Chapter 21
Forest Influences on Streamflow: Case Studies from the Tatsunokuchi-Yama Experimental Watershed, Japan, and the Leading Ridge Experimental Watershed, USA

Koji Tamai, Elizabeth W. Boyer, Shin'ichi Iida, Darryl E. Carlyle-Moses, and Delphis F. Levia

21.1 Introduction

Forests are vital for rural and urban populations all over the world, providing multiple ecosystem benefits to society and playing a key role in the supply of fresh water and the regulation of climate. The influence of forest vegetation and soils on the generation of streamflow has long been recognized. Incoming precipitation to forested watersheds is subject to evapotranspiration by vegetation, as well as runoff delay via infiltration, storage, flow paths, and residence times through forest soils. Changes in vegetation or soil characteristics in turn affect the characteristics of discharge from forested watersheds. Changes in the landscape raise concerns about the volume of water flowing to streams, timing of those flows, water quality, and human well-being. Paired watershed studies have been widely

K. Tamai (✉)
Forestry and Forest Products Research Institute, Tsukuba, Ibaraki, Japan
e-mail: a123@affrc.go.jp

E. W. Boyer
Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA, USA

S. Iida
Department of Disaster Prevention, Meteorology and Hydrology, Forestry and Forest Products Research Institute, Tsukuba, Ibaraki, Japan

D. E. Carlyle-Moses
Department of Geography and Environmental Studies, Thompson Rivers University, Kamloops, BC, Canada

D. F. Levia
Departments of Geography and Plant & Soil Sciences, University of Delaware, Newark, DE, USA

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used to quantitatively evaluate such changes (Hewlett 1982). With this method, two or more forested watersheds with similar hydrological conditions (such as lithology, geographical features, soils, weather, and vegetation) are monitored along with precipitation and discharge for a calibration period spanning a range of climatic variability. Next, the state of forests in one basin is changed (treatment watershed) while the other watershed is untouched (control watershed), and hydrological monitoring continues during this treatment period. The relationship between the state of a forest and the water balance is elucidated by comparing the relative precipitation-discharge relation at the control catchment and the treatment catchment between the control period and the treatment period.

In this chapter, we review two classic paired watershed studies carried out in temperate forests in contrasting world regions. We present results from watershed manipulation experiments at the Tatsunokuchi-Yama Experimental Watershed in Japan (Tamai et al. 2004; Tamai 2005 and 2008) and at the Leading Ridge Experimental Watershed in the United States (Lynch et al. 1985; Lynch and Corbett 1990; Hornbeck et al. 1993).

21.2 Overview of the Experimental Watersheds and Their Vegetation Manipulation

The Tatsunokuchi-Yama Experimental Watershed (34.7°N, 133.97°E) is located in a hilly area in Okayama Prefecture of Japan, consisting of two adjoining catchments of Minami-dani (MN, 22.6 ha) and Kita-dani (KT, 17.3 ha). Its lithology is classified as Paleozoic, consisting of hard sand stones and clay stones, except that igneous rocks, including quartz porphyry, occupy about one-third of the KT catchment, while its soil is a little cohesive unripe clay loam. The mean annual temperature is 14.3 °C, and the mean annual precipitation is approximately 1200 mm year^{-1}. Due to the rainy season and the occurrence of tropical cyclonic storms (typhoons), June, July, and September are the wettest months. Winter is the driest season and snow coverage is rare.

The vegetation history and forest management history of the Tatsunokuchi-Yama Experimental Watershed is described by Tamai (2010) and is summarized in Table 21.1. Both the KT and MN catchments were natural forests of *Pinus densiflora* Sieb & Zucc. (Japanese red pine) at the beginning of the observation period in 1937. However, all of the *Pinus densiflora* trees were cut between 1944 and 1947 because of die-off by a pine wilt disease (Mamiya 1988) that led to enormous timber loss throughout northern Japan. The change of streamflow discharge was investigated at the KT and MN catchments individually utilizing a single-catchment experiment methodology. The catchments were at that time covered in broadleaf forest, though disturbances of various scales and forms have occurred in the MN treatment catchment. The major events are included in cases when the brush within 19.5 ha of broadleaf forests was cut down in 1954–1957. Subsequently, *Chamaecyparis obtusa* Sieb. & Zucc. (Japanese cypress, hinoki) and *Pinus thunbergii* Parl. (black pine) were planted. However most of the planted trees died (Kishioka et al. 1981).

Table 21.1 Major events of vegetation change and management in the Tatsunokuchi-Yama Experimental Watershed (Japan) and the Leading Ridge Experimental Watersheds (United States)

Year	Tatsunokuchi-Yama Experimental Watershed, Japan
1937	KT and MN observations of hydrological balance began
1947	KT and MN vegetation removal via clearcut
1954–1957	MN vegetation removal (partial) via brush cutting (Case 1, Fig. 21.4)
1959	MN vegetation removal of completion via forest fire (Case 2, Fig. 21.4)
1962	MN vegetation removal (selected riparian locations) via clearcut
1967	MN vegetation removal via forest fire
1977	MN vegetation removal (selected locations) via clearcut
1978–1980	MN vegetation removal via pine wilt disease (Case 3, Fig. 21.4)
1998	MN vegetation change via thinning

Year	Leading Ridge Experimental Watershed, United States
1957	LR1 LR2, LR3 observations of hydrological balance began
1967	LR2 vegetation removal (phase 1, lower slope) via clearcut
1971–1972	LR2 vegetation removal (phase 2, middle slope) via clearcut
1974	LR2 vegetation removal (lower & mid slope) via herbicide
1975–1976	LR2 vegetation removal (phase 3, upper slope) via clearcut
1976	LR2 vegetation removal (whole basin) via clearcut
1976	LR3 vegetation removal (selected locations) via cutting with best practices
1977	LR2 vegetation removal (whole basin) via herbicide

In September 1959, a fire destroyed the vegetation and litter layer over most of the MN catchment. *Pinus thunbergii* was subsequently planted over the entire MN catchment in March 1960 (Kishioka et al. 1981). The *Pinus thunbergii* forest, however, was destroyed by pine wilt decease during 1978–1980 (Abe et al. 1983). A natural broadleaf deciduous forest has since prevailed.

