Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Minor changes of water conservation capacity in 50 years of forest growth: analysis with data from the Ananomiya Experimental Forest, Japan

MICHIO HASHINO[1] & HUAXIA YAO[2]

1 *Department of Civil Engineering, The University of Tokushima, 2-1 Minami-josanjima, Tokushima 770-8506, Japan*

2 *Environmental Protection Branch, Department of Environment, Province of Saskatchewan, Box 3003, Prince Albert, Saskatchewan S6V 6G1, Canada*

hyao@serm.gov.sk.ca

Abstract Forest planting and growth over 50 years have not produced significant water conservation in an experimental watershed in Japan. Comparisons of hydrological responses between two periods (1930–1937, and 1983–1990) showed that the afforested watershed had increased annual evapotranspiration by 12% and water storage of soil by 15%, and reduced flood flows by about 20%. However, annual runoff from the watershed was reduced by 8.5% and low flows became even smaller, which was unfavourable for both water conservation and water supply. The minor increase in soil storage capacity produced a very limited water conservation effect and so flood reduction. In contrast, the increased evaporative consumption made annual runoff and low flows smaller.

Key words forest growth; water conservation; flood; low flow; water supply; soil storage; rainfall; evapotranspiration; Japan

INTRODUCTION

The hydrological impacts of afforestation and forest growth have been researched by a vast body of scientists in the past 100 years. A summary and review (Bosch & Hewlett, 1982) of 94 catchment experiments showed that increases in forest cover have resulted in reductions of water yield, and decreases in cover have resulted in increases of water yield. Schulze & George (1987) reviewed the effects of afforestation on water yield in South Africa, and applied a process model to simulate the effects. Results from South African experiments identified decreases in water yield because of increases in evapotranspiration by the forest. The effects of afforestation in Scotland on water resources (Johnson, 1995) showed that both mean flow and annual minimum flow were reduced and the flow duration curves were shifted downwards.

Recently, Farley *et al*. (2005) completed a global synthesis on the effects of afforestation on water yield by analysing 26 catchment data sets selected from many countries. They identified the differences caused by the original land use (grassland or shrubland), climate region (wetter or drier), and plantation species (Eucalyptus or pine). Most of the data were from paired catchment studies in which the streamflow of grassland or shrubland catchments was compared with that of nearby afforested catchments. They did not include data from non-paired or single catchment studies where streamflow data before and after afforestation were available at the same catchment. Their data sets also excluded other countries such as Japan and China. Paired catchments are good for avoiding climate effects on streamflows, but include possible effects of different geology and topography. Single catchments include climate effects, but exclude basin property effects and therefore would be valuable additions to a global synthesis analysis.

Lane *et al*. (2003) proposed a technique of separating the climate and vegetation impacts on the annual flow regime following afforestation, and applied it to ten catchments in Australia, New Zealand and South Africa. They characterized flow changes due to forest plantations without using the paired-catchment method, and both annual water yield and low flows (including zero flow days) were the focus. However, there were very few data from the single catchments.

The vast literature on forest hydrology has given a strong impression that a plantation forest's contribution to the basin's water conservation capacity is limited in its amount and direction. Minor or minimal change in the capacity could be created when a watershed is converted to a forested condition within a short time such as 10–50 years, especially when the watershed was originally sparsely vegetated. Furthermore, when a forest reduces flood flows, it does not increase low flows at a later time or in the same year, but decreases low flows and annual water yield. Additional examples of single catchment studies with long duration data sets are needed to enrich the general impression. Therefore, this paper presents a single-catchment study using 60 years of data from the Ananomiya Experimental Forest, The University of Tokyo, in the Aichi Prefecture of Japan. The reasons for flow decreases—evaporative increase and minimal change in soil water storage—are analysed.

