Sensitivity of annual runoff to interannual precipitation variations for forested catchments in Japan

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Abstract:

This study examined interannual variations in runoff from forested catchments in Japan, corresponding to interannual variations in precipitation. We hypothesized that interannual variations in runoff are comparable to those in precipitation in Japan under the assumption of high annual precipitation (P) relative to annual potential evapotranspiration (Eₚ). We collated P and annual runoff (Q) data derived from 20 catchments in Japan and 37 catchments in other regions around the world (including Australia and the United States). We calculated a sensitivity index (s), which is defined by the slope of the relationship between P and Q, for each catchment. The majority of the data (70%) for Japan satisfied s ≥ 0.80. No data satisfied s < 0.40. These results contrast with those for other regions: only 35% of the data satisfied s ≥ 0.80 and there were several data satisfying s < 0.40. We also confirmed that high s values were observed for regions with high P relative to Eₚ and that P was higher than Eₚ for all catchments in Japan. Our results indicate that interannual variations in Q are generally comparable to those in P for forested catchments in Japan.

KEYWORDS catchment; forest; interannual variations; Japan; precipitation; runoff

INTRODUCTION

As precipitation is an important factor determining catchment runoff, examining the relationship between precipitation and runoff has been a critical goal in hydrology (Wards and Robinson, 2000). In Japan, forests cover 67% of the land surface and are mainly distributed in water-source areas; i.e., upstream of urban and agricultural areas (Sawano et al., 2005). Therefore, numerous researchers in Japan have measured precipitation and runoff for forested catchments and have examined the relationship between precipitation and runoff at various time scales, such as hourly, monthly, and annual scales (Gomi et al., 2010; Komatsu et al., 2010a).

The relationship between annual precipitation (P) and annual runoff (Q) is useful for representing the catchment water cycle. Previous studies in Japan (Hattori, 1992; Maita, 2005; Komatsu et al., 2008) have examined the relationship using data for the mean annual precipitation (Pₘ) and runoff (Qₘ) for the measurement period. For example, Hattori (1992) reported that annual evapotranspiration calculated as

\[ Pₘ \text{ minus } Qₘ \]  

for forested catchments in Japan is generally comparable to that in mid-latitude regions and lower than that in low-latitude regions. Thus, for a given Pₘ, Qₘ in Japan is generally comparable to that in mid-latitude regions and higher than that in low-latitude regions.

Besides determining the relationship between Pₘ and Qₘ, it is important to clarify interannual variations in Q corresponding to those in P, which represent the stability of Q and therefore water resources. According to Koster and Suarez’s (1999) theoretical study, the sensitivity of Q to interannual variations in P could vary among regions owing to climatological differences. For regions with low sensitivity, interannual variations in Q are less significant than those in P, suggesting stability of water resources. For regions with high sensitivity, interannual variations in Q are comparable to those in P, suggesting variability of water resources. Thus, information about the sensitivity for each region is practically important especially for water resource management (Koster and Suarez, 1999; Potter and Zhang, 2009).

Despite this importance, there have been no studies examining the sensitivity of Q to interannual variations in P for forested catchments in Japan. This study collates P and Q data derived from forested catchments (typically 10⁶ km² in area) in Japan and in other regions across the world. Comparing the data for Japan with those for other regions, we aim to clarify characteristics of the sensitivity for forested catchments in Japan. We use Budyko’s (1974) evapotranspiration model to develop our hypothesis. Koster and Suarez (1999), using a global circulation model, suggested that Budyko’s model could be used to explain the sensitivity. Succeeding studies (Milly and Dunne, 2002; Potter and Zhang, 2009) verified the applicability of this model using observation data at a large-watershed scale (typically larger than 10⁵ km² in area). However, the applicability of the model has not been verified using observation data at a catchment scale. Thus, another aim of this study is to confirm the applicability of Budyko’s model to data at this scale.

HYPOTHESIS

Assuming no change in catchment water storage between hydrological years and no subsurface inflow/outflow, Q is written as

\[ Q = P - E \]
\[ Q = P - E, \]  
\[ (1) \]

where \( E \) is annual evapotranspiration. The validity and limitations of assuming no change in catchment water storage are discussed later in this paper. Partially differentiating Equation (1) by \( P \), we obtain

\[ \frac{\partial Q}{\partial P} = 1 - \frac{\partial E}{\partial P}. \]  
\[ (2) \]

