Comparison of Rainfall-Runoff Characteristics in Forested Catchments Underlain by Granitic and Sedimentary Rock with Various Forest Age

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Abstract:

This study examines rainfall-runoff characteristics of catchments underlain by granitic and sedimentary rock. Differences in bedrock geology and forest age for sedimentary rock catchments were considered. In granitic catchment, the quick flow ratio was small and baseflow was sufficient even during dry conditions because of large water storage within the soil and the relatively homogenous weathered bedrock. In sedimentary rock catchments, water that infiltrated to the soil and fractured bedrock drained quickly, causing large quick flow over short, rainstorm timescales. The peak flow was lower in sedimentary rock catchments with older forest where the soils were more developed over longer periods of forest growth. The differences among sedimentary rock catchments by forest age were smaller than the differences between granitic and sedimentary rock catchments. Bedrock geology is of primary importance for categorizing and identifying universal rainfall-runoff characteristics.

KEYWORDS granitic rock, sedimentary rock, rainfall-runoff characteristics, forest age, water yield function

INTRODUCTION

Researchers and the general public have long been concerned with the effects of forests on water resources. In Japan, forests cover approximately 67% of the country and are expected to contribute to public welfare, by mitigating floodwater discharge and drought and by helping to protect water quality. Many paired catchment studies have been conducted to determine the magnitude of water yield changes resulting from changes in vegetation. These studies show that generally forest cutting leads to decreased evapotranspiration rates, resulting in increased annual water yields (e.g., Bosch and Hewlett, 1982; Brown et al., 2005). However, paired catchment studies often assume that other than vegetation conditions, catchment conditions are equivalent; thus, it is difficult to identify the effects of other factors or to conduct interregional comparisons.

The water yield function depends not only on vegetation conditions, but also on other diverse catchment characteristics. Shimizu (1980) examined the rainfall-runoff characteristics of 70 river basins (area: 22.2–471.0 km²) in Japan considering geology, landform, and vegetation. The study found high fluctuations in runoff from sedimentary rock basins, but relatively stable runoff from igneous rock basins. Onda (1994) found clear differences of hydrological characteristics between Paleozoic sedimentary rock and granite catchments, and these differences were shown to affected slope processes and topography of the catchments. Many recent studies have demonstrated the importance of permeable bedrock as water pathways or storage media (e.g., Montgomery and Dietrich, 2002; Katsuyama et al., 2005). These studies imply an important relationship between rainfall-runoff characteristics and bedrock geology, including bedrock groundwater dynamics. However, the direct observation of groundwater geology, including bedrock groundwater dynamics, still remains challenging due to available techniques and associated costs. In addition to this, few studies have considered the effects of forest age on rainfall-runoff characteristics because of difficulties in finding appropriate field sites or conducting continuous long-term observations. We discuss rainfall-runoff characteristics in forest catchments with different bedrock types and forest ages based on rainfall and discharge rate data, which are relatively easy to observe.

SITE DESCRIPTION

Observations were conducted at Kiryu Experimental Watershed (KEW: 34°58’N, 136°00’E; 190–255 m AMSL), Shiga Prefecture, and at Mt. Gomadan Experimental Forest (GEF: 34°04’N, 135°35’E; 860–1370 m AMSL), Nara Prefecture, both located in central Japan. The topographic maps are shown in the Supplements. KEW is underlain by Cretaceous biotite granite, called Tanakami Granite. The area around KEW was long denuded of vegetation, although hillside and forestation works have been carried out over the last century to prevent soil erosion and establish commercial forests. Consequently, 50-yr-old Japanese cypress (Chamaecyparis obtusa Sieb. et Zucc.) covers the watershed. KEW was established in 1967 to study hydrological circulation and related roles of forests, trees, and soil (Lab. Forest Hydrology, Kyoto University, 2006). We used rainfall and discharge rate data from the entire KEW watershed, which included the KH catchment. The catchment covers an area of 5.99 ha and has a mean gradient of 9.2°; mean annual precipitation of 1631.0 mm (1972–2005), and air temperature of 13.5°C (1997–2005). The soil depth ranged from < 1 m to several meters, and the area was abundant with sandy soil. The underlying bedrock had properties of saprolite and was homogeneous weathered (Katsuyama et al., 2005). GEF is underlain by Cretaceous sedimentary rock composed of alternating beds of sandstone and shale with some mudstone. The natural forest was clear-cut
and then afforested mainly with Japanese cedar (Cryptomeria japonica) around this area for timber use from 1912 to 1916. The forest has been well managed. Since 1958, timber harvesting by skyline logging and replanting have coincided with subcatchment boundaries, resulting in a mosaic of variously aged subcatchment stands. Therefore, chronosequence data can be obtained from simultaneous observations in multiple subcatchments (Fukushima and Tokuchi, 2008).