The Leading Ridge Experimental Watershed (40.66°N, 77.93°W) is located in the Appalachian Mountain region of the eastern United States. The site was selected to be representative of approximately four million ha of forest land within the Ridge and Valley Province of central Pennsylvania. There are three adjacent catchments of varying sizes, including Leading Ridge catchment 1 (LR1, 123 ha), catchment 2 (LR2, 42 ha), and catchment 3 (LR3, 104 ha). The catchments have a southeastern aspect and range in elevation from 274 to 442 m. They are underlain by the Rose Hill shale formation (over 200 m thick, underlying the entire study area), Castanea sandstone (over 150 m thick), and Tuscarora quartzite. The forests covering the catchments are even-age coppice forests. *Quercus montana* Willd. (chestnut oak) is currently the most dominant tree species in the watershed in both tree density and basal area, followed by *Q. rubra* L. (northern red oak), *Q. alba* L. (white oak), and *Acer rubrum* L. (red maple). Other tree species occurring in the watershed include *Tsuga canadensis* (L.) Carrière (eastern hemlock), *Pinus strobus* L. (eastern white pine), and *Q. velutina* Lam. (black oak) (Brubaker 2011). The oak-hickory cover type dominates the watershed while an oak-hemlock community exists in the moist valley floor areas.

The vegetation and forest management history of the Leading Ridge Experimental Watershed is described by Lynch and Corbett (1990) and Hornbeck et al. (1993, 1995) and is summarized in Table 21.1. Catchment LR1 is the control watershed and has not been actively managed. The forest on the control watershed was mature and in reasonably steady state considering biomass accumulation and annual evapotranspiration. However, both the control and the treatment catchments were subject to occasional periods of defoliation by gypsy moths over the period of record (Hornbeck et al. 1993, 1995). As part of the vegetation manipulation experiments, catchments LR2 and LR3 received various treatments between 1967 and 1977. Catchment LR2 had 100% of its vegetation removed in a three-phase clear-cutting and herbicide experiment, after a 7-year calibration period from 1959 to 1966. Phase 1 in 1967 was a complete riparian clear-cut of 21 acres (8.5 ha), with subsequent spraying of 2,4,5-T and 2,4-D herbicides to remove any remaining vegetation. Phase 2 on LR2 in 1971–1972 was a middle slope clear-cut of 27 acres (10.9 ha). Herbicide was applied to both the lower slope (phase 1) and middle slope (phase 2) areas of watershed 2 in 1974. Phase 3 on LR2 in 1975–1976 was an upper slope and ridge top clear-cut of 42 acres. Herbicide was applied to the entire 90-acre (36.4 ha) clear-cut on watershed 2 to remove all vegetation throughout the basin in 1977. Catchment LR3 had about 43% of its vegetation removed, in an experiment aimed at evaluating the use of best forest management practices during forest management operations (Lynch et al. 1985; Lynch and Corbett 1990). A commercial clear-cut of a portion of LR3 following best practices occurred during 1976–1977.

Hydrological fluxes enabling water balance calculations have been made at both experimental watersheds, with observations at the Tatsunokuchi-Yama Experimental Watershed beginning in 1937 and at the Leading Ridge Experimental Watershed in 1957. Here, we present results from monitoring of these watersheds from 1937 to 2002 in Japan and from 1957 to 2007 in the United States. The annual hydrological fluxes from the watersheds during both the control and treatment periods over the years of observation are shown in Fig. 21.1. In the Tatsunokuchi-Yama sub-catchments (KT and MN), annual precipitation ranged from approximately 600 to 1730 mm with an average of 1220 mm year^{-1}. In the Leading Ridge sub-catchments (LR1, LR2, LR3), annual precipitation ranged from about 470 to 1470 mm with an average of 1060 mm year^{-1}. Using the average values of precipitation (*P*), evapotranspiration (*ET*), and discharge (*Q*) measured at the watersheds, about 33% of the average annual precipitation is delivered to streamflow in the KT and MN watersheds, while about 45% of the average annual precipitation is delivered to streamflow in the LR1, LR2, and LR3 watersheds. Results from experimental watersheds in Japan and the United States show that increases in water yield occur on small watersheds in response to removal of vegetation and that increases in streamflow diminish as vegetation is replanted or naturally recovers.

