A paired-catchment experiment in the Tatsunokuchi-yama Experimental Forest, Japan: the influence of forest disturbance on water discharge

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Abstract

We proposed a new index for estimating the short-term influence of forest disturbance on discharge rates. The new index was based on the comparison of discharge duration curves between paired-catchment. Using this index, the influence of slight disturbance and recovery speed from disturbance was estimated for a 22.61 ha watershed in Japan as follows.

1) The discharge rate was increased by forest extinction in areas larger than 3.45 ha.
2) The establishment of a hinoki plantation, in combination with the lack of live stem clearing, and hinoki thinning did not influence the discharge rate.
3) The influence of pine die-off on low and drought water discharge remained even 20 yrs after disturbance, probably because of the absence of afforestation following the disturbance.
4) Afforestation following disturbance leads to a rapid decrease in discharge rate.

Keywords: paired-watershed experiment, discharge duration curve, forest management.

1 Introduction

Forests influence water discharge via transpiration and infiltration into deeper soil. The former process results in decreased discharge rates, especially peak discharge, and thereby contributes to flood prevention. The latter process delays water discharge and is thought to increase base flow. Therefore, forests affect base flow antithetically, both decreasing it by transpiration and increasing it by
infiltration. The relationship between forest characteristics and base flow rate varies with geological, topological, and meteorological features. While the relationships between forest disturbance and discharge levels have been described, such understanding is primarily qualitative. Ideally, these relationships should be quantified across discharge duration curves.

Tamai et al. [4] analyzed 68 yrs of discharge duration curve data from the Tatsunokuchi-yama Experimental Forest and reported that forest decline resulted in increased discharge on all days in the discharge duration curve, with greater increase ratio on days with lower discharges. Unfortunately, Tamai et al. [4] simply categorized the watershed vegetation as “forest” and “extinct forest” even though forests actually develop year by year, and the influence on discharge of a forest should vary by successional stage. Moreover, the influence of smaller disturbances should also be estimated. In this study, we propose a new index for estimating the relationship between forests and annual discharge. With the new index it is possible to estimate the variation in the influence of forest recovery from various degrees of disturbance on discharge.

2 Site description

2.1 Location

The Tatsunokuchi-yama Experimental Forest is located at 34° 42' N, 133° 58' E. Annual precipitation and mean air temperature are approximately 1200 mm and 14.3°C, respectively, and there is no seasonal snow cover. The experimental forest consists of two adjacent catchments, Kitadani (KT, 17.27 ha) and Minamidani (MN, 22.61 ha), and is mainly underlain by Paleozoic formations. Discharge and precipitation have been measured at or near the site since 1937; discharge is measured in the forest using a wire gauge, and precipitation is measured at an adjacent weather station using a tipping bucket.

Figure 1: Annual precipitation and discharge.
Table 1: The disturbance on the forest in Minamidani catchment.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Year</th>
<th>Disturbance</th>
<th>Area (ha)</th>
<th>After Management</th>
<th>I(year,i) fluctuation</th>
<th>Period shown in Figure 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1954</td>
<td>Clear cut</td>
<td>7.5</td>
<td>Hinoki planted</td>
<td>Increased to 0.5–1.0</td>
<td>1955–1958</td>
</tr>
<tr>
<td>2</td>
<td>1959</td>
<td>Forest fire</td>
<td>22.3</td>
<td>Pine planted</td>
<td>Increased to 1.0–1.5</td>
<td>1960–1970</td>
</tr>
<tr>
<td>3</td>
<td>1976</td>
<td>Clear cut</td>
<td>3.45</td>
<td>Hinoki planted</td>
<td>Increased slightly</td>
<td>1976–1979</td>
</tr>
<tr>
<td>4</td>
<td>1977</td>
<td>Clear cut</td>
<td>0.35</td>
<td>Hinoki planted</td>
<td>Not increased</td>
<td>1978–1979</td>
</tr>
<tr>
<td>5</td>
<td>1978–80</td>
<td>Pine wilt disease</td>
<td>18.8</td>
<td>Natural regrowth</td>
<td>Increased to 1.0–1.5</td>
<td>1980–2002</td>
</tr>
<tr>
<td>6</td>
<td>1982</td>
<td>Dead stem removed</td>
<td>2.5</td>
<td>Hinoki planted</td>
<td>Not increased</td>
<td>1982–1983</td>
</tr>
<tr>
<td>7</td>
<td>1997</td>
<td>Hinoki thinning</td>
<td>2.34</td>
<td>Not increased</td>
<td></td>
<td>1997–1998</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
<td>Hinoki thinning</td>
<td>2.53</td>
<td>Not increased</td>
<td></td>
<td>2000–2001</td>
</tr>
</tbody>
</table>

