Effects of bedrock groundwater dynamics on runoff generation: a case study on granodiorite headwater catchments, western Tanzawa Mountains, Japan

Yutaka Abe¹, Yoshimi Uchiyama¹, Masahiko Saito², Mitsuru Ohira³ and Takahide Yokoyama¹

¹Kanagawa Prefecture Natural Environment Conservation Center, Japan
²Faculty of Agriculture, Ehime University, Japan
³Department of International Environmental and Agricultural Science, Tokyo University of Agriculture and Technology, Japan

Abstract:
This study investigated runoff to clarify the effect of bedrock groundwater dynamics on runoff generation processes in granodiorite headwater catchments (NA and NB) located in the western Tanzawa Mountains, Central Japan. The rainfall–runoff response and water balance calculated using the hydrological cycle (HYCY) model with outflow were also analyzed based on the observed precipitation, runoff, and bedrock groundwater level (at a depth of 50 m). In 2013, the annual runoff rate was 398 mm (21% of the rainfall) in NA and 1209 mm (63% of the rainfall) in NB, respectively. The bedrock groundwater level varied for approximately 3 m, and responded to 30-mm rainfall events. The significant relationship between the base flow and bedrock groundwater level indicated that the bedrock groundwater markedly influenced base flow generation. The calculated annual bedrock infiltration values of 656 mm (34% of the rainfall) in NA and 52 mm (3% of the rainfall) in NB significantly influenced the runoff rate. Our results demonstrated that significant and negligible amounts of bedrock groundwater infiltration were observed, even in neighboring catchments. Those bedrock groundwater dynamics significantly influenced the observed differences in the runoff rate and base flow generation.

KEYWORDS runoff; bedrock groundwater infiltration; granodiorite; HCYC model with outflow; Tanzawa Mountains

INTRODUCTION
Several studies have investigated runoff generation systems in small catchments based on rainfall, runoff, and water quality observations (Dunne and Black, 1970; Mosley, 1979; Fukushima and Suzuki, 1986). These studies assumed that the permeabilities of bedrock in the catchments were low and that the infiltration of water into the bedrock and the outflow to other catchments were small. However, groundwater infiltration into bedrock has been observed in several catchments at high rates (Shimada et al., 1981; Kosugi et al., 2006). Furthermore, many studies have reported that bedrock groundwater plays a significant role in runoff generation (Onda et al., 2001; Uchida et al., 2003).

Indirect methods have been developed to estimate the infiltration rate and bedrock groundwater discharge because of difficulties associated with performing direct measurements. Bedrock groundwater infiltration is often estimated based on a water budget analysis that considers rainfall, runoff, and evapotranspiration observations or estimations (Terajima et al., 1993; Katsuyama et al., 2010). Oda et al. (2013) quantified bedrock flow using a chloride mass balance method, which can accurately estimate bedrock infiltration without observations of evapotranspiration. They observed that the base flow rate could be determined by groundwater flow through bedrock and inter-catchment groundwater transfer in second- and third-order catchments. Further, Wakahara et al. (2014) modified the hydrological cycle (HYCY) model (Fukushima, 1988) to quantify outflow from catchments in the form of deep infiltration or lateral flow and demonstrated that low base flow was caused by outflow escaping from the basin. Kosugi et al. (2006) directly measured bedrock infiltration. They conducted hydrometric observations using soil and bedrock tensiometers and clarified the importance of the soil layer properties as a water storage buffer to prevent the infiltration of water into the bedrock. However, investigations of runoff generation processes, including the quantitative bedrock groundwater infiltration rate, are limited. Furthermore, direct observations of bedrock groundwater are rare in the case of headwater catchments, even though these observations can be used to examine the relationship between the observed bedrock groundwater levels and runoff generation to understand bedrock groundwater storage and discharge systems (Kosugi et al., 2011; Iwagami et al., 2010).

In this paper, we clarify bedrock groundwater dynamics and its role in runoff generation processes in granodiorite headwater catchments. We conducted runoff analysis based on observed hydrological data, including the direct bedrock groundwater level, and modeling to quantify groundwater infiltration and clarify the effects of bedrock groundwater on runoff generation.