We used data from four subcatchments: S11, S12, S17, and S20. The forest ages in 2005, catchment areas, and hillslope gradients were 29 yr, 6.52 ha, and 25.5° for S11; 17 yr, 7.13 ha, and 29.7° for S12; 90 yr, 3.15 ha, and 31.3° for S17, and 43 yr, 9.55 ha, and 28.1° for S20, respectively. However, in summer 2005, S17 was clear-cut and then reforested. The mean annual precipitation was 2951.2 mm (2004–2006), with snowfall in winter. Soils were shallow, typically ranging from 0.2 to 0.7 m in depth, and composed of much gravel. Arai et al. (2007) found that silt made up approximately 70% of the soil profile at the Kyoto University Wakayama Forest Research Station, which is located 4 km west of GEF and has the same underlying geology. Fukushima and Tokuchi (2008) provide a general description of GEF.

We used the antecedent precipitation index (APIi) as an index of soil moisture, defined as:

\[ API_i = \frac{\sum_{i=1}^{10} (P_{i-10}/i)}{10} \]

where \( P_{i-10} \) is the total rainfall amount \( i \) days beforehand.

**RESULTS**

*Comparison of Rainfall-Runoff Characteristics in Granitic and Sedimentary Rock Catchments*

Catchments KH and S20 had forests of equivalent age. The annual rainfall and discharge rate in 2006 were 1858.7 and 913.4 mm in KH and 2952.7 and 1951.1 mm in S20, respectively (Figure 1). As the annual rainfall in 2006 was typical in both catchments, these hydrographs may be representative in each catchment. Discharge increased quickly in response to rainfall in both catchments. APIi was relatively small and stable in KH compared to S20 during spring and summer, and similar in both catchments at October and November. Rainfall intensity and peak discharge were smaller in KH. Baseflow increased to summer rainy season and decreased to winter dry season. In contrast, after the peak in S20, discharge rates quickly decreased to a similar level as was observed before the rainfall. Baseflow rate is kept about 1 mm, however it largely decreased in November. Generally, the quick flow ratio, (Hewlett and Hibbert, 1967), was smaller under dry conditions in both catchments, and this may be a result of initial soil moisture deficit (Figure 2). The ratio was similar or smaller in S20 than in KH under small rainstorms (<50 mm). When the total rainfall exceeded 50 mm, the ratio was larger even under dry conditions in S20 than that observed in KH under wet conditions. The maximum ratio was approximately 40% for KH and >60% for S20. These trends observed in GEF were similar to results from other sedimentary rock catchments (Tani, 1997).

*Comparison of Rainfall-Runoff Characteristics among Sedimentary Rock Catchments with Forests of Different Age*

The standardized flow duration curves (FDC; Appendix A) calculated from the daily discharge rate and annual rainfall from 2004 to 2006 clearly differ between the granite catchment KH and the sedimentary rock catchments (Figure 3). The plentiful discharges were larger in GEF catchments than that in KH. However, the low and scanty discharges were similar or smaller in GEF than in KH, and the scanty discharges were very small in S12 and S17. The flow conditions varied less throughout the year in KH. The catchment with the oldest forest (S17_06) always had smaller discharge, and the low discharge decreased after the clear-cut (S17_06). The catchment with the young forest (S12) had large plentiful discharge and small low and scanty discharge. The differences between S11 and S20 were small.