2.2 Vegetation history

Red pine (*Pinus densiflora*) was the dominant species at the site in 1937 when observations first began. The forest began declining in 1940 as a result of pine wilt disease, and timber was harvested in all areas of both the KT and MN watersheds. Natural regrowth of red pine, oak (*Quercus serrata*), and bamboo (*Pleioblastus chino*) occurred in both watersheds, and no difference between the vegetation in both watersheds was observed until 1954. Deciduous broad-leaved trees have always dominated KT since then, but vegetation in MN was disturbed at many times as followings (Table 1). At first, in November 1954, the trees in a 7.5 ha area in MN was cut and removed, and hinoki (*Chamaecyparis obtusa*) were planted at a density of 3000 stem ha⁻¹ (Case 1). Furthermore, in September 1959, a forest fire burned the forest and litter in 22.3 ha of MN, and pine was planted in March 1960 at 3000 stem ha⁻¹ (Case 2). Trees in 3.45 ha (1976) and 0.35 ha (1977) of MN were removed and hinoki were planted (Case 3 and 4, respectively). Until 1978, pines in MN reduced to 1250–2650 stem ha⁻¹ by natural thinning. In 1978–1980, Around 96.5% of the remained pines, mainly in MN, again died from pine wilt disease (Kobayashi et al., [2]) and the forest in MN was practically extinct, except for the area planted with hinoki. No afforestation occurred following the removal of the dead pines, and broad-leaved trees regrew naturally (Case 5). 2.50ha area in MN was planted with hinoki in 1982 after removal of the dead pines (Case 6). Subsequently, 2.34 ha (1997) and 2.53 ha (2000) of hinoki forest in MN were thinned artificially (Case 7 and 8, respectively).
3 Methodology

3.1 Previous study in the Tatsunokuchi-yama Experimental Forest

This study expands on the work of Tamai et al. [4]. Therefore, the analysis methods and results reported by Tamai et al. [4] are reviewed here. The annual discharge rate from KT ($Q_{KT}$) exceeded that from MN ($Q_{MN}$), when the forest in MN was healthy. This was thought to occur because of the steeper slope in KT, resulting in higher levels of direct run-off than in MN (Nakano, [3]). However, Hattori [1] reported that following a forest fire, $Q_{MN}$ exceeded $Q_{KT}$ from 1960 until 1968, after which $Q_{KT}$ again exceeded $Q_{MN}$. $Q_{MN}$ in turn exceeded $Q_{KT}$ in 1980, following the outbreak of pine wilt disease, and remained higher than $Q_{KT}$ until 1994.

Tamai et al. [4] defined the years when $Q_{MN}$ was greater and less than $Q_{KT}$ as periods of forest decline and forest normalcy, respectively. Eqn. (1) defines the regression line between daily discharge from MN ($Q_{MN}(year, i)$) and KT ($Q_{KT}(year, i)$) over 365 days of the duration curve, with $Q_{MN}(year, i)$ and $Q_{KT}(year, i)$ as the dependent and independent variable, respectively, in each period:

$$Q_{MN}(year, i) = A(p, i) Q_{KT}(year, i)+B(p, i)$$  \hspace{1cm} (1)

where $i$ indicates the day in the duration curve, $A(p, i)$ is the regression coefficient, and $B(p, i)$ is the regression constant. The periods of decline and normalcy are indicated by $p = d$ and $p = n$, respectively. Examples of Eqn.(1) are shown in Figure 2. Compared with both the regression lines of decline and normalcy periods with plentiful water discharge ($i = 95$), ordinary water discharge ($i = 185$), and low water discharge ($i = 275$), $A(d, i)$ is larger than $A(n, i)$, and $B(d, i)$ is almost equal to $B(n, i)$. In contrast, under drought water discharge conditions ($i = 355$), $A(d, 355)$ is almost equal to $A(n, 355)$, and $B(d, 355)$ is greater than $B(n, 355)$.

