Research Report

Use of Historical Data as a Decision Support Tool in Watershed Management: A Case Study of the Upper Nilwala Basin in Sri Lanka

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International Water Management Institute

Research Reports

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Contents

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Summary

Watershed analysis provides a framework for ecosystem management, which is currently the best option for conservation and management of natural resources. The water cycle regulates and reflects the natural variability of the physical processes which impact on ecosystems. Considering the constraints associated with presently available techniques for evaluating land use impacts on the water cycle, such as paired catchment method and modeling, this study provides an alternative approach to ascertain the actual changes in hydrologic response of a particular watershed to land use transformations made in the past. In this alternative rapid approach, not only are long-term historical time series data on streamflow, rainfall, and land use analyzed to discern changes in hydrologic effects but also landscape-level history, conditions, and response potential are used as a guide to identify appropriate land use management options depending on the degree of variation in hydrologic response of the watershed compared to that of the stable conditions, which existed with a substantial forest cover in the past.

In 1940, about 50 percent of the watershed studied was under natural forests. This had decreased to 43 percent in 1948 and to 30 percent in 1964. This conversion of natural forests into other agricultural land uses has resulted in an increase in annual total water yield with increased storm runoff and base flow. However, this effect has been masked by declining rainfall during 1940–1947, which has brought about a reduction in flow. The mean annual water yield had increased by 17.5 cm during 1948–1964 compared to the 1940–1947 period and 80 percent of the increase is due to increased flow during periods with substantial base flow. During the 1965–1997 period, forest cover further decreased from 30 percent to less than 15 percent. Though mean annual water yield during 1965–1997 reached that of 1940–1947, there were variations in flow regimes compared to those before the 1965 period. The major changes include reduction in contribution to runoff by base flow while storm runoff was high during high rainfall months. Consequently, very conspicuous changes in flow regimes have occurred after 1965 with forest cover declining from 30 percent to 15 percent. The increase in base flow during 1948–1964 with clearance of forest cover from 43 percent to 30 percent was short-lived because the base flow has declined thereafter. This could be attributed to the establishment of home gardens and tea in 20 percent and 50 percent, respectively, of the watershed area. The increased storm runoff generation has continued despite the establishment of a new cover. As a result, in the 1990–1997 period, when forest cover was less than 15 percent of the watershed area, changes in flow regimes were at their peak, compared to the 1940–1947 initial conditions. This change in flow regimes implies that the new cover dominated by tea and home gardens is not well-managed to be as effective as natural forest cover in maintaining desirable high infiltration rates and arresting the high storm runoff.

The observed adverse environmental impacts were directly related to changes in flow regimes. Rapid runoff was responsible for high soil erosion rate, loss of land productivity, and more frequent flash floods. The high rate of sediment supply due to accelerated erosion has caused aggradation of stream channels, increasing the likelihood of flash floods, reduced land productivity in rice fields with deposition of coarse material, and silting of irrigation canals. During dry spells, relative droughts and irrigation water shortages have occurred. Downstream, reduced low flows have threatened the dependable supply of good quality water and increased the salinity intrusion at the river mouth

whereas increased high flows have aggravated the flooding.

From the integration of field assessments with historical analyses and response potential, it was obvious that the observed adverse impacts have resulted mainly from the conversion of natural forests into other land uses that, in turn, have produced rapid surface runoff and decreased dry weather flow. Linking these cause-effect relations, revealed by watershed analyses, land management prescriptions were developed to major land use categories in the catchment studied so that the hydrologic response would be closer to the desired conditions that existed with a great percentage of forest cover. Suitable land use management practices for agricultural land uses were identified mainly based on their ability to mimic the forest ecosystems. However, in some instances, management of impacts has become a must to alleviate the adverse effects, for instance, maintenance of lock-and-spill drains in tea lands to temporarily retain high storm runoff for gradual infiltration.

