Long-term effects of evapotranspiration on the flow duration curve in a coniferous plantation forest over 40 years

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Abstract:

We quantified long-term trends in evapotranspiration, runoff, and deep percolation using 40 years of hydrological data, examining the effects of evapotranspiration on runoff during forest development in a coniferous species. Using the flow duration curve, we evaluated the effects of evapotranspiration on the entire range of flow stages (high to low flows). During the 40-year forest development, deep percolation ranged from 97 mm to 105 mm. Annual evapotranspiration increased by 623–766 mm, which appeared to be caused by increased air temperature as well as forest development. Annual runoff consequently decreased by 937–777 mm. In particular, pronounced decreases in daily flow were found with an exceedance probability of >11% in the flow duration curve. Long-term effects of evapotranspiration on runoff during forest development continued for a longer period than predicted by previous catchment studies of ~20 years duration. Our results suggest that the long-term patterns of evapotranspiration and runoff during forest development would differ from those reported by previous catchment studies under climate warming conditions and highlight the need for further research into separating the effects of forest development and increasing air temperature on evapotranspiration in long-term hydrological data.

KEYWORDS climate warming; deep percolation; evapotranspiration; forest development; flow duration curve; long-term hydrological data

INTRODUCTION

Forests dominate the headwater landscape and supply downstream urban and agricultural areas with water. Approximately one third of the world’s largest cities obtain a significant proportion of their drinking water from forest areas (Dudley and Stolton, 2003). In Japan, forests comprise 66% of the terrestrial surface, including headwater areas. Examination of forest factors affecting water availability, as well as flood and drought severity is a crucial step for water resource management.

Previous paired catchment studies have shown that forest management practices alter runoff from headwater forest catchments. Forest clearcutting typically leads to decreases in evapotranspiration, thus resulting in short-term runoff increases (Bosch and Hewlett, 1982; Swank et al., 2001; Brown et al., 2005). Conversely, because of the increase in evapotranspiration, runoff decreases as forests grow (Hornbeck et al., 1997; Brown et al., 2005; Ise et al., 2013). These results indicate that forest development limits water use in downstream areas. This effect seems to continue for approximately 20 years (Brown et al., 2005), but increases in evapotranspiration (decreases in runoff) over the following decades remain unclear (Kosugi and Katsuyama, 2007; Brookhouse et al., 2013). Based on a review of paired catchment studies, Brown et al. (2005) concluded that runoff decreases for up to 20 years after planting a forest. Kosugi and Katsuyama (2007) reported that evapotranspiration based on the catchment water balance (Precipitation P – Runoff Q) did not show any clear changes for 33 years regardless of tree growth, succession, occasional cutting and natural disturbance. On the other hand, high flow rates in spring persisted for up to 35 years after forest clearcutting in coniferous forest basins in the United States (Jones and Post, 2004). In order to consider downstream water resources, long-term evapotranspiration and runoff data is still required to understand variations related to tree species and climate conditions as well as forest development.

Recently, the effects of climate warming on water yield from forest headwater catchments have also created great concern given their key role as water-supply areas (Jones et al., 2012). Long-term hydrological data in headwater forest catchments, which were initially used to investigate the effects of forest management practices on runoff (Bosch and Hewlett, 1982), are now increasingly valuable for exploring climate warming effects on water supply. Previous studies using long-term hydrological data have shown that water yield responses to climate warming differ among forest types and precipitation conditions in North America (Campbell et al., 2011; Creed et al., 2014; Jones et al., 2012). Creed et al. (2014) found that conifer forests experience larger or smaller water yields compared to model pre-

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dictions, whereas mixed coniferous deciduous forests show little or no changes in water yields across North America between 5-year cool and warm periods. They also reported that eastern catchments in countries with generally summer-dominated precipitation tend to have small water yield changes in response to climate warming, as opposed to western catchments with winter-dominated precipitation. These differences in water yield responses can be attributed to the differences in evapotranspiration responses to climate variability among species and precipitation conditions (Creed et al., 2014). Climate warming may affect long-term patterns of evapotranspiration during forest development depending on forest types and precipitation conditions, but information on this issue is still limited.