Storm hydrographs for the four sedimentary rock catchments in December 2004, July 2005, and June–July 2006, illustrate that peak discharge decreased in the following order: S12, S11, S17, and S20 (Figure 4). This suggests that the peak discharge substantially decreased with the increase in forest age. However, the peak discharge was larger for S17 (90-yr-old forest) than for S20 (43-yr-old forest). The effects of clear-cut and reforestation in 2005 at S17 on the discharge rate for 2006 were unclear because only skyline logging was conducted, resulting in little disturbance to the ground surface and conserving the soil structure.

**Discussion**

*Effects of Differences in Bedrock Geology on Rainfall-Runoff Characteristics*

The hillslope gradient affects colluvium sedimenta-
tion and riparian zone development. Riparian zones affect runoff generation and hydrochemical processes in catchments with gentle slopes (McGlynn et al., 1999). KH had a gentle hillslope, allowing for the presence of riparian zones in the headwater subcatchment and along the main stream. Katsuyama et al. (2005) reported that KH had permeable saprolite bedrock, and plentiful bedrock groundwater recharged the riparian zone and that the close relationships between the riparian zone and bedrock groundwater controlled the hydrological processes of the catchment. In contrast, Onda et al. (2006) observed runoff generation processes in extremely steep terrain underlain by relatively unweathered granite and shale catchments. Although the maximum runoff peak coincided with the rainfall peak in the granite catchments, the peak was delayed or a secondary peak occurred after a rainstorm in the shale catchments. Such delayed and secondary peaks were formed by soil water that percolated into the bedrock. However, the quick flow ratio was 40% in the granite catchments, it was 80% in the sedimentary rock catchments (Onda et al., 2006). These findings indicate that granite catchments have greater water storage potential, and much groundwater stored within the soil, weathered bedrock, and riparian sediments will be contributed to baseflow compared to sedimentary rock catchments.

Tani (1997) reported that a small catchment of sedimentary rock with relatively gentle slope (23.8°) produced large storm runoff volumes with high flow peaks; the runoff ratio reached 100% during rainstorms when the antecedent soil conditions were sufficiently wet. Montgomery and Dietrich (2002) reported based on observations in steep sandstone catchments that storm runoff occurred as subsurface flow in which water passed through partially saturated soil, into the shallow fractured bedrock, to emerge as subsurface partial source areas near the channel head. They concluded that the hydrological response of steep catchments appears to be insensitive to slope. Therefore, the soil water and groundwater will quickly drain through relatively shallow pathways in sedimentary rock catchments regardless of hillslope gradient, and the response in GEF will be explained by these mechanisms.

Holmes et al. (2002) showed the influence of geology on the water storage potentials and on the gradient of a standardized FDCs in the United Kingdom. The study found that impermeable catchments have high gradient curves reflecting a very variable flow regime because low storage of water in the catchment results in a quick response to rainfall and low flows in the absence of rainfall. Low gradient FDCs indicate that the variance of daily flows is low, because of the damping effects of groundwater storages provided naturally. Kato et al. (2000) also found similar patterns of FDCs based on observations in granitic and mesozoic sedimentary rock catchments with steep gradients. Granite catchments were found to have low gradient FDCs (Kato et al., 2000). Some sedimentary rock catchments had high gradient FDCs, though others had low gradient FDCs like granite catchments, and they concluded that sedimentary rock catchments have a variety of flow characteristics.

Durner and Flüehler (2005) have shown that for typical soil hydraulic properties, which are products of weathering; there is little runoff of soil water stored in micro-pores at high tension under dry conditions in silty or clayey soils. This trend was found to be common in sedimentary rock eluvium. As GEP had a silty soil, there might be few pores into which water could infiltrate during rainstorms. In contrast, the soil water content suddenly decreased under dry conditions in sandy soil which are common in granite eluvium. The soils in KEW have such characteristics (Kosugi et al., 2006). Therefore, much rainwater could infiltrate the soil during rainstorms, and the discharge rate under drier conditions would be sustained by stored water in KH.

Therefore, the differences in the rainfall-runoff processes of the catchments resulted from the bedrock geology and resultant soil characteristics. The small quick flow ratios and sufficient baseflow observed in the granite catchment resulted from large water storage within the catchment, including in the relatively homogeneous weathered bedrock medium. In the sedimentary rock catchments, in contrast, infiltrated water to the soil and fractured bedrock drained quickly, causing large quick flow over short, rainstorm timescales. These patterns may result from the weathering pattern, that is, the homogeneous weathering encourages the storage of water, and the heterogeneous fractures promote rapid transmission of water.