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Introduction

Watershed management projects are based on the premise that hydrologic units are appropriate for conceptualizing strategies and planning investment for conservation and management of natural resources aimed at sustainable development. Ecosystem management in a landscape ecology perspective is an evolving philosophy adopted in the multiuse sustained resources management. Frissel and Bayles (1996) have concluded that ecosystem management is currently our best option for conserving resources and opportunities for the future. Jensen et al. (1996) have shown that linkage of public expectations and resource conditions in ecosystem management is better suited to developing sound public policy than to previous management philosophies. Montgomery, Grant, and Sullivan (1995) have clearly demonstrated that watershed analysis provides the framework for delineating the spatial distribution and linkage between physical processes and biological communities in an appropriate physical context for an ecosystem approach.

Technical aspects of many watershed projects focus mainly on correcting problems caused by deforestation, declining soil fertility and productivity, erosion including landslides and sedimentation, flooding, reduced downstream water quality, and nondependable water supply, etc., but in many cases without a proper understanding of the root causes for such problems. Changing hydrologic behavior triggers a chain of reactions in other processes such as soil erosion, nutrient leaching, water quality, and spatial and temporal distribution of water. Therefore, the emphasis in watershed development is generally on agriculture, forestry, land uses, and other structural and nonstructural interventions. Such interventions affect the hydrologic response of the watershed through increased infiltration rate of the soil, decreased surface runoff, control and retardation of flow and flash floods, storage of water, and recharge of the aquifer, or some of their combinations. Therefore, in implementing an ecosystem approach to land use decision making and land management, a better understanding of the hydrologic response of the watershed is required. Failures to approach planning on a watershed-wide scale with a better understanding of the hydrologic response can lead to incorrect priorities resulting in waste of resources. Under these circumstances, the assessment of the hydrologic effects of land use transformations on both water yield and flow regimes—the basic processes that trigger the other environmental impacts—is an important aspect in watershed management.

State of the Art of Measuring Hydrologic Impacts of Land Use Transformations at the Watershed Scale

A simple method to assess hydrologic impacts of different land uses is to compare streamflow characteristics of different catchment areas with contrasting land use types. This would enable comparison of the hydrologic response of a catchment consisting of degraded lands where watershed management is to be introduced with catchments that already have the desired land use characteristics anticipated to be achieved. Such a comparison may lead to wrong conclusions as shown by Bruijnzeel (1990) after reviewing the catchment water balance studies related to land use transformation in the tropics. This is mainly because of the possibility of differences in catchment leakage through bedrock-underlying valley fills or weathering mantles. In many small headwater catchment areas, streams have not cut through the entire weathering mantle that may reach considerable depths in tropics leading to large volumes of leakage (Burnham 1989). Also larger streams may lose substantial amounts of water to their floodplains. For example, in measuring water yield in small catchments, Richardson (1982) has reported considerable differences in total water yield in Madagascar suggesting catchment leakage. Qian (1983) and Dyhr-Nielsen (1986) have shown that in the tropics, another factor complicating the evaluation of hydrologic effects of land cover transformation is the strong interannual variability of weather.

An effective method evolved to overcome the above problems encountered in catchment water balance studies is the "paired catchment method," where hydrologic comparison is made between two (or more) catchments of similar size, geology, slopes, exposure, and vegetation, and situated close to one another. Here the "control" is left unchanged while land use changes are effected in the "experimental" or "treatment" catchment (Roche 1981; Hewlett and Fortson 1983). In addition to the comparison made after treatment, a comparison is also made during the initial calibration phase of several years (depending on rainfall variability) before changes in land use are effected in the control catchment. The degree to which linear regression equations or double mass curves correlating the streamflows of the two catchments change after the treatment compared to that during the calibration period is a measure of the hydrologic effect of land use change (Hsia and Koh 1983). The total duration of experiments with the paired catchment method may easily span a decade (Bruijnzeel 1990). Moreover, the results may be rather site-specific due to an area's geological or pedological setting (Fritsch 1987; Dano 1990). Therefore, in recent years there has been an increasing trend to predict hydrologic changes brought about by land cover transformations in the tropics by robust models employing data obtained during relatively short but intensive measuring periods (Shuttleworth et al. 1990; Institute of Hydrology 1990).

