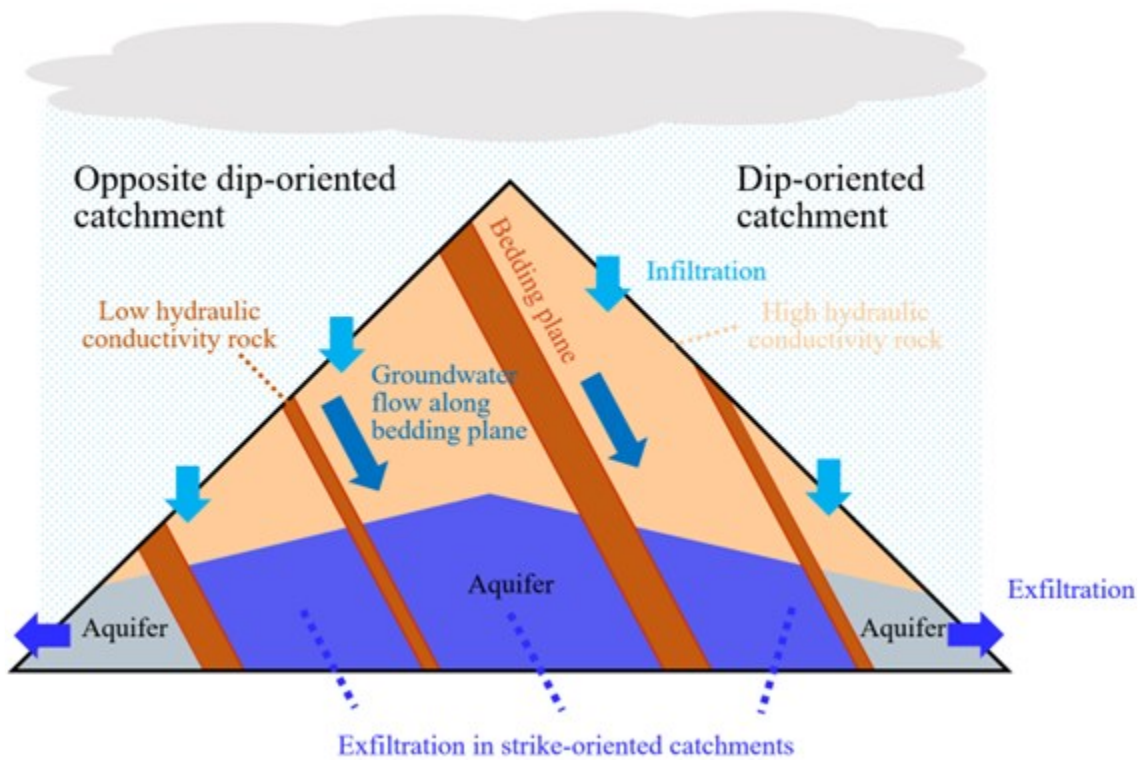


Figure 3.9. Cross section image of the study site. The figure shows geological stratigraphy consisting of high and low hydraulic conductivity rocks, distribution of bedrock aquifer, and water flow pathways.

Figure 3.10, which shows detailed slope analyses, revealed the relationship between the upstream area and the topographical slope for each of 1×1 m grids located in each catchment. Given that the raw data showed wide scatter, this figure shows the running average of the slope and area values, which were calculated using the neighboring 300 data with respect to the upstream area. To discuss overland flow movements, slope values with small upstream areas should be neglected. If I focus on the slope value in the region where the upstream slope area is greater than 400 m^2 , the slope angles of the QSF catchments will be greater than those of the DSF catchments. Thus, slope angles could be one of the main factors that can be used to describe the differences between the runoff responses of QSF and DSF catchments, i.e., the opposite dip-oriented catchments have steeper topography, which resulted in the quicker storm flow generation, while the dip-oriented catchments have gentler topography, which resulted in the more delayed storm flow generation.

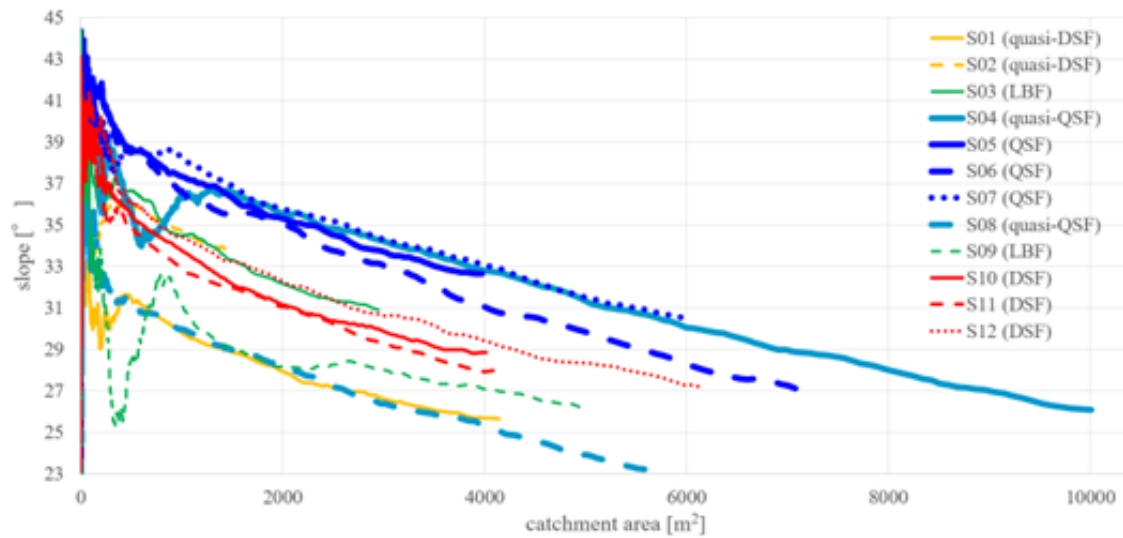


Figure 3.10. Relationship between slope angle and catchment area for each catchment, showing running average values for neighboring 300 data with respect to the catchment area. Slope angles and catchment area were calculated by using SAGA plugins from QGIS (ver. 3.4.12) (QGIS Development Team, 2019).

Ford (1983) and Yeh *et al.* (2014) reported that in sedimentary rock mountains, the differences in the erosion resistance of each of the deposited layers result in the development of a landform called *cuesta*, where the slope is gentle on dip sides and steep on opposite dip sides. This trend has been reported in several studies (Aramaki *et al.*, 1984; Suzuki & Nakanishi, 1990; Iwahashi *et al.*, 2006; Yagi *et al.*, 2007). Thus, the differences in the slope angles of the dip-oriented and opposite dip-oriented catchments shown in Figure 3.10 are probably typical of many sedimentary rock mountains.

As shown in Figure 3.10, the strike-oriented catchments, S03 and S09, have relatively small slope angles. This probably resulted in the restricted increases in storm peak discharge, resulting in a drop in Q_i^* values during the storm events (Figures 3.3, 3.4, and 3.5).

Our findings in this study are supported by some previous studies such as Jencso and McGlynn (2011) and Payn *et al.* (2012). Both studies are conducted in the Tenderfoot Creek Experimental Forest (TCEF), located in central Montana, USA. The bedrock of TCEF is sedimentary rocks, partially including quartz monzonite. These studies concluded that topography is the main factor affecting storm flow, whereas subsurface structure is the dominant factor influencing baseflow generations.

A summary of the effects of geological structures on rainfall–runoff responses in sedimentary rock mountains is shown in Figure 3.11. The effect of the geological structures could be attributed to the different classes of the catchments, i.e., strike-oriented, dip-oriented, and opposite dip-oriented catchments. In strike-oriented catchments, a significant quantity of groundwater, which flowed along the bedding plane owing to hydraulic anisotropy, exfiltrated and sustained the large amount of baseflow. Thus, the geological structure had a direct influence on the runoff characteristics of strike-oriented catchments. For dip-oriented and opposite dip-oriented catchments, the difference in geological structures resulted in surface topography differences. The slopes associated with dip-oriented catchments were found to be gentler than those associated with opposite dip-oriented catchments. This resulted in delayed storm flow occurrence in dip-oriented catchments and in quick storm flow occurrence in opposite dip-oriented catchments. Therefore, even though surface topography directly controls rainwater discharges in dip-oriented and the opposite dip-oriented catchments, differences in runoff characteristics are basically attributed to geological structures.

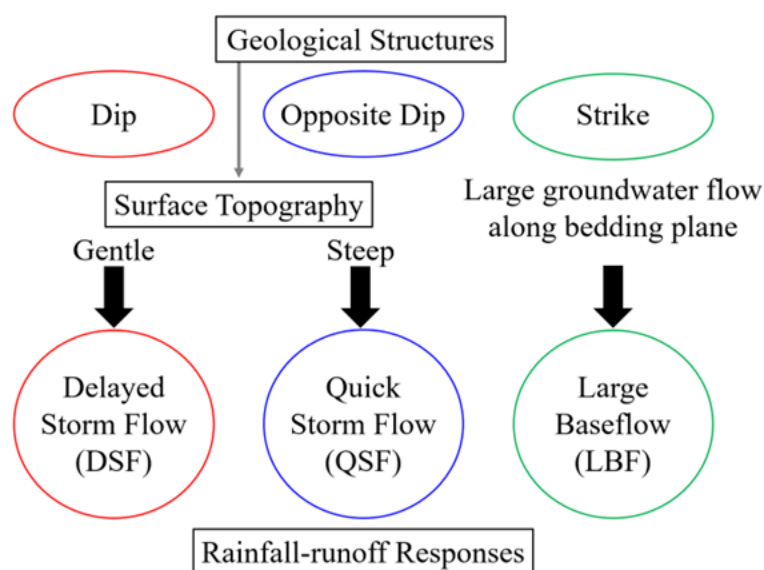


Figure 3.11. Effects of geological structures on the rainfall–runoff responses of the sedimentary rock mountain studied.

and delayed storm flow (DSF). These groups were analyzed by focusing on the relationship between flow directions and geological structures based on the dips and strikes typical of sedimentary rocks. The results obtained showed that LBF, QSF, and DSF catchments corresponded to catchments with flow directions oriented toward the strike, opposite dip, and dip directions, respectively.

In the strike-oriented catchments, the runoff characteristics were directly controlled by the geological structures, i.e., owing to the hydraulic anisotropy of the sedimentary rocks, large quantities

3.5. Conclusion

By investigating rainfall–runoff responses at 12 catchments that extend radially from the peak of Mt. Kanayama, which is underlain by sedimentary rocks, it was found that the catchments could be classified under 3 groups as characterized by large baseflow (LBF), quick storm flow (QSF),

of groundwater flowed along bedding planes, sustaining the large amount of baseflow discharge. On the other hand, based on the geological structures, the opposite dip-oriented catchments have slopes that are steeper slopes than those of the dip-oriented catchments. Thus, the opposite dip-oriented catchments were characterized by quick storm flow, while the dip-oriented catchments showed delayed storm flow. These findings indicate that in dip-oriented and opposite dip-oriented catchments, runoff characteristics are indirectly controlled by the geological structures.

Therefore, in this study, the effects of geological structures on rainfall–runoff responses in headwater catchments located in sedimentary rock mountains were clarified. Future research should focus on the hydrological processes in each catchment by conducting detail analyses of topographical effects on storm discharge hydrographs and identifying bedrock groundwater flow pathways.

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CHAPTER 4

Effects of geological differences on rainfall–runoff characteristics based on field measurements

4.1. Introduction

Rainfall–runoff characteristics in headwater catchments are affected by many factors, including topography, geology, and vegetation (e.g. Kirkby *et al.*, 2002; Tani *et al.*, 2012). Previous studies have often focused on granitic catchments when investigating geological effects (e.g. Fujimoto *et al.*, 2008, 2011; Kosugi *et al.*, 2011; Masaoka *et al.*, 2021). Fujimoto *et al.* (2008, 2011) revealed differences in hydrological processes in granitic catchments by focusing on the locations and shapes of hillslopes; they also revealed, by considering the area and ratio of these hillslopes, that their hydrological characteristics affect the runoff characteristics of the catchments. Kosugi *et al.* (2011) conducted dense groundwater measurements in a headwater catchment and found that bedrock groundwater markedly affected the runoff characteristics of the catchment.

Some hydrologists have opted to target sedimentary rock catchments (e.g. Carlier *et al.*, 2018; Gabrielli *et al.*, 2018). Carlier *et al.* (2018) studied catchments in Switzerland and showed that, in 54% of the catchments, the runoff characteristics could be explained by the amount of sandstone in the bedrock determining its permeability. Gabrielli *et al.* (2018) conducted direct groundwater measurements and demonstrated a large effect on bedrock groundwater in sedimentary rock catchments.

Previous studies have compared the runoff characteristics of different bedrock types (Musiake *et al.*, 1981; Pfister *et al.*, 2017; Shimizu, 1980). Musiake *et al.* (1981) and Shimizu (1980) studied many catchments in Japan and concluded that volcanic rock and granitic catchments have stable runoff, whereas sedimentary rock catchments have unstable runoff. Other previous research have examined the differences in runoff characteristics between granitic and sedimentary rock catchments (e.g. Kato *et al.*, 2000; Katsuyama *et al.*, 2008; Onda, 1994; Onda *et al.*, 2006; Tani *et al.*, 2012). Kato *et al.* (2000) showed that, although granitic catchments have similar runoff characteristics, sedimentary rock catchments have several types of runoff characteristics. By comparing runoff and water temperatures in both granitic and sedimentary rock catchments, Onda (1994) found that runoff

characteristics depended on the local geology: sedimentary rock catchments had direct flows only in large events and hydrograph recessions were steep, while granitic catchments had frequent direct flows and hydrograph recessions were gentle. Onda *et al.* (2006) also recorded the runoff in four catchments (*i.e.*, large and small catchments in two different geological settings) and the hillslope groundwater distribution in each geological setting. In sedimentary rock catchments, bedrock groundwater was dominant and bedrock infiltration occurred during rainfall; however, in granitic catchments, saturated throughflow was dominant. Katsuyama *et al.* (2008) focused on the weathering process and suggested that granites exhibit uniform weathering, which enables recharge of large amounts of groundwater; in contrast, sedimentary rocks exhibit uneven weathering, which causes rapid discharge of rainwater.

Overall, granitic and sedimentary rock catchments exhibit different runoff characteristics; however, previous studies have grouped catchments according to their geological characteristics and neglected the runoff differences within each bedrock geology.

Runoff observations from 12 catchments lying radially from a single isolated sedimentary rock mountain peak were compared and found that runoff was regulated by geological structures such as dips and strikes around the catchments (Chapter 3; Figure 4.1). Catchments located in the strike direction exhibited a characteristic of large baseflow, and bedrock groundwater flow from neighboring catchments was thought to be the source. The other catchments were divided into dip and opposite-dip catchments based on the relationship between strike and runoff directions. Differences in runoff characteristics between these catchments (*i.e.*, the time lag between relative runoff peaks) were explained by differences in slope gradient, which indirectly reflect the geological structures. However, the hydrographs of only two events were analyzed in the Chapter 3; investigations of direct flow or recession from long-term hydrographs containing hundreds of events have not yet been conducted. The effects of geological structures on runoff characteristics have not yet been comprehensively studied. In granitic catchments, Masaoka *et al.* (2021) conducted runoff and groundwater observations in several catchments using a highly dense borehole network and concluded that bedrock topography controls runoff; however, they did not conduct long-term hydrograph analysis. Analysis of long-term hydrographs is important to elucidate the universal influence of the geological structures on rainfall–runoff characteristics. However, it is difficult to fully exclude the characteristics of the rainfall from the analysis of a few events. By analyzing a large number of events based on long-term observations and understanding the characteristics of runoff that are common to all of these events, the influence of

rainfall characteristics can be eliminated.