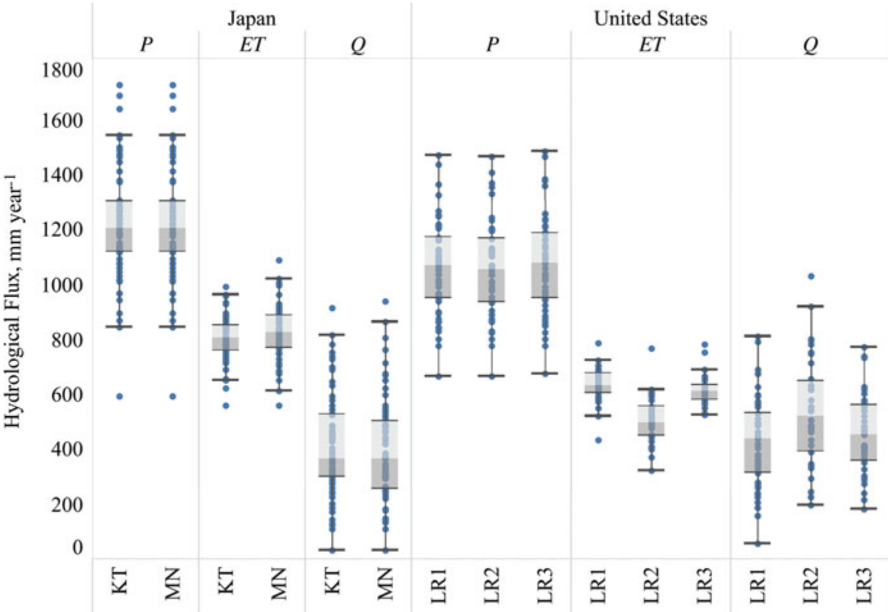

Fig. 21.1 Annual fluxes of precipitation (*P*), evapotranspiration (*ET*), and discharge (*Q*) observed over the period of long-term monitoring at the Tatsunokuchi-Yama Experimental Watershed, Japan (1937–2003, KT and MN catchments), and at the Leading Ridge Experimental Watershed, United States (1957–2007, LR1, LR2, and LR3 catchments). In this box and whisker plot, the boxes indicate the middle 50% (the middle two quartiles) of the data distribution. The line in the middle of each box represents the median value. The upper and lower whiskers are 50% higher and lower than the inner quartile range. Observations outside of the whiskers represent extreme events

21.3 Results and Discussion from the Tatsunokuchi-Yama Experimental Watershed, Japan

21.3.1 Determination of Periods in the Paired Catchment Experiments

The relative change in discharge under the influence of forest fires and pine wilt disease was investigated with a paired catchment experiment in the Tatsunokuchi-Yama experimental watershed (Abe and Tani 1985; Hattori 1994). Because it was in the MN catchment that forests were disturbed (Table 21.1), the MN catchment was designated as a treatment catchment and the KT catchment as a control catchment in these previous studies. ΔQ, the difference of annual discharge of the KT catchment from that of the MN catchment (Eq. 21.1), is positive for most years, but is negative for 1960–1966 and 1981–1994, presumably due to decreased transpiration as a consequence of forests in the MN catchment was recovering from forest fire damage in 1959 and pine wilt disease in 1978–1980, respectively. Discharge from the MN catchment increased in a relative sense (Hattori, 1994).

$$\Delta Q = Q_{\text{kobs}} - Q_{\text{mobs}} \tag{21.1}$$

where Q_{kobs} and Q_{mobs} represent the observed annual discharge from KT and MN catchments, respectively.

The paired catchment experiment analyses were conducted from 1960 to 1966 and 1981 to 1994 when ΔQ was negative, in 1959 and 1978–1980 when deforestation took place due to forest fire and pine wilt disease (disaster periods), while all other years were considered control periods. Years 1967, 1974, 1991, 1993, and 1995–1997 included days when discharge was not measured (due to observation system maintenance, etc.) and were excluded from analyses. Accordingly, a treatment period of 19 years (1960–1966, 1981–1994 except for 1991 and 1993), a disaster period of four years (1959, 1978–1980), and a control period of 37 years (1937–1958, 1967–1977, 1995–2003 except for 1967, 1974, 1995–1997) are defined.

21.3.2 Discharge Characteristics of the Control and Treatment Periods

A discharge duration curve sorts the 365 daily discharge values for a year in descending order. The larger discharge side of the curve represents the daily discharge at the time of a flood, whereas the smaller discharge side represents that at low discharge. The 95th most of the 365 daily discharges is designated as "plentiful water discharge," the 185th is "ordinary water discharge," the 275th is "low water discharge," and the 355th is "drought water discharge." These discharges from both catchments of Tatsunokuchi-Yama Experimental Watershed were compared. Figure 21.2 shows discharge from the MN watershed as a treatment watershed on the vertical axis and that from the KT watershed as a control watershed on the horizontal axis. Each figure has 19 open squares (□) representing the treatment periods, 36 closed diamonds (◆) representing the control periods, and 4 asterisks (∗) representing the disaster periods. Discharge values from the two catchments were highly linearly correlated for the treatment periods and for the control periods (Tamai et al. 2004):

$$Q_{\text{mobs}}(\text{year}, i) = a_{p,i} Q_{\text{kobs}}(\text{year}, i) + b_{p,i} \tag{21.2}$$

where $Q(\text{year}, i)$ represents the daily discharge (mm day^{-1}) on day i of the discharge duration curve of the year and $a_{p,i}$ and $b_{p,i}$, respectively, express the slope and y-intercept of the linear regression equation. Subscript p denotes the period of the paired catchment experiment, subscript t represents the treatment period, and subscript c denotes the control period.