DATA

The Ananomiya watershed (Fig. 1(a)) is located at latitude 35°15′N and longitude 137°06′E, with an area of 13.9 ha and altitude of 140–218 m a.m.s.l. The original vegetation in the 1920s was sparse shrubs and pine trees, and the initial planting of pine trees for soil erosion prevention started in 1925. The plantations were further extended during the 1930s to 1960s. The forested area reached 6.3 ha or 45% coverage in the 1930s and increased to 13.5 ha or 97% coverage in the 1980s (Fig. 1(b)). Daily meteorological and hydrological data were collected during the 60-year period, 1930–1990.

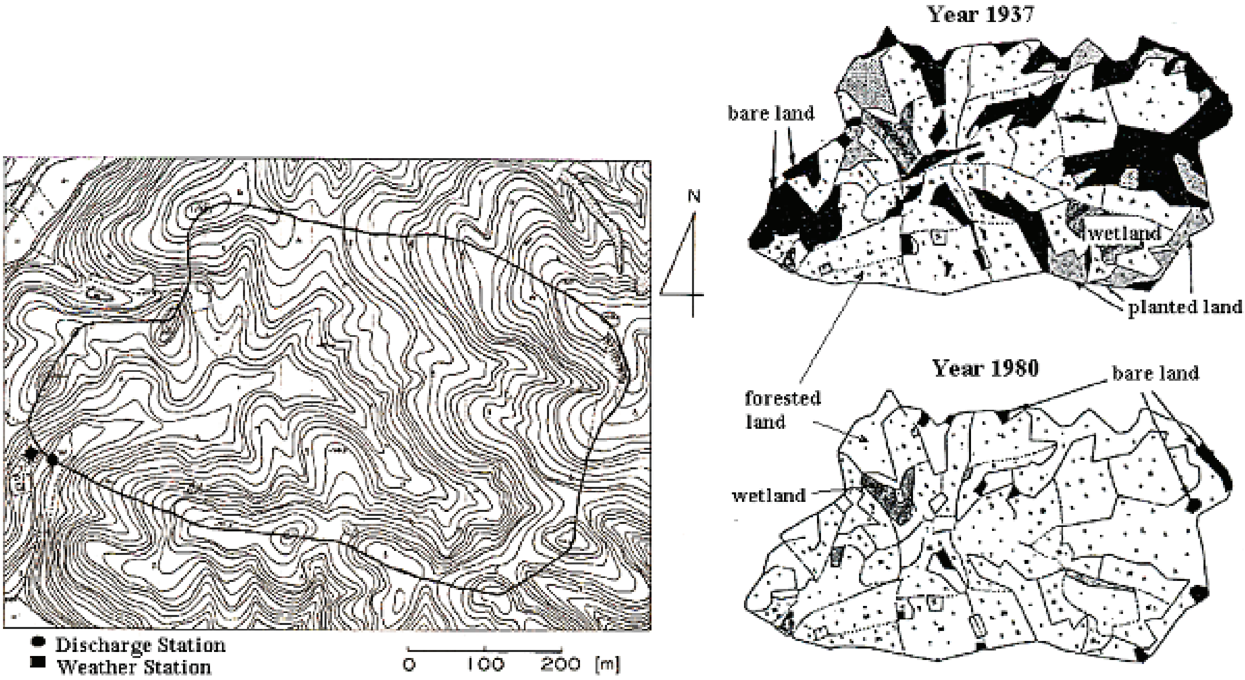

Fig. 1 (a) Ananomiya watershed and observation stations. (b) Forested and bare lands in 1930s and 1980s.

METHOD

Two representative periods were selected for comparison analysis: the eight years 1930–1937 when forest coverage was 45%, and another eight years, 1983–1990, when the forest coverage was 97%. A favourable situation for comparison of runoff or evaporation is given by the similarity of the precipitation and temperature regimes (mean annual precipitation 1580 mm and mean temperature 15°C) for both periods. The number of days having more than 50 mm rainfall are also the same at 8 days per year on average, and the days having 100 mm storm rain are similar at 1 day per year, during both eight-year periods. Comparisons of storm events, annual runoff and soil storage between the two periods were conducted.