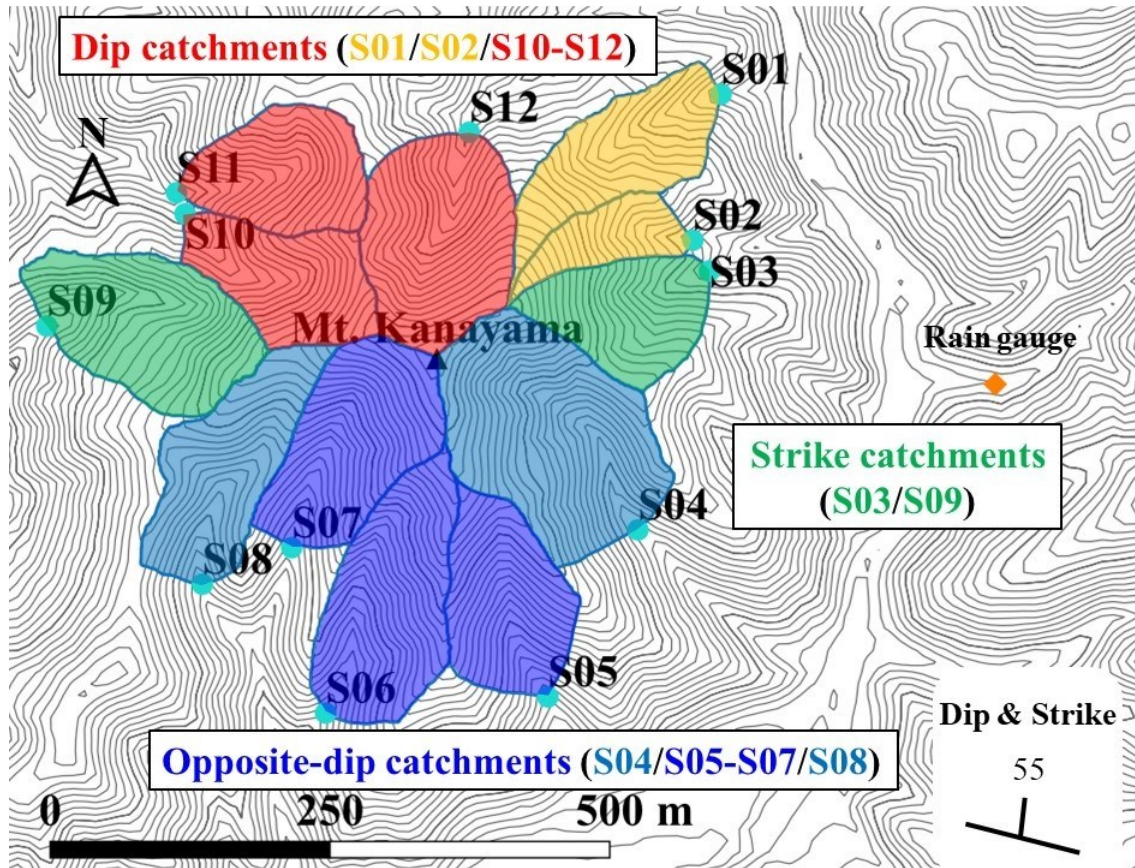


Figure 4.1. Catchment classification considering geological structures in site S. The detail is written in Chapter 3. Strike catchments are S03/S09 catchments, opposite-dip catchments are S04–S08 catchments, and dip catchments are S01/S02/S10–S12 catchments, shown in green, blue/blue–green, and red/orange respectively.

Our aim is to clarify the effects of different geological settings and structures on the rainfall–runoff characteristics using long-term hydrograph observations, while verifying the validity of our previously suggested runoff mechanisms of bedrock groundwater. In the following, we present the analysis of direct flows and hydrograph recessions of many events that occurred during the observed period.

4.2. Methods

4.2.1. Site descriptions

The study sites were the experimental Shigaraki and Fudoji Forests (sites S and G in Figures 2.1(b) and 2.1(c), respectively), which are located in central Japan. Details are written in Chapter 2.

In both forests, runoff observations were conducted for approximately three years (site S: 2014/6/5–2017/6/10; G: 2012/8/21–2015/11/9). We used V-notch weirs (Table 2.1) and employed data loggers (HIOKI LR5042) to record the water level every five minutes. Precipitation was monitored in open spaces close to each forest by using tipping-bucket rain gauges with 0.5 mm resolution. The observation point at site S is shown in Figure 2.1(b), while the one at site G was located approximately 350 m north of the weir in catchment G0; it is not shown in Figure 2.1(c).

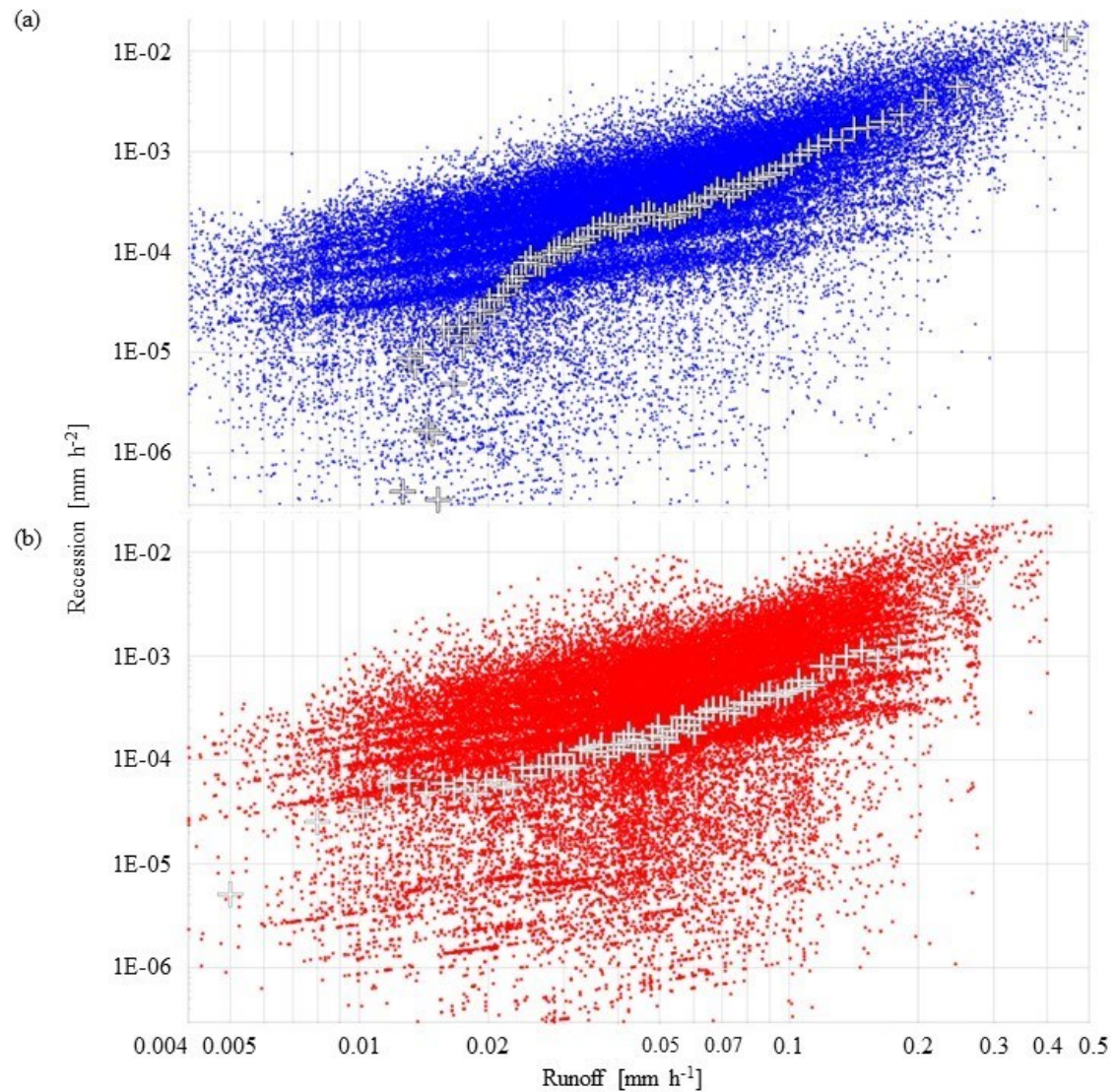


Figure 4.2. Results of hydrograph recession analysis. Hydrograph recession was calculated from the observed runoff at a certain time and the runoff an hour before that time. Results for (a) sedimentary rock catchments and (b) granitic catchments; the average results for each geological setting are indicated by black and gray crosses, respectively.

4.2.2. Direct flow analysis

To calculate the direct runoff, we used the method described by Hewlett and Hibbert (1967). The slope of the straight line separating the direct runoff and baseflow was $0.0072 \text{ mm h}^{-1} \text{ day}^{-1}$ for all catchments. Next, one rainfall event was defined as a no-rainfall period of 24 h or longer, whereas one runoff event was defined by the onset and end of direct flow, regardless of rainfall events. Thus, when the direct flow due to a certain rainfall event did not end before the onset of the following rainfall

event, these two rainfall events comprise a single runoff event.

4.2.3. Recession analysis

Hydrograph recessions were analyzed using the method applied by Kirchner (2009).

Assuming that the runoff Q_i [mm h⁻¹] of catchment i is a function of the storage S_i [mm h⁻¹]:

$$Q_i = f(S_i) \quad (4.1)$$

From water balance:

$$\frac{dS_i}{dt} = P - E_i - Q_i \quad (4.2)$$

where P and E_i represent precipitation [mm h⁻¹] and evapotranspiration [mm h⁻¹], respectively. By differentiating Equation (4.1) by time t and considering Equation (4.2), Equation (4.1) can be expressed as follows:

$$\frac{dQ_i}{dt} = \frac{dQ_i}{dS_i} \frac{dS_i}{dt} = \frac{dQ_i}{dS_i} (P - E_i - Q_i) \quad (4.3)$$

Because it is difficult to directly observe S_i at the catchment scale (Kirchner, 2009), we must calculate dQ_i/dS_i using elements that are observable as in Equation (4.4):

$$\frac{dQ_i}{dS_i} = \frac{\frac{dQ_i}{dt}}{P - E_i - Q_i} \quad (4.4)$$

If we consider $P \ll Q_i$ and $E_i \ll Q_i$:

$$\frac{dQ_i}{dS_i} \approx \frac{-\frac{dQ_i}{dt}}{Q_i} \quad (4.5)$$

Equation (4.5) indicates that dQ_i/dS_i can be predicted by plotting $-dQ_i/dt$ and Q_i in the scatter plot. dQ_i/dS_i represents the runoff difference per unit change in storage, and can be used to analyze the runoff characteristics from the relations between $-dQ_i/dt$ and Q_i . The unit discharge change $-dQ_i/dt$ [mm h⁻²] can be calculated using the equation below:

$$-\frac{dQ_i}{dt} = \frac{Q_{i,t-\Delta t} - Q_{i,t}}{\{t - (t - \Delta t)\}} \quad (4.6)$$

where $Q_{i,t}$ and Δt represents runoff of catchment i at time t and difference of t and $t - \Delta t$, respectively.

In concrete, Δt is one hour in this study.

Data that were used for the assumption proposed by Kirchner (2009) met the following two conditions: (i) no precipitation was evident from six hours before to two hours after the applicable data (Kirchner, 2009), and (ii) the duration of sunlight was ≤ 0.1 h from one hour before to one hour after the applicable data. To exclude noisy data, data after the applicable data were included in the conditions. Kirchner (2009) used average solar radiation for the second condition; however, in our case, there was no solar radiation monitoring around the study sites, and we employed sunshine duration data collected at Shigaraki station of the JMA instead (JMA, 2021b). Data that satisfied these two conditions were recorded mainly at night, with no rainfall.

4.3. Results

4.3.1. Observation results

The observational results from the 19 catchments are shown in Figure 4.3, which shows the results for one hydrological year (starting in November 2014) containing the granitic catchments exhibited similar maximum runoff for large events; however, baseflow was smaller in sedimentary rock catchments. Thus, the flow conditions were stable in granitic catchments and unstable in sedimentary rock catchments.

Figures 4.3(a)–(d) reveal extremely large baseflows in catchments S03 and S09, depicted by the green lines. Additionally, the baseflow rate in catchment S10 was noticeably low (Figure 4.3d). The other nine catchments exhibited similar hydrographs. Figures 4.3(e)–(f) reveals a remarkably large baseflow in catchment G3. In contrast, catchments G2 and G4 exhibited low runoff, and catchment G5 exhibited moderate baseflow. The other three catchments (*i.e.*, G0/G1/G6) exhibited similar hydrographs.

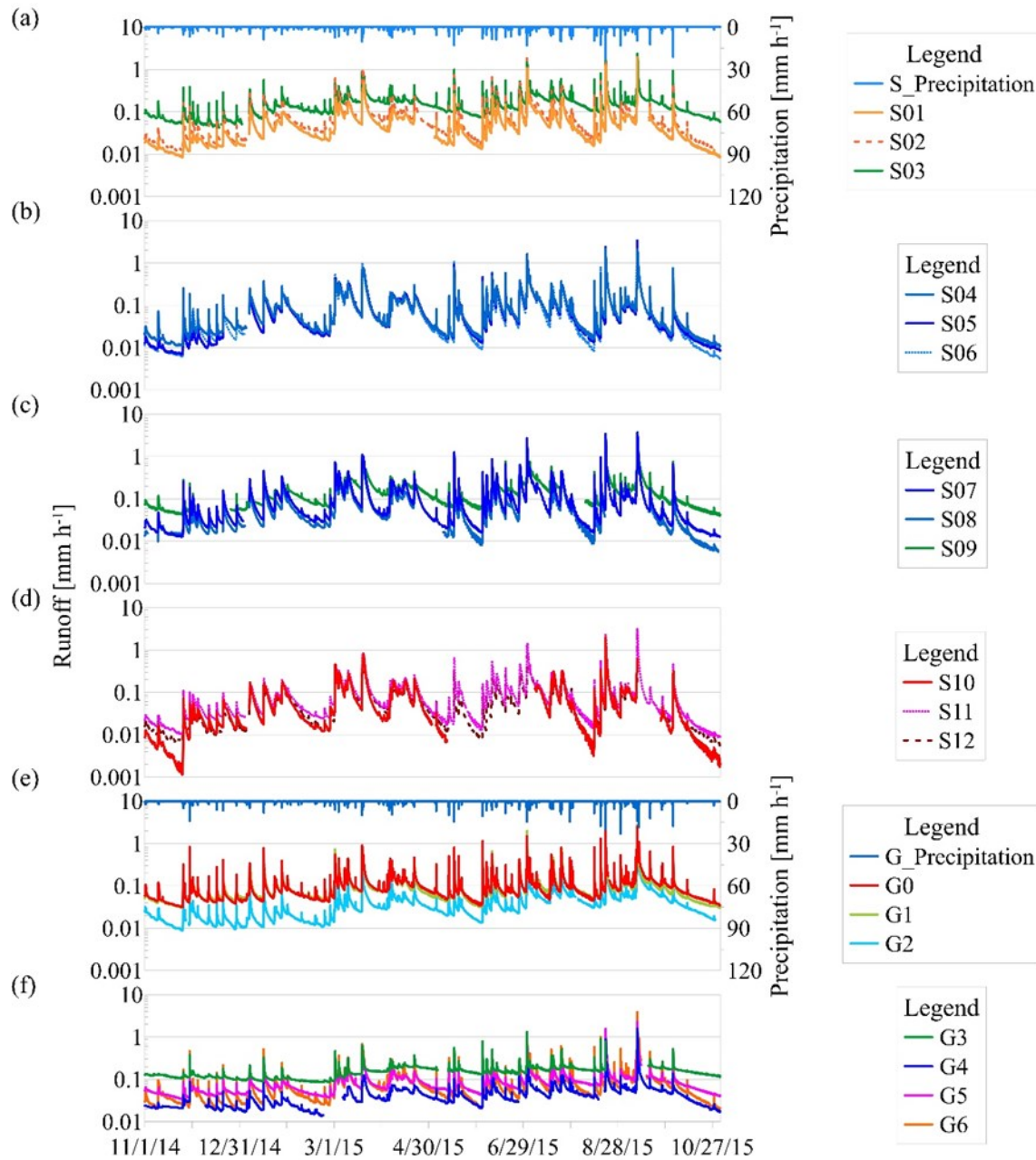


Figure 4.3. Hydrograph observations between November 2014 and October 2015 from catchments (a) S01–S03, (b) S04–S06, (c) S07–S09, (d) S10–S12, (e) G0–G2, and (f) G3–G6. All panels have the same y-axis length for one order.