© The Author(s) 2020. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
METHODS

Site description

This study was conducted in a neighboring headwater catchment located in the Nutano experimental watershed in the western Tanzawa Mountains, northwestern Kanagawa Prefecture (35°28.0'N, 139°03.8'E), Central Japan (Figure 1). Two observation catchments were established for paired catchment analysis to monitor the effects of forest management on the water cycle. Catchment NA (3.8 ha) is for the management of a deer-enclosure fence established in April 2014, whereas catchment NB (3.1 ha) is for untreated control conditions. The elevation is 530–705 m above sea level (a.s.l.). The geology comprises Miocene granodiorite. Catchment NA is a deep V-shaped valley, whereas NB has a gentle slope. The soil depth in the steep slopes occupying the majority of the catchments is several tens of centimeters, whereas that in the ridges and flat plateau downstream reaches 2–3 m. The forest structure and vegetation conditions in the two catchments are similar and primarily comprise broadleaved forests, including Japanese hornbeam (Carpinus laxiflora) and Japanese zelkava (Zelkova serrata), as well as Japanese cedar (Cryptomeria japonica) and cypress (Chamaecyparis obtusa) to some extent. Several sabo dams were constructed up to 2005 in response to landslide disasters in 1972. All the dams in NA are filled with sediments, except for the most upstream dam, and surface water often disappears by infiltrating into the sediments. However, as the majority of the dams in NB are not filled with sediments, the surface flow is almost continuous along the entire length of the channel throughout the year (Yokoyama et al., 2013). The mean annual precipitation from 2009 to 2018 was 2400 mm (Tanzawako Lake, AMeDAS), and the mean temperature was 12°C (Uchiyama et al., 2015).

Measurement

V-notch weirs (90°) were installed to observe the runoff at the end of catchments NA and NB at identical elevations of 530 m a.s.l. (Figure 1). The water level was monitored from April 2011 at 10-min intervals using a pressure-type water-level gauge (UIZ-GY1000A, UIZIN Co., Ltd). The amount of runoff flow (Q) was calculated from the overflow water level (H) using the H–Q equation determined from in situ measurements (Uchiyama et al., 2015). Furthermore, precipitation was measured using a tipping bucket rain gauge (OW-34-BP, Ota Keiki Seisakusho Co., Ltd.) installed near the NA runoff observation point. A 50-m-deep groundwater observation well was dug on a ridge at the border of these catchments (ground level at 585 m a.s.l.). Core samples indicated weathered quartz diorite with several cracks throughout the depth of the observation well; strong weathering can be particularly evident from the surface to a depth of 31 m and from a depth of 42–50 m (Yokoyama et al., 2013). The groundwater level was measured at 1-h intervals using a pressure-type water level meter (UIZ-WL1000-N19, UIZIN Co., Ltd). A single rainfall event can be defined as ≥1 mm of precipitation for analyzing the runoff response to a given rainfall event. Consecutive rainfall events were separated by a period in which there was no rainfall for more than 24 h after the precipitation ceased. The runoff was separated into quick and base flow using the method proposed by Hewlett and Hibbert (1967) with a time-based separation line of 0.0055 L/s/ha/h.

In this study, we used the HYCY model (Fukushima, 1988) by incorporating the outflow factor proposed by Wakahara et al. (2014) to estimate outflow such as groundwater flow into bedrock or other watersheds. The outflow component representing the bedrock groundwater infiltration was attached to the base flow tank and was calculated by multiplying the outflow ratio and the base flow rate under the assumption that bedrock infiltration mainly occurs through the stream bed. The model can output runoff, base flow, evapotranspiration, and bedrock infiltration based on the observed runoff and rainfall input. This is an effective method to understand rainfall runoff generation and estimate water balance, including bedrock infiltration, when runoff and rainfall observations are available. Furthermore, we used the evapotranspiration parameters of Fukushima (1988). Even though their study site was located 300 km west of our site, their parameters can be applied to perform a brief estimation because of similar annual evapotranspiration. The difference in annual evapotranspiration estimated with a formula based on the annual temperature (Komatsu et al., 2008) was 20 mm between these two sites. Meanwhile, Kondo et al. (1992) estimated 800–900 mm of annual evapotranspiration around both sites. The parameters shown in Table I were determined by minimizing the difference between the calculated and observed runoff on the base flow and duration curves in the hydrograph as well as the total annual amount. The calculated amount of bedrock infiltration was verified based on the annual water balance as follows:

![Figure 1. Location and topography of the study site](image-url)
\[ R = Q + ET + B + \Delta S \]  

where \( R \) (mm) is the annual rainfall, \( Q \) (mm) is the runoff, \( ET \) (mm) is the evapotranspiration, \( B \) (mm) is the bedrock infiltration, and \( \Delta S \) (mm) is the change in storage.

Annual runoff characteristic analysis was conducted with respect to the observation period from 2012 to 2018. We focused on 2013 (January 1 to December 31, 2013) to eliminate the effect of vegetation changes owing to forest management on the rainfall–runoff response and water balance analysis. This is the only period that both catchments were untreated and groundwater level data were obtained.

**RESULTS**

**Annual changes in runoff, rainfall, and groundwater level**

The total runoff, mean groundwater level, and annual rainfall exhibited similar interannual trends (Figure 2a). The annual runoff was 330–1340 mm (mean: 600 mm; SD: 251 mm) in NA and 1210–1870 mm (mean: 1490 mm; SD: 233 mm) in NB. The total runoff in NB was 1.4–4.1 times greater than that in NA. In addition, the stream flow ceased in NA for up to 128 days in a year; however, this phenomenon was not observed in NB (Figure 2b). The mean annual groundwater level was 564.7–565.5 m a.s.l. The total runoff and mean annual groundwater level increased simultaneously when the total rainfall became greater than 2500 mm in 2012, 2015, and 2018. However, reduced runoff was observed when the rainfall was less than 2000 mm in 2013, 2014, and 2017.

**Runoff and groundwater level response**

The base flow in both catchments exhibited similar groundwater level trends, and runoff in NA and NB increased when a rainfall event occurred (Figure 3). Maximum runoff values of 46.5 and 47.8 mm/day were observed in NA and NB, respectively, for a 350.5-mm rainfall event during September 15–17, 2013. The base flow in NA was 0–3.1 mm/day, with a mean of 0.7 mm/day, whereas that in NB was 1.4–5.2 mm/day, with a mean of 2.8 mm/day. Furthermore, the groundwater level was 563.4–566.7 m a.s.l. The baseline for runoff variations was similar to the tempo-

| Parameters | NA   | NB   |
|------------|------|------|
| C          | 0.035| 0.035|
| j          | 2    | 2    |
| \( D_{16} \) | 38   | 18   |
| \( D_{50} \) | 100  | 120  |
| \( K_c \)  | 2    | 2    |
| \( K_b \)  | 3    | 6    |
| \( K_{in} \) | 3    | 2    |
| \( P_b \)  | 0.1  | 0.1  |
| \( K_{1} \) | 2100 | 4000 |

**Figure 2. Annual variation in (a) rainfall, runoff and groundwater level and (b) number of days with no runoff**

**Figure 3. Hyetograph and hydrograph of the observed runoff and groundwater level**
eral groundwater level variations. However, in November and December, the runoff in NA decreased to 0 mm even though the groundwater level and runoff in NB were not the lowest.

Examining the relationship between the rainfall event and runoff components shows that the runoff and quick flow in the catchments were positively correlated with the amount of event rainfall ($p < 0.01$) (Figure 4a). The quick flow in NA began to increase in some rainfall events of more than ~30 mm. The quick flow in NB was observed to clearly increase in the case of rainfall events of more than ~15-mm. Furthermore, the increase in groundwater level, which is the height difference between the initial and peak levels in a rainfall event, was positively correlated with the rainfall amount of the event ($p < 0.01$) and began increasing for >10-mm rainfall events (Figure 4a). A smaller increase (up to 20 cm) or no groundwater level response were observed during 10–30-mm rainfall events. The increase in groundwater level was 7–300 cm for 30–350-

Figure 4. (a) Runoff and groundwater responses to a rainfall event and (b) relationship between the daily base flow and groundwater level