The objective of this study is to clarify the long-term effects of evapotranspiration on runoff with forest development and climatic variations such as air temperature and precipitation. Kosugi and Katsuyama (2007) originally analyzed hydrological data for the 33 years (1972–2004) available at the time of their study. With data now extending to 2016, we quantified long-term variations in evapotranspiration, runoff, and deep percolation, as well as climate factors in a temperate coniferous plantation watershed over a 40-year period. Based on an analysis of the flow duration curve, we evaluated the long-term effects of evapotranspiration on the entire flow stage (high to low flows).

METHODS

Site

This study was conducted in the Kiryu Experimental Watershed (KEW; 34°58′N, 136°00′E) in the Tanakami Mountains in Shiga Prefecture, central Japan. KEW covers 5.99 ha and ranges in elevation from 190 to 255 m (Fig. S1). The topography of KEW is a slight northward inclination of approximately 9.2°. The mean annual air temperature and the mean annual precipitation measured in an open space was 13.5°C (2001–2016) and 1660 mm (1972–2016). KEW is underlain by granite, which has the properties of saprolite and is homogenously weathered and permeable (Katsura et al., 2014). Continuous hydrological observations have been conducted since 1972 in KEW (Fukushima et al., 1978; Suzuki, 1980; Kosugi and Katsuyama, 2007). A meteorological observation tower is located in a small catchment within KEW (Fig. S1), and continuous measurements of ecosystem fluxes and micrometeorological factors have been conducted since 2001 (Kosugi et al., 2007, 2013).

The vegetation in KEW consisted of mainly Japanese red pine (Pinus densiflora) and Japanese cypress (Chamaecyparis obtusa) in the 1970s (Suzuki et al., 1979; Figs. S1, S2, S3). In 1974, the vegetation of the upstream right bank was 15-year-old Japanese red pine and 15-year-old Japanese cypress (Kato et al., 1975; A in Fig. S1). In 1977, Japanese red pine trees and broad-leaved trees were logged downstream of both banks and the valley to counter pine wilt disease (C in Fig. S1). Shrubs grew thickly in the logged area. After shrub removal, Japanese cypress saplings were planted downstream of both banks and the valley in 1984 (C in Fig. S1). Since the late 1980s, tree falls of red pine became conspicuous, concurrent with an increased incidence of pine wilt disease (Hobara et al., 2001; Text S1). Over 25% of the area of zone A was affected by pine wilt disease (Ohte et al., 2003). From 1989 to 1998, the total basal area of red pine in the upper part (the pine wilt disease area) of zone A decreased from 18.6 to 1.9 m² ha⁻¹, while that of Japanese cypress in the lower part (the Japanese cypress area) increased from 23.1 to 35.1 m² ha⁻¹ (Ohte et al., 2003). Recent analysis shows the KEW right bank (A in Fig. S1) is covered with mainly 56-year-old Japanese cypress (Figs. 1, S2; Text S1). Relatively large Japanese cypress planted in the 1920s are also scattered on the left bank (B in Fig. S1). Thinning practices are not conducted in KEW. Standing dead trees, probably caused by self-thinning, has been observed in these forests (Kosugi et al., 2016).

Hydrological observations

Precipitation (P) was measured using a 0.5-mm tipping bucket in an open space which was located at the center of KEW (Fig. S1). The P data were corrected using another storage-type rain gauge which was also installed in the open space. Runoff (Q) was continuously monitored using a V-notch weir. We used the P and Q data from 1972 to 2016. Gaps in the runoff data (Fig. S4; Table I) were filled using the runoff model HYCYPMODEL, which was developed based on observations at several catchments in the Tanakami mountains including KEW by Fukushima and Suzuki (1986) and Fukushima (1998) (Text S2). Meteorological factors such as air temperature and humidity were measured at a height of 28.5 m on a meteorological observation tower in KEW since 2001.