For watershed development projects in the developing countries, the application of the paired catchment method to identify the suitable land use interventions has practical limitations. Several years of watershed calibration prior to actual implementation of the project is not practical in many instances as such projects are implemented mostly with donor funding soon after their appraisal. Even if calibration of catchments is accomplished successfully prior to effecting land use changes in the treated catchment, it takes time to evaluate the actual hydrologic changes brought about by land use transformations. If the evaluation reveals that desired results are not achieved, it is too late to correct the already introduced land use transformation. In other words, this technique does not predict the hydrologic impacts of any set of anticipated land use transformations in a given locality unless the paired catchment method has been applied in the past to evaluate land use transformations in the areas with similar physio-geographical conditions. Such an accumulated knowledge with previous studies is either scanty or not available in most of the tropical countries. Under these circumstances, one can expect to overcome these constraints by the application of suitable models.

Effects of land use changes on runoff characteristics of a watershed have been studied using several types of models, which varied from strictly empirical to physical-based distributed models. Reciprocity in hydrologic processes and the mosaic landscape are scale-dependent and nonlinear, and due to such relations the success of both physical and empirical cause-effect modeling is increasingly questioned (e.g., Beven 1989). Investigating natural, potential, and human-induced impacts on hydrologic systems commonly requires complex modeling with evolving data requirements, plus massive amounts of one to four dimensional data at multiple scales and formats (Hay and Knapp 1996). Most hydrologic models are traditionally based on deductionistic cause-effect relationships developed for the temperate region but the sustainable management of vulnerable and extreme regions, such as the tropics, demands a new holistic and transparent approach relying on first principles and integration of processes and landscape patterns (Gumbricht et al. 1997). Considering the requirements of various models and their limitations in the application to predict hydrologic changes with land use transformations, it is reasonable to conclude that dependence on models is not feasible in developing-countries of the tropics, at least in the near future. The major constraints are the knowledge gap in hydrology-related processes and parameter values, the cost involved and time consumed even if minimum data requirements are to be achieved, and the problems in calibration and validation of such models with reliable historical data.

The Methodology Employed in the Study and Its Rationale

Considering technical, financial, and time constraints associated with the current state of the art of assessing hydrologic impacts of land use transformation at the watershed scale, particularly in the tropics, the following method was tested with the objective of using this methodology as a guide to identify appropriate land use transformations and land use policy interventions at the watershed scale. In this study, an attempt is made to ascertain the changes in the hydrologic response of the same watershed with changed land uses, which took place in the past. The historical time series data on streamflow, rainfall, and land use are used for the analysis. The variability in the hydrologic response brought about by the year-to-year variation in weather is removed by establishing the correlational relationships among hydrologic variables based on long-term time series data. Moreover, instead of annual data, 5-year moving averages are used in the trend analysis of hydrologic data to minimize the effect of interannual variations. This is an approach to compare hydrologic behavior of a single catchment before and after land use transformation. This method holds scope for planning suitable land use transformations in the tropics with a rapid assessment of their possible impacts at the watershed scale if historical time series data of rainfall, streamflow, and land use are available. Further, this technique of rapid appraisal would become very useful with the availability of remote-sensed data.

Most of the crucial watersheds in the tropics had substantial forest covers in the past and they have gradually degraded with deforestation, expanding agricultural practices, and physical infrastructure development without proper planning. The spatial and temporal distribution of water with steady state conditions is an important component not only in maintaining the ecological equilibrium but also in meeting human demands. Therefore, the suggested methodology would give many clues as to what the plans should be and what the extents for adoption of conservation practices, agro-forestry, etc., should be, depending on the degree of variation in the hydrologic response of the watershed compared to that of the steady state conditions that existed in the past.[1]

Watershed analyses must rely on integrating field analyses and assessments, historical analyses, and landscape scale models of geomorphological and ecological processes. The watershed analyses include landscape-level ecological processes, history, conditions, and response potential. Therefore, understanding of the changes in the hydrologic response is a vital component of watershed management planning. As shown by Montgomery, Grant, and Sullivan (1995), the planning framework linked to watershed analyses uses this information to either manage environmental impacts or identify desired conditions and develop land management prescriptions to achieve those conditions. Under either approach, watershed analyses should collect the evidence and present the logic underlying land management decisions. It is also important to acknowledge the variable intrinsic capabilities and limitations of different parts of the landscape to sustain those activities through time and the potential for some disturbances or impacts to propagate downstream. Therefore, planning needs to recognize the spatial and temporal scales over which natural systems operate. As such, watershed analyses should produce information, knowledge, and understanding necessary for scientific interpretation to support informed decision making.

