Effects of Forest Workings on Streamflow and Water Quality (Part 1)

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Many kinds of forest workings such as logging, planting, herbicide spraying, fertilizing, forest road building, forest recreation activities, etc. appear to affect streamflow and water quality.

Of the expected effects of these workings, that of logging has been regarded as most important in public discussions since old time. As a matter of fact, the public interest in an early forest hydrology was arisen by a desire to know the relation between flood damage and overcutting of mountain forests. This problem still remains to be most important even to-day.

It was about 1933 that an increasing attention came to be paid to the relation between forest and low streamflow. With the development of forest road networks and recreation facilities expanding into the back mountain areas in recent years, these undertakings have come to attract more serious public attention with respect to their effects on streamflow.

It is also of late years that the effects of these workings on water quality have been called in question. First, the spread of herbicide use has come into question, and next, the road building has come to be taken up for discussion. After this the forest fertilization was also called in question. But the most important issue on water quality in future will be the problem of the pollution caused by recreation activities.

In these days the conversion of forest land to other land use has caused public concerns with regard to flood and water pollution. The typical conversions are the construction of golf courses and villa lands in hills near cities or the foot of volcanic mountains. The forest lands with gentle slope in piedmont districts of volcanoes are often changed into grazing lands for beef cattle. This also is becoming a matter of interest of the persons concerned in watershed management.

As stated above, the initial forest hydrological studies in Japan started in examining the relation between forest and flood flow and water yield, namely, comparing the hydrological effects between broad leaved forest and coniferous forest, middle-aged forest and young forest, and superior forest and inferior forest, and further detecting the effect of clear cutting. Thus eight forest experimental watersheds were established in 1906 for the first time.

Interception, rainfall increase and transpiration of forest were also begun to be measured at experimental plots going abreast with the said watershed experiments. The early stage survey was carried out on the infiltration of forest land too.

These initial studies marked the first step of Japanese forest hydrology by around 1930. The early studies concluded that the forest has a desirable function for water conservation so that a desirable type of forest should be sustained in catchment area for flood control and conservation of water resources, and forest workings should be circumspectly practiced in respect to the water conservation.

The protetcion forest system for water conservation had been already established by the Forest Law in 1897 on the basis of empirical facts and knowledges. Results obtained from the initial forest hydrological studies provided the technical basis for the system and contributed to the later sound growth of the system.

The studies in the early days, however, were not necessarily satisfactory with regard to research methodology—method of measurement, probation, location and so on. The results, therefore, were not always entirely supported by the public opinion, so that a variety of questions were repeatedly raised and detailed explanations on the forest function were earnestly required.

Thus, the new forest watershed experiment was started in 1935. From 1935 to 1956, 18 forest experimental watersheds in 5 districts were established successively. Over many years since then, experiments were carried out to detect changes in the streamflow after clear cutting, selective cutting, partial cutting and other forest treatments in these watersheds. Many of these experiments have been continued up to now.

On the other hand, investigations to compare high and low streamflows among many actual watersheds with different forest vegetation were initiated at 77 watersheds in 3 districts during a period of 1966–1969.

In 1956, the study on infiltration of forest land was taken up again, and since then the infiltration capacity has been investigated in relation to forest types using the simple mountain infiltrometer newly designed. Similarly the measurement of interception was again started with principal forest types too.

The followings are the outline of main results of the forest hydrological experiments conducted at the Forestry and Forest Products Research Institute since 1935.

Individual hydrological function of forest

1) Interception loss

The process of rainfall interception by forest canopy was studied with the model experimental sprinkling with the cut foliage in a laboratory and with the semi-theoretical studies.

On the other hand, the interception loss was actually detected for each close stand of *Cryptomeria japonica, Pinus densiflora, Chamaecyparis obtsusa* and *Larix leptolepis*, measuring the through fall, stem flow and net precipitation using a usual method[1,2].