We assumed that \( E \) is determined by \( P \) and annual potential evapotranspiration \( (E_p) \) on the basis of Budyko’s (Budyko, 1974) and other Budyko-like models employing limiting theory (Zhang et al., 2001):

\[ E = P \]  
\[ (3) \]  
\[ \text{where } P/E_p \ll 1, \]

\[ E = E_p \]  
\[ (4) \]  
\[ \text{where } P/E_p \gg 1. \]

Partially differentiating these equations by \( P \) and then substituting them into Equation (2), we obtain

\[ \frac{\partial Q}{\partial P} = 0 \]  
\[ (5) \]  
\[ \text{where } P/E_p \ll 1, \]

\[ \frac{\partial Q}{\partial P} = 1 \]  
\[ (6) \]  
\[ \text{when } P/E_p \gg 1. \]

where we assumed \( \frac{\partial E}{\partial P} = 0 \). This assumption was made on the basis of Koster and Suarez’s (1999) study, which reported interannual variations in \( E_p \) that were much less than those in \( P \). Equation (5) indicates that interannual variations in \( P \) are shifted to those in \( E \) (not \( Q \)) where \( P \) is much less than \( E_p \). Equation (6) indicates that interannual variations in \( P \) are shifted to those in \( Q \) (not \( E \)) where \( P \) is much more than \( E_p \). When assuming that \( E \) is generally greater than \( E_p \) in Japan, we obtain the hypothesis that most data for forested catchments in Japan satisfy \( \frac{\partial Q}{\partial P} \approx 1 \).

In this study, we examined the above hypothesis using \( P \) and \( Q \) data derived from earlier publications in the manner described in the next section. Additionally, we examined two assumptions required for this hypothesis: (i) \( \frac{\partial Q}{\partial P} \) is higher for regions with higher \( P/E_p \) (Equations (5) and (6)) and (ii) \( P \) is greater than \( E_p \) for Japan. We used the equation developed by Komatsu et al. (2012) for \( E_p \) estimates (Supplement Text S1). \( E_p \) in their model is written as a function of the mean annual temperature \( (T_m) \): \( E_p = 0.488 T_{m^2} + 27.5 T_m + 412 \), where \( E_p \) and \( T_m \) have units of millimeters and degrees Celsius, respectively.

### DATA USED

We collated \( P \) and \( Q \) data derived on the basis of catchment measurements from earlier papers using two criteria concerning catchment area and vegetation and the data period.

First, the catchment area must be no more than 10,000 ha and no less than 70% of the catchment must be covered with forests. Catchments in Japan generally satisfied these conditions. This treatment was performed to exclude data obtained for catchments whose spatial scale was quite different from that typical for catchments in Japan.

Second, the data period must be no less than five years. During the data period, there must not be any disturbance such as clearcutting, thinning, or forest fire. In addition, the catchment must not have experienced clearcutting or forest fire in the 10 years before the data period, or thinning in the five years before the data period. If the data period was more than 10 years, we selected data for 10 years for analysis.

This treatment was performed to reduce the effect of gradual changes in vegetation and climate on \( Q \). If it was possible to define several data periods satisfying the above conditions for a catchment, we selected the period with the least disturbance.

In addition, we excluded several data that were observed for catchments where subsurface inflow/outflow was estimated to be significant (Oda et al., 2008). Applying Equation (1) to such data would be inappropriate. The amount of subsurface inflow/outflow was not reported in most papers. We simply used data reported in such papers without data screening. However, we confirmed that our conclusions did not change when excluding data observed at small catchments (less than 10 ha in area) where significant inflow/outflow might be possible.

Using the collated data, we calculated the slope (s) of the relationship between \( P \) and \( Q \) during the data period for each catchment (Supplement Text S2). The parameter \( s \) represents the sensitivity of \( Q \) to interannual variations in \( P \). \( s = 1 \) indicates comparable interannual variations of \( P \) and \( Q \). \( s = 0 \) indicates no interannual variations in \( Q \) corresponding to those in \( P \). According to our hypothesis, \( s \) would be \( -1 \) for most forested catchments in Japan.