Effects of Forest Age on Storm Flow Peak Discharge

In the sedimentary rock catchments in our study, storm flow peak discharge was substantially decreased in older forest (Figure 4). Generally, forest disturbance will cause the increase of discharge rate because evapotranspiration rate will decrease (Brown et al., 2005). Fukushima (2006) simulated hydrographs for granite catchments, including the KH, at various forest ages and conditions using a rainfall-runoff model and found that the hydrographs for the bare catchment had rapid changes and wide fluctuations, whereas the hydrographs for a catchment > 100 yr after restoration had only mild changes. The change in evapotranspiration was unclear in GEF, however, the evapotranspiration may contribute less to storm flow peak discharge. In contrast, the soil layer development with forest age may be important. The depths of Ai, soil layer were increased in GEF along with forest growth; mean (s.d.) depths were 1.52 (1.42), 4.40 (1.83), 5.15 (1.84), 6.67 (2.49), 7.08 (1.83) cm in 5, 18, 33, 44, 90 yr forest, respectively (Fukushima, Unpublished data). Ai soil layer will act as a buffer for quick flow, and these patterns are agreeable with the peak discharge, that is, both the peak flow height and Ai soil depth reach the ceiling around 40-yr-old forests (Figure 4). Moreover, the chronosequence data about forest growth in GEF (Tateno, Unpublished data) indicate that the growth rate slows down around 40-yr-old forests. The reason for the increase in peak discharge in S17 (90-yr-old) is uncertain and may be concerned with such forest dynamics. However, peak flows in older forests (S20 and S17) were clearly smaller than in younger (S12 and S11) forests. Therefore, forest growth can mitigate flood runoff. Moreover, the peak flow was unchanged after the clear-cut and skyline logging was carried out because the area was immedi-
COMPARISON OF RAINFALL-RUNOFF CHARACTERISTICS

atley reforested and the forest floor undisturbed. Moreover, Japanese cedar roots begin to decay several years after cutting (Tsukamoto, 1987). Therefore, the effects of timber harvesting might not be actualized yet. Further continuous monitoring will help to clarify changes in flow conditions in relation to forest management for timber use.

CONCLUSIONS

We examined the effects of bedrock geology and forest age on rainfall-runoff characteristics in forested catchments. In the context of the water yield function of forests, granite catchments showed greater potential to mitigate both floodwater discharges and drought. In sedimentary rock catchments, the peak discharge mitigated with the development of forest soil. However, the effects of bedrock geology were stronger than those of forest age. The water yield potential of sedimentary rock catchments showed little improvement in relation to forest establishment and growth, even for well-managed plantation forests. Therefore, bedrock geology appears to be a critical parameter for categorizing and identifying universal rainfall-runoff characteristics and for accurate evaluation of water yield function.

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SUPPLEMENTS

S1. Topographic map of KEW (Left) and GEF (Right)

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APPENDIX A: DEFINITION OF THE FLOW DURATION CURVE (FDC)

The commonly used FDC in Japan, particularly for river engineering and water resources managements, differs slightly from that used in other countries, although it is translated into English as “flow duration curve”.

Definition in Japan is a curve that shows the descending order of annual daily discharge rate. The y-axis indicates the daily discharge rate; the x-axis indicates the order of day. The discharge rates on the 95th, 185th, 275th, and 355th day are defined as plentiful, ordinary, low, and scanty discharges, respectively.

Definition of outside Japan is a curve that shows the percentage of time during which the flow of a stream is equal to or greater than a given amount, regardless of chronological order. The y-axis indicates the discharge rate (not necessarily daily discharge); the x-axis indicates the percentage of time that the indicated discharge was equaled or exceeded.

We followed the definition in Japan, though we standardize the y-axis by annual rainfall. Strictly, these definitions and methods are different; however, the difference presents no problem for practical comparisons. According to the definition of outside Japan, plentiful, ordinary, low, and scanty discharges correspond to 26, 51, 75, and 97% of the x-axis, respectively.