4.3.2. Storm flow analysis

We calculated the total rainfall and direct flow for each runoff event. The results varied markedly; thus, it was difficult to determine trends. We averaged runoff in each geological setting for each 5-mm precipitation interval (Figure 4.4a). Runoff events with total rainfall >80 mm were limited,

and only 2 events with 80–90 mm precipitation were normally observed in catchments G2 and S11; hence, discussing this precipitation range was difficult and these events are not shown in the figure. Figure 4.4(b) shows an enlarged view of the ≤ 30 mm precipitation in Figure 4.4(a).

When total rainfall was >30 mm, the direct flows of site S catchments were greater than those of site G catchments (Figure 4.4a); when total rainfall was <25 mm, the direct flows of site G catchments were greater than those of site S catchments (Figure 4.4b). Therefore, owing to geological differences, runoff characteristics changed when total rainfall exceeded a certain amount (*i.e.*, 25–30 mm in this study).

We also found anomalous catchments. Catchments S03 and S09 of site S exhibited approximately 0.1–1.0 mm direct flow when total rainfall was <25 mm, which was similar to site G catchments (Figure 4.4d). Direct flow of Catchment S01 was smaller than those of the other site S catchments (Figure 4.4c). Direct flow in Catchment S07 was larger than that in the other catchments when total rainfall was >30 mm. Catchment S10 often had ≤ 0.01 mm direct flow when total rainfall was ≤ 10 mm, which is extremely small.

Granitic catchments were divided into large (*i.e.*, G0/G1/G6) and small (*i.e.*, G2/G4) direct flow groups. Catchments G3 and G5 exhibited anomalous characteristics. Catchment G3 exhibited large direct flows with total rainfall <10 or >70 mm, while it exhibited average direct flows with 10–70 mm rainfall (Figures 4.4e–f). Catchment G5 exhibited small direct flow when total rainfall was ≤ 50 mm and average direct flow in case of larger events.

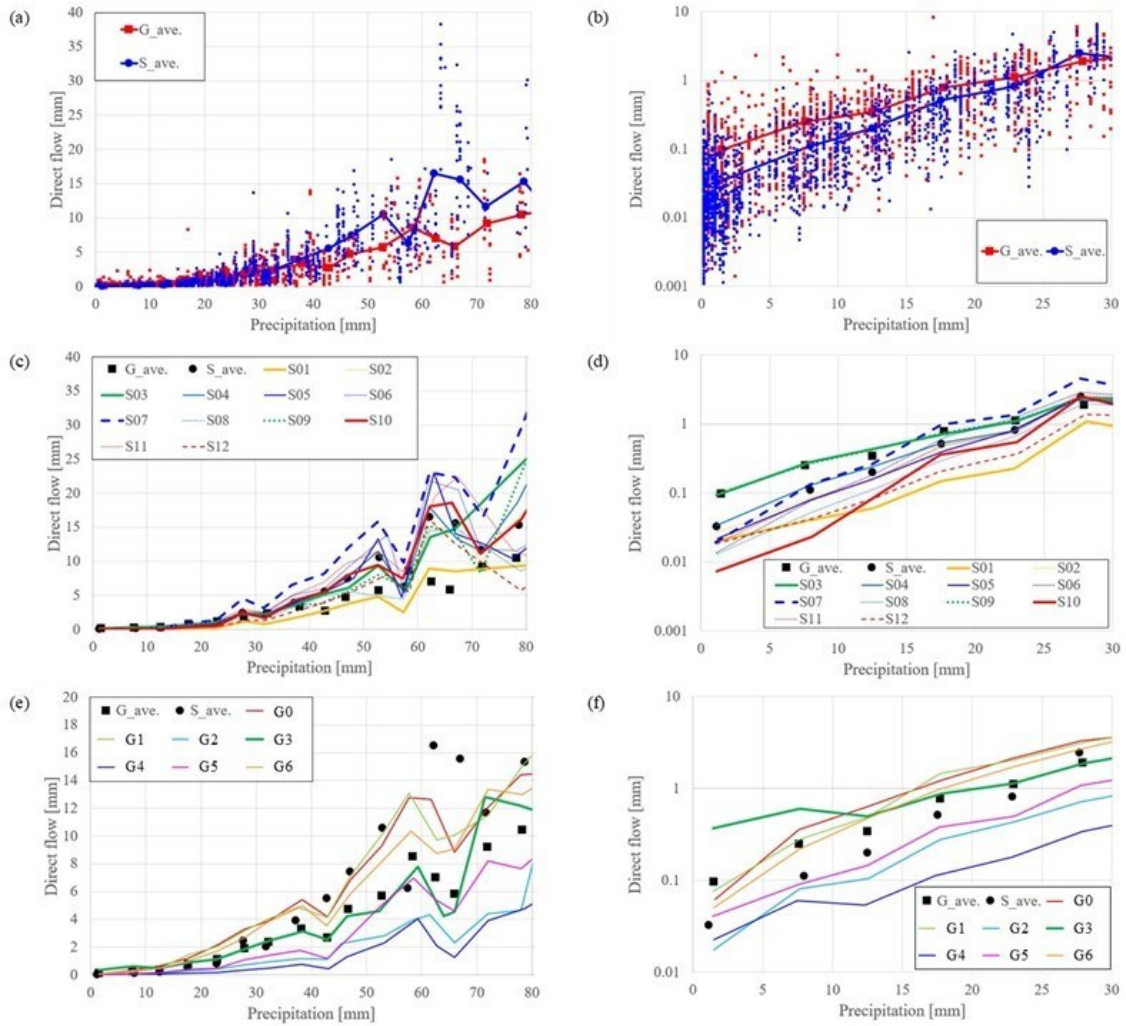


Figure 4.4. Results of direct flow analysis. (a) Total rainfall and corresponding amount of direct flow for each geological setting; red and blue colors correspond to sites G and S, respectively. (b) Enlarged view of precipitation less than 30 mm in panel (a). (c) Results for each catchment in site S. (d) Enlarged view of precipitation less than 30 mm in panel (c). (e) Results for each catchment in site G. (f) Enlarged view of precipitation less than 30 mm in panel (e).

4.3.3. Hydrograph recession analysis

The results of the hydrograph recession analysis are shown in Figure 4.2. The blue and red dots represent the individual data for sites S and G, respectively. Black and gray dots represent the average of 1000 data points in each geological setting when the data are arranged in descending order of specific discharge. The results for individual catchments are shown in Figure 4.5; the calculation method used was the same as that described above.

When runoff was $\geq 0.05 \text{ mm h}^{-1}$, site G catchments had smaller recessions than site S catchments. In contrast, when runoff was $< 0.05 \text{ mm h}^{-1}$, it was difficult to separate clearly each geological setting (Figure 4.5).

Nevertheless, some catchments did not follow this trend. Catchments S03 and S09 at site S and G3 at site G had a gentler recession trend than the other catchments (Figure 4.5), which was because their baseflows were larger than those of the others (Figures 4.3a, c, and f). Also, catchment G2 at site G has a steeper recession, similar to that at site S (Figure 4.5).

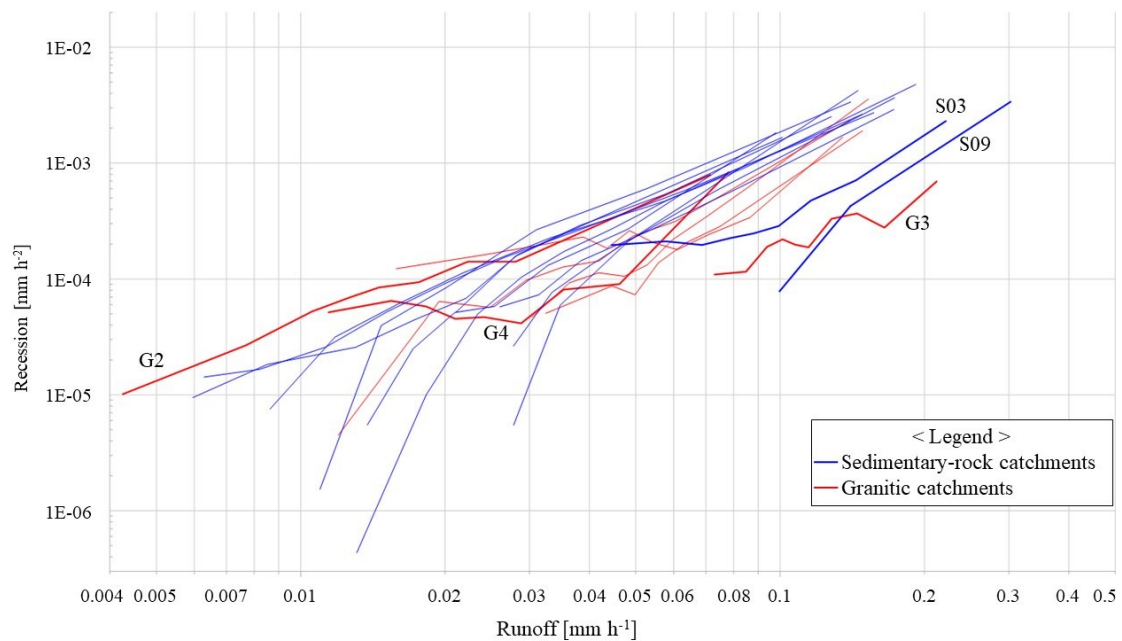


Figure 4.5. Results of hydrograph recession analysis. Hydrograph recession was calculated from the observed runoff at a certain time and the runoff an hour before that time (see also Figure 4.2). Blue and red lines correspond to sedimentary rock and granitic catchments, respectively.

4.4. Discussion

4.4.1. Effects of geological differences on rainfall–runoff characteristics

The geological differences had significant effects on the rainfall–runoff characteristics. When total rainfall was $< 25 \text{ mm}$, the direct flow occurred in granitic catchments, while a relatively small direct flow occurred in sedimentary rock catchments (Figure 4.4). With increasing total rainfall, the sedimentary rock catchments exhibited larger direct flows than those in the granitic catchments

(Figure 4.4); hydrograph recession was steeper in the sedimentary rock catchments and gentler in the granitic catchments (Figure 4.5).

Onda (1994) and Onda *et al.* (2006) also reported that sedimentary rock catchments exhibited larger direct flows than those in granitic catchments in case of moderate rainfall. They did not refer to smaller volumes of rainfall, but Katsuyama *et al.* (2008) showed that when total rainfall was <50 mm, granitic catchments exhibited larger direct flows than sedimentary rock catchments, and vice versa for larger total rainfall. Ando and Yoshida (1986) suggested the same trend, and our results corroborate these findings.

In case of low rainfall, granitic catchments exhibited larger direct flows than those in sedimentary rock catchments; this was because of the evident larger baseflow and wetter riparian zones facilitating direct flow. Onda (1994) also indicated that the larger baseflow in granitic catchments was due to the large amount of groundwater recharged by weathered bedrock.

Moreover, when total rainfall exceeded 30 mm, the direct flow increased more significantly in sedimentary rock catchments (Figure 4.4c). Katsuyama *et al.* (2008) explained this well: they suggested that sedimentary rocks were unevenly weathered, rainwater was discharged rapidly, granite was uniformly weathered, and the infiltrated water was recharged greatly. Differences in the weathering processes and the geological characteristics of the bedrock may change the hydraulic conductivity of slopes and runoff processes in catchments.

4.4.2. Anomalous catchments greatly affected by geological structures

Our results are in accordance with those of previous studies and show that the effect of the geological setting on runoff characteristics is general. In contrast, our study also revealed catchments with unique runoff characteristics (*i.e.*, catchments S01/S03/S07/S09/S10/G2–G5). Catchments S03/S09 at site S and catchment G3 at site G had unique runoff characteristics compared to the average runoff affected by geology. For other anomalous catchments, we refer to Section 4.4.3.

In catchments S03 and S09, the characteristics of the direct flow were similar to those of the average of the granitic catchments (Figures 4.4c–d). Relatively large direct runoff occurred when total rainfall was ≤ 10 mm (Figure 4.4d). Moreover, the hydrograph recession trend was gentler than that in the other site S catchments (Figure 4.). These catchments were grouped in strike-oriented catchments because the runoff directions of these catchments were approximately the same as the direction of the bedrock strike (Chapter 3). A greater amount of baseflow was observed in strike-

oriented catchments (Chapter 3), and they tended to have wetter riparian zones. This is thought to be the reason for catchments S03 and S09 exhibiting larger direct flows. Chapter 3 discussed the mechanism underlying large baseflow in strike-oriented catchments; they assumed that groundwater flows along bedding planes due to the hydraulic anisotropy and conductivity of sedimentary rock, which varies in each bedding.

Catchment G3 exhibited larger direct runoff than the rest of site G catchments when total rainfall was ≤ 10 mm; it also exhibited gentle hydrograph recession. Masaoka *et al.* (2021) indicated the occurrence of bedrock groundwater inflow from the neighboring catchments G2/G4; therefore, catchment G3 has a larger baseflow and wetter riparian zone resulting in a larger direct flow even in case of low rainfall. Masaoka *et al.* (2021) analyzed groundwater levels at site G using nested boreholes and found that catchments were defined by bedrock topography-controlled runoff; this is the cause of the large baseflow in catchment G3. In granitic catchments, large valleys tend to develop along joints (Ikeda, 1998). Around site G, the dominant joints extend approximately north to south, and catchment G0 is one of the valleys that developed along this orientation (Figure 2.4). Groundwater flows are generated from the right bank (*i.e.*, catchments G1/G2) and the left bank (*i.e.*, catchments G4–G6), and subsequently gather in the channel of catchment G0 (Figure 2.4). In this process, the small surface topography separating the site G catchments cannot segregate the groundwater flow, and groundwater converges in the large channel (Masaoka *et al.*, 2021); this is because (east–west oriented) conjugate joints often develop at the north–south joints. Catchment G3 is located at the headwater of catchment G0 (Figure 2.4), which suggests that groundwater is gathered by the same mechanism.

Overall, geological structures, such as dips and strikes in the bedding planes of sedimentary rocks and joints of granites, cause unique runoff characteristics.

4.4.3. Other anomalous catchments

Detailed groundwater data have not yet been reported for catchments other than S03/S09/G3, and the detailed runoff mechanisms are unclear. In this study, the characteristics of surface topography that may affect runoff are discussed below.

In catchment S01, the direct flow was smaller than the other site S catchments. This catchment has a gentle slope in its headwaters, and the channel is not well-developed (Figure 2.1b). Thus, a gentle slope is expected to be composed of uneroded weathered bedrock, which promote rainfall infiltration. Moreover, owing to the undeveloped channel, the direct flow derived from the

channel rainfall would be small.

Catchment S07 exhibited a larger direct flow than the other site S catchments. The straight channel development may be one of the reasons for this (Figure 2.1b). It may also have a less weathered bedrock, which then leads to less groundwater infiltration. In addition, the direct flow derived from channel rainfall was larger than that of the other catchments. Chapter 3 reported that dip catchments have relatively late runoff peaks, and opposite-dip catchments have relatively quick runoff peaks. This study revealed that the quasi-dip catchment (*i.e.*, catchment S01) has a small direct flow, and the opposite-dip catchment (*i.e.*, catchment S07) has a large direct flow, which corresponds with the result.