We extracted the amount of deep percolation from the catchment water balance data as seen in Matsumoto et al. (2011). Evapotranspiration (ET) was estimated as ET = P – Q – D, where D is deep percolation. Matsumoto et al. (2011) reported that interannual variations in eddy covariance-based evapotranspiration including dry-canopy evaporation and wet-canopy evaporation during and after rainfall (ET,sub) were relatively small, whereas the residuals of water balance (P – Q) showed larger interannual varia-
LONG-TERM VARIATION IN FDC

Table I. Annual water balance of the Kiryu Experimental Watershed (KEW). The values were averaged over 10 years

| Period          | Precipitation (mm) | Runoff$_{hve}$ (mm) | Missing data (€) | Evapotranspiration (mm) | Deep percolation (mm) |
|-----------------|--------------------|---------------------|------------------|-------------------------|-----------------------|
| 1972–1981 (I)   | 1672 ± 305         | 937 ± 275           | 11 ± 13          | 623 ± 50                | 105 ± 50              |
| 1982–1991 (II)  | 1648 ± 240         | 918 ± 199           | 3 ± 5            | 626 ± 55                | 102 ± 39              |
| 1992–2001 (III) | 1615 ± 301         | 849 ± 288           | 4 ± 7            | 667 ± 67                | 97 ± 49               |
| 2002–2011 (IV)  | 1645 ± 310         | 777 ± 250           | 0                | 766 ± 35                | 101 ± 51              |
| 2012–2016       | 1779 ± 147         | 887 ± 121           | 0                | 768 ± 46                | 123 ± 24              |

1 Missing data were filled with HVCYMODEL.
2 Percentage of missing 1-hour data
3 Evapotranspiration ($ET$) was estimated as $ET = P - Q - D$, where $P$ was precipitation, $Q$ was runoff, and $D$ was deep percolation.

Results and positive dependence on annual precipitation from 2001 to 2008. $D$ ($= P - Q - ET_{daily}$) showed thus positive dependence on annual precipitation and could be calculated as $D = 0.1639P - 168.22$ mm (Matsumoto et al., 2011). These $D$ estimates were applied from 1972 to 2016, $ET$ being estimated using the catchment water balance methods for that period.

Data analysis

To examine the time series trend in air temperature, vapor pressure deficit (VPD), and solar radiation in KEW, we used the data collected at three stations of the Japan Meteorological Agency Automated Meteorological Data Acquisition System for 1972–2016 (Higashi-Omi and Shigaraki stations for 1979–2016, Hikone station for 1972–2016), which is ~45 km far from KEW. VPD was calculated using the water vapor pressure and air temperature data collected at Hikone station. The time series trends in meteorological and hydrological data of KEW from 1972 to 2016 were tested using the Mann–Kendall test.

To consider not only total runoff but also runoff stages, we analyzed the flow duration curve (FDC), which shows daily flows in descending order for one water year (e.g., Jencso and McGlynn, 2011). Interannual variations in daily flow in the FDC were greatly affected by those in annual precipitation (Maita and Suzuki, 2008). To consider the effects of interannual variations in annual precipitation on the FDC, we divided the 45-year records for KEW into four 10-year periods during which the mean annual precipitation remained near to steady; 1672 mm in (I) 1972–1981, 1645 mm in (II) 1982–1991, 1615 mm in (III) 1992–2001, and 1645 mm in (IV) 2002–2011 (Table I). Mean annual precipitation in the remaining years (2012–2016) was larger than in the preceding four decades (1779 mm; Table I), and thus we did not use the 2012–2016 data for analysis using the FDC. The FDC of each period was calculated as the descending order of mean daily flow of each exceedance probability averaged over 10 years. In KEW, annual minimum daily flow is observed from December to early February for 24 years during 1972–2016. Water year was defined as January–December. We then examined the relationship between evapotranspiration and daily flow in the FDC among the four periods. This analysis is valid under the condition that there are i) smaller differences in the period mean annual precipitation compared with those in the period annual evapotranspiration among the four periods and ii) no systematic variations in the distribution and intensity of precipitation during the four periods (see Results).

Relatively large daily flow in the high stage of the FDC is affected by large storm events for one year (Liu et al., 1998). To examine the effects of storm events on daily flow of the FDC, we analyzed the precipitation duration curve (Liu et al., 1998) which represents daily precipitation in descending order for one year, and examined the effects of storm events on daily flow in the high stage of the FDC for the four periods.