The interception loss varied with kinds of forest, precipitation and other climatic conditoins, etc. Annual canopy interception loss for the aforesaid coniferous forest ranged around 15 to 20% of the annual net precipitation. The loss by undergrowth in stand was about 1 mm for every storm, and that by litter 2 to 4 mm[1,2]. Thus the interception by the whole forest including undergrowth and litter exceeds the canopy interception loss by several percent.

Moreover, percentage interception of the said coniferous trees ranged about 5 to 10% at the time of a storm amounted to 100 to 200 mm[2].

2) Evapotranspiration

Annual evapotranspiration of forest land was measured as the annual water loss in the water budget for experimental watershed[3]. The results showed a mean annual water loss of about 600 mm for a 645 ha watershed covered with the natural mixed middle-aged forest consisted of *Picea jezoensis, Abies sachalinensis, Quercus mongolica var. grosseserrata, Betula Ermani*, etc. in Hokkaido district with cold weather. Similarly, the mean water losses were about 850 mm for a 22.6 ha watershed with the natural middle-aged forest of *Pinus densiflora* in Chugoku district with warm and relatively little rainfall, about 1100 mm for a 6.6 ha watershed with the natural middle-aged forest consists of *Castanopsis cuspidata, Pasania edulis, Machilus Thunbergii*, etc. in Kyushu district with much rain, and about 400 mm for a 118 ha watershed with the natural middle-aged forest consisted of *Fagus crenata, Quercus mongolica var. grossesserrata, Thujopsis dolabrata, Pinus parviflora*, etc. on a high mountain in Kanto district.

The evapotranspiration loss from a specific stands was measured with the heat energy method, but yet a fully reliable value has not been obtained.

The measurement of the loss was made with another method as well. The change in weight of a leaf or foliage immediately after cut off was measured and regarded as the unit amount of transpiration from the close stand. The total amount of stand transpiration was calculated from the unit transpiration multiplied by the total amount of foliage of stand. The actual value obtained for the close stand approximated to the amount of water loss estimated in water balance.

3) Infiltration capacity of forest land

It is generally said that infiltration capacity of forest land is higher than that of other land. A simple sprinkling type infiltrometer was newly designed and used for the field measurement of infiltration capacity of mountainous forest land. An instance of the results from many comparative measurements is indicated in Table 1[1].

Effect of forest working on runoff

1) Forest cutting and water yield

The most popular working in Japan is the single storied forest system by clear cutting because of the high efficiency of wood production and reliable regeneration. With the presumption that the working may give the most severe effect on runoff by removing all trees from whole watershed even though temporarily, the experiment was begun to detect the effect of clear cutting and logging.

On 4 experimental watersheds, changes in annual, summer, winter and monthly runoffs after clear cutting were examined[3]. The watersheds used were a 2.5 ha watershed with the natural middle-aged forest consists of *Quercus mongolica* var. *grosseserrata, Fagus crenata*, etc., with the partial artificial middle-aged stand of *Cryptomeria japonica* and *Chamaecyparis obtusa*, a 17.3 ha watershed with the natural middle-aged forest of *Pinus densiflora* with the partial artificial young forest of *Chamaecyparis obtusa*, and two other watersheds, 22.6 ha and 645 ha each, mentioned in the preceding section *2) Evapotranspiration.*

After the calibration period over 7 to 11 years, the forests were clear-cut, and changes in runoff were analyzed based on the comparison between control watershed and the treated watershed, or the relation between climatic condition and runoff of the treated watershed during the calibration period.

Results showed that annual runoff and its percentage to annual precipitation were increased similarly in all the watershed after the clear cutting and logging.

The increments in annual runoff were 200 to 260 mm, with the largest one occurring in the next year after the logging was completed. The rates of increase were 10 to 45%. The increment, however, varies with the watershed

Table 1. Final infiltration capacity as related to ground cover condition

Ground cover condition	Coniferous[1] forest land	Broad-leaved[2] forest land	Cut-over[3] land	Grass land	Slided land	Foot path
Final infiltration capacity (mm/hr)						
Mean	246	272	160	191	99	11
Range	104–387	87–395	15–289	22–193	24–281	2–29

Notes: 1) Artificial forests of *Pinus densiflora, Cryptomeria japonica, Chamaecyparis obtusa, Larix leptolepis*, 22–45 years old, diameter breast high 6–35 cm, tree height 7–22 m.