Determining the activity appropriate for a watershed rests on weighing potential future conditions against planned objectives. Planning is the forum within which management options are identified and developed based on coupling knowledge with objectives (Montgomery, Grant, and Sullivan 1995). Therefore, the assessment of the hydrologic response of various land use transformations through the suggested technique in this study would guide watershed management projects more in the context of an ecological approach, providing the required knowledge on historical conditions and response potential, though it may not be very useful as a black box model for prediction. More importantly, for countries with little or no experience in hydrologic modeling, the suggested method provides a simple, yet appreciable decision support tool that could be quickly applied with a limited set of data.

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[1] Steady state conditions of a watershed hydrologic response refer to the state of response of a watershed with minimum human interference to the forest ecosystem.

Source of Data and Method of Analysis Used in the Case Study

For the analysis of runoff changes in the study catchment, daily discharge measurements at the Bopagoda hydrometric station for the period 1940–1997 were obtained from the Hydrology Division of the Irrigation Department, where records have been maintained continuously. Although discharge records from two nearby hydrometric stations (one at Bopagoda and the other at Bingamara) in the Nilwala basin were available, the Bopagoda station was selected for the study in view of the reliability of its data and continuity extending over a long period of time. Daily rainfall data for the stations of Anninkanda, Arpthorp, and Mawarala, which are located around the watershed, were obtained from the Meteorological Department. The basin average rainfall calculated for the study area, based on these stations using the Thiessen polygon method, gave a poor correlation with flow data. The best correlation with flow data was shown by the Mawarala rainfall data and therefore, this station was selected to represent the average rainfall of the study catchment. It is important to note that the Mawarala station represented more than 70 percent of the study area when Thiessen polygons were constructed. Moreover, a double mass analysis revealed the availability of consistent rainfall records for this station from 1940. Under these circumstances, the selection of this single station as synoptic of the study catchment of 379.5 km^2 was justified.

Long-term trends in rainfall and stream flow were analyzed using the conventional techniques of moving averages and linear regression models. Analyses involved variations in annual runoff to reveal the changes in total water yield in the context of variations in rainfall and land use. Also, variations in runoff during low-flow and high-flow periods were separately analyzed to discern the trends in storm runoff (or direct runoff of storm events) and base flow (or the contribution from groundwater). The annual and seasonal values were considered because factors like the antecedent rainfall and seasonal effect, which affect the runoff from a rainstorm of certain depth and duration, vary only in negligible amounts during a hydrologic year or a season.

Data of historical land use transformations in the catchment were obtained mainly by comparison of land use depicted by sequential aerial photographs available for 1956, 1972, and 1983. As these data could not reveal the continued land use changes during the entire period from 1940 to 1997 considered for the study, information was gathered from key informants. Such information included not only the major changes in land use during different time periods but also the causes underlying such changes. The key informants included local residents with a long history of relation to the study catchment. This group included various categories of people from priests, retired government officers (such as school headmasters and village headmen) to farmers. Also many government officers such as land officers and *grama niladharis* (administrators at the grass-roots level) attached to various line agencies and presently working in the study area with a long service were consulted.

Various environmental impacts associated with natural resources, mainly soil, water, and land productivity, were identified by interviewing a large number of residents for their experience over years and for their perception of the problems. Also the problems associated with natural resources management were identified by the authors during frequent field visits to the study area from 1995 to 1997 for activities related to the Shared Control of Natural Resources Project, besides consulting key informants on this aspect during such visits.