Differences in hydrological responses to storm rainfall events or annual precipitation are revealed by the comparisons. If discharges in dry seasons became less and annual water yield became less because of forest growth, the water conservation represented by reduced flood flows would be weakened. Forest could not both reduce floods and increase low flows.

Water conservation capacity is strongly related to the water storage capacity of soils. A conceptual largest soil storage (LSS) for the watershed is defined as the largest volume of water stored in the soil for a month. It is neither the saturated water storage nor the maximum storage in

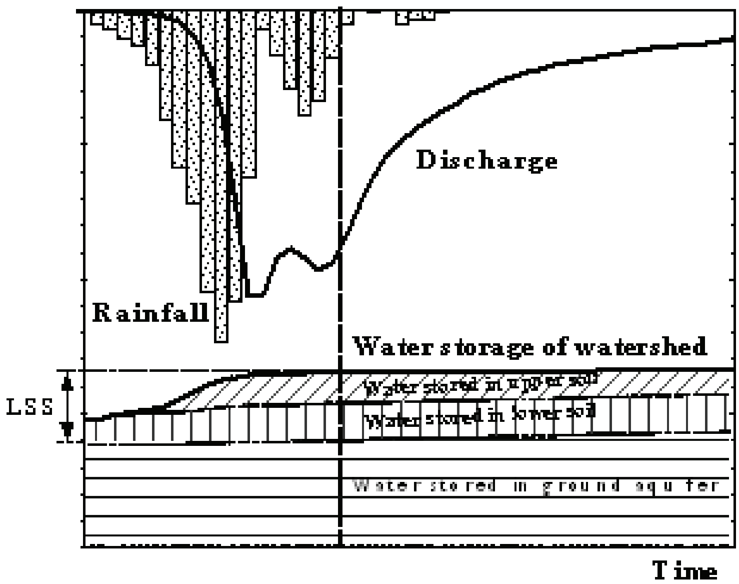

Fig. 2 Illustration of water storage of soil, and the largest soil storage (LSS).

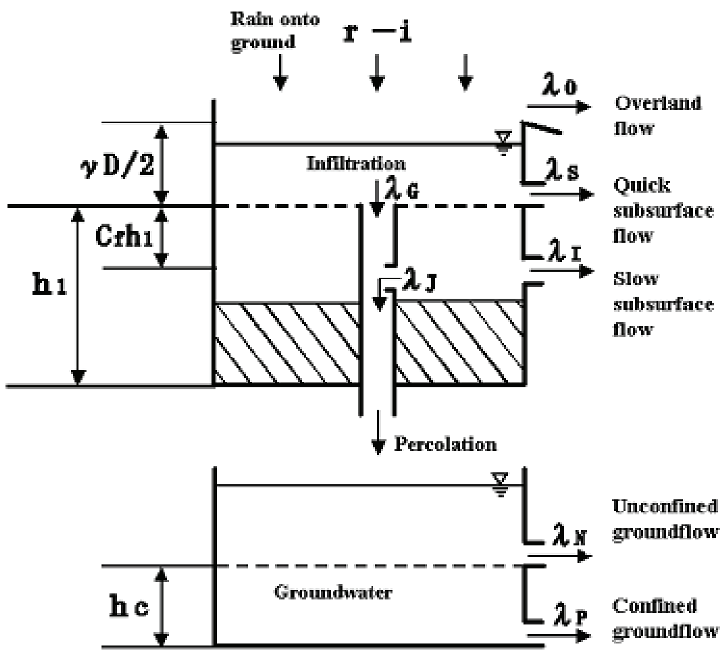

Fig. 3 Tank model of water movement and storage in soil and groundwater aquifer.

a year, but rather the relatively largest value in any month. Therefore LSS changes from month to month, and from year to year. A typical LSS is illustrated in Fig. 2.