3.2 Analysis methods

Tamai et al. [4] obtained regression lines for the relationship between $Q_{MN}(year, i)$ and $Q_{KT}(year, i)$ in two periods, i.e., decline (line D) and normalcy (line N). As forest growth varies throughout the year, however, the values for both $Q_{KT}(year, i)$ and $Q_{MN}(year, i)$ should vary around the two regression lines. Thus, we defined $i$ and the two regression lines. The objective of this study was to estimate the changes in discharge caused by forest regrowth and slight forest disturbance using the new index together with forest information. This forest information should ideally be quantitative data, such as tree volume. Unfortunately, only recent quantitative data were available. Therefore, we also used historical qualitative data in this study.
3.3 Defining the new index

Water discharge levels, i.e., plentiful (i=95), ordinary (i=185), low (i=275), and drought (i=355), were analyzed among the discharge duration curves. The new index was defined with distinction between for plentiful, ordinary, and low water discharge levels.
discharge levels that had similar values of \( B(d, i) \) and \( B(n, i) \), and for drought water discharge level that had similar values of \( A(d, 355) \) and \( A(n, 355) \).

The definition of the new index for drought water discharge is explained in Figure 3(a). Tamai et al. [4] determined that \( A(d, 355) = 0.9602 \) and \( A(n, 355) = 1.0154 \), with an average value of 0.9878. Line Y passing through Point Q indicating \((Q_{KT}(year, 355), Q_{MN}(year, 355))\) in any year with a slope of 0.9878 was obtained as Eqn. (2):

\[
Q_{MN}(year, 355) = 0.9878 Q_{KT}(year, 355) + b(year) \tag{2}
\]

For values of \( b(year) \) closer to 0.0271 and 0.0767, Point Q is plotted closer to Line N and Line D, respectively. This relationship was standardized in Eqn. (3):

\[
I(year, 355) = \frac{(b(year) - 0.0271)}{(0.0767 - 0.0271)} \tag{3}
\]

Values of \( I(year, 355) \) smaller than 0.0, larger than 1.0, and at 0.5 indicate that Point Q fell under Line N, above Line D, and between these two lines, respectively.

![Figure 3: The definition of I(year, i). (a) Drought water discharge, (b) Plentiful, ordinary and low water discharge.](image)

The definitions of the new index for plentiful, ordinary, and low water discharges are explained in Figure 3(b). As shown in Figures 2(a), (b) and (c), Line N and Line D intersect at Point P. The coordinates of Point P were \((0.05716, 0.157207)\), \((-0.00517, 0.06842)\), and \((0.01334, 0.06198)\) for plentiful, ordinary, and low water discharge, respectively. Line Y connecting Points Q and P was obtained for every year. Thus, the relative distances between Point Q and Lines N and D can be estimated by comparing the slopes of Lines D, N, and Y. This relationship was calculated with Eqn. (4) as follows:

\[
I(year, i) = \frac{\theta_{QPH} - \theta_{NPH}}{(\theta_{DPH} - \theta_{NPH})} \tag{4}
\]

where \( \theta_{QPH} \), \( \theta_{NPH} \) and \( \theta_{DPH} \) indicate the angles in degrees between Line Y, Line N, and Line D, respectively, and Line H, which paralleled the X-axis. Values of
I(year, 355) smaller than 0.0, larger than 1.0, and at 0.5 indicate that Point Q was plotted under Line N, above Line D, and between these two lines, respectively.

I(year, i) calculated with Eqn. (3) and (4) is the new index proposed in this study. The period of analysis was 1937–2002, although the 1967, 1974, 1991, 1993, and 1995–1997 data were excluded because they were incomplete. Duration curves in KT and MN were obtained for the period from January to December.

4 Results and discussion

4.1 Fluctuation of I(year, i) and forest information

The fluctuation of I(year, i) is shown in Figure 4. Values ranged from -0.5 to 0.5 in 1937–1954 and 1967–1979 and from 0.5 to 1.5 in 1955–1966 and 1980–1994. This trend agreed well with the decline periods caused by the forest fire in 1959 (Case 2) and pine wilt decease in 1978–1980 (Case 5). From 1998 to 2003, the range of values varied with values of i: from I(year, 95) to I(year, 185), the values were scattered from -0.5 to 0.5; for I(year, 275) the values ranged from 0.5 to 1.5; and for I(year, 355) the values were around 0.5.