Description of the Study Catchment

The Nilwala river originates at Panilkanda at an altitude of 1,050 m and after traversing 70 km the river flow is discharged into the sea at Matara. The area of the river basin is 1,073 km^2. The river flows across two distinct zones. The upstream up to Bopagoda traverses a hilly terrain with a steep longitudinal slope and the river bed in this zone is rocky with fairly high-flow velocities. The longitudinal slope decreases towards downstream. At Bopagoda, located 36 km upstream of the sea, the longitudinal slope is about 0.4 m per km. In the upper part of the basin floods do not cause any considerable inundation along its major course due to very narrow floodplains though flash floods are a recurrent feature in its tributaries. The longitudinal slope downstream of the river is 0.25 m per km at Kadduwa located 18 km upstream of the sea and the average slope of the river bottom is almost zero along the last 13 km of the river where a broad valley is located. This lower basin extending inland up to about 12 km from the coastline is subject to severe flooding with southwest monsoonal rains experienced from May to June and with convectional and cyclonic activities from October to November. The intensity and duration of floods vary depending on the location.

The hydrometric gauging point, which demarcates the study catchment, is located at Bopagoda. The total watershed area demarcated by the Bopagoda reference point is 42,000 hectares. However, there is a trans-basin diversion to carry water (about 2.83 m^3/s) from the western flowing Urubokka Oya to Urubokka Ganga through the existing 3-mile channel and Ginneli Oya. This diversion into the Tangalla and Ranna regions in the dry zone commenced three centuries ago. The total land area of the Upper Nilwala catchment, which contributes its runoff to this diversion is 4,050 hectares and hence the actual watershed area with runoff contribution to the reference point is only 37,950 hectares. The watershed area covered by this study includes the sub-watersheds of the major tributaries of Kotapola Oya, Urubokke Oya (only the lower part), Hulandawa Oya, and Siyambalagoda Oya (fig. 1).

The predominant soil type of the upper basin is red yellow podzolic soils (Rhodudults) and it is associated with dissected, hilly, and rolling terrain. Alluvial soils are confined to the river valleys of the middle and lower parts of the basin while bog and half-bog soils are found in the poorly drained lower reaches of the floodplain.

Land Use Transformations in the Study Catchment

The land use pattern of the study catchment for 1956, 1972, and 1983 as revealed by the available aerial photos is given in table 1. Land use changes are discussed below mainly in the context of major land use transformations during different time periods that showed different hydrologic responses in the data analysis (i.e., 1940–1947; 1948–1964; and 1965–1997).

The 1940–1947 Period

Land use data from aerial photos are not available for the period prior to 1956. However, according to the national forest inventory, the natural forest cover of the country was about 70 percent at the beginning of the century and it had declined to 44 percent in 1953. Compared to

FIGURE 1.
Nilwala river basin.