### RESULTS

**Description of the data derived**

We obtained data for 57 catchments: 20 for Japan and 37 for other regions such as Australia and the United States (Supplement Table S1). Thirty-three of the 37 catchments were located in mid-latitude regions (no less than 30 degrees in latitude). The other four were located in low-latitude regions (less than 30 degrees in latitude). \( P_m \) and \( Q_m \) were significantly (\( p < 0.001 \)) correlated for both Japan and other regions according to a two-tailed Pearson’s correlation coefficient test (Figure 1). We did not observe any significant (\( p > 0.05 \)) differences in the slope and intercept of the regression line between data for Japan and that for other regions according to analysis of covariance. This agrees with the results of Hattori (1992, see introduction) and with the fact that most of the data for other regions obtained in this
The mean ± standard deviation (SD) of $P_m$ was 2006 ± 733 mm year$^{-1}$ for Japan and 1455 ± 777 mm year$^{-1}$ for other regions (Figure 2a). The difference in the mean $P_m$ was mainly caused by the presence of data with $P_m$ no less than 3000 mm year$^{-1}$ for Japan. Corresponding to higher $P_m$ for Japan than that for other regions, $Q_m$ for Japan was greater than that for other regions; the mean ± SD of $Q_m$ was 1214 ± 574 mm year$^{-1}$ for Japan and 643 ± 544 mm year$^{-1}$ for other regions (Figure 2b).

**Examination of the hypothesis**

The value of $s$ differed greatly among catchments (Supplement Table SI). Figure 3 shows $P$ and $Q$ data for two catchments with contrasting $s$. For the Kamabuchi #1 catchment in Japan, interannual variations in $Q$ corresponded to those in $P$ (Figure 3a), resulting in relatively high $s$ (0.92, Figure 3b). For the Lewis catchment in Australia, interannual variations in $Q$ were much smaller than those in $P$ (Figure 3c), resulting in relatively low $s$ (0.15, Figure 3d).

Among the 20 data for Japan, the majority (70%) satisfied $s \geq 0.80$ (Figure 4). Some portion of the data (30%) satisfied $0.40 \leq s < 0.80$. No data satisfied $s < 0.40$. Although some data (35%) among the 37 data for other regions satisfied $s \geq 0.80$, the percentage was lower than that for Japan. Forty-six percent of the data satisfied $0.40 \leq s < 0.80$. There were several data satisfying $s < 0.40$, although the percentage was not high (19%). These data with $s < 0.40$ were derived from catchments in Australia, Mexico, New Zealand, South Africa, and Spain, where precipitation was relatively low (Supplement Table SI). The high $s$ for Japan observed here (Figure 4) agrees with our hypothesis.

**Examination of the assumptions**

Figure 5a shows the relationship between $P_m/E_p$ and $s$ for the 57 catchments around the world. Data with high $s$ tended to appear in the area with relatively high $P_m/E_p$ (typically no less than 1.0). Data with low $s$ tended to appear in the area with low $P_m/E_p$ (typically less than 1.5). Figures

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**Figure 2.** Histograms of data for Japan and other regions according to (a) mean annual precipitation ($P_m$) and (b) mean annual runoff ($Q_m$)

**Figure 4.** Histograms of the sensitivity ($s$) of annual runoff to annual precipitation for Japan and other regions

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**Figure 3.** (a) Time series of annual precipitation ($P$) and runoff ($Q$) and (b) the relationship between $P$ and $Q$ for the Kamabuchi #1 catchment in Japan (Supplement Table SI). (c, d) The same as Figures 3a and 3b, respectively, but for the Lewis catchment in Australia (Supplement Table SI). We assumed that $P$ in the Lewis catchment was identical to that in a nearby catchment (the Hansen catchment). The relationships in Figures 3b and 3d are standardized using the mean annual precipitation ($P_m$) and runoff ($Q_m$)
in western Japan for three years using the Bowen ratio method. $E$ ranged between 902 and 1003 mm year$^{-1}$ for the three years, while $P$ ranged between 2126 and 3156 mm year$^{-1}$. The range in $E$ accounted for only 9.8% of that in $P$. Kosugi and Katsuyama (2007) measured $E$ at a forest site in central Japan for three years using the eddy covariance method. $E$ ranged between 720 and 750 mm year$^{-1}$ for the three years, while $P$ ranged between 1179 and 1971 mm year$^{-1}$. The range in $E$ accounted for only 3.8% of that in $P$. The same results were obtained when using eight-year data for the site (Matsumoto et al., 2011). Thus, interannual variations in $E$ were much smaller than those in $P$, indicating low sensitivity of $E$ to $P$.

Many studies (Kumagai et al., 2008; Tsuruta et al., 2008; Komatsu et al., 2010b) making continuous measurements of forest-canopy transpiration using the sap-flux method have succeeded in modeling canopy transpiration (or conductance) without considering soil water availability. A few studies (Hattori et al., 1993; Komatsu et al., 2007) have reported a clear reduction in canopy transpiration (or its substitute) due to soil water availability. However, the reduction in canopy transpiration generally persists for only about one month. Thus, the limitation of canopy transpiration by soil water availability does not seem to be very important in determination of $E$ for forests in Japan.