RESULTS

Mean annual air temperature in KEW was in the range of those in the three meteorological stations (Fig. 2a). Interannual VPD and solar radiation variations in KEW were similar to those measured at Hikone station (Fig. 2b, c). An increasing trend in mean annual temperature was detected in the three stations from 1972 (or 1979) to 2016 ($p < 0.001$ for all three stations). We also detected an increasing trend in VPD in Hikone station from 1972 to 2016 ($p < 0.001$). Significant increases in summer (June to August) air temperature were detected at three meteorological stations ($p < 0.001$; Fig. S5). Significant increases in autumn (September to November) air temperature were detected at two stations ($p < 0.001$). Increases in spring (March to May) and winter (December to February) air temperatures were less significant than those in summer and autumn at three stations ($p > 0.001$).

Annual precipitation and runoff fluctuated greatly in KEW for 45 years compared with evapotranspiration and deep percolation (Fig. 2d). Systematic variations in a frequency distribution of daily precipitation were not observed for 45 years (Fig. S6). An increasing trend was detected for evapotranspiration ($p < 0.001$), but not for annual precipitation, runoff, and deep percolation ($p > 0.1$). Annual evapotranspiration in period (I) was comparable to that in period (II) ($623 \pm 50$ and $626 \pm 55$, respectively; Table I). Annual evapotranspiration in periods (III) and (IV) ($667 \pm 67$ and $766 \pm 35$, respectively) were larger than those in periods (I) and (II). Annual runoff gradually decreased from period (I) to period (IV).

Large year-to-year variations in the FDCs and precipitation duration curves were observed from 1972 to 2016 in

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Figure 2. Time series of (a) mean annual air temperature collected in the Hikone, Higashi-Omi, and Shigaraki meteorological stations and the Kiryu Experimental Watershed (KEW), (b) vapor pressure deficit (VPD) and (c) solar radiation in the Hikone station and KEW, and (d) annual precipitation (open circle), runoff (cross), evapotranspiration (closed circle), and deep percolation (open square) in KEW from 1972 to 2016.

Figure 3. Relationships between annual precipitation and daily flow in exceedance probabilities of (a) 0.27%, (b) 20%, (c) 40%, (d) 60%, (e) 80%, and (f) 100% for periods I (1972–1981), II (1982–1991), III (1992–2001), IV (2002–2011), and 2012–2016 in the Kiryu Experimental Watershed.

Figure 4. (a) Precipitation and flow duration curves for periods I (1972–1981), II (1982–1991), III (1992–2001), IV (2002–2011) in the Kiryu Experimental Watershed (y-axes are presented on a logarithmic scale). (b) Precipitation and flow duration curves in exceedance probability of 10%–100% (y-axes are presented on a normal scale). Shaded areas in (a) indicate exceedance probability of 10%–100% as presented in (b).
LONG-TERM VARIATION IN FDC

Table II. Daily flows in exceedance probability of every 20% on the flow duration curves in the Kiryu Experimental Watershed (KEW) (mm day$^{-1}$)

| Period       | 0.27% (Min) | 20% | 40% | 60% | 80% | 100% |
|--------------|-------------|-----|-----|-----|-----|------|
| 1972–1981 (I)| 36.2        | 3.11| 2.02| 1.46| 1.08| 0.60 |
| 1982–1991 (II)| 44.0        | 3.09| 1.89| 1.31| 0.90| 0.49 |
| 1992–2001 (III)| 34.9        | 2.79| 1.79| 1.29| 0.93| 0.51 |
| 2002–2011 (IV)| 26.9        | 2.63| 1.65| 1.18| 0.88| 0.45 |