The HYCY model and annual water balance

The calculated runoff in NA and NB was approximated from the observed runoff by setting the parameters as shown in Table 1 in the HYCY model with outflow. The plots used to compare the calculated and observed runoff in the daily unit were mostly located on a one-to-one line (Figure 5a). Furthermore, temporal variation in the calculated runoff approximately fitted the observed runoff baseline (Figure 5b). The calculated annual runoff amounts of 421 and 1208 mm closely reproduced the observed annual runoff amounts of 398 and 1209 mm in NA and NB, respectively. However, there were some periods during which we could not completely reproduce the runoff amounts in NA, particularly during January and

Figure 5. A comparison of the observed and calculated daily runoff with (a) scatter diagram and (b) hydrograph
September–December. For example, we could not reproduce the rapid decrease in runoff in NA from November to December (Figure 5b).

The estimated annual bedrock groundwater infiltration in NA and NB were 656 and 52 mm, respectively. The model also provided annual evapotranspiration of 737 and 738 mm in NA and NB, respectively. When compared with the annual evapotranspiration rate of 799–898 mm in the forest catchment located 13 km east from our catchments in Tanzawa Mountains (Momiyama et al., 2019), our values suggest an underestimation. We obtained the following annual amounts (mm) and percentages to rainfall (%) for the water balance components in equation (1) in NA and NB for 2013: \( R \): 1920 mm; \( Q_{\text{vai}} \): 398 mm (21%); \( ET_{\text{vai}} \): 737 mm (38%); \( B_{\text{vai}} \): 656 mm (34%); \( \Delta S_{\text{vai}} \): 129 mm (7%); \( Q_{\text{ai}} \): 1209 mm (63%); \( ET_{\text{ai}} \): 738 mm (38%); \( B_{\text{ai}} \): 52 mm (3%); and \( \Delta S_{\text{ai}} \): –79 mm (–4%). The small \( \Delta S \) values (7% and –4%) in the catchments indicated that our estimated values were suitable in the water balance. Furthermore, the water loss was 1522 mm in NA and 711 mm in NB.

**DISCUSSION**

*Bedrock groundwater dynamics*

The groundwater level varied by approximately 3.3 m in a given year (Figure 3) and responded to >30-mm rainfall events, despite the 50-m-deep observation well representing the bedrock groundwater level (Figure 4). Several studies have reported that groundwater water levels varied from 6 to 25 m in 12–69-m-deep observation wells in granite mountainous catchments (Kosugi et al., 2011; Fujimoto et al., 2014; Katsura et al., 2014). The granite bedrock in these studies included strongly weathered rocks. In our case, the bedrock also comprised strongly weathered quartz diorite and several cracks in the observation well were evident (Yokoyama et al., 2013). The large temporal variations in the groundwater level and the response of groundwater level to rainfall were probably due to rapid rainwater infiltration through the strongly weathered bedrock and/or cracks.

The estimated annual amount of bedrock groundwater infiltration represented a significant rate in NA (656 mm, 34% of the rainfall), but was negligible in neighboring NB (52 mm, 3% of the rainfall). The large difference in the annual amount of observed water loss between NA (1522 mm) and NB (711 mm) may support the notion of a significant rate of bedrock groundwater infiltration in the strongly weathered bedrock through bedrock or cracks.