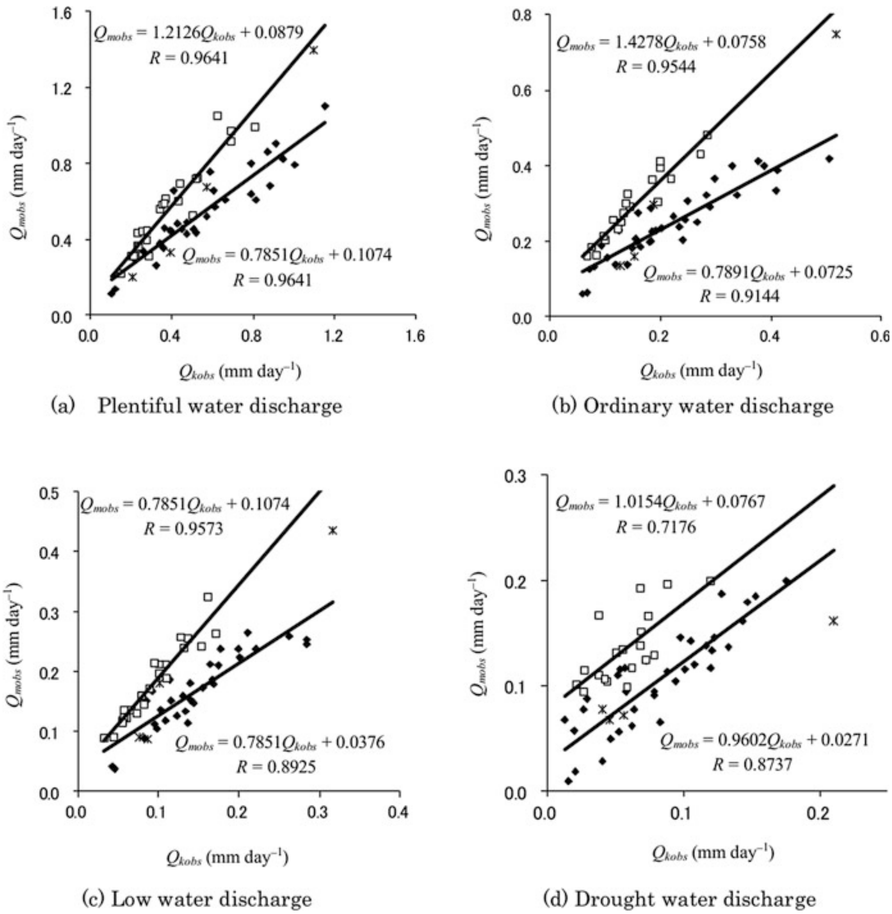

Fig. 21.2 Relationships between daily discharge in discharge duration curves for the Kita-dani and Minami-dani catchments, Tatsunokuchi-Yama Experimental Watershed (from Tamai et al. 2004). □: Treatment period (1960–1966, 1981–1994 except for 1991 and 1993). ◆: Control period (1937–1958, 1967–1977, 1995–2003 except for 1967, 1974, 1995–1997). ∗: Disaster period (1959, 1978–1980)

Equation 21.3 expresses $Q_{\text{mcal}}(\text{year}, i)$ as computed by substituting the observed discharge $Q_{\text{kobs}}(\text{year}, i)$ from the KT control catchment during the treatment period for Eq. (21.2). $Q_{\text{mcal}}(\text{year}, i)$ is regarded as the estimated discharge from the MN catchment expected when the forest in that catchment is not disturbed (or stressed).

$$Q_{\text{mcal}}(\text{year}, i) = a_{c,i}Q_{\text{kobs}}(\text{year}, i) + b_{c,i} \tag{21.3}$$

As computed by Eq. (21.4), $\Delta Q_m(\text{year}, i)$ represents the relative change in discharge from the MN catchment with forest disturbance compared with the control KT catchment as indicated below, where Q_{mobs}(year, i) is the observed discharged from MN catchment during the treatment period. Thus, the difference between observed runoff of the MN catchment (Q_{mobs}) and estimated runoff of MN (Q_{mcal}) is assumed to be equal to the change in runoff caused by disturbance.

$$\Delta Q_m(\text{year}, i) = Q_{mobs}(\text{year}, i) - Q_{mcal}(\text{year}, i) \tag{21.4}$$

21.3.2.1 Indices for Evaluating the Influence of Forestry Operations

A regression line between daily discharge from the MN and KT catchments with high correlation was obtained for each of the control periods and treatment periods, respectively (Fig. 21.2). The forests within both catchments, especially within MN, have experienced disturbances of various scales in addition to the complete loss of forest by fire in 1959 and by pine wilt disease in 1978–1980. Brush cutting of 7.5 ha, 7.2 ha, and 4.8 ha was performed in 1954, 1955, and 1957, respectively. A 0.4 ha portion of forest along a mountain stream was clear-cut in 1962 and 1964, respectively, and left to natural recovery (Forest Influence Unit and Okayama Experimental Site, Kansai Branch Station, 1979). Forests of 0.4 ha were lost to fire in 1974 and were afforested with *Chamaecyparis obtusa* in 1976 (Tani and Abe 1987). Additionally, 0.4 ha of forest was clear-cut in 1977 and a further 2.3 ha was cut in 1982 and afforested with *Chamaecyparis obtusa*. Stands of *Chamaecyparis obtusa* having areas of 2.3 ha and 2.5 ha underwent thinning in 1998 and 2001, respectively (Goto et al. 2006). Consequently, the plots of daily discharge from both catchments are anticipated to fluctuate around two regression lines for the control and treatment periods presented in Fig. 21.2 according to recovery from disturbances of various scales and removal.

21.3.2.2 Definition of a Discharge Index at Plentiful, Ordinary, and Low Water Discharge Values

We define an index that expresses whether a particular annual Q value is closer to the control or treatment (i.e., disturbance) regression. This enables an investigation into the status and years of the influence of forest disturbances on discharge. The slopes of two regression lines ($a_{p,\ i}$) differ greatly at plentiful water discharge, ordinary water discharge, and low water discharge (Figs. 21.2a–c). Index I(year, i) is defined in Eq. (21.5) and Fig. 21.3a. Lines OT and OC represent the regression lines for treatment and control periods, respectively (Fig. 21.3).

$$I(\text{year}, i) = 2 \cdot (\theta_{QOH} - \theta_{COH})/(\theta_{TOH} - \theta_{COH}) - 1 \tag{21.5}$$

Therein, I(year, i) is an index of discharge on i-th day of the year on a discharge-duration curve, θ is an angle designated by a subscript, and OH is a horizontal