In catchment S10, the direct flow was extremely small when the total rainfall was ≤ 10 mm. This may be due to its location that lies north of catchment S09 (Figure 2.1b), which has groundwater flow from neighboring catchments. Bedrock groundwater recharged in catchment S10 might flow into catchment S09, and Figure 4.3(d) shows that it had a small baseflow. This may lead to drier riparian zones, reducing the direct flow.

The catchments G2 and G4 exhibited a small direct flow (Figures 4.4e–f). This is the effect of groundwater flow to catchment G3 revealed by Masaoka *et al.* (2021), which led to a decrease in baseflow and some storm flow during rain, finally resulting in a drier riparian zone. However, the trend of hydrograph recession was not the same, and G2 catchment had a steeper hydrograph recession, while G4 catchment had a gentler hydrograph recession, similar to other site G catchments (Figure 4.5). This was because the amount of inflow to catchment G3 was larger in catchment G2 and smaller in catchment G4 (Masaoka *et al.*, 2021).

In catchment G5, it exhibited a small direct flow when total rainfall was ≤ 50 mm, and direct flow became moderate when total rainfall was > 50 mm. The undeveloped channel and spring at the bottom of the catchment derived from the joint could be the reason for this characteristic. Since it has uneroded weathered bedrock, the average slope gradient is gentler than that of catchments G1 or G6, which have developed channels (Figure 2.1c; Table 2.1).

Thus, some unique runoff characteristics are observed, although they are not as clear as S03/S09/G3 catchments. These characteristics were suggested to have been formed by water movement regulated by topography and geology.

4.5. Conclusion

By conducting long-term runoff observations in 19 catchments with different geological characteristics, we obtained the following results. (1) The runoff characteristics of catchments were affected by their geological characteristics, thereby exhibiting clear differences. When the total rainfall was <25 mm, direct flows of 0.1–1.0 mm occurred in granitic catchments, while smaller direct flows occurred in sedimentary rock catchments. When total rainfall was >30 mm, sedimentary rock catchments tended to exhibit larger direct flows than those in granitic catchments. In addition, sedimentary rock catchments had steeper hydrograph recessions than granitic catchments. (2) Some catchments (*i.e.*, catchments S03/S09/G3) did not follow these average trends. These catchments had larger baseflows, making their riparian zones wetter, thereby facilitating direct flows, even in case of small rainfall. The suggested mechanism for a large baseflow is the convergence of bedrock groundwater owing to geological structures. In other words, sedimentary rock catchments had groundwater flow along the bedding plane, while water gathered at the catchment, which extended in the strike direction due to the hydraulic anisotropy of the bedrock. Granite catchments developed well along joints, and groundwater inflow came from both banks, regardless of the small surface topography. (3) In addition to catchments S03/S09/G3, some catchments exhibited minor differences from the average runoff characteristics, and they were also thought to be affected by topography and geology.

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CHAPTER 5

Validating the effect of topography and geology on rainfall–runoff in mountainous catchments using the improved HYdrologic CYcle model

5.1. Introduction

Many attempts have been made to reproduce hydrographs computationally (Beven & Kirkby, 1979), one of which is the “HYdrologic CYcle (HYCY) model” (Fukushima & Suzuki, 1986; Fukushima, 1988; Wakahara *et al.*, 2012). It was developed as a physical model to reproduce the runoff in mountainous catchments. Because this model has less parameters and high reproducibility (Fukushima, 1988), it has been used to complement missing data in flow observations (Tsuruta *et al.*, 2020).

However, the HYCY model was developed ~40 years ago, and catchment hydrology has progressed extensively since the 1980s, which makes the physical meaning of each parameter ambiguous in the following two points. First, the effect of bedrock groundwater on rainfall–runoff in mountainous catchments has been clarified, but the HYCY model does not consider this effect. Gabrielli *et al.* (2018) and Kosugi *et al.* (2011) directly observed bedrock groundwater using boreholes in sedimentary and granitic rock catchments, respectively, and clarified the substantial effect of bedrock groundwater on catchment runoff. Moreover, Jefferson *et al.* (2006) revealed the effects of bedrock groundwater on igneous rock catchments.

Second, although the effects of geology on runoff have been clarified, the appropriate parameter sets for each type of geology remain unclear. Farvolden (1963) and Shimizu (1980) reported the effects of geology on rainfall–runoff in mountainous catchments before the 1980s; however, some hydrologists consider that topographical effects are larger than geological effects (Beven & Kirkby, 1979; Horton, 1933), and this is still one of the major points of hydrological discussions today. Recently, Sakai *et al.* (2009) revealed the effect of geological structures, such as dips and strikes, on sedimentary rock catchments, suggesting that the conventional effect of topography is an indirect impact of geology owing to the crustal movement of Earth. Masaoka *et al.* (2021) studied granitic

catchments and demonstrated runoff regulation by the bedrock topography, which acted as a hydrological basement. This phenomenon can be interpreted as a geological effect, such as granitic joints limiting the groundwater flow (Chapter 4). Granitic and sedimentary rock catchments have been compared with different geologies (Katsuyama *et al.*, 2008; Onda *et al.*, 2006). These catchments can lead to differences in the permeability of the soil and bedrock and cause different runoff mechanisms. Moreover, different geologies undergo different weathering processes, leading to the establishment of different runoff mechanisms (Katsuyama *et al.*, 2008).

Therefore, some studies have attempted to improve the HYCY model. Wakahara *et al.* (2012) added an outflow factor to consider water losses, such as bedrock infiltration and the inter-catchment flow of bedrock groundwater. In catchments where bedrock groundwater has a significant impact, the improved model reproduces the hydrograph particularly better than the original model, but it has fewer applications (*e.g.*, Abe *et al.*, 2020). Furthermore, validation is required by applying the method to many catchments.

Even with the improved model, the effects of different geologies and geological structures have not yet been clarified. We recently analyzed long-term observed hydrographs (*i.e.*, ~3 years) of 19 catchments with sedimentary and granitic bedrock. We clarified the effects of different geologies and geological structures on rainfall–runoff characteristics (Chapter 4). The same hydrographs can be used to optimize the improved HYCY model and compare its parameters to further clarify how different geologies and geological structures affect the calculation results.

Therefore, we aimed to (1) reproduce 19 hydrographs of 2 different geologies using the improved HYCY model and validate its reproducibility for many catchments, and (2) clarify how topography and geology affect runoff simulations.

5.2. Materials and methods

5.2.1. Study site

The study sites were 12 and 7 catchments in the Shigaraki Experimental Forest (S) and Fudoji Experimental Forest (G), respectively. Detailed information about the study sites and observations is provided in Chapter 2.

5.2.2. Topographical analysis

A topographical analysis of the two sites was performed. This analysis aimed to determine topographic indices that could express the topographic characteristics of the studied catchments independent of geology. The calculated indices were the catchment area and volume, drainage mean height, average slope, valley density, and basin form ratio. Catchment areas, volumes, and average slopes were calculated using QGIS (ver.3.16.7; QGIS.org, 2021). Catchment volume was defined as the volume of the mountain body located above the lowest elevation point in each catchment. The mean drainage height, which represented the average catchment relief, was calculated by dividing the catchment volume by the catchment area. Yoshiyama (1990) stated that when the erosion model of Kashiwaya (1986) is assumed, the mean drainage height is proportional to the average erosion rate of the catchment.

To calculate the valley density, generally the sum of the channel lengths was divided by the catchment area. However, we calculated it using topographical interpretation because all the studied catchments are mountainous headwaters, where it is difficult to determine a constant mountain stream. A curvature and slope (CS) topographical map (Toda, 2014) was used to interpret the topography. The CS topographical map overlaps the slope and curvature maps, which were calculated from digital elevation model data and colored in a specified manner using a geographic information system to easily interpret the topography. We used a plug-in to easily create CS topographical maps using QGIS (Asahi, 2017). The valley is colored blue-gray on the map. We calculated the area of a series of blue-gray zone in each catchment and divided it by the catchment area. Note that we did not define the entire blue-gray area as a valley area because springs on mountain slopes are also colored blue-gray, and independent blue-gray patches may exist.

The basin form ratio (Nakayama, 1998) is an index of the catchment shape and is a topographic index obtained by dividing the square of the maximum length by the catchment area. The larger this value, the more elongated the catchment shape.

Table 5.1 lists the topographical indices of all catchments. Figure 5.1 shows these results as boxplots, revealing that geology affected topography. The studied catchments were all zero-order or 1st order basins, except for catchment G0. When there are differences in geological conditions, the erosion resistance will differ, leading to differences in the valley density (*i.e.*, small and large in S and G, respectively). This difference led to differences in the catchment area, catchment volume, and drainage mean height. The difference in valley density between the different geologies followed the same trend reported in previous studies (Onda *et al.*, 2004). The average slopes were large and small

for S and G, respectively, suggesting geological effects (Figure 5.1). The slope gradients were developed by tectonic movements and may have been affected by geology. However, no differences in basin form ratios were observed based on geology. Therefore, the basin form ratio is the most appropriate topographical index for discussing the effects of topography on runoff independent of geological effects.

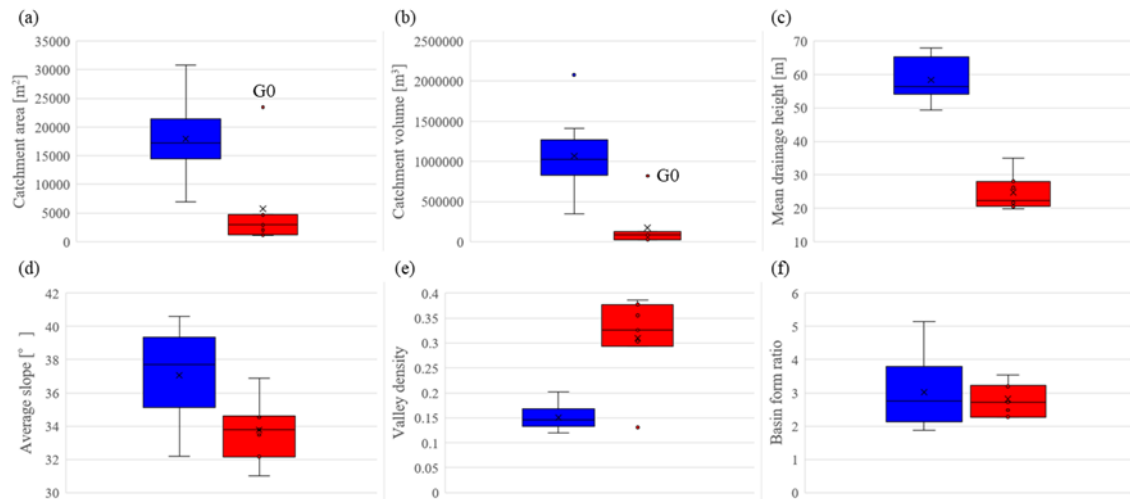


Figure 5.1. Relationships between topography and geology. The blue and red boxes represent Shigaraki Experimental Forest (S) and Fudoji Experimental Forest (G), respectively. Each panel shows (a) catchment areas, (b) catchment volumes, (c) mean drainage height, (d) average slope, (e) valley density, and (f) basin form ratio.

Table 5.1. Catchment areas, volumes, mean drainage heights, average slopes, valley densities, and basin form ratios for the 19 studied catchments.

Catchment	Area [ha]	Volume [$\times 10^4$ m ³]	Mean drainage height [m]	Average Slope [°]	Valley density	Basin form ratio
S01	1.53	82.9	53.99	32.2	0.176	5.14
S02	0.696	34.4	49.35	35.1	0.202	4.46
S03	1.37	75.5	55.25	35.4	0.150	2.53
S04	3.08	207.9	67.46	39.4	0.148	1.87
S05	1.63	110.8	68.01	40.6	0.119	2.91
S06	2.15	141.1	65.55	40.2	0.132	3.49
S07	2.01	129.8	64.48	39.2	0.144	2.46
S08	1.83	93.8	51.33	34.0	0.140	3.89
S09	2.13	117.6	55.29	35.1	0.134	2.61
S10	1.44	83.3	57.93	37.8	0.169	3.04
S11	1.47	84.3	57.50	38.1	0.166	2.03
S12	2.19	119.7	54.63	37.6	0.120	1.90
G0	2.34	81.9	34.97	33.8	0.293	2.48
G1	0.293	8.22	28.04	36.9	0.326	2.72
G2	0.465	12.2	26.12	31.0	0.131	3.23
G3	0.106	2.17	20.52	34.5	0.303	2.27
G4	0.206	4.08	19.80	32.2	0.377	3.19
G5	0.116	2.59	22.35	33.5	0.355	3.53
G6	0.472	10.2	21.67	34.6	0.386	2.26

5.2.3. HYCY model

Next, the hydrological model was optimized using observational data. We used the HYCY model (Wakahara *et al.*, 2012) as the hydrological model because it is superior to other models, primarily in the following three aspects: it considers bedrock infiltration (Wakahara *et al.*, 2012); its parameters have physical meaning; and it can reproduce accurate hydrographs, although it has fewer parameters (Fukushima, 1988). Wakahara *et al.* (2012) used the term outflow to express water loss, including bedrock infiltration; however, this is confusing because outflow generally refers to runoff. Therefore, in this study, we use the term deep bedrock flow (DBF), which has the same meaning as outflow in Wakahara *et al.* (2012).

The HYCY model was developed by Fukushima (1988), and Fukushima and Suzuki (1986). The structure of the model is illustrated in Figure 5.2. The structure is briefly described in this section. First, the precipitation received in mountainous catchments is distributed across channels and slopes. The related parameter C represents the ratio of rainfall that enters the channel system. Precipitation in the channel system is regarded as the channel precipitation that runs into tank V. Precipitation in the slope system was reduced owing to interception loss in tank I. The interception model for tank I was developed by Suzuki *et al.* (1979), and its structure is shown in Figure 5.3. Throughfall and stem flow ran into tank II, and after transpiration was reduced, the water reaching the surface was distributed into the overland flow as effective rain or percolated groundwater in the slope system. The water distributed to the effective rain flowed into tank IV. Overland flow development was calculated using an effective rain model (Fukushima, 1988; Fukushima & Suzuki, 1986). The water distributed to the percolation groundwater then runs into tank III and is distributed into the baseflow and DBF. The DBF is water loss and is included in the bedrock percolation.

Storage and runoff of tank II is described in the following equation:

$$S_u(t) = S_u(t-1) + R_n(t) - R_e(t) - Q_{in}(t) - E_t(t) \quad (5.1),$$

where t , $S_u(t)$, $R_n(t)$, $R_e(t)$, $Q_{in}(t)$, and $E_t(t)$ represent the time, storage in tank II, throughfall, effective rain, soil percolation, and transpiration, respectively.

In addition, the relationship between storage and runoff in the four tanks (i.e., tanks II–V) is described as follows:

$$S_i = K_i \times Q_i^{P_i} \quad (5.2),$$

where S_i and Q_i represent the storage and runoff of tank i , respectively; and K_i and P_i are the parameters of tank i .

The effective rainfall generation rate m , which determines the inflow into tank IV, was calculated using the following equations:

$$R_e(t) = m \times R_n(t) \quad (5.3),$$

$$m = \int_{-\infty}^{\xi} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\xi^2}{2}\right) d\xi \quad (5.4),$$

$$\xi = \frac{1}{\sigma} \log \left\{ \frac{S_u(t-1) + R_n(t)}{D_{50}} \right\} \quad (5.5),$$

$$\sigma = \log \left(\frac{D_{50}}{D_{16}} \right) \quad (5.6),$$

where ξ is a parameter, and σ is the standard deviation of D_{16} and D_{50} , which represent effective topsoil depths in which the ratio of the contributing area is equivalent to 16 and 50 %, respectively.