2) Natural forest consists of *Fagus crenata, Quercus mongolica* var. *grosseserrata, Quercus serrata, Prunus spp.*, etc. 60–190 years old, DBH 16–80 cm, TH 12–22 m.

3) Including the places disturbed by logging.

conditions including forest condition, and with the climatic conditions including precipitation, so that it is impossible to give a definite figure as a general one.

In the watershed on which clear cutting was practiced over 2 or 3 years, the increment in annual runoff became gradually larger as the cutting progressed. In the watershed on which regrowth was allowed on the cut-over area, the increment became smaller as the regrowth developed. The increment in runoff after clear cutting and logging coincided well with the quantity of forest vegetation (Fig. 1).

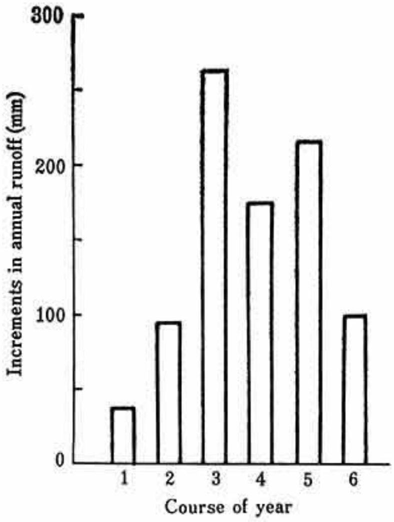
Although summer and winter runoff were increased after logging, two types of watershed were recognized, i.e., the watershed which showed larger increment in winter runoff than in summer runoff, and the watershed which showed larger increment in summer runoff than in winter runoff. In any case, however, monthly runoff was generally increased with the following exceptions.

In the watershed with snowpack, monthly runoff was increased clearly during an early half of thawing period, but it decreased distinctly during the later half of the thawing period (Fig. 2).

On the other hand, in the watershed under a warm and less rain climate, monthly runoff during the period of late spring to summer became less than that before cutting. July is the month of rainy weather. (Fig. 3).

Changes in annual, summer and winter runoffs caused by the selective cutting were examined on the above-mentioned 118 ha watershed.

After a 11 year period for calibration, the 50% area-wise selective cutting was practiced. Changes in runoff after the cutting were determined by comparing the runoff of the treatment watershed with that of control



Notes:
1. Wind damages by typhoon.
2. Beginning of cutting.
3. Cutting of the most stand of watershed.
4. Cutting of the rest stand of watershed except the riparian one, and beginning of regrowth on the cut-over area.
5. Logging of the riparian stand, and development of the regrowth.
6. Development of the regrowth.

Fig. 1. Increase in annual streamflow caused by forest removal and changes in the increment with the development of regrowth. (645 ha watershed)

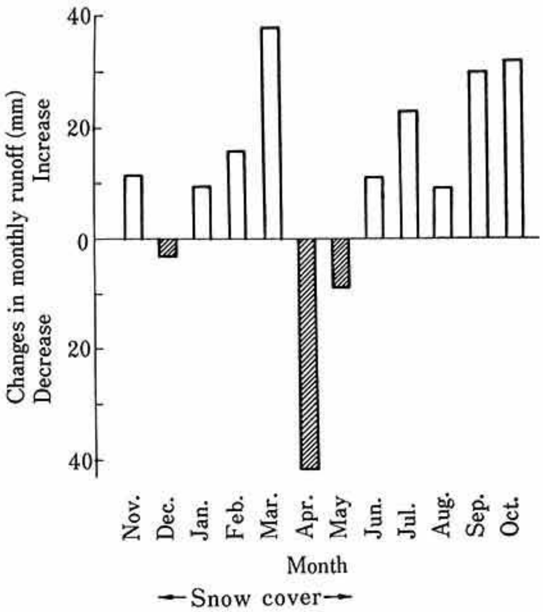


Fig. 2. Changes in monthly runoff after clear cutting of forest (2. 5 ha watershed).