The daily soil water storage and the LSS of each month are not measured but calculated using a lumped two-layer Tank model (Hashino *et al.*, 2004). The model structure (not including the canopy and its interception) is shown in Fig. 3 and its parameters are calibrated separately for the eight years in the 1930s and the eight years in the 1980s. The soil water storage of each day and largest soil storage of each month are estimated by the model. The LSS, as representative of soil storage capacity, will indicate how large the difference of storage capacity is for the two periods.

In the model, after calculations of rainfall interception by the forest canopy and associated interception evaporation, the rain falling onto the ground surface (the rainfall rate *r* above canopy minus interception rate *i*) infiltrates into a soil layer (or tank), and then percolates to a groundwater aquifer tank. When rainfall infiltration reaches the saturation level of the soil tank, surface storage and overland flow will occur. Otherwise runoff from the soil (quick and slow subsurface flows), the upper and lower groundwater aquifers constitute the total runoff from the watershed. Parameter h_1 is the soil saturation content, C_f is related to the initial water storage in the soil tank, *hc* is the initial water sorted in aquifer tank and λ_O is related to the overland flow coefficient. λ_G, λ_J are infiltration coefficients, λ_S, λ_I, λ_N, and λ_P are the outflow coefficients respectively for quick and slow subsurface flows, unconfined groundwater flow, and confined groundwater flow, while γD is a parameter related to quick subsurface flow. The parameters are calibrated using a Simplex method (Nocedal & Wright, 1999).

RESULTS

Runoff responses of storm events

Twelve storm events that have more than 100 mm rainfall volume were chosen from the period 1930–1937, and eight storm events were chosen from the period 1983–1990. Runoff responses of storm events differed between the two periods, with the ratios of runoff volume to rainfall for the 1980s being, on average, 20% less than that for the 1930s among the chosen events, as shown in Fig. 4. This indicates the extent to which flood volumes were decreased by forest plantation and tree growth. Possible reasons for a reduction in flood response include increased evaporation and transpiration due to increased leaf area and rooting depth, different rainfall characteristics such as duration and intensity, and increased soil water storage.

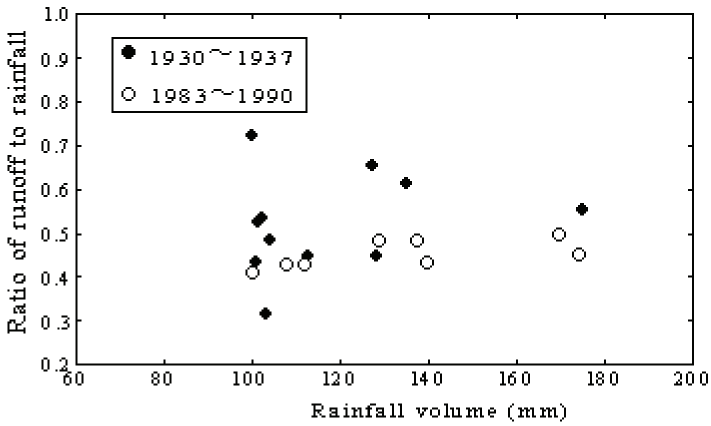

Fig. 4 Ratios of runoff volume to rainfall volume for storm events over 100 mm.

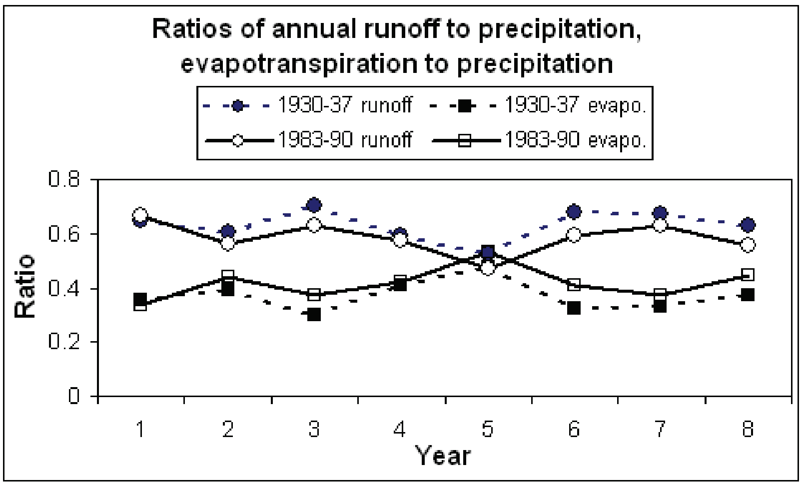

Fig. 5 Difference of annual runoff or annual evapotranspiration between two periods.