Effects of evapotranspiration on daily flow on the flow duration curve

Evapotranspiration mainly consists of wet-canopy evaporation and transpiration (Monson and Baldocchi, 2014). These two components may affect different stages of the FDC, because wet-canopy evaporation occurs during and after rainfall in relatively high stages of the FDC, while transpiration occurs during dry days in relatively low stages. Under the condition of exceedance probability of $<$48% on the precipitation duration curve when rainy days were observed, daily flow in period (IV) was smaller than that in periods (I)–(III) (Fig. 4, Table II). This result suggests that wet-canopy evaporation increased in period (IV) when compared to the other periods, resulting in a decrease in daily flow. Wet-canopy evaporation is influenced by aerodynamic conductance, for which canopy height is a critical parameter (Monson and Baldocchi, 2014), and also leaf area index (LAI), which contributes to canopy water storage capacity (Tanaka, 2002). Both canopy height and LAI would have increased with forest growth in KEW in relation to increases in DBH during the 40 years (Fig. 1), which may have caused increases in wet-canopy evaporation. Indeed, several previous studies reported that wet-canopy evaporation increased with stand age for *Picea abies* and *Quercus robur* in Denmark and southern Sweden (Rosenqvist et al., 2010; Schumacher and Christiansen, 2015).

Under the condition of exceedance probability of $>$49% (i.e., dry days), daily flow in the FDC decreased in periods (I)–(IV) (Fig. 4). This daily flow reduction in dry days may have been caused by increases in transpiration during the 40 years while the Japanese cypress forest grew. Ueyama et al. (2011) showed that the Japanese cypress forest in KEW had continuously accumulated CO$_2$ as a carbon sink since the 1980s, after acting as a carbon source in the initial young stage, using the BIOME-BGC model simulation. This result suggests that growth rate of the current mature Japanese cypress forest would be larger than that in the young stage. The forest may use more water and assimilate more carbon in the current mature stage than in the initial young stage.

Possible causes of increased evapotranspiration in KEW for 40 years

In this study, considering deep percolation and year-to-year variations in precipitation, we found increases in evapotranspiration from 623 to 766 mm between periods (I)–(IV) (Table II). Previous catchment studies reported the long-term effects of evapotranspiration due to forest development lasting for approximately 20 years (Jones and Post, 2004; Brown et al., 2005; Ide et al., 2013), but the effects continued for at least 40 years in KEW. In this site, Kosugi and Katsuyama (2007) previously reported that water loss in the catchment water balance ($P - Q$) did not show any clear changes for 33 years (1972–2004) despite tree growth, succession, occasional cutting and natural disturbance. In this study, evapotranspiration gradually increased from 623 to 667 mm in periods (I) to (III) (Table I). This increase was smaller than the increase in evapotranspiration from 667 to 766 mm in periods (III) to (IV). Because relatively large evapotranspiration was observed in period (IV), an increase in evapotranspiration in the four periods is apparent when compared to the findings of Kosugi and Katsuyama (2007). Although an increased incidence of pine wilt disease was observed after the late 1980s, clear decreases in evapotranspiration were not observed in the period (Fig. 2; Table I). This suggests that the effects of pine wilt disease would be small, as reported by Kosugi and Katsuyama (2007).
This increase in evapotranspiration may have been caused by multiple effects of forest development (Fig. 1) and increasing air temperature (Fig. 2) (Tani and Hosoda, 2012). In KEW, gradual stem growth of Japanese cypress trees was observed until 2011 (Fig. 1), suggesting that current mature Japanese cypress trees might use more water now than in initial, younger stages. In addition, an increasing trend in mean annual temperature and VPD was detected in three meteorological stations for the 1972–2016 period (Figs. 2, S5) which influenced evapotranspiration in KEW. Climate warming is expected to intensify or accelerate the hydrological cycle and change evapotranspiration (Huntington, 2006; Jung et al., 2010). Indeed, global evapotranspiration increased by 7.1 mm per year per decade on average from 1982 to 1997, with the increase seemingly continuing until at least 2008 (Jung et al., 2010). In three meteorological stations around KEW, significant increasing trends in summer and autumn air temperature were detected (Fig. S5). Air temperatures during summer and autumn may affect increases in evapotranspiration in KEW.

Considering increases in evapotranspiration from period (III), development of the Japanese cypress forest after pine wilt decease in the late 1980s would be a stronger determinant of increases in evapotranspiration than increasing air temperature. Because increasing air temperature was observed around KEW from 1972 to 2016, increasing air temperature may also affect the increases in evapotranspiration. We need further research separating the effects of forest development and increasing air temperature on evapotranspiration.