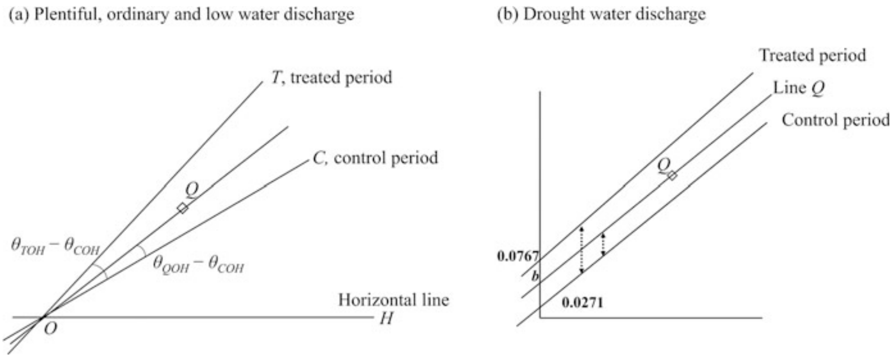

Fig. 21.3 Definition of a discharge index *I* (*year, i*) for the Tatsunokuchi-Yama Experimental Watershed. (Adapted from Tamai 2005)

straight line parallel to the x-axis passing through intersection O. When I(year, i) is −1 or 1, point Q is located on a regression line for the control period or the treated period, respectively. Otherwise, when I(year, i) is 0, Q is located at the midpoint of two regression lines.

21.3.2.3 Definition of a Discharge Index at Drought Water Discharge Values

The slopes of regression lines for the control and treatment periods at drought water discharge (the 355th water discharge in duration curve) are almost equal (see Fig. 21.2d). Accordingly, an index is computed using Eqs. 21.6 and 21.7 (Fig. 21.3b).

$$b(\text{year}) = Q_{\text{mobs}} \cdot (\text{year}, 355) - 0.9878 \cdot Q_{\text{kobs}}(\text{year}, 355) \tag{21.6}$$

$$I(\text{year}, 355) = 2 \cdot \frac{b(\text{year}) - 0.0271}{0.0767 - 0.0271} - 1 \tag{21.7}$$

The slope value 0.9878 of Eq. 21.6 represents the average values of slopes $a_{t,\ 355}$ (1.0154) and $a_{c,\ 355}$ (0.9602) given by Eq. (21.2) for the treatment and control periods at drought water discharge, respectively. b(*year*) is the y-intercept of a straight line of slope 0.9878 that passes along point Q representing discharge in any year. Additionally, the values 0.0767 and 0.0271 in Eq. 21.7 are the respective values of $b_{t,\ 355}$ and $b_{c,\ 355}$, the y-intercepts given by Eq. 21.2 in the treatment and control periods at drought water discharge. When I(*year*, i) is either -1 or 1, points Q are located on the regression lines for the control or the treatment periods, respectively; otherwise when I(*year*, i) is 0, Q is located at the midpoint of the two regression lines.

21.3.2.4 Overview of Discharge Index Fluctuation

Figure 21.4 depicts the change of the discharge index $I(\text{year}, i)$ over the years 1937–2003. When values of $I(\text{year}, i)$ are positive and negative, open squares (□) and closed diamonds (◆), representing discharges from both the KT and MN catchments in Fig. 21.2, are located near the regression lines for the treatment period and the control period, respectively. The threshold of $I(\text{year}, i)$ for estimating the influence of forest treatment is defined as 0, which implies that $I(\text{year}, i)$ is located at the midpoint of the two regression lines for the control and treatment periods. Almost all values of $I(\text{year}, i)$ are positive for the periods of 1960–1966 and 1981–1994, defined as treatment periods in Sect. 21.3.1, so that discharge from the MN catchment is regarded as having been influenced by forest removal. However, negative values were observed in 1981, the first year of the treatment period with pine wilt disease, demonstrating the effects of this stressor on discharge. This may be a consequence of defining a water year for the computation of the discharge-duration curves as spanning January 1 to December 31. Two dry seasons, one from January–April and another in December, are contained in one discharge-duration curve (Inaba et al. 2007). Only drought water discharge has the possibility to undergo the influence of precipitation events in the year prior to the year of analysis. Years when only the change of drought water discharge is delayed one year compared with that of other amounts of discharge and years with no delay might be mixed.

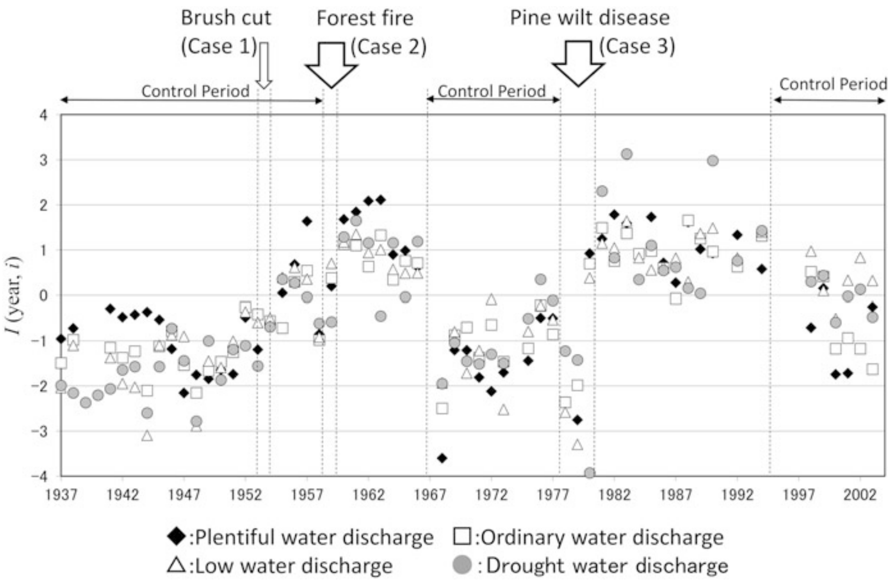

Fig 21.4 Long-term fluctuation of discharge index *I* (year, *i*) at the Tatsunokuchi-Yama Experimental Watershed from 1937 to 2003. (Adapted from Tamai 2005, 2008)