The annual water balance indicates that the low annual runoff rate in NA (398 mm, 21% of the rainfall) can be attributed to a significant rate of bedrock groundwater infiltration (656 mm, 34% of the rainfall) when compared with the runoff (1209 mm, 63% of the rainfall) and bedrock infiltration (52 mm, 3% of the rainfall) in NB. A significant amount of bedrock infiltration probably caused a lower runoff rate in NA. Furthermore, the bedrock groundwater level significantly influenced the base flow generation in both catchments (Figure 4). Several studies on tracer analysis and hydrological observations denoted the fact that bedrock groundwater substantially influences base flow generation (e.g. Onda et al., 2001; Katsuyama et al., 2005; Oda et al., 2013). Our results support the findings of previous studies that bedrock groundwater has a considerable effect on base flow rates. However, the runoff in NA decreased to 0 mm when the groundwater level and runoff in NB were not at their lowest values in November and December (Figure 3). Our model could not accurately reproduce the runoff in NA during that period (Figure 5b). Kosugi et al. (2011) investigated three small bedrock aquifers that were divided by fault lines in a 2.1-ha granite catchment and suggested that the spatial expanse of each aquifer and interaction among the aquifers controlled the temporal base flow pattern and multiple peak responses of the streamflow. Such runoff generation processes, which are related to multiple groundwater storage with different residence time and discharge timing, may possibly explain the significant decrease in runoff that only occurred in NA. Moreover, groundwater storage in the soil or bedrock may be changed by the movement of the sediments present near the stream by large storm events because these discrepancy periods were categorized based on the occurrence of large storm events. A simple system that employs a static percentage of the base flow rate for estimating the bedrock infiltration in our model could not express the temporal variations in runoff during some periods in NA. This poor fit may indicate that the runoff processes in NA involve a complex storage system, including a long-term or large-scale groundwater storage and discharge system, groundwater interaction in the neighboring catchments, or temporal changes in runoff patterns.

**CONCLUSIONS**

Runoff and modeling analyses were conducted to quantify bedrock groundwater dynamics and clarify its effects on runoff generation in two neighboring granodiorite headwater catchments NA and NB. The following conclusions were reached:

1. The underlying granodiorite rock in our study area was permeable owing to the presence of strongly weathered bedrock or faults, and rapid rainfall infiltration occurred through bedrock or cracks.

2. The mean base flow in NB (2.8 mm/day) was four times greater than that in NA (0.7 mm/day). The base flow rates in these catchments are likely to be controlled based on the bedrock groundwater level.
3. Annual bedrock infiltration amounts of 656 mm (34% of the rainfall) and 52 mm (3% of the rainfall) were estimated in NA and NB, respectively, using the HYCY model with outflow. Bedrock infiltration contributed to substantially reduced rates of annual runoff and base flow in NA when compared with those in NB.

4. The discrepancies in the observed and calculated runoff rate using a simple bedrock groundwater infiltration estimation model, based on the static percentage of the base flow rate in some period, may indicate that the runoff processes include a complex and/or long-term groundwater storage and discharge system in NA.

These results demonstrate that the occurrence of significant and negligible amounts of bedrock groundwater infiltration in neighboring catchments led to significant differences in the runoff and base flow generation characteristics. Further research on the long-term groundwater storage and discharge system, including complex bedrock groundwater dynamic processes, is necessary for elucidating these processes. Soil water and evapotranspiration should be further investigated to better understand the runoff and groundwater generation processes.

ACKNOWLEDGMENTS

This study was supported by a research project on the environmental conservation of water resources by the Kanagawa Prefectural Government, Japan.

REFERENCES

Dunne T, Black RD. 1970. An experimental investigation of runoff production in permeable soils. Water Resources Research 6: 478–490. DOI: 10.1029/WR006i002p00478.

Fujimoto M, Kosugi K, Tani M, Banba N, Fukagawa R. 2014. Evaluation of Bedrock Groundwater Movement in a Weathered Granite Hillslope Using Tracer Methods. International Journal of Erosion Control Engineering 7: 32–40. DOI: 10.13101/ijec.7.32.

Fukushima Y, Suzuki M. 1986. Hydrologic cycle model for mountain watersheds and its application to the continuous 10 years records at intervals of both a day and an hour of Kiryu Watershed, Shiga Prefecture. Bulletin of the Kyoto University Forests 57: 162–185 (in Japanese with English summary).

Fukushima Y. 1988. A model of river flow forecasting for a small forested mountain catchment. Hydrological Processes 2: 167–185. DOI: 10.1002/hyp.3360020207.

Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In Forest hydrology, Sopper WE, Lull HW (eds). Pergamon Press, New York; 275–290.

Iwagami S, Tsujimura M, Onda Y, Shimada J, Tanaka T. 2010. Role of bedrock groundwater in the rainfall–runoff process in a small headwater catchment underlain by volcanic rock. Hydrological Processes 24: 2771–2783. DOI: 10.1002/hyp.7690.