Annual runoffs and low flows

Annual runoff volumes during the 1980s are less than those of the 1930s. In contrast, annual evapotranspiration during the 1980s was definitely higher (Fig. 5). The 8-year-mean runoff of

1983–1990 was 928 mm, 8.5% less than the mean of 1014 mm for 1930–1937. The 8-year-mean evapotranspiration of 1983–1990 was 649 mm, 12% more than the mean of 578 mm for 1930–1937. Increased trees and leaves have increased consumptive evaporation or transpiration not only during the flood seasons, but also during dry seasons, causing the reduction of annual runoff. Forest plantation and growth did improve flood control as discussed above, but did not improve water resource supply in the dry seasons.

The ten smallest daily flows in a year were used as representative of the low flows of the watershed. The ten smallest flows were chosen from each year of the two periods, and a period-averaged value was obtained for each of the ten smallest. For example, the average first smallest flow in 1930–1937 was 0.6 mm day^{-1}, the averaged tenth smallest flow in 1930–1937 was 1.5 mm day^{-1}. As shown in Fig. 6, all the smallest flows in the period 1983–1990 were less than those in 1930–1937, clearly indicating a reduction in low flows following plantation growth.

Changes of LSS

The Tank model was calibrated for the periods 1930-37 and 1983-90. Two examples of simulated and observed flows are shown in Fig. 7, for year 1937 and 1990, respectively. The model gave reasonably good estimations of daily flows.

The values of largest soil storage (LSS) for each of the two periods were estimated using the calibrated model, and are shown in Fig. 8. The horizontal axis represented the accumulated rainfall of those rain events that appeared before a LSS was formulated in the soil (also see Fig. 2). In total, 65 LSSs for period 1930–1937, and 53 LSSs for period 1983–1990 were included in Fig. 8, and they did not show a significant difference between the two periods. The average LSS for the two periods was 27.3 mm and 27.8 mm.

It was noted that the soil water would be saturated when accumulated rainfall was around 150 mm or more. If only taking into consideration the LSSs when the accumulated rainfall was more than 150 mm, the 8-year-averaged LSS for 1930–1937 was 48.6 mm, while the averaged LSS for 1983–1990 was 56.0 mm. Therefore, the soil water storage capacity might have been increased by 7.4 mm (or 15%) which could not account for the reduction in flood flow that was mentioned previously.

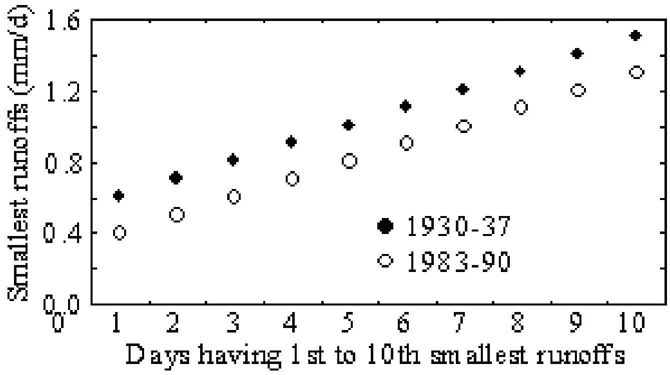

Fig. 6 Difference of smallest daily runoffs between two periods.