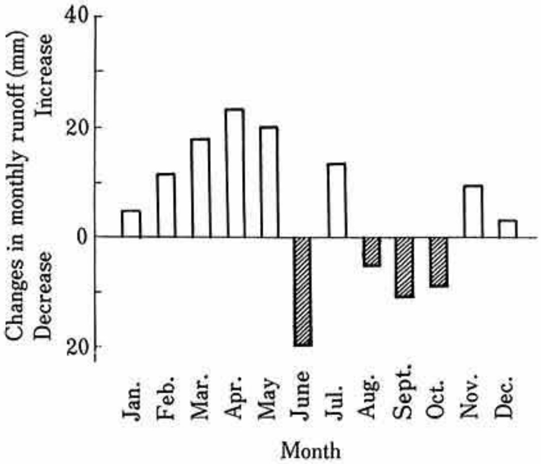
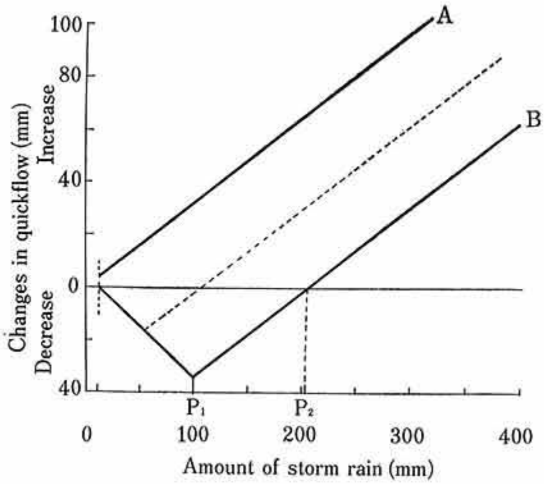


Fig. 3. Changes in mothly runoff after clear cutting of forest (17.3 ha watershed without snow).



Notes: A: Quickflows due to storms which occurred at the time of relatively high base flow.
B: Quickflows due to storms which occurred at the time of relatively low base flow.

Fig. 4. Relation among the changes in quickflow after clear cutting, initial water retention of watershed immediately before storms, and amounts of storm rain (17.3 ha watershed)

watershed.

Result showed increases in annual, summer and winter runoffs, and in their percentages to precipitation. But the increment was less as compared to the case of clear cutting.

2) Forest cutting and high streamflow

The effect of clear cutting on high streamflow was examined with the data from the aforesaid 2.5 ha and 17.3 ha watersheds[3].

The quickflow caused by most of storms on both watersheds became larger comparing with that before cutting. The runoff at some storms, however, became less depending upon the water retention of watershed, mainly soil moisture right before storm begins, and rainfall condition. Namely, in the case of very little water retention owing to little antecedent rainfall, the quickflow due to a storm with a total rain below about 200 mm obviously became less than that before cutting. However, the flood due to a storm (P_2 in Fig. 4) with more than about 200 mm of rain became larger than that before cutting irrespective of the soil moisture in watershed. The above-stated situation is shown in Fig. 4.

The increment in high streamflow occurring after cutting can not be expressed by a generalized figure, because it depends upon the difference in forest, rainfall and other conditions. But the average amounts were calculated from the data of two watersheds in order to obtain a provisional standard value in disregard of the amount of storm rain, antecedent rain and other conditions. According to the result, the quickflow after cutting was 1.58 and 2.03 times these before cutting and the flow due to the heavy rain with a total amount of 200 to 500 mm was 1.30 and 1.65 times.

As stated above, the quickflow decreased after cutting under the specific condition. This also can not be indicated by a generalized figure. In both watersheds mentioned above, the quickflows were 0.75 and 0.49 times that before cutting in averages respectively, disregarding the amount of storm rain, antecedent rain and other conditions. A 100 mm storm (P_1 in Fig. 4) following the extremely little antecedent rain made a quickflow diminished by around 35 mm.