Katsura S, Kosugi K, Yamakawa Y, Mizuyama T. 2014. Field evidence of groundwater ridging in a slope of a granite watershed without the capillary fringe effect. Journal of Hydrology 511: 703–718. DOI: 10.1016/j.jhydrol.2014.02.021.

Katsuyama M, Ohte N, Kabeyama N. 2005. Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment. Water Resources Research 41: W01010. DOI: 10.1029/2004WR003275.

Katsuyama M, Tani M, Nishimoto S. 2010. Connection between streamwater mean residence time and bedrock groundwater recharge/discharge dynamics in weathered granite catchments. Hydrological Processes 24: 2287–2299. DOI: 10.1002/hyp.7741.

Komatsu H, Maita E, Otsuki K. 2008. A model to estimate annual forest evapotranspiration in Japan from mean annual temperature. Journal of Hydrology 348: 330–340. DOI: 10.1016/j.jhydrol.2007.10.006.

Kondo J, Nakazono M, Watanabe T, Kuwagata T. 1992. Hydrological climate in Japan (3) Evapotranspiration from forest. Journal of Japan Society of Hydrology and Water Resources 5(4): 8–18 (in Japanese with English summary). DOI: 10.3178/jjshwr.5.4_8.

Kosugi K, Katsura S, Katsuyama M, Mizuyama T. 2006. Water flow processes in weathered granite bedrock and their effects on runoff generation in a small headwater catchment. Water Resources Research 42: W02414. DOI: 10.1029/2005WR004275.

Kosugi K, Fujimoto M, Katsura S, Kato H, Sando Y, Mizuyama T. 2011. Localized bedrock aquifer distribution explains discharge from a headwater catchment. Water Resources Research 47: W07530. DOI: 10.1029/2010WR009884.

Momiyama H, Kumagai T, Egusa T. 2019. Reproducing monthly evapotranspiration from a coniferous plantation watershed in Japan. Journal of Forest Research 24: 197–200. DOI: 10.1080/13416979.2019.1604606.

Mosley PM. 1979. Streamflow generation in a forested watershed, New Zealand. Water Resources Research 15: 795–806. DOI: 10.1029/WR015i004p00795.

Oda T, Suzuki M, Egusa T, Uchiyama Y. 2013. Effect of bedrock flow on catchment rainfall-runoff characteristics and the water balance in forested catchments in Tanzawa Mountains, Japan. Hydrological Processes 27: 3864–3872. DOI: 10.1002/hyp.9497.

Onda Y, Komatsu Y, Tsujimura M, Fujihara J. 2001. The role of subsurface runoff through bedrock on storm flow generation. Hydrological Processes 15: 1693–1706. DOI: 10.1002/hyp.234.

Shimada J, Momota H, Ono Y. 1981. Role of Groundwater in the Bedrock for Underground Oil Storage: A Hydrological Case Study of Small Granite Island. Subsurface Space 1: 393–400. DOI: 10.1016/B978-1-4832-8427-1.50061-2.

Terajima T, Mori A, Ishii H. 1993. Comparative study of deep percolation amount in two small catchments in granitic mountain. Journal of Japanese Association of Hydrological Sciences 23: 105–118 (in Japanese with English summary).

Uchida T, Asano Y, Ohte N, Mizuyama T. 2003. Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope. Water Resources Research 39: 1018. DOI: 10.1029/2002WR001298.

Uchiyama Y, Yokoyama T, Masatoshi M. 2015. Runoff characteristics in Nutanosawa Watershed in Tanzawa Mountains. Bulletin of the Kanagawa Prefecture Natural Environment Conservation Center 13: 39–47 (in Japanese).

Wakahara T, Shiraki K, Suzuki M. 2014. Comparison of runoff characteristics of two adjacent basins in a tropical rainforest using a modified hydrologic cycle model with outflow. Hydrological Processes 28: 509–520. DOI: 10.1002/hyp.9602.

Yokoyama T, Uchiyama Y, Yamane M. 2013. Characteristics of hydrogeology and discharge of the Nutanosawa, a branch of Nakagawa River in the Western Tanzawa Mountains. Bulletin of the Kanagawa Prefecture Natural Environment Conservation Center 10: 101–113 (in Japanese).