Examining the fluctuations of I(year,i) in other cases in Table 1, I(year,i) increased after the timber removal in November 1954 and hinoki afforestation in the 7.5 ha area in MN (Case 1). The clear-cut and hinoki afforestation in the 3.45 ha area in MN in 1976 would make I(year, i) larger for 1976–1977 (Case 3). Moreover, from 1998 to 2003, I(year, 275) and I(year, 355) were 0.5–1.5 and around 0.5, respectively. The influence of the pine wilt disturbance from 1978 to 1980 (Case 5) would remain for low and drought water discharges and would recover for plentiful and ordinary water discharges in 1998–2003.

Figure 4: Fluctuations of I(year,I).

In contrast, the hinoki plantations in the 0.35 ha and 2.50 ha areas in MN in 1977 and 1982, respectively, did not have increased values for I(year, i) in Case 4 and 6, respectively. The lack of increase in I(year, i) following the 1982 hinoki planting may be a result of removing only dead pines. The hinoki artificial thinning in 1997 and 2000 in the 2.34-ha and 2.53-ha areas in MN, respectively, also did not result in increased values of I(year, i) in Case 7 and 8, respectively.
All values of $I(\text{year}, 95)$, $I(\text{year}, 185)$, and $I(\text{year}, 275)$ were very low, ranging from -7 to -2, in 1939 and 1940. The pine wilt die-off started to spread in both watersheds for the first time during this period. The annual precipitation in 1939 and 1940 was the lowest and tenth lowest, respectively, in the 67-yr analysis period. Point Q plotted near Point P in years with low precipitation and low discharge (Figure 3). This means that small changes in $Q_{KT}(\text{year}, i)$ and $Q_{MN}(\text{year}, i)$ led to large changes in $I(\text{year}, i)$. Thus, all values of $I(\text{year}, 95)$, $I(\text{year}, 185)$, and $I(\text{year}, 275)$ should have calculated to be very low.

Five indices, i.e., $I(1944, 275)$, $I(1968, 95)$, $I(1978, 95)$, $I(1979, 275)$, and $I(1980, 355)$ were calculated to be in the range of -2 to -1. Annual precipitation ranked fourth, second, and sixteenth lowest in 1944, 1968, and 1978, respectively. However, annual precipitation was high in 1979 and 1980, ranking 48 and 62, respectively, in lowest annual precipitation. These years corresponded to the borders between decline and normalcy periods. For example, the forest in MN was thought to recover from the forest fire disturbance in 1968 (Case 2), and the pine wilt die-off started to expand in MN in 1978–1980 (Case 5). This factor may be the reason for low values of $I(\text{year}, i)$, but must be discussed in more detail in the future.

### 4.2 Forest regrowth and fluctuations of $I(\text{year}, i)$

The fluctuations of $I(\text{year}, i)$ in decline periods are discussed above. The periods, disturbances, and management practices are summarised in Table 1. Forest disturbance caused increased ratios or increased rates of discharge. However, these values were affected by annual precipitation; Point P is far from the origin in Figure 2. The fluctuations of $I(\text{year}, i)$ after disturbance are shown in Figure 5. The first year of the after disturbance was the same year when the disturbance occurred in Case 3 and 5, and one after year in Case 1 and 2. This depends on the month when the disturbance was occurred.

The values of $I(\text{year}, i)$ 1–3 yrs after disturbance ranged from 1.0 to 1.5 in Case 2 and 5 with a disturbed area of 18–23 ha and 0.2 to 0.7 in Case 1 and 3 with a disturbed area of 3–8 ha. This indicates that large disturbed areas lead to large $I(\text{year}, i)$ 1–3 yrs after disturbance.

The forest was almost completely extinct in MN in Case 2 and 5. However, pine was planted in Case 2, and broad-leaved forest regrew naturally in Case 5. The difference of the effect on $I(\text{year}, i)$ between Case 2 and 5 was not observed until yr 7. $I(\text{year}, i)$ decreased rapidly after yr 9 to around 0.0 in Case 2. In contrast, $I(\text{year}, 275)$ and $I(\text{year}, 355)$ remained around 0.5, even after 20 yrs in Case 5. This difference was caused by different forest management practices following the disturbance. In Case 1 and 3, $I(\text{year}, i)$ decreased rapidly to 0.0 in yr 3–4, because only a small area was disturbed and hinoki were planted after the disturbance.
Figure 5: Comparison of the I(year,i) fluctuation between disturbance cases.

References