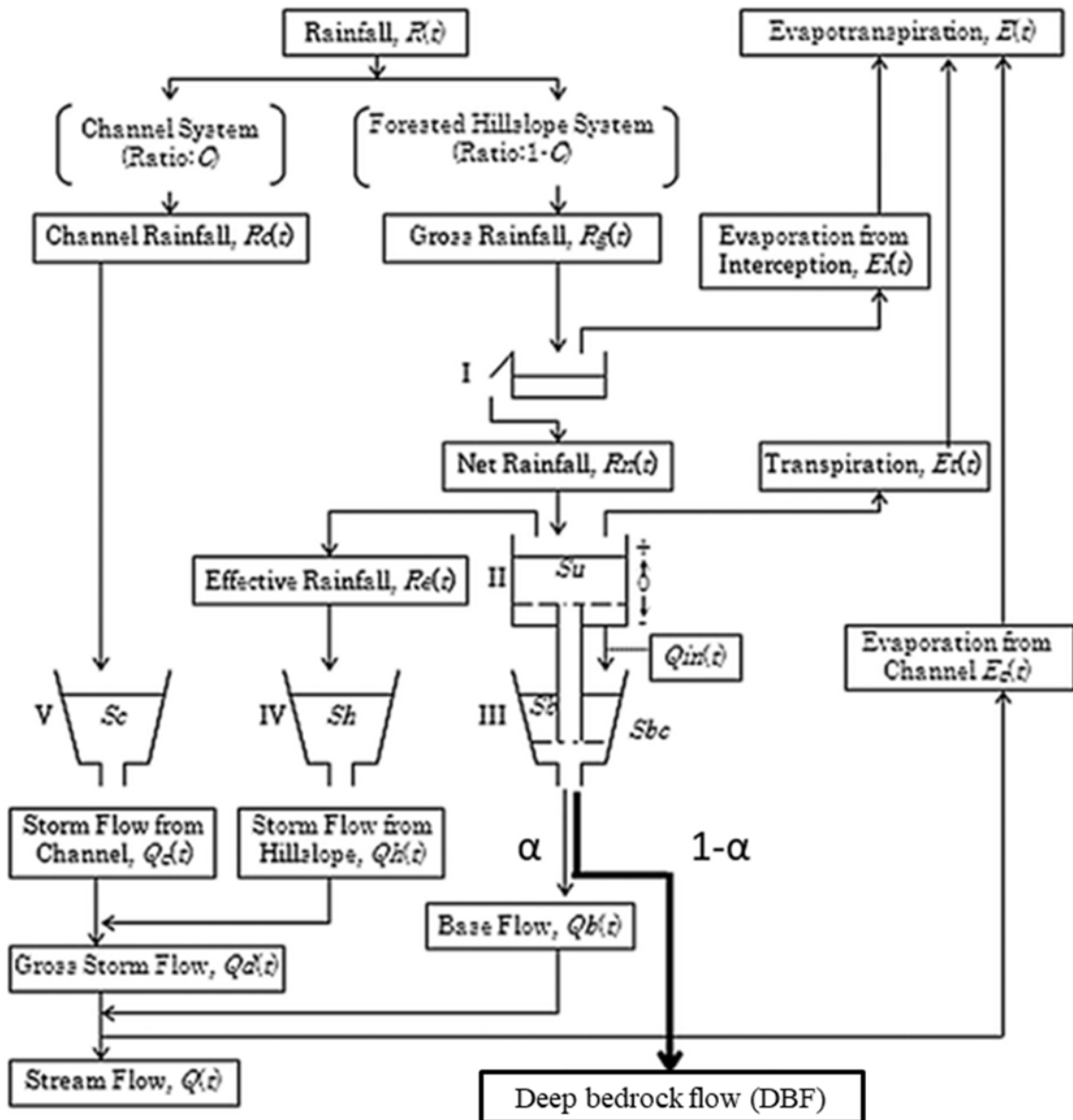


Figure 5.2. Structure of the Hydrologic Cycle (HYCY) model. Authors additionally wrote new parameter α and revised Out flow as deep bedrock flow (DBF) for Figure 4 of Wakahara *et al.* (2012).

5.2.4. Calculation of deep bedrock flow (DBF)

In this study, the calculation method for the DBF (outflow; Wakahara *et al.*, 2012) was slightly improved. Wakahara *et al.* (2012) calculated the DBF as $K1 \times Q_b$, derived from tank III. K1

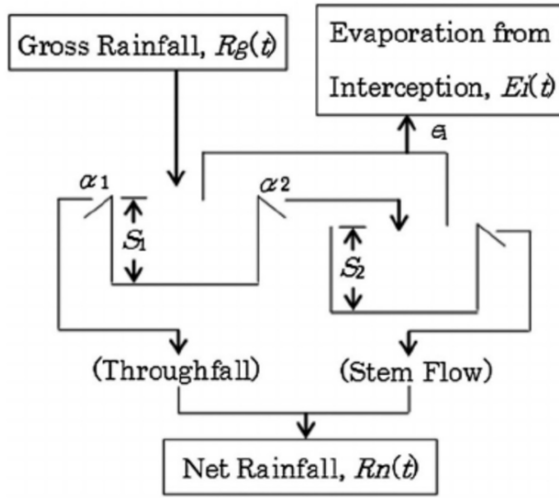


Figure 5.3. Structure of the crown interception model at tank I. Figure 5 quoted from Wakahara *et al.* (2012).

and Q_b represents the water loss ratio from tank III and the baseflow, respectively. However, we used a new parameter α , which satisfies $0 < \alpha \leq 1$. The DBF was calculated by $(1 - \alpha) \times K_b$ (Figure 5.2). Both methods use two parameters for the baseflow (*i.e.*, parameter K_b , which calculates the baseflow hydrograph of tank III runoff, and $K1$ or α , which calculates the DBF). Therefore, there were no significant differences between our method and that of Wakahara *et al.* Furthermore, our new expression can be easily understood when groundwater flows over a topographical catchment boundary, as explained in Section 5.4.1.

5.2.5. Parameter settings

C was calculated for each catchment by using QGIS. We defined the channel as the smallest upper area of 5000 m² or more and calculated the channel length. The channel width was set as 4 m. This setting was consistent with the results of our field survey. Moreover, the calculated C was ~ 0.035 , which has also been used in previous studies (Fukushima, 1988; Nakashima *et al.*, 1992) (Table 5.2).

Figure 5.2 shows the tanks in rectangular and open trapezoids. They were calculated in linear and nonlinear ways, respectively (Fukushima, 1988; Fukushima & Suzuki, 1986). In this study, we kept the P_i parameters the same as those used in previous studies (Table 5.3).

In addition, the interception calculation, shown in Figure 5.3, includes many parameters. We used the values reported by Suzuki *et al.* (1979) (Table 5.3), who conducted their study in the Kiryu Experimental Watershed, Japan, which is located in the same area as the study sites (Figure 2.1a). All three sites had the same vegetation; thus, we believe that interception at the three sites occurs in the same way.

Table 5.2. Optimized results for each catchment. The Nash–Sutcliffe efficiency (NSE) was calculated according to Nash and Sutcliffe (1970).

Catchment	C	D_{16}	D_{50}	K_c	K_h	K_{in}	K_b	α	NSE
S01	0.032	28.45	57.05	9.998	7.699	31.83	453.0	0.3451	0.840
S02	0.018	13.80	41.08	6.045	9.637	50.40	473.2	0.5331	0.887
S03	0.016	53.61	8319	0.9636	8.403	34.86	814.1	1.288	0.807
S04	0.023	16.85	29.87	4.767	13.06	50.15	305.7	0.5607	0.875
S05	0.026	17.72	34.98	5.583	7.615	18.31	307.4	0.4346	0.830
S06	0.028	13.71	26.07	7.739	4.279	8.229	244.5	0.4713	0.867
S07	0.026	7.797	26.28	8.220	13.09	50.40	309.6	0.6631	0.889
S08	0.032	18.61	33.00	10.00	7.707	50.40	299.4	0.3940	0.824
S09	0.023	140.5	34979	3.096	3.594	2.412	616.9	1.189	0.857
S10	0.033	17.53	26.66	9.996	11.08	50.40	121.4	0.2514	0.720
S11	0.030	12.47	26.89	9.997	5.705	50.40	257.2	0.5105	0.885
S12	0.021	13.62	17.69	5.312	0.8855	1.856	214.1	0.3997	0.763
G0	0.035	11.29	2219	2.038	10.69	10.61	1093	0.7528	0.814
G1	0.030	4.911	4614	2.008	11.78	11.43	1101	0.6958	0.836
G2	0.064	58.46	197.0	10.00	30.00	50.40	1251	0.2007	0.702
G3	0	180.8	90999	--	3.392	7.889	1905	1.428	0.746
G4	0.019	44.19	149.7	10.00	12.09	17.85	1374	0.3304	0.795
G5	0	20.00	112.2	--	14.81	50.23	1308	0.6708	0.723
G6	0.038	10.93	5335	3.651	13.55	23.63	780.1	0.5134	0.836
Initial value	--	10	50	2	10	21.7	808	0.5	--

Table 5.3. Fixed parameters.

Parameter	Value	Meanings
P_c	0.6	Parameter related to tank V
P_h	0.6	Parameter related to tank IV
P_{in}	1	Parameter related to tank II
P_b	0.1	Parameter related to tank III
α_1	0.81	Ratio of throughfall [%]
α_2	0.11	Ratio of trunks and stems [%]
S_1	1.44	Maximum storage on canopy [mm]
S_2	0.53	Maximum storage on trunks and stems [mm]
e_i	0.1618	Evaporation rate [mm/h]
PTA	35	Coefficient for mean of monthly transpiration distribution
PTB	30	Coefficient for fluctuation of monthly transpiration distribution
PTC	5	Coefficient for phase delay of monthly transpiration distribution

The transpiration was calculated using the model proposed by Fukushima and Suzuki (1986). The monthly distribution of transpiration was set for each catchment and was reduced from tank II, which represents the surface soil. For the monthly distribution of transpiration, we used the same data as Fukushima and Suzuki (1986). However, the aforementioned study was conducted more than 40 years ago, and the Kiryu Experimental Watershed has recently exhibited different trends in transpiration (Tsuruta *et al.*, 2020). Therefore, we used a 1.09 times larger transpiration to adjust for the recent trend based on detailed observations using the eddy correlation method (Kosugi *et al.*, 2007). Moreover, when the soil becomes dry, transpiration is assumed to be suppressed by the critical depth S_{bc} as follows:

$$E_t(t) = e_p(i) \quad \text{if } S_u > 0 \quad (5.7),$$

$$E_t(t) = e_p(i) \quad \text{if both } S_u \leq 0 \text{ and } S_b > S_{bc} \quad (5.8),$$

$$E_t(t) = e_p(i) \times \frac{Q_b(t)}{Q_{bc}} \quad \text{if both } S_u \leq 0 \text{ and } S_b \leq S_{bc} \quad (5.9),$$

where S_u and S_b represents the storage in tanks II and III, respectively. When tank II was stored, the transpiration was calculated using Equation 5.7. When the tank II had no storage, water for transpiration would flow up immediately from deeper tank III for the time being (Equation 5.8). When there was a water shortage and storage of tank III went below S_{bc} , transpiration was calculated using

Equation 5.9, which reduced transpiration linear to storage of tank III.

5.2.6. Parameter optimization

In this study, we optimized the following seven parameters: K_{in} , K_b , K_h , K_c , D_{16} , D_{50} , and α . The parameters are listed in Table 5.4. We set the range for each parameter based on previous studies (Fukushima, 1987; Fukushima *et al.*, 1988; Fukushima *et al.*, 1989; Fukushima *et al.*, 1992; Fukushima & Suzuki, 1986; Nakashima *et al.*, 1992; Tanaka *et al.*, 1998; Tani *et al.*, 2012) as follows:

$$0 < D_{16} < D_{50}; 0 < K_c \leq 10; 0 < K_h \leq 30; \text{ and } 0 < K_{in} \leq 50.4; 0 < K_b \quad (5.10)$$

Table 5.4. Parameters optimized using the least-squares method.

Parameter	Meanings
K_{in} [h]	Storage function parameter in tank II
K_b [mm ^{9/10} h ^{1/10}]	Storage function parameter in tank III
K_h [mm ^{2/5} h ^{3/5}]	Storage function parameter in tank IV
K_c [mm ^{2/5} h ^{3/5}]	Storage function parameter in tank V
D_{16} [mm]	Effective depth of topsoil in which the ratio of the contributing area of hillslope (<i>i.e.</i> , m) is 16 %
D_{50} [mm]	Effective depth of topsoil in which the ratio of the contributing area of hillslope (<i>i.e.</i> , m) is 50 %
α	Ratio of baseflow in the runoff from tank III

Parameter optimizations were conducted using three years of observed hydrographs and hyetographs via the least-squares method. It was difficult to adjust all parameters simultaneously. Thus, we optimized D_{16} and D_{50} , followed by four K_i parameters, K_c , K_h , K_{in} , and K_b , and finally α . The parameters were optimized from the upper to lower water flow processes. For the initial values, we used the parameters Fukushima and Suzuki (1986) developed for the Kiryu Catchment. Furthermore, we used 0.5 for the newly introduced α parameter (Table 5.2). First, initial values were assigned to the parameters. In the calculation, only D_{16} and D_{50} were adjusted. The values that calculated the hydrographs with the smallest errors from the observed values were selected and used for the further calculations as tentative optimal values. Subsequently, K_c , K_h , K_{in} , and K_b were adjusted. The values that yielded the hydrographs with the smallest errors from the observed values were selected and used

for further calculations. Then, α was adjusted using the same method, and tentative optimal values were selected. Finally, all parameters were set with tentative optimal values and calculated to determine their true optimal values.

The Nash–Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970) was used to evaluate the goodness-of-fit. This index evaluates the goodness-of-fit from 0 to 1. When the index is close to 0 or 1, the goodness-of-fit is incompatible or optimum, respectively.

5.3. Results

5.3.1. Parameter optimization results

Table 5.2 lists the optimization results of the HYCY model. All catchments had 0.7 or larger NSE. Figure 5.4 illustrates an example of the calculation results. The observed hydrograph is shown as “catchment name + discharge,” and the optimized calculation results are indicated as Q1. This calculation accurately reproduced the observed hydrograph.

Parameter K_b was small and large for S and G, respectively (Figure 5.5). Hydrograph recession demonstrated the same trend (Figure 4.5). The storage of tank III increased with an increase in K_b , which steadied the baseflow, and the recession was gentler. Namely, in the sedimentary rock catchments, except S03 and S09, K_b had a small value (Figure 5.5), corresponding with the steep recession in Figure 4.5. In catchments S03 and S09, K_b had relatively large values compared to the other sedimentary rock catchments (Figure 5.5), and this corresponds to a relatively gentle recession compared to the other sedimentary rock catchments in Figure 4.5. In the granitic catchments, K_b had large values (Figure 5.5), and Figure 4.5 shows a gentle recession by the granitic catchments.