21.3.2.5 Influence of Disturbance and Forestry Operations on Discharge

The Minami-dani catchment has experienced various disturbances and forestry operations. Cases exist in which the increment in water discharge was or was not observed as a consequence of these events. Accordingly, incremental discharges that occurred in the following three cases were compared (Fig. 21.5). Two cases among three are forest fire in 1959 with 22.3 ha damaged area (Case 2) and pine wilt decease in 1978–1980 with 18.8 ha damaged area (Case 3). Their treatment periods are 1960–1966 and 1981–1994, respectively. The remaining Case 1 was from brush cutting in 1954–1957. However, the influenced years of this operation is not clear. Considering the continuity of the operated years of the brush cut and followed by Case 2 (i.e., forest fire), the disturbed period and the treatment period in Case 1 are defined to be 1954–1955 and 1956, respectively. The operated area in 1954–1955 was 14.7 ha. The brush cut in 1957 with 4.8 ha operated area is not evaluated here.

In Fig. 21.5, the ratio $Q_{\mathrm{mobs}}/Q_{\mathrm{mcal}}$ in cases 2 and 3 is approximately equal in the range of $i < 270$, while the result in Case 1 is much smaller. This is attributed to the fact that the damaged area and expected decreased vegetation volume in cases 2 and 3 are wider and larger than those in Case 1. In comparison with the forest fire in 1959 where the vegetation was burned out, and the pine wilt disease in 1978–1980 when almost all trees died, the vegetation volume reduction by brush cut in 1954–1955 is considered to be small. This suggests that the decline of the amount of leaves reduced transpiration and consequently enhanced the incremental discharge. Further, $Q_{\mathrm{mobs}}/Q_{\mathrm{mcal}}$ is greater for larger i in all cases. This also reflects the influence of transpiration by forest vegetation. Runoff at low discharge is constituted mainly by

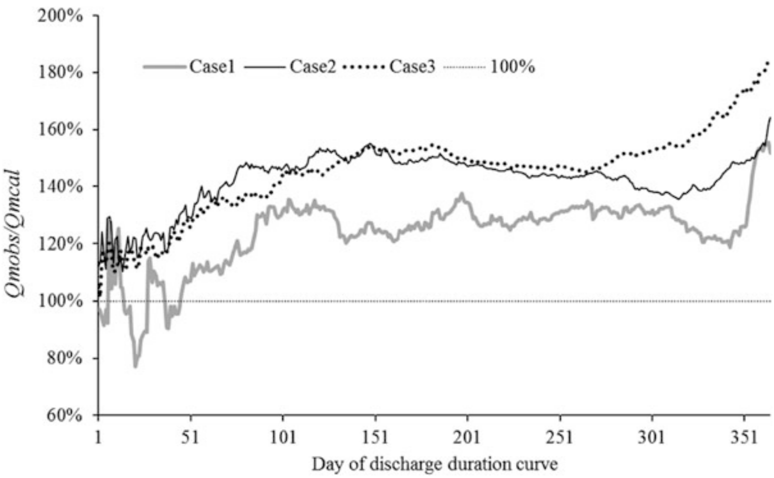

Fig. 21.5 Increased discharge ratio after forest disturbance or forestry operation in the Minami-dani catchment. Case 1: Treatment period is 1957 after brush cut in 1954–1955. Case 2: Treatment period is 1960–1966 after forest fire in 1959. Case 3: Treatment period is 1981–1994 after pine wilt decease in 1978–1980

base flow originating from groundwater. Rainwater that falls in a forest permeates the soil over a long time from the forest floor to a water table to turn into groundwater, under the continuous influence of transpiration. However, runoff during a flood includes a direct runoff component by which rainwater flows down promptly at the shallow part of forest soil, in addition to the base flow. The residence time of direct runoff in a catchment is so short that the influence of transpiration is small. Accordingly, it is inferred that $Q_{\mathrm{mobs}}/Q_{\mathrm{mcal}}$ is larger when i in a discharge duration curve is larger.

Tani et al. (2012) optimized the parameters of a process-based model to simulate the water movements in the catchments, so that runoff data can be reproduced properly from each of two adjacent catchments (34.92°–34.93°N, 135.97–135.98°E) in Shiga Prefecture. One catchment has bare ground catchment (named Rachidani) and the forested catchment (named F2) protected as the temple grove of a temple founded in the ninth century. The difference between the simulated discharge duration curves shows the effects of the forest vegetation and soils. The flow duration curves of both catchments were estimated from discharge data computed by the process-based model given identical meteorological data and evapotranspiration rates. Thus the difference between the simulated discharge duration curves primarily reflects the delay of runoff by forest soil. The simulated discharge duration curve from the bare ground catchment (Rachidani) indicated more discharge at a flood and less at a drought compared with that from the forest catchment (F2) suggesting that runoff delay by forest soil has affected discharge. A simulated discharge duration curve was similarly obtained with the actual water balance difference between precipitation and discharge given as the amount of evapotranspiration. In this comparison, the given evapotranspiration rate in the bare ground catchment (Rachidani) was smaller than in the forest catchment (F2). So, the difference between the simulated discharge duration curves shows the effects of runoff delay by forest soil and of evapotranspiration by vegetation. Then discharge from the bare ground catchment (Rachidani) was greater than that from the forest catchment (F2) throughout the simulated discharge duration curve including at the low discharge. The smaller evapotranspiration in the bare ground catchment (Rachidani) led to the larger low water discharge than the forest catchment (F2). This implies that evapotranspiration by vegetation has more effects on runoff than runoff delay by forest soil.