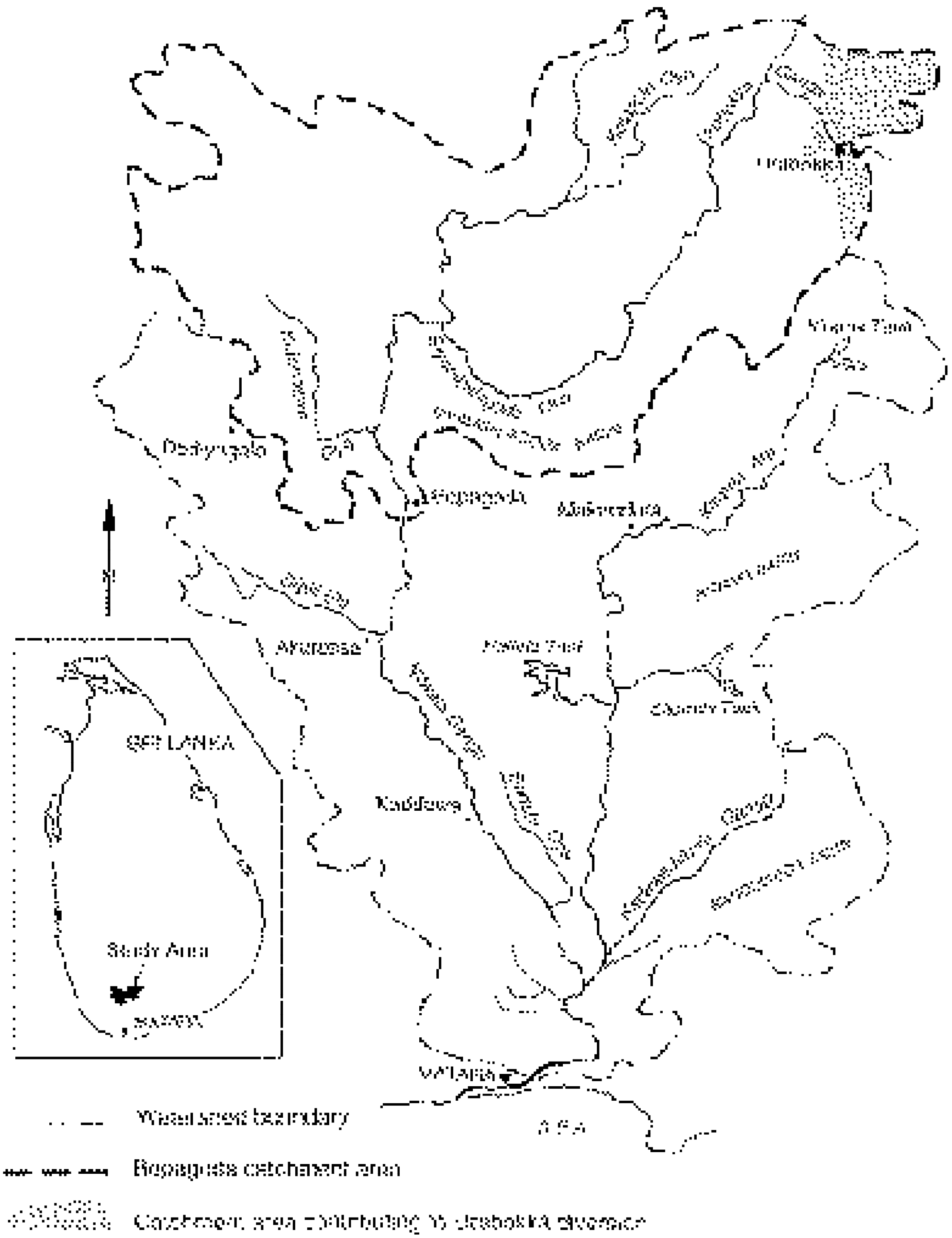


TABLE 1.
Area of the catchment under different land use categories in different years.

Land use category	Percentage of the area under each category		
	1956	1972	1983
Dense natural forests	34.17	20.06	16.31
Degraded forests	2.38	3.13	1.85
Scrublands	0.5	11.79	8.21
Forest plantations	0.18	0.18	1.43
Large tea plantations	12.97	14.13	10.28
Tea smallholdings	1.37	15.71	16
Rubber plantations	7.86	5.3	3.16
Coconut plantations	0.06	0.09	0.12
Cinnamon plantations	0.04	–	0.07
Land cleared for cultivation	12.57	3.1	11.52
Rice fields	5.88	7.98	9.51
Grasslands	4.9	3.21	0.83
Barren lands	–	–	0.05
Home gardens	16.01	14.17	19.94
Towns, villages, and other buildings	0.04	0.13	0.24
Water bodies	1.07	1.07	1.07
Total	100	100	100

other parts of the country, the upper Nilwala basin is remote and destruction of natural forests was relatively slow and late. As revealed by key informants, forests covered at least 50 percent of the study catchment in 1940. Therefore, the natural forest cover of the catchment should have declined during 1940–1956 from more than 50 percent to 36.6 percent of the total land area as identified through aerial photos. Deforestation in 13.4 percent of the entire watershed area during 1940–1956 indicates a deforestation of 27 percent of the natural forest cover that existed at the beginning of this period (i.e., in 1940). Therefore, the deforestation during 1940–1956 has taken place at an annual rate of 1.67 percent of the 1940 forest cover resulting in 43 percent forest cover in 1948. As the land use data in 1956 indicate, the conversion of these forests is reflected mainly in tea plantations that covered 13 percent of the total land area; others include rubber (8%), shifting cultivation (13%), and home gardens (16%) (table 1). Though the actual land use data for 1947 are not available, the type of land use transformations identified with 1953 land use data represents the major changes that occurred during 1940–1947, with forest cover declining from 50 percent to 43 percent.