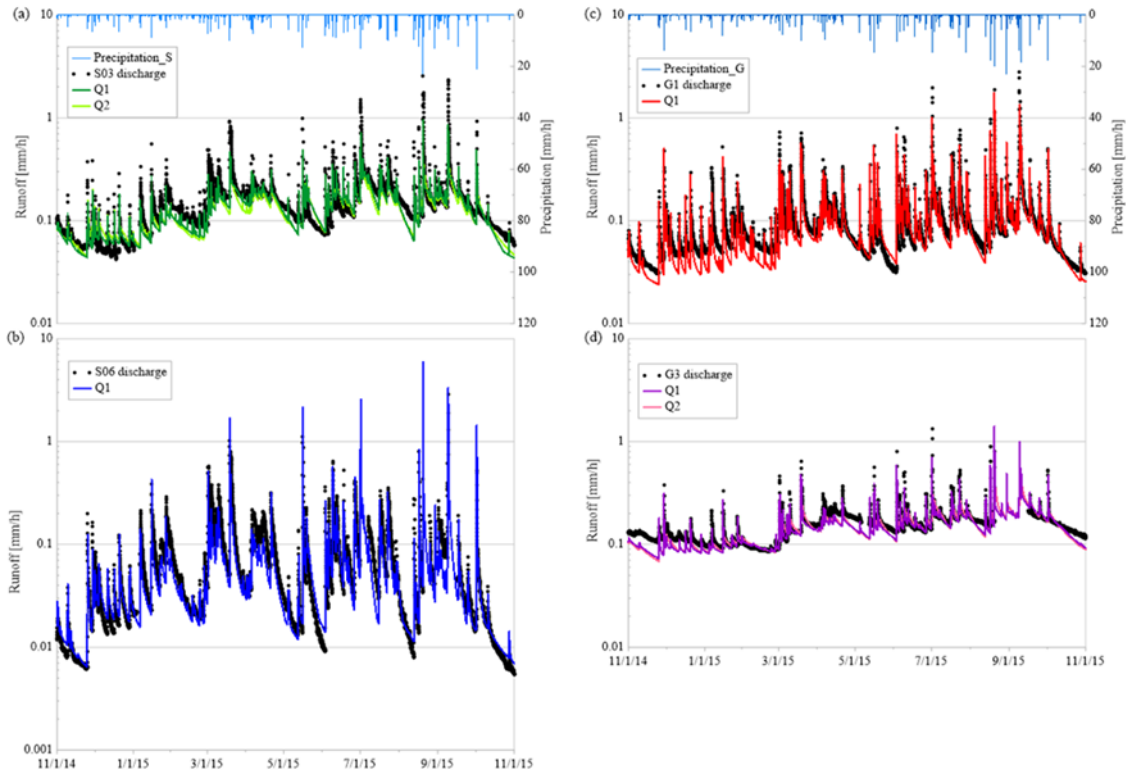


Figure 5.4. Observational, optimized (Q1), and calculation results considering bedrock groundwater inflow from adjacent catchments (Q2). Each panel shows results from November 1, 2014, to October 30, 2015, for catchments (a) S03, (b) S06, (c) G1, and (d) G3.

Moreover, α and the runoff rate during the observation period (*i.e.*, runoff over precipitation) demonstrated a good correlation (Figure 5.6). Parameter α decides the baseflow rate of the runoff from tank III, which suggests the substantial impact of baseflow on the catchment runoff rate. Furthermore, catchments S03, S09, and G3 had values greater than or equal to one for α (Table 5.2; Figure 5.6). They are thought to receive groundwater inflow from adjacent catchments (Chapter 4). Parameter α is defined as equal to or smaller than one, and this problem will be discussed in Section 5.4.1.

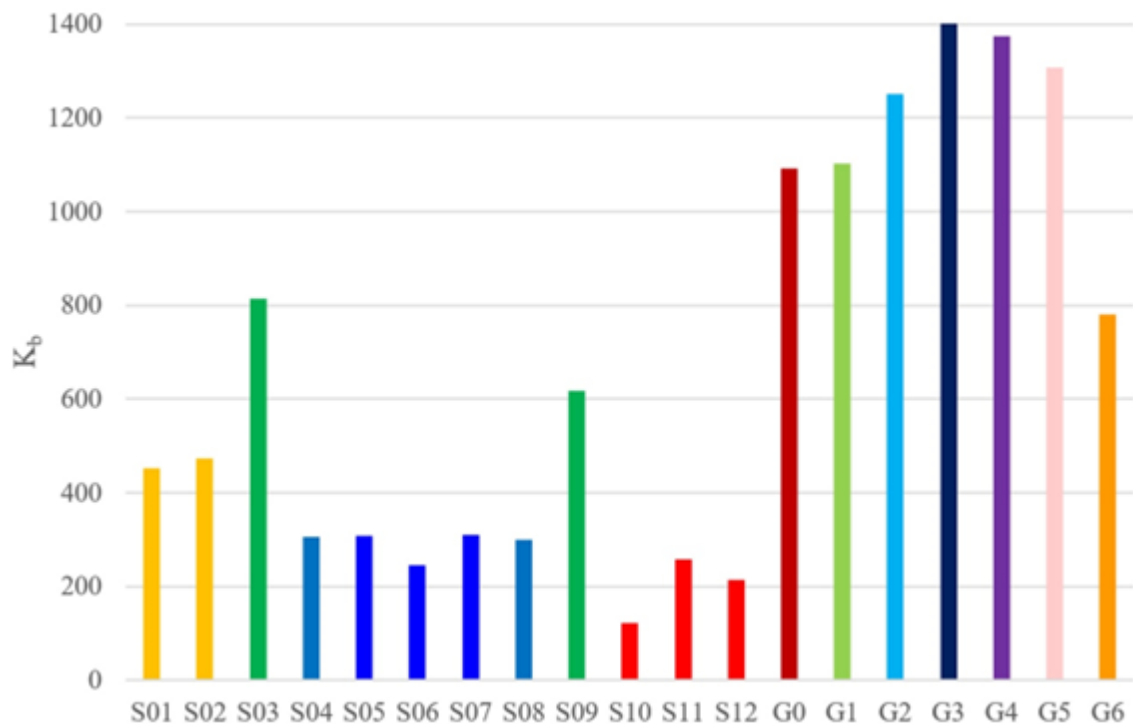


Figure 5.5. Distribution of K_b , which calculated the baseflow hydrograph.

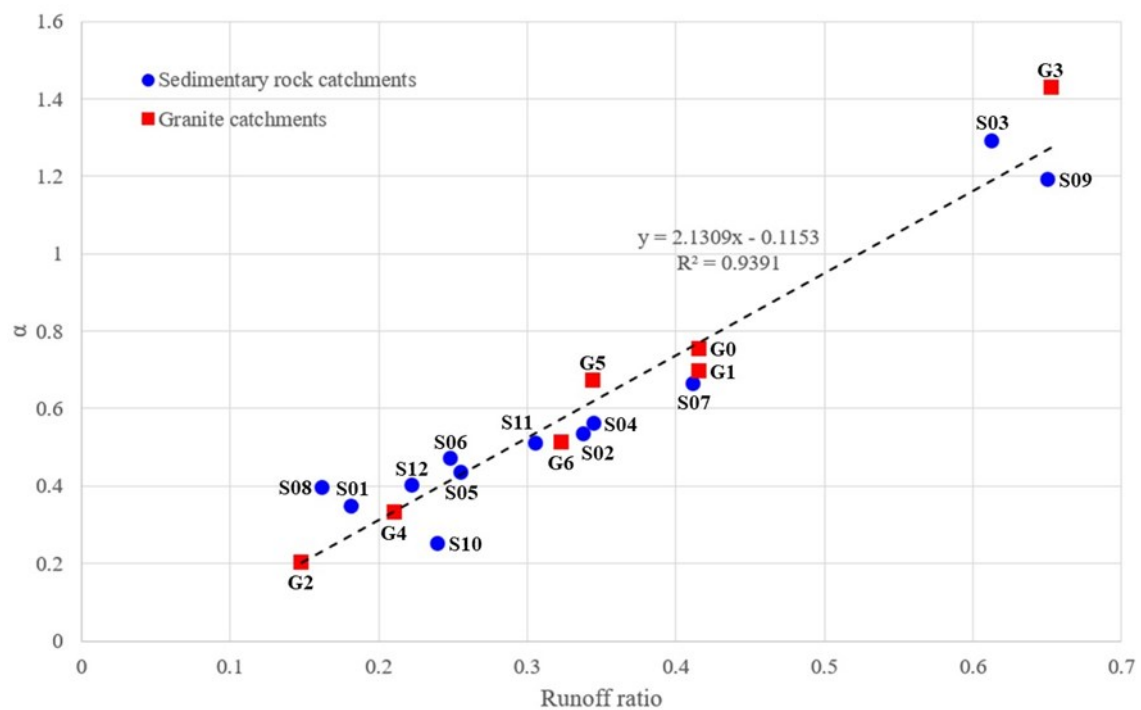


Figure 5.6. Relationship between α (*i.e.*, baseflow rate of the runoff from tank III) and runoff ratio (*i.e.*, runoff divided by rainfall). The blue and red plots represent sedimentary rock and granite catchments, respectively.

5.3.2. Catchment classification results using parameter m

From Equations 5.4–5.6, the relationship between the amount of water in tank II (*i.e.*, sum of tank II storage in time $t-1$ and throughfall amount in time t) and m can be considered as the relation between the soil layer storage and the ratio of variable source area to catchment area. Therefore, this is the most important parameter in the HYCY model. Hereafter, we consider the amount of water in tank II as the soil layer storage (Fukushima, 1988; Fukushima & Suzuki, 1986).

The values of D_{16} and D_{50} were optimized for each catchment, and parameter m was calculated using Equations 5.4–5.6, as shown in Figure 5.7. The 19 catchments studied were classified based on these results, as in Tani *et al.* (2012). At S site, eight catchments (*i.e.*, S02/S04–S06/S08/S10–S12) had a sigmoid curve with larger values corresponding to the rainfall amount. These eight catchments exhibited the same increasing trend in m when the soil layer storage was 10 mm or less. The remaining catchments exhibited anomalous trends. Catchments S03 and S09 exhibited lower values when the soil layer storage increased in the saturated curves. Catchment S01 required much more storage in the soil layer than the other sedimentary rock catchments to increase m . Catchment S07 had trends that were different from the major trends of the eight catchments. It had larger m values when the soil layer storage was 15 mm or less. At G site, catchments G0, G1, and G6 exhibit similar saturation curves. Catchment G3 also exhibited a saturation curve, but its largest m value was smaller than those of the other three catchments. Catchments G2, G4 and G5 exhibited sigmoid curves similar to those of the S site catchments. This classification result is similar to the results of a direct flow analysis of the observed data (Chapter 4), which again confirms that the parameter m is related to direct runoff.

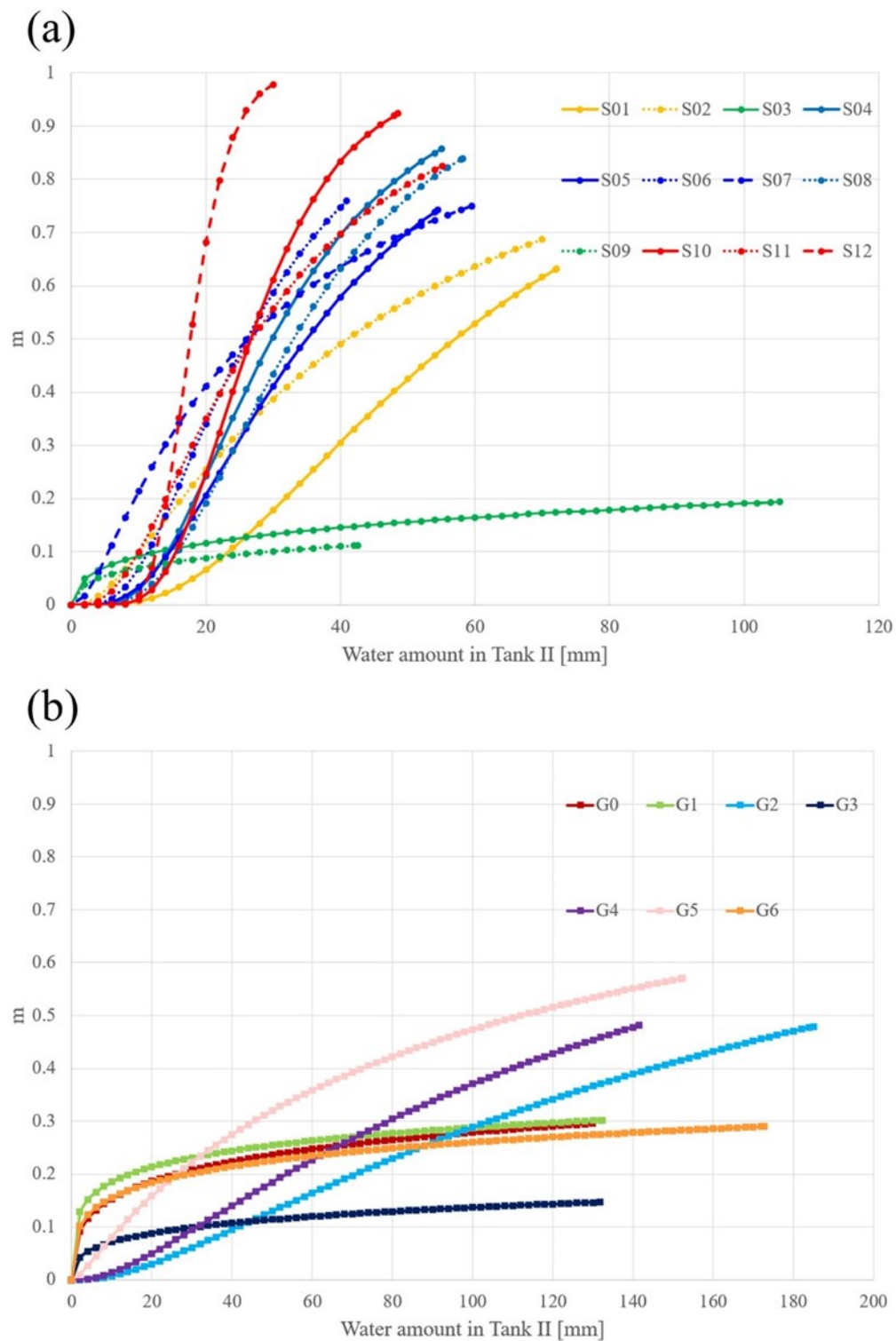


Figure 5.7. Relationship between the amount of water in tank II and parameter m (*i.e.*, the occurrence of effective rainfall). Each panel shows (a) Shigaraki and (b) Fudoji Experimental Forest catchments.

5.3.3. Anomalous catchment results

In this study, we verified whether these parameters could explain the observed results for anomalous catchments (Chapter 4).

In catchments S03 and S09, direct flow exhibited characteristics similar to those of the granite catchments. In addition, the recession hydrograph was gentle (Figures 4.3a and c). These characteristics were generated by converged groundwater flowing into strike-oriented catchments on the bedding planes, because of the hydraulic anisotropy of the sedimentary rocks (Chapter 4). The corresponding parametric results show the characteristics of the relationship between the soil layer storage and m , which are similar to those of many granite catchments (Figure 5.7). This relationship yields saturation curves for both catchments. This led to larger and smaller m values in these catchments than those in other sedimentary rock catchments when the soil layer storage was 10 mm or less and 18 mm or more, respectively. Among the S site catchments, these catchments had extremely large K_b and α values greater than one. These characteristics reflect groundwater inflow into these catchments from adjacent catchments.

In catchment G3, the bedrock topography facilitated the inflow of groundwater from adjacent catchments due to granitic joints. Thus, the catchments have a larger baseflow and gentle recession (Chapter 4; Figure 4.5). In this study, the relationship between the soil layer storage and m had a saturation curve, and the largest m value of catchment G3 was smaller than that of the other granitic catchments. Furthermore, α was greater than one. These characteristics are consistent with the observed characteristics (Figures 5.4a and 5.6).

Catchment S01 had a smaller direct flow than the other S site catchments with rainfall events of 25 mm or less. Furthermore, the increase in the direct flow was small when the rainfall event was 30 mm or more (Chapter 4). Thus, a small m value, regardless of the soil layer storage, was the corresponding result (Figure 5.7b). Chapter 4 revealed that infiltration into uneroded weathered bedrock may actively occur because of the gentle slope of the headwater (Figure 2.1b). In this study, the α value became as small as 0.3451 (Table 5.2), which suggests active bedrock infiltration.