Consequently, in the Japanese watersheds, the influences of forest extinction and forestry operations can have similar explanations (after Tamai, 2008). The number of years it took for discharge to return to the level of the control period was shorter in the case of the forest fire in 1959 when *P. thunbergii* was planted than in the case of pine wilt in 1978–1980 when the vegetation was left to natural recovery. Years taken for the discharge to return to the level of the control period were shorter at plentiful water discharge and ordinary water discharge than at low water discharge and drought water discharge in the case of the pine wilt decease in 1978–1980. Plentiful water discharge, ordinary water discharge, low water discharge, and drought water discharge were incremented in about 22.6 ha of the MN catchment during 1955–1956, caused by the forestry operations such as about 14.7 ha brush cutting and planting. No distinct influence on discharge was observed for periods when treatments were performed in an area smaller than 3.5 ha, such as a small forest fire in 1974, small-scale clear-cutting in 1977, brush cutting and *C. obtusa* planting in 1982, and *C. obtusa* thinning in 1998 and 2001. Cases with broader disturbed forests or greater tree volumes regarded as becoming extinct showed greater incremental discharge. Moreover, the rate of increase of discharge was greater on days with less discharge than days with more discharge in a discharge duration curve. This result highlights the markedly higher influence of evapotranspiration by forest vegetation than runoff delay by forest soil on streamflow.

21.4 Results and Discussion from the Leading Ridge Watershed, United States

A similar methodology using the paired watershed approach as presented for the experimental catchments in Japan was used at the Leading Ridge watersheds in the United States. Regression equations were used to develop the relationship between annual water yield from the control catchment (LR1) and the treatment catchments (LR2 and LR3) and to elucidate the effects of the vegetation removal treatments.

The manipulation experiment at watershed LR2 was a complete (100%) removal of the forest and other vegetation on the catchment (Table 21.2), in order to evaluate questions about the magnitude of change in streamflow that could result from removing the forest. Complete removal of vegetation from the LR2 catchment occurred via clear-cutting in three phases, along with the application of herbicides to eliminate vegetation regrowth. The results of the vegetation removal treatments on streamflow water yield are shown in Fig. 21.6, using data adapted from Hornbeck et al. (1995). The timeline shown begins at 1967, the time of the initial treatment on the catchment. Vegetation from the catchment was removed in three phases, with phase 1 clear-cut in the lower third (1967), phase 2 clear-cut in the middle third (1971–1972), and phase 3 clear-cut in the upper third (1975–1976). In 1977 herbicide was applied to the entire clear-cut across the watershed to remove all vegetation. A photo of the LR2 catchment after the second phase is shown in Fig. 21.7.

The vegetation removal treatments in LR2 resulted in substantial streamflow increases of up to 35%, with the maximum increases occurring (not surprisingly)

Table 21.2 Relative to the control watershed, the seasonal and annual discharge increased in the clear-cut basin, with the largest increases occurring once vegetation was fully removed

Forest vegetation removal in the treatment watershed	Water years	Growing season (%)	Annual year (%)
Lower third (phase 1)	1967-71	6.7	5.2
Middle third (phase 2)	1972-73	5.9	7.2
Upper third (phase 3)	1974-75	14.4	8.6
Entire basin (final phase)	1976-78	24.1	15.5

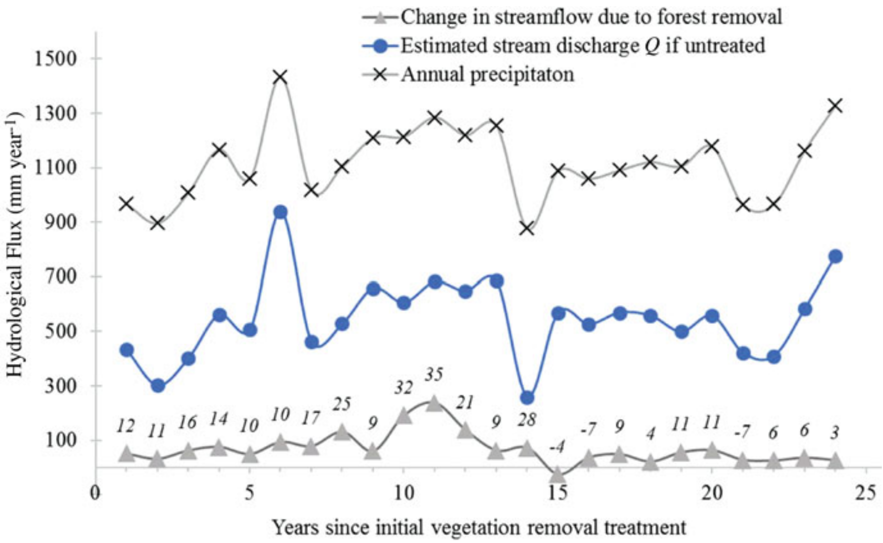

Fig. 21.6 Changes in streamflow water yield at the Leading Ridge Experimental Watershed LR2 in response to forest vegetation removal. Results are shown from 1967, the time of the initial treatment. Vegetation was removed in three phases, with phase 1 clear-cut in the lower third of the catchment (1967), phase 2 clear-cut in the middle third (1971–1972), and phase 3 clear-cut in the upper third (1975–1976). In 1977, herbicide was applied to the entire clear-cut across the catchment to remove all vegetation. Changes in streamflow from the vegetation removal treatments are shown with the triangles (in units of mm year^{-1}) and are labeled with the percentage change (in italics) attributed to vegetation removal

Fig. 21.7 Aerial view of Leading Ridge catchment LR2, after the second phase clear-cut of the middle third of the forest in 1972–1973