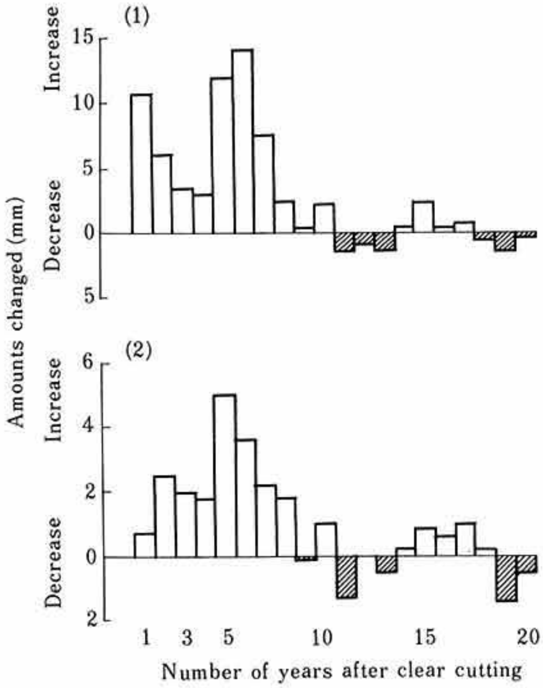
In the same way, the peak discharge also increased or decreased after clear cutting. The extent of increase was averaged to be 1.62 and 1.91 times that before cutting with each experiment, but 1.35 and 1.70 times for the flood due to the heavy storm with rain of 200 to 500 mm.

And the extent of decrease was 0.65 and 0.47 times with each experiment.

3) Forest cutting and low streamflow

The effect of clear cutting on low streamflow was analyzed with the data from the 2.5, 17.3 and 22.6 ha watersheds stated above[3].

All daily runoffs throughout a water year were re-arranged in the order of runoff amount to make a daily runoff series, and the sums of runoffs for 50 and 85 days counted from the least runoff day in the series were defined as scanty and low runoffs respectively.



Notes: (1): Low runoff
(2): Scanty runoff
1: Beginning of clear cutting
3: End of the cutting
4–20: Development of the regrowth

Fig. 5. Change in low streamflow after clear cutting and subsequent development of regrowth. (17.3 ha watershed)

The low and scanty runoffs increased after cutting in all the experiments.

The extent of increase changed with forest situation, rainfall, air temperature and other conditions, and the rate of increase amounted to the maximums of 44, 149 and 187% in 3 experiments respectively.

In the watershed where the regrowth was allowed on cut-over area, the increment in low streamflow decreased year by year. And it was recognized that low streamflow returned to the same level as that before cutting roughly in 10 to 15 years. (Fig. 5)

4) The reason for the change in runoff

The followings are considered as the reasons for the changes in high streamflow after cutting[3]. The first reason is the increased surface runoff with the declined infiltration capacity of soil due to disturbing and compacting by logging. The second one is the diminished initial loss of direct runoff by the decrease in evapotranspiration loss due to the removal of trees.

But, in late spring and summer seasons when evaporation takes place very much the surface soil in the cut-over watershed without forest canopy is extremely dried, being exposed directly to the scorching sunshine. The cutting, therefore, increases the initial loss and then decrease the high streamflow.

A reason for the increase in low streamflow during no rainfall period after cutting is considered to be due to the diminished transpiration, which is more than offsetting the increased ground surface evaporation, and the deterioration of infiltration capacity. The increase in low streamflow during snowdrifting period appears to be due to a combined effect of the diminished snow interception, the increased soil moisture replenishment in fall owing to the diminished transpiration, and the promotion of snowmelting without forest canopy.