Catchment S07 has a larger direct flow than the other sedimentary rock catchments (Chapter 4). It had a larger m value (Figure 5.7a) when the soil layer storage was 6–14 mm, which reflected the observed characteristics.

Catchment S10 had a small baseflow due to its location, i.e., north of catchment S09, which collects groundwater from its neighbors (Chapter 4). In this catchment, α was extremely small i.e.,

0.25 (Table 5.2), suggesting that bedrock infiltration was greater than baseflow generation.

Catchments G2 and G4 had smaller direct flows than the other granitic catchments (Chapter 4), which was reflected by the smaller m values (Figure 5.7b). However, as shown in Figure 5.7(b), when the soil layer storage reached 100 mm or more, the m values of catchments G2 and G4 were larger than those of the other G site catchments. This result cannot be used to reproduce the observed results. In contrast, situations in which the soil layer storage exceeded 100 mm corresponded to huge rainfall events of 200 mm or more. Observational data analysis (Chapter 4) was conducted for rainfall events of 80 mm or less. There should be some discussion on whether the observational data can be extrapolated to larger rainfall events. Thus, more observational data on large rainfall events and analysis of rainfall–runoff characteristics are needed to discuss the parameter m with a large soil layer storage, such as 80 mm or more. Moreover, catchment G2 had a steeper recession than the other G site catchments, including catchment G4, which is similar to that of the S site catchments (Figure 4.5). Chapter 4 stated that catchment G2 had a larger bedrock groundwater leakage into catchment G3 than into catchment G4. Catchment G2 had a smaller α value than catchment G4, and the HYCY model reproduced the scale of the groundwater recharge (Table 5.2).

When rainfall is less than 50 mm, direct runoff in the G5 catchment is smaller than in other granitic catchments, which is similar to the G2 and G4 catchments. On the other hand, when rainfall is greater than 50 mm, direct runoff in the G5 catchment shows similar variability as in other granitic catchments (Chapter 4). This is also reflected in the distribution of the m parameter, which takes on relatively small m values when Tank II storage is low, as in the G2 and G4 catchments, but tends to be slower than in the G2 and G4 catchments as storage increases, with the m parameter increasing at a smaller rate with increasing water storage.

5.4. Discussion

5.4.1. Calculations considering bedrock groundwater inflow from adjacent catchments

Table 5.2 shows the α values greater than one for the three catchments (*i.e.*, S03, S09, and G3). These three catchments have bedrock groundwater inflows from adjacent catchments (Chapter 3; Masaoka *et al.*, 2021). An α value greater than one reflected these water movements. However, this implies that the baseflow runoff was larger than the runoff from tank III. In this study, baseflow was defined as tank III runoff excluding the DBF. Thus, α values greater than one were unfavorable.

Therefore, other simulations were performed to calculate these inter-catchment groundwater flows with an α value of one for these catchments. If more runoff was needed to optimize the calculated runoff, we assumed that some water from the DBF of adjacent catchments flowed into the baseflow of these catchments. In other words, added water is the sum of the groundwater flowing from adjacent catchments. A summary of the simulation results is presented in Figure 5.8.

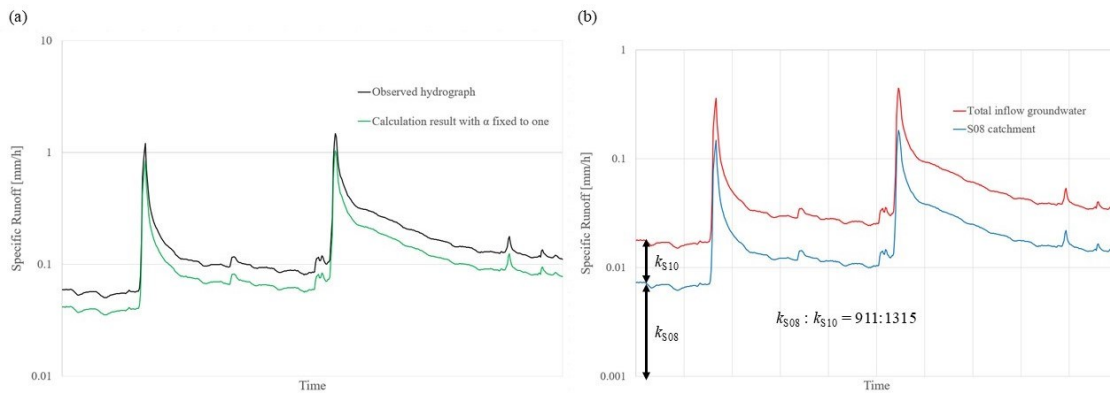


Figure 5.8. Calculation image of additional simulation with α fixed to one. As an example, the runoff in the S09 catchment is shown. (a) The total inflow of groundwater to the S09 catchment can be obtained as the difference between the observed hydrograph and the calculation result with α fixed to one. (b) Total groundwater inflow can be determined by the sum of groundwater inflows from adjacent catchments, in this case the S08 and S10 catchments; the ratio of groundwater derived from the S08 and S10 catchments is defined by the ratio of the catchment boundary length that each catchment shares with the S09 catchment.

First, calculations were performed for the S03, S09, and G3 catchments with α replaced by the number one within the optimal parameter set (Table 5.2). Next, the differences between the calculation results and observed hydrographs were determined. When α is one, by the definition of α , runoff from tank III can be considered as baseflow, and no bedrock percolation occurs. Therefore, the differences obtained here can be considered to represent the total inflow from adjacent catchments.

Then, using the least-squares method, the total catchment inflow from adjacent catchments was assigned to each. To simplify the calculation, we assumed that the ratio of the inflows from each catchment was always constant and obtained coefficient k_i , where i is the catchment name. The coefficient k_i was obtained using the bedrock groundwater catchment area (annual average) (Masaoka *et al.*, 2021) for the catchments at site G. For the catchment at site S, the length of the shared catchment

boundary was used because groundwater analysis was not reported. This assumes that the longer the shared catchment boundary, the greater the opportunity for groundwater to flow in and out of the subsurface across the catchment boundary. The specific shared catchment boundary lengths were 3.1 m, 202.6 m, 170.4 m, and 0.5 m for the S03 catchment and the S01, S02, S04, and S12 catchments, respectively; 91.1 m and 131.5 m for the S09 catchment and the S08 and S10 catchments, respectively. Masaoka *et al.* (2021) reported that bedrock groundwater catchment areas (annual average) were about 2200 m² and 1300 m² in catchments G2 and G4, respectively.

In the last, the coefficient k_i was multiplied by the DBF of each catchment. This considers that some of the DBF in the adjacent catchment are discharged out of the catchment. This is the overall procedure for obtaining the total groundwater inflow.

Finally, the total groundwater inflow from the adjacent catchments and the results of the calculations with α set to one in the catchment to be inflowed, and were added to obtain a calculation result that accounts for groundwater movement across the catchment boundary.

The calculation results are shown in Figure 5.4. The results considering the groundwater inflow are indicated as Q2. The goodness-of-fit (determined using the NSE) was 0.782, 0.846, and 0.659 for catchments S03, S09, and G3, respectively (Table 5.5). These values were almost the same as the results admitting $1 < \alpha$ (*i.e.*, S03: 0.807, S09: 0.857, and G3: 0.746). Although groundwater movement across the catchment boundary from adjacent catchments was calculated very simply in this study, the groundwater flow inferred from the observations of Chapter 4 was represented by the HYCY model. Though this method of expression is inconsistent with the original definition of the parameter α , the accuracy is comparable even when groundwater movement in principle is considered as in this calculation, indicating that the value of α larger than one has no problem for simple calculations.

Table 5.5. Nash–Sutcliffe efficiency (NSE) considering bedrock groundwater inflow from adjacent catchments and coefficient k for estimating deep bedrock flow (DBF).

Catchment	NSE	Coefficient k_i for deep bedrock flow (DBF)							
		S01	S02	S04	S12	S08	S10	G2	G4
S03	0.782	0.00372	0.243	0.205	0.000600	--	--	--	--
S09	0.846	--	--	--	--	0.148	0.213	--	--
G3	0.659	--	--	--	--	--	--	0.109	0.0644

5.4.2. Effects of topography and geology on each parameter

This section discusses the effects of topography and geology on the seven parameters. The effect of geology is defined as the effect of geological differences, such as the differences between the permeability of soil and bedrock, or the differences in runoff mechanisms. As described in Section 5.2.2, we use the basin form ratio as the topographical index. Table 5.6 lists the correlation coefficients between the basin form ratio and each parameter. Table 5.6 presents the correlation coefficients for the three catchment groups, namely, sedimentary rock, granitic rock, and all catchments.

First, D_{16} and D_{50} were used to calculate m using Equations 5.4–5.6 as described above. These parameters alone have no significance, and their effects on m should be discussed. The correlation coefficients between the basin form ratio and m_{10} , m_{30} , and m_{60} are shown in Table 5.6 to describe the m value with 60 mm soil layer storage (m_{60}). As an example, the relationship between m_{30} and the basin form ratio is shown in Figure 5.9(a). There seems to be no relationships between the m values and basin form ratio when all catchments are considered. However, we observed different relationships between the m values and basin form ratio when geology was considered separately. In granitic catchments, the basin form ratio had strong positive relationships when the soil layer storage was large, such as in m_{60} . However, the correlation weakened as the soil layer storage decreased and became negative for smaller soil storages. In sedimentary rock catchments, there was almost no relationship between the basin form ratio and the m value. However, this result includes outliers, particularly when the soil layer storage becomes large. S03 and S09 catchments exhibited small m values. Without these catchments, sedimentary rock catchments have a negative correlation with the m values (Figure 5.9a). The effects of the basin form ratio on the overland flow generation rate were not affected by geological differences. Thus, the effects of topography on m values were small.

Although the geological effect was not clear for m_{10} (Figure 5.10a), m_{30} and m_{60} showed clear differences in m values. This suggests that geology affects the overland flow generation rate.

Ohta (1988) studied factors that may affect the overland flow generation rate in sedimentary rock catchments based on field measurements, where bedrock was formed in the Neogene or Quaternary (Ueki *et al.*, 2013), and found that the thickness of the soil layer and surface hydraulic conductivity have a substantial effect on the overland flow generation rate. The catchments in this study have different weathered bedrock thicknesses in the sedimentary rock catchments (Chapter 4); however, granitic catchments have high hydraulic conductivity at the surface because of the developed joints in all catchments (Chapter 4). Thus, granitic catchments have a low overland flow generation rate because even if overland flow happens to occur, the water immediately re-infiltrate the ground. Figures 5.7 and 5.9(a) illustrate this situation using m , revealing that the sedimentary rock catchments had larger values than the granitic catchments with the same soil layer storage. Moreover, strike-oriented catchments (*i.e.*, S03 and S09; Chapter 3) in sedimentary rock catchments have structures that gather groundwater from adjacent catchments owing to dips and strikes, which leads to a relationship between the soil layer storage and m values similar to those in granitic catchments. In most sedimentary rock catchments, the m value increased, implying that the entire catchment easily became wet and had overland flow from a large area. Nonetheless, strike-oriented and granitic catchments had relatively small m values, and limited wet areas along the riparian zone contributed to the direct runoff.

Table 5.6. Correlation coefficients between the basin from ratio and parameters. Correlation coefficients were calculated for all, sedimentary rock, and granite catchments. The background of each cell is colored in blue and red, which represent positive and negative correlation, respectively, and the darkness represents the absolute value (*i.e.*, 1 or -1, which is the darkest).

Parameter	All catchments	Sedimentary rock catchments	Granite catchments
m_{10}	-0.30	-0.22	-0.58
m_{30}	-0.23	-0.40	-0.15
m_{60}	0.018	-0.14	0.49
m_{100}	0.16	0.039	0.84
K_c	0.44	0.39	0.86
K_h	0.11	0.070	0.56
K_{in}	0.25	0.12	0.75
K_b	-0.063	0.13	0.058
α	-0.35	-0.30	-0.56

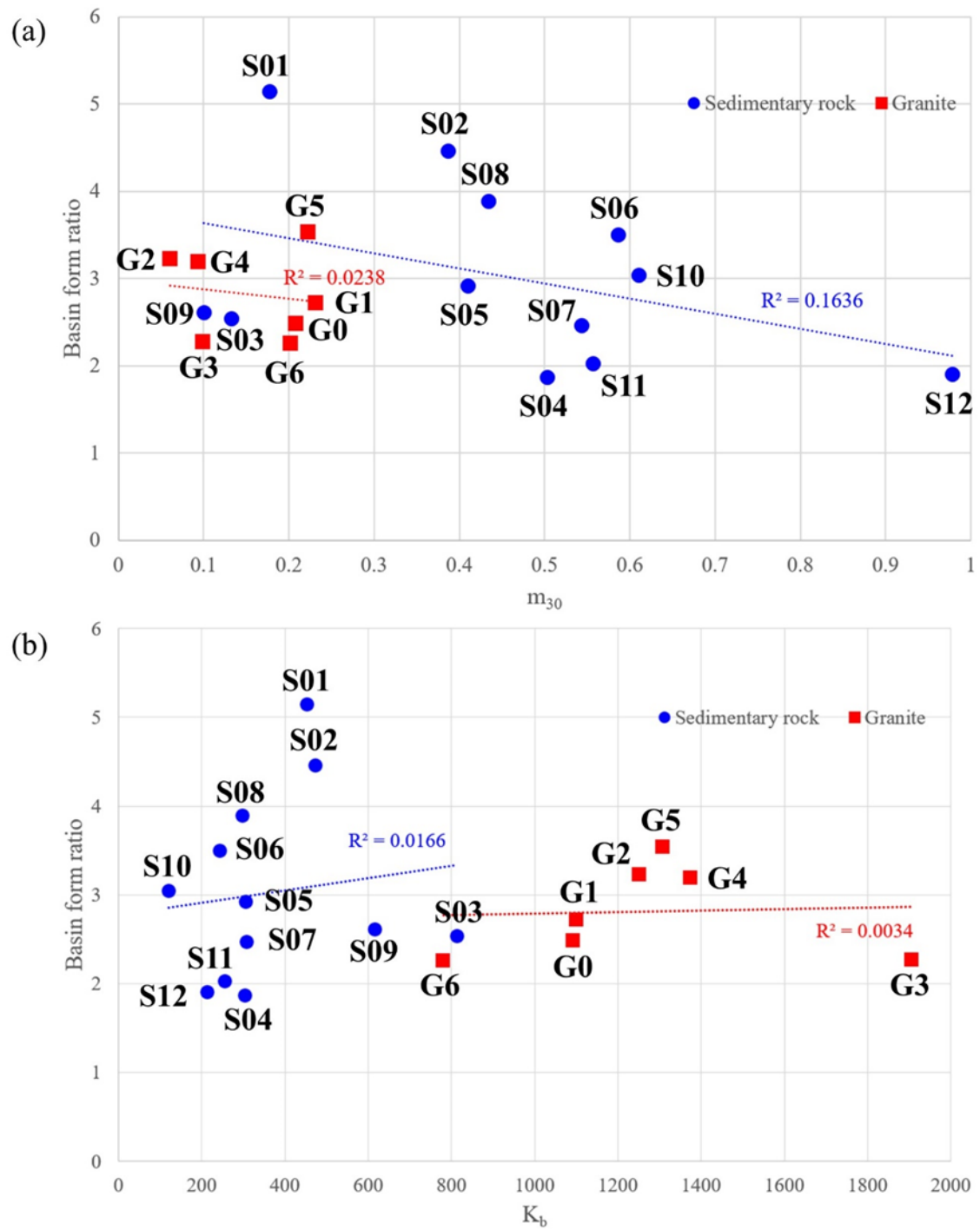


Figure 5.9. Relationships between topography (basin form ratio) and (a) m_{30} (*i.e.*, the value of the occurrence of effective rainfall when the soil layer storage in tank II is 30 mm) and (b) parameter used to calculate baseflow hydrograph (K_b).