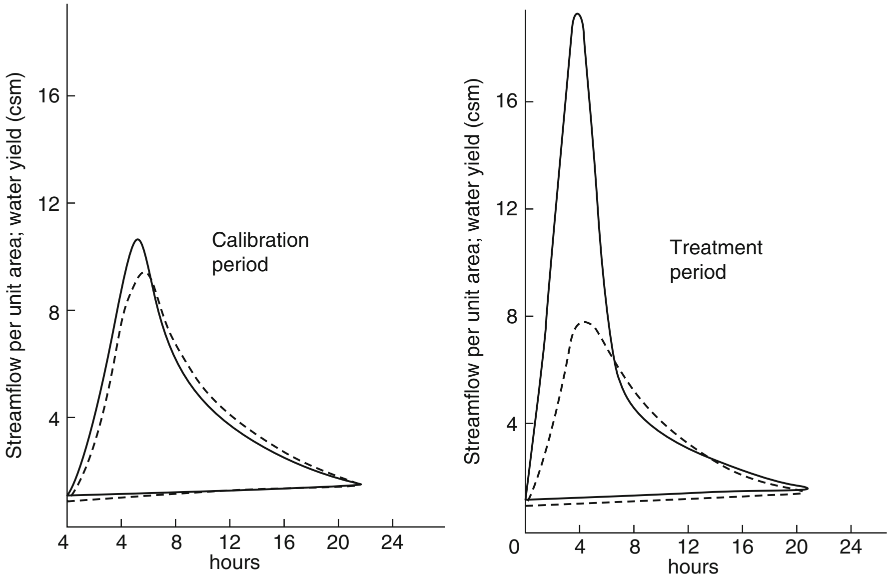

Fig. 21.8 Average hydrographs produced by Leading Ridge catchment LR1 (control, dotted line) and LR2 (clear-cut treatment, solid line), during the calibration period before vegetation removal (left) and during the treatment period after vegetation removal (right). The water yield is reported in cubic feet per second per square mile (csm)

after all of the vegetation was removed from the catchment. Water yield increases during the first 1–3 years after clear-cutting occurred during both the growing and dormant season, but mostly during the growing season as augmentation of base flow (Lynch et al. 1972). Mean peak flow during the growing season increased by more than 150%. Overall, the increases in water yield due to removing the forest vegetation declined quickly as natural regrowth of vegetation occurred (Hornbeck et al. 1993, 1995). Considering changes to individual precipitation and stormflow events, the clear-cutting greatly increased peak flows, as evidenced by individual hydrographs considered during the calibration period compared to during the treatment period after vegetation removal (Fig. 21.8). Results showed that substantial increases in peak flows on small watersheds occurred in response to clear-cutting, especially for small discharge events.

The manipulation experiment at catchment LR3 evaluated the question of how streamflow and water quality are affected by the use of best management practices during forest harvesting, with careful attention to protection of hydrologically sensitive areas. In this experiment, a timber sale was advertised and a commercial clear-cut operation took place on LR3 while following a comprehensive suite of forest best management practices (Lynch et al. 1985). During the vegetation removal operations, a protective buffer strip 100 ft (30.5 m) wide was left on each side of all streams. Skidding over perennial streams, except over approved culverts, was prohibited. Slash was not permitted within 25 ft (7.6 m) of any perennial or intermittent stream. Main skid trails, logging roads, and log landings were carefully laid out by a forester. After the operations, culverts were removed and water bars and other drainage devices installed on all logging roads and major skid trails, and roads were gated and grated to prelogging conditions. Lastly, filtration strips between road surfaces and stream channels were used.

In addition to the ongoing measurements of the water balance and streamflow, stream hydrochemistry data were collected on both the control catchment (LR1) and the treatment catchment from 1973 to 1979, with over three years of monitoring in the calibration phase before the vegetation removal (Lynch et al. 1985; Lynch and Corbett 1990). Comparing the control (LR1) to the catchment that was clear-cut along with using best practices (LR3) revealed only minor changes in stream turbidity and sedimentation. In contrast, turbidity and erosion were significantly impaired following vegetation removal in the LR3 catchment, where the forest was removed (via clear-cutting and application of herbicides) without considerations of protection of hydrologically sensitive areas or efforts to reduce erosional losses. Results showed that the use of forestry best management practices were effective at controlling nonpoint source pollution during and following the logging harvest operations (Lynch et al. 1985; Lynch and Corbett 1990). The results of this study were influential in establishing recommendations for use of forestry best management practices in operations throughout the eastern United States.

21.5 Future Directions

Paired watershed studies from around the world collectively have provided understanding of how land use changes affect the water balance and streamflow and how the responses vary across heterogeneous environmental settings. Results from the watersheds discussed here as well as other experimental watersheds highlight that the increases in water yield that accompany forest vegetation removal observed at individual watershed sites are highly variable (e.g., Bosch and Hewlett 1982). Best et al. (2003) and Brown et al. (2005) provide a critical review summarizing the limitations of the paired watershed approach, noting the results gleaned from the research across experimental watersheds are hard to generalize and that results from individual watershed studies cannot be easily translated to larger regions or to catchments with different conditions. Nonetheless, information from experimental watersheds have been key to informing strategies for watershed management and forest restoration, toward conserving and protecting water resources. Comprehensive monitoring data from watersheds are invaluable and foundational resources for understanding the effects of long-term changes in climate and landscapes on nutrient cycles, ecosystems, and water resources – where external effects shaping these processes can be subtle and long duration. Long-term watershed monitoring data are becoming increasingly useful to link the impacts of changing climate, vegetation, soil, and water as the data are synthesized and shared publicly, allowing application to new research questions and hypotheses (Tetzlaff et al. 2017).

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