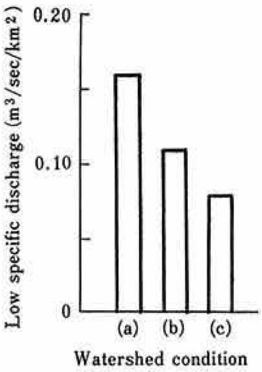
Annual, summer and winter, and monthly runoffs are all the sum of quickflow and base flow during the corresponding periods. As both flows for most of month increased after cutting, the total runoffs for these period naturally increased. The runoffs for some months during late spring and summer seasons decreased as quickflow during the seasons had diminished after cutting.

The increase in monthly runoff during the first half of snowmelting period and at the same time the decrease in the runoff during the second half are considered to be mostly due to the change in monthly allotment of snow water owing to the early-thawing brought about by the removal of forest canopy.

5) Quality of forest vegetation and high and low streamflow

The relation between streamflow and forest condition was examined on many of relatively larger watersheds selected in a district. Thirty watersheds equally covered by the forest consisted of *Chamaecyparis obtusa, Chamaecyparis pisifera, Tsuga Sieboldii* and others were selected in a mountainous area. Their geophysical conditions were almost the same: granite, brown forest soil and steep topography. After the watershed conditions including the forest area percentage and bare land area percentage were surveyed, peak discharge for each storm and low streamflow between each storm during growing season were measured over three years[2].

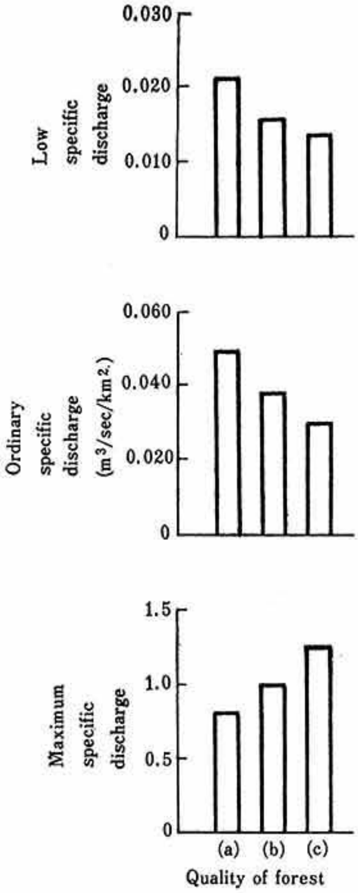
Twenty five peaks and low discharges respectively were measured on 17 watersheds in common. Rain of 25 storms ranged from 20 mm to 450 mm, and their intensity from 3 to 38 mm/hr. And each storm brought about the nearly uniform amount and intensity of rainfall on the whole area including 17 watersheds.



Notes:

	Numbers of watershed	Area in ha	Forest area percentage	Range of high specific discharge	Range of low specific discharge
(a)	7	60–238	80–92	1.4–3.7	0.06–0.27
(b)	6	66–135	54–77	1.0–4.7	0.05–0.25
(c)	4	74–191	9–45	1.0–4.6	0.05–0.10

Fig. 6. Forest area percentage and low specific discharges.



Notes: (a) Best forest
(b) Good forest
(c) Poor forest

Fig. 7. Quality of forest and discharge

These 17 watersheds were divided into three groups according to the forest area percentage and bare land area percentage. The average spesific peak and low discharges were calculated for each watershed group. Fig. 6 shows the relation between specific discharge and the forest area percentage.

Average specific low discharge of the watershed group with larger forest area percentage is fairly larger than that of the other groups. There is a clear difference in the low discharges among 3 watershed groups.

Similarly, the relation between average specific low discharge and bare land area percentage was investigated too. A watershed group with the largest bare land area percentage had clearly the least low discharge than that of other two groups.

The same examination was also practiced in other districts. Many watersheds with forest area covering 90% and more of the whole area, were adopted for the survey and divided into three watershed groups according to the quality of forest. Low, ordinary and maximum specific discharge were measured over many years and averaged for each watershed group. As given in Fig. 7, the watershed group with the best quality of forest showed obviously the largest low and ordinary specific discharge, and, on the contrary, the smallest values of maximum specific discharge.

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