In KEW, Matsumoto et al. (2011) previously reported relatively small interannual variations in eddy covariance-based evapotranspiration from 2001 to 2008 (742 ± 21 mm year$^{-1}$), which was similar to the evapotranspiration rate in Period (IV) of this study (766 ± 35 mm year$^{-1}$). Interannual variations in evapotranspiration were affected by variations in meteorological factors such as VPD, solar radiation, and air temperature from 2001 to 2007 in KEW (Tsuruta et al., 2016). Although interannual variations in evapotranspiration over several years were relatively small, the multiple effects of forest development and increasing air temperature may cause an increasing trend in evapotranspiration for 45 years in KEW.

Matsumoto et al. (2011) reported that medium- (5–10 mm half-hour$^{-1}$) and high-intensity rainfall (>20 mm half-hour$^{-1}$) induced smaller and larger $D$, respectively, from 2001 to 2008 in KEW, even though total amounts of rainfall were similar. These findings suggest that the variation in rainfall intensity may affect $D$ and hence $ET$ estimates for 45 years. However, systematic variations in rainfall intensity were not observed for 45 years (Fig. S6), suggesting that $D$ estimates would not cause systematic overestimates or underestimates of $ET$ in this study.

Our results suggest that the long-term effects of evapotranspiration on runoff would continue under climate warming conditions for a longer period than predicted by previous catchment studies. We need further research separating the effects of forest development and climate warming on evapotranspiration (wet-canopy evaporation and transpiration) in long-term hydrological data.

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SUPPLEMENTS

Text S1. Detailed description of vegetation dynamics in the Kiryu Experimental Watershed

Text S2. Gap filling of runoff data using HYCYMODEL

Figure S1. (a) Location of the Kiryu Experimental Watershed (KEW) in Japan, and (b) topographic map of KEW and the zones of different-aged Japanese cypress forests (A–D)

Figure S2. Chronological tables of vegetation (Japanese cypress and red pine), catchment water balance, and eddy covariance flux in the Kiryu Experimental Watershed

Figure S3. Aerial photographs of the Kiryu Experimental Watershed (KEW) in 1961, 1974, 1982, 1987, 2000, 2008, and 2010

Figure S4. Day-to-day variations in rainfall and calculated (line) and observed (closed circle) runoff during the periods of the gaps of runoff data in (a) 1973, (b) 1974, and (c) 1998

Figure S5. Time series of seasonal average temperature of spring (March–May; blue line), summer (June–August; red line), autumn (September–November; green line), and winter (December–February; black line) in (a) the Hikone, (b) Higashi-Omi, and (c) Shigaraki stations

Figure S6. Frequency distributions of daily precipitation of (a) >50 mm, (b) 10–50 mm, (c) 0–10 mm in the Kiryu Experimental Watershed (KEW) from 1972 to 2016

Figure S7. Flow duration curves for (a) period I (1972–1981), (b) period II (1982–1991), (c) period III (1992–2001), (d) period IV (2002–2011), and (e) 2012–2016 in the Kiryu Experimental Watershed

Figure S8. Precipitation duration curves for (a) period I (1972–1981), (b) period II (1982–1991), (c) period III (1992–2001), (d) period IV (2002–2011), and (e) 2012–2016 in the Kiryu Experimental Watershed

Figure S9. Coefficient of correlation between annual precipitation and daily flow on the flow duration curve in the Kiryu Experimental Watershed from 1972 to 2016

Figure S10. Relationship between maximum daily precipitation and maximum daily flow on the flow duration curve for periods I (1972–1981), II (1982–1991), III (1992–2001), IV (2002–2011), and 2012–2016 in the
Kiryu Experimental Watershed

Figure S11. Precipitation and flow duration curves in exceedance probability of 1%–4% in periods I–IV of the Kiryu Experimental Watershed (KEW)

Table SI. Parameters of HUCYMODEL for the Kiryu Experimental Watershed

Table SII. Annual water balance of the Kiryu Experimental Watershed (KEW) from 1972 to 2016

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