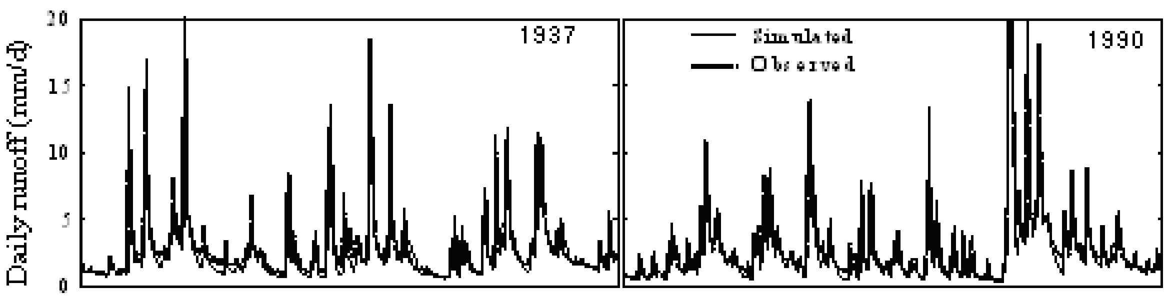

Fig. 7 Examples of simulated runoffs *vs*. observed runoffs.

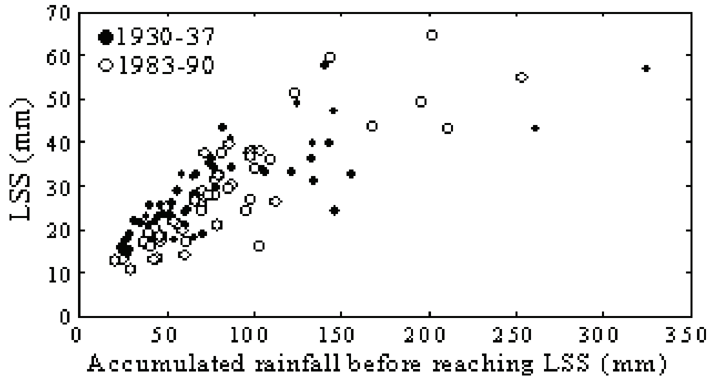

Fig. 8 Estimated LSS of two periods.

In conclusion, tree planting and growth at Ananomiya watershed have increased evapotranspiration and therefore decreased runoff, both for flood and dry seasons. The foliar change in the short time of 50 years did not appear to produce significant increases in soil storage capacity. The forested watershed was not acting as a reservoir that reduces flood flows and increases low flows. This is a further contribution to the body of science on the impacts of afforestation.

Acknowledgements The authors are grateful to Dr Denis Hughes for providing suggestions and comments that improved the manuscript.

REFERENCES

Bosch, J. M. & Hewlett, J. D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* **55**, 3–23.

Farley, K. A., Jobbagy, E. G. & Jackson, R. B. (2005) Effects of afforestation on water yield: global synthesis with implications for policy. *Global Change Biology* **11**, 1565–1576.

Hashino, M., Tamura, T., Tabuchi, M. & Fujikawa, Y. (2004) Separation of interception evaporation, transpiration and non-overland flow in a forest watershed. *J. Hydraul. Engng, JSCE* **48**, 31–36 (in Japanese with English summary).

Johnson, R. C. (1995) Effects of upland afforestation on water resources, the Balquhidder Experiment 1981–1991. *Institute of Hydrology Report no. 116.* Wallingford, UK.

Lane, P., Best, A., Hickel, K. & Zhang, L. (2003) The effects of afforestation on flow duration curves. *Technical Report 03/13, Cooperative Research Centre for Catchment Hydrology*. Monash University, Australia.

Nocedal, J. & Wright, S. J. (1999) *Numerical Optimization.* Springer-Verlag, New York, USA.

Schulze, R. E. & George, W. J. (1987) Simulation of effects of forest growth on water yield with a dynamic process-based user model. In: *Forest Hydrology and Watershed Management* (ed. by R. H. Swanson, P. Y. Bernier & P. D. Woodard), 575–584. IAHS Publ. 167. IAHS Press, Wallingford, UK.