The results of micrometeorological and sap-flux measurements in Japan contrast with those in other temperate forests with relatively low $P_m$, where many studies have reported more significant interannual variations in $E$ (or annual canopy transpiration) relative to those in $P$ and the limitation of evapotranspiration (or canopy transpiration) by soil water availability (Granier et al., 2008; Llorens et al., 2010).

Novelty and implications of this study

We showed that interannual variations in $Q$ primarily correspond to those in $P$ rather than those in $E$ in Japan (also see Supplement Text S3). Thus, interannual variations in $Q$ would increase when interannual variations in $P$ increase in Japan. Note that these results are readily expected from Budyko’s model. The novelty of this study is that we confirmed the results on the basis of observed $P$ and $Q$ data for Japan, and not on the basis of model calculations such as in Koster and Suarez (1999). Further, this study is novel in that it pointed out the results are supported by evapotranspiration data on the basis of micrometeorological and sap-flux measurements.

Although we focused on the sensitivity of $Q$ to interannual variations in $P$ in Japan, this study is related to similar studies in other regions. If long-term $P$ and $Q$ data for many catchments were available in the target region, the methodology we used in this study could be directly used to clarify characteristics of the sensitivity for the region. There are regions (e.g., Cambodia, Laos, and Papua New Guinea) where long-term $P$ and $Q$ data are available for only a few catchments (Komatsu et al., 2012). Even in this case, data for $P_m$ and $Q_m$ are generally available. If the data were plotted as in Figure 5a, a qualitative assessment of the sensitivity would be possible. This assessment could be a starting point for clarifying the sensitivity for the region, although the validity of this assessment should be investigated in the future on the basis of observation data.

DISCUSSION

Comparison with evapotranspiration measurements

Our results (Figure 4) indicate that interannual variations in $Q$ are generally comparable to those in $P$ for forested catchments in Japan. This suggests low sensitivity of interannual variations in $E$ to those in $P$ (see Equation (2)). It also suggests that $E$ in Japan is primarily limited by $E_p$ rather than $P$ and therefore soil water availability (see below).

These suggestions are supported by the results of micrometeorological and sap-flux measurements for forests in Japan. Shimizu et al. (2003) measured $E$ at a forest site...
Additionally, this study is important in that it confirmed the applicability of Budyko’s model to small forested catchments, typically $10^{-3}$ km$^2$ in area (see introduction). Despite there being numerous $P$ and $Q$ observations for small catchments (Brown et al., 2005), there have been no theories explaining differences in the sensitivity of $Q$ to interannual variations in $P$ among catchments. This study showed that Budyko’s model is useful for this purpose.

Conversely, we note limitations of Budyko’s model in explaining the sensitivity of $Q$ to interannual variations in $P$. Budyko’s model explains general characteristics of the sensitivity for catchments in a specific region qualitatively. When explaining the sensitivity for a specific catchment quantitatively, we need daily hydrological models (Shinohara et al., 2009). However, Budyko’s model has an advantage over daily hydrological models in that it requires only data for precipitation and runoff at one-year time resolution and therefore enables more comprehensive comparison of the sensitivity among various catchments. We thus recommend using Budyko’s and daily hydrological models in a complementary manner. When analyzing the sensitivity for catchments in a specific region, we should begin by using Budyko’s model (or other Budyko-like models) to explain the general characteristics of the sensitivity for the target region. A large discrepancy between the sensitivity predicted using Budyko’s model and that obtained using observed $P$ and $Q$ data would suggest significant influences of other factors on the determination of the sensitivity (Sankarasubramaninan et al., 2001; Potter et al., 2005). For example, low sensitivity might be caused by significant water storage capacity and/or snow accumulation, which generally stabilize temporal variations in $Q$. High sensitivity might be caused by winter-dominant precipitation seasonality and/or high precipitation intensity. (However, note that these two conditions are not generally satisfied simultaneously.) Precipitation is not effectively used by evapotranspiration under these conditions, resulting in low sensitivity of $E$ to interannual variations in $P$ and therefore high sensitivity of $Q$ to interannual variations in $P$. To analyze the discrepancy between the sensitivity predicted using Budyko’s model and that obtained using observed $P$ and $Q$ data, daily hydrological models should be used.

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SUPPLEMENTS

Text S1. Estimates of annual potential evapotranspiration ($E_p$)

Text S2. Runoff sensitivity index

Text S3. Variation in the sensitivity among catchments in Japan

Table S1. Description of the data collected in this study

REFERENCES


SENSITIVITY OF RUNOFF TO PRECIPITATION