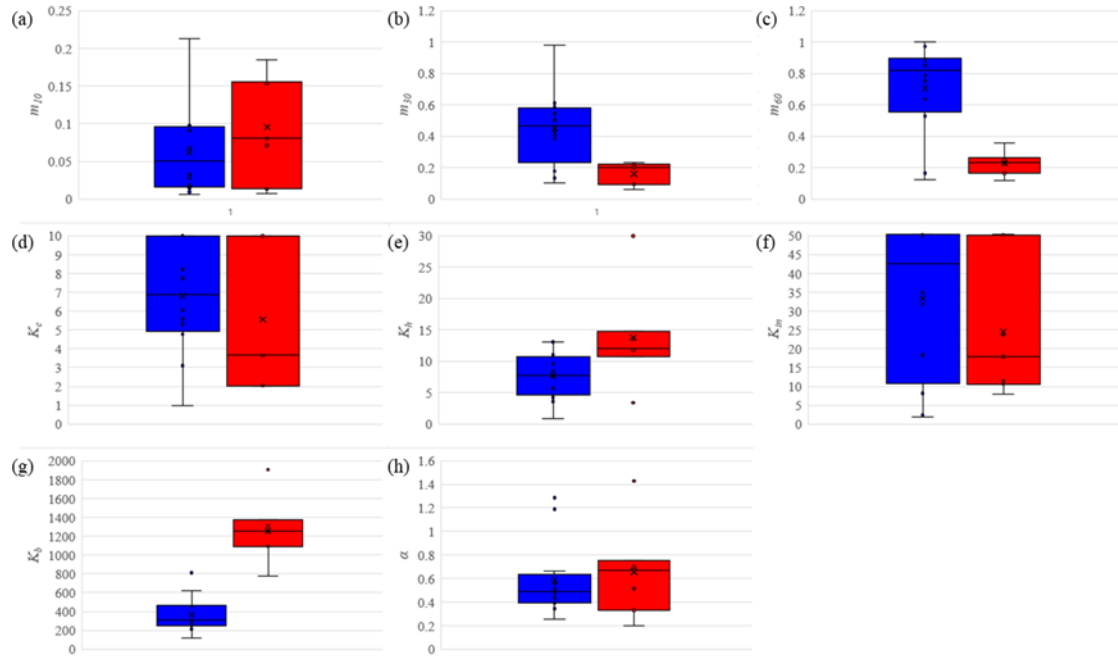


Figure 5.10. Relationships between different parameters and geologies. The blue and red boxes in each panel represent Shigaraki and Fudoji Experimental Forest catchments, respectively. Each panel indicates (a) m_{10} , (b) m_{30} , (c) m_{60} , (d) K_c , (e) K_h , (f) K_{in} , (g) K_b , and (h) α . m_{10} represents the value of the occurrence of effective rainfall when the soil layer storage in tank II is 10 mm. For the definition of other parameters, see Table 5.4.

Second, K_c showed little positive correlation with the basin form ratio when all catchments were considered. When considered separately, they differed according to geology (Table 5.6). The granitic catchments had strong positive coefficients, whereas the sedimentary rock catchments had weak positive correlations (Table 5.6). The positive correlation between K_c and the basin form ratio indicated that the longer the catchment, the more directly the runoff derived from channel rainfall. In elongated mountain headwaters, 1st order catchment merges with many zero-order catchments, which is thought to facilitate the collection and discharge of overland flow. In contrast, in rounded mountain headwaters, 1st order catchments are less likely to develop, and there may be many zero-order catchments or groundwater converged in a few springs. Therefore, the overland flow derived from channel rainfall is likely to occur in long and narrow catchments, which is thought to be the reason for its positive correlation with K_c . Figure 5.10(d) shows the small effect of geology on K_c value.

Third, K_h and the basin form ratio showed almost no correlation in any catchments. However, there are differences in the geology. There was a positive correlation in the granitic catchments, and it included catchment G2 as an outlier, which had the largest value for the K_h range (Inequality 5.10).

Without the outlier, a positive correlation was observed ($R^2 = 0.320$). Catchment G2 may have lost most of its groundwater to catchment G3 due to leakages (Masaoka *et al.*, 2021). This causes the overland flow to have an extremely gentle hydrograph, even if it occurs, which calculates K_h to be the largest. In the sedimentary rock catchments, K_h and basin form ratios showed almost no correlation (Table 5.6). Thus, K_h did not affect the topography. Figure 5.10(e) shows the effects of geology. The K_h values were relatively small and large in the sedimentary rock and granitic catchments, respectively (Figure 5.10e). Sedimentary rock catchments have steep overland flows, whereas granitic catchments have gentle overland flows. This result corresponds to the trend in parameter m .

Fourth, K_{in} had a weak positive correlation with the basin form ratio in all catchments. However, there are differences in the geology. The granitic catchments had a strong positive correlation (Table 5.6). However, in the sedimentary rock catchments, there was almost no correlation (Table 5.6). This difference was thought to be explained by differences in groundwater movement. Since granite mountain soils are relatively uniform sandy soils with high permeability, there is little need to form water channels for drainage (Mizuyama *et al.*, 1994). Therefore, differences in the degree of weathering affect the variation in K_{in} . Here, we consider the relationship between the degree of weathering and topography, such as catchment shape. As mentioned in the discussion on K_c , long and narrow catchments are often considered to have well-developed 1st order channels. During their development, they are thought to have eroded large amounts of mountain bodies composed of weathered bedrock. The weathered bedrock layer is highly permeable because of the numerous fractures, and the lack of this layer is thought to result in poor permeability and large values of K_{in} in elongated catchments. However, sedimentary rock soils have low permeability, and when considered as an entire catchment, the permeability depends on the degree of pipe network development (Mizuyama *et al.*, 1994). Therefore, the variation in K_{in} also depends on the degree of pipe network development and is not related to its topography. This may explain why no correlation was found between the topography and K_{in} in the sedimentary rock catchments. In summary, we conclude that topography does not significantly affect K_{in} , and Figure 5.10(f) suggests that geology also has no effect on K_{in} .

The relationship between K_b and the basin form ratio is presented in Table 5.6 and Figure 5.9(b). No correlations were observed in any catchments. When considered geologically, granitic catchments did not correlate with the basin form ratio because of the outliers in catchment G3. However, they had a strong positive correlation ($R^2 = 0.794$) without this data. Catchment G3 is an outlier because it has an extremely wet riparian zone and a large baseflow due to groundwater inflow from adjacent catchments (Chapter 4). The same was true for catchments S03 and S09, which had

larger values than those expected for the basin form ratio, although the value for S09 catchment was not an outlier (Table 5.2). The sedimentary rock catchments also positively correlated without the outlier S03 catchment ($R^2 = 0.124$). Thus, K_b was thought to have some effect on topography without outlier catchments, although the effect was smaller than the effect of geology, as stated below.

In addition, K_b had a substantial effect of the geology (Figures 5.5, 5.9b, and 5.10g). Figure 5.9(b) shows that even if the basin form ratio was the same, the K_b value was different owing to geology. In other words, most sedimentary rock catchments have small K_b values and steep baseflow recessions, leading to steep recessions in the runoff hydrographs. In contrast, granitic and strike-oriented catchments have large K_b values and gentle baseflow recessions, which caused gentle recessions in the runoff hydrographs.

Finally, Table 5.6 shows that the average slope and α had small correlation. In addition, their correlation with geology was small (Figure 5.10h).

Therefore, among the improved HYCY model parameters, K_c and K_b exhibited topographical effects that determined the hydrograph of the storm flow from channels and baseflow. In contrast, m , K_h , and K_b showed geological effects.

5.5. Conclusions

Runoff observations were conducted in 12 and 7 sedimentary rock and granitic catchments, respectively (Chapter 4), and the HYCY model (Wakahara *et al.*, 2012) was optimized using the observed hydrographs. The HYCY model accurately reproduces the observed hydrographs. Moreover, the substantial effects of geology and geological structures on runoff in mountainous headwater catchments, as shown by observational data analysis (Chapter 4), were reproduced by analyzing the HYCY model parameters. The results of the observational analysis were primarily explained using two parameters: m and K_b .

In addition, we developed a new expression using the parameter α to distribute the deep bedrock percolation and baseflow. Parameter α defined the ratio of baseflow to runoff from tank III, with the remaining water as DBF. In some catchments, it was greater than one. Additional simulations reveal that the results expressed using an α greater than one reproduce observed flows with the same degree of accuracy as simple estimates of inflows from the adjacent catchments, and the HYCY model

with physical meaning reproduces these observed flows.

The effects of topography and geology on HYCY model parameters were determined. Parameter m was strongly correlated with topography in the granitic catchments, but the correlations changed with the amount of soil layer storage. Since the correlation was weak in the sedimentary rock catchments, the topographical effect on m was considered to be almost zero. K_c had little positive correlation with topography in all the catchments. The development of catchments is thought to determine the catchment topography and affect the runoff of channel precipitation. K_h did not correlate with the topography. Considering the groundwater inflow over the catchment boundary, catchment G2 was an outlier with a large value because of groundwater leakage into the adjacent western catchment. In K_{in} , no relationship was observed between the topography and geology. In K_b , a topographical effect was observed, suggesting that the large basin form ratio of the catchment made the baseflow hydrograph steeper. The degree of correlation differed among the different geologies. This can be explained by considering the groundwater inflow over the catchment boundary, which causes some catchments to have an extremely wet riparian zone and a gentler baseflow hydrograph as expected from their basin form ratio. However, geological differences and the resulting susceptibility of overland flow, or differences in recession hydrographs of overland flow and baseflow, have a significant influence on the parameters m , K_h , and K_b .

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CHAPTER 6

Conclusions

Among sediment disasters, deep-seated landslides often cause significant damage, and while countermeasures have been proposed; however, the understanding of the mechanisms of occurrence remains insufficient, preventing the implementation of effective solutions. This study examines rainfall–runoff in mountain headwaters, with a particular focus on rainfall–runoff regulated by geological structures in sedimentary rock mountain headwaters. The research integrates knowledge from related fields, such as geology and hydrology, to contribute to a deeper understanding of the mechanisms behind the occurrence of deep-seated landslides.

The study is based on runoff data observed at the Shigaraki Experimental Forest, located in Koka City, Shiga Prefecture, central Japan (site S). Long-term hydrographs spanning 3 years in 12 headwater catchments located on a sedimentary rock mountain revealed the following:

First, the analysis of simple waveform events from the observed hydrographs showed that even catchments located on the same mountain with identical rainfall, geology, and vegetation exhibited different hydrograph patterns and can be classified into three main categories (Chapter 3). These catchments were named as strike-oriented catchments, dip-oriented catchments, and opposite dip-oriented catchments. The strike-oriented catchments were characterized by a baseflow 10 times higher compared to the other catchments, likely due to the inflow of bedrock groundwater beyond the surface catchment boundary. Differences in the relative flow peaks were observed between dip-oriented and opposite dip-oriented catchments, with the dip-oriented catchments tending to have discharge peaks relatively later than the opposite dip-oriented catchments. These differences were attributed to the variations in the slope gradients of the respective catchment groups. The classifications also corresponded with the dip and strike of the bedrock. By considering the relationships between slope gradient and bedrock dip, as well as the permeability anisotropy of the bedrock sedimentary rock, it was possible to estimate the bedrock groundwater flow at site S, which was consistent with the hydrograph observations.

The entire period of observed hydrographs was subsequently analyzed, and it was found that the runoff characteristics described in Chapter 3 persisted throughout the observation period (Chapter 4). This chapter analyzes and compares the hydrographs observed in neighboring granite catchments

at approximately the same time. The geological impact on rainfall–runoff characteristics was examined through the relationship between direct runoff and total rainfall or recession analysis. When the total rainfall was >30 mm, the sedimentary rock catchments exhibited larger direct runoff, whereas when the total rainfall was <25 mm, the granite catchments had larger direct runoff. Additionally, the recession trend was steeper in sedimentary rock catchments than in granite catchments. However, these geological trends did not explain all runoff behaviors, as some catchments displayed anomalous runoff patterns. Geological structures had a significant impact on these catchments. The strike-oriented catchments exhibited more direct runoff than other sedimentary rock catchments when the total rainfall was <10 mm, and their runoff trends were similar to those of the granite catchments. Recession analysis also revealed catchments with anomalous gentle recession, which were strongly influenced by bedrock groundwater due to geological structures, such as sedimentary bedrock dip and strike or granite joints, which may lead to wet riparian zones.

Furthermore, the improved HYdrologic CYcle (HYCY) model was optimized using the hydrographs from Chapter 4, and the influence of geological structure was incorporated into the various parameters (Chapter 5). Each tank of the HYCY model represents different rainfall–runoff processes, such as infiltration or evapotranspiration. By analyzing the optimized parameters, it is possible to determine which process is more influenced by topography or geology. In this study, the HYCY model (Wakahara *et al.*, 2012) was further improved, particularly in the calculation of bedrock groundwater. In concrete, after runoff from tank III was calculated, newly introduced parameter α was multiplied by the runoff to calculate the baseflow amount. The remaining groundwater was defined as bedrock groundwater. The improved HYCY model effectively reproduced each observed runoff. The analysis of the optimized parameters revealed the influence of topography on channel runoff and baseflow, and the impact of geology on baseflow waveforms and overland flow. For instance, parameter m governs the occurrence of overland flow, and relationship between m and the amount of water in tank II typically shows sigmoid curves in most sedimentary rock catchments while most granite catchments show saturation curves. The geological effects on direct runoff (Chapter 4) align well with these trends. In addition, the strike-oriented catchments, despite having sedimentary rock bedrock, display saturation curves similar to that of the granite catchments. However, this trend also corresponds to the analysis in Chapter 4. Moreover, parameter K_b , which determines the waveform of baseflow, tends to be smaller in sedimentary rock catchments and large in granite catchments; it is also larger in strike-oriented catchments, similar to granite catchments. The findings align with the recession analysis described in Chapter 4. While the HYCY model previously only considered runoff

from the topography and soil layers, this study enables the model to calculate rainfall–runoff, including the bedrock layers.

Thus, although this study is based solely on data from the Shigaraki Experimental Forest, it provides valuable insights into the rainfall–runoff mechanism in sedimentary rock mountains. To apply these results to deep-seated landslide countermeasures, further research is required to resolve bedrock groundwater in the Shigaraki Experimental Forest and other sedimentary rock mountains. Through such studies, the characteristics of catchments that tend to converge with bedrock groundwater can be clarified, and research methods can be established.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my greatest gratitude to Dr. Ken'ichirou Kosugi, Dr. Shusuke Miyata, Dr. Naoya Masaoka, and Dr. Kana Nakatani, who have supported my laboratory life. In particular, I would like to thank Dr. Ken'ichirou Kosugi for presenting the core research idea of this study described in Chapter 3 to me, a third-year undergraduate student, who had no idea what to expect, and for his help in every aspect, including writing the submitted papers and obtaining research fundings. I am also grateful to Dr. Naoya Masaoka for his help with a number of small-scale studies and accompanying field observations that were not included in this thesis.

In addition to the professors, I am very grateful to my lab mates at the Laboratory of Erosion Control, Kyoto University. In particular, I am grateful to my juniors for helping me with my hard field observations many times, even though it was difficult to say no. I am also grateful to Dr. Satoshi Itokazu, and alumnus of the laboratory, and other senior members of the laboratory for their frequent visits to the Shigaraki Experimental Forest to maintain the weirs and collect the data. Plus, Ms. Michiko Fukuda of the administrative office responded flexibly to complex and urgent requests for research and travel expenses. Thank you very much.

Lastly, I would like to write a note of thanks to my family for understanding and watching over my research life.

January 2025

Jun Inaoka

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