This is further confirmed by the following information revealed by the key informants. Plantation crops, mainly tea, were introduced more than 100 years ago but a substantial expansion of tea plantations in the study area took place from 1930 onwards resulting in the migration of labor into the area from 1940 onwards increasing the population density. In 1935, the government leased 0.1–0.8 hectare landholdings to poor families. Though smallholders did not adopt tea at this time, a few affluent people established a few large-scale plantations. In 1938, middle class allotments were alienated and such lands were as large as 20 to 40 hectares each. As a result of the worldwide food shortage in 1942, each farmer was entitled to a 0.8-hectare land for food production. However, tea was not attractive to them due to inadequate know-how of tea growing, the need to go to the capital city of Colombo for obtaining permission from the Tea Controller's Department for tea cultivation in 0.8-hectare lands, and the drop in tea price in the world market. In 1947, lands were given on lease for cultivation to those who already had at least 10 hectares. In 1950, a tea fertilizer subsidy was granted to those having more than 20 hectares of tea. By this time, smallholders had started to gain the knowledge of tea growing and had started to grow tea but such smallholdings did not expand due to financial constraints and the lack of any advisory services.

The 1948–1964 Period

Land use data are available for 1973 but not for 1964. The major changes that can be identified between 1956 and 1972 include reduction of the forest cover that occupied most of the headwater areas from 36.6 percent to 23.2 percent of the total catchment area. Deforestation during this period in 13.4 percent of the entire watershed area is equal to 27 percent of the natural forests that existed in 1940. Therefore, the annual rate of deforestation from 1956 to 1972 is about 1.67 percent of the forest cover that existed in 1940, which is equal to the deforestation rate from 1940 to 1956. Therefore, the forest cover should have been 30 percent in 1965. During 1956–1972, shifting cultivation was reduced from 13 percent of the land area to 3 percent due to replacement of annual crops by tea and other perennials. The area under tea has expanded from 14 percent of the area in 1956 to 30 percent in 1972. The important feature is that in 1956, tea was mostly grown as large plantations but the expansion after 1956 was almost due to tea smallholdings, which occupied mostly the steep terrain of the upper watershed.

Local people revealed that introduction of a tea subsidy scheme for smallholders in 1958 and high yielding vegetatively propagated (clones) tea in the 1960s have caused an extensive adoption of tea planting in smallholdings by local residents and by migrants who encroached into the forest front. Similarly, tea has replaced shifting cultivation due to many reasons, such as continuous high income assured throughout the year, prevailing suitable climatic conditions for tea compared to alternative crops, and government support for tea, etc. As a result, the extent under tea has increased very rapidly with smallholdings as almost every family has ventured into tea growing. Therefore, the pattern of land use changes reported between 1956 and 1972 is representative of the major land use transformations during 1948–1964, with forest cover declining from 43 percent to 30 percent.

The 1965–1997 Period

The forest cover has been continuously disturbed during this period and the land use changes reported between 1972 and 1983 have taken place exclusively during this period. From 1972 to 1983 the forest cover was reduced from 23.2 percent to 18.1 percent of the watershed area. Besides encroachments, large-scale logging operations effected in some forests in the 1970s have led to gradual land use transformations since timber extraction was much above the level that would promote regeneration. This 5.1 percent reduction of forest cover at the total watershed scale is about 10 percent of the forest cover that existed in 1940. Therefore, the annual deforestation rate during 1972–1983 is at 0.92 percent of the forest cover that existed in 1940. This rate is relatively less compared to the deforestation rate of 1.67 percent observed during the previous period (i.e., 1940–1972). The extent of large tea plantations has slightly decreased during 1972–1983 due to abandoning of some of the plantations with the introduction of land ceilings on individual ownership size and subsequent deterioration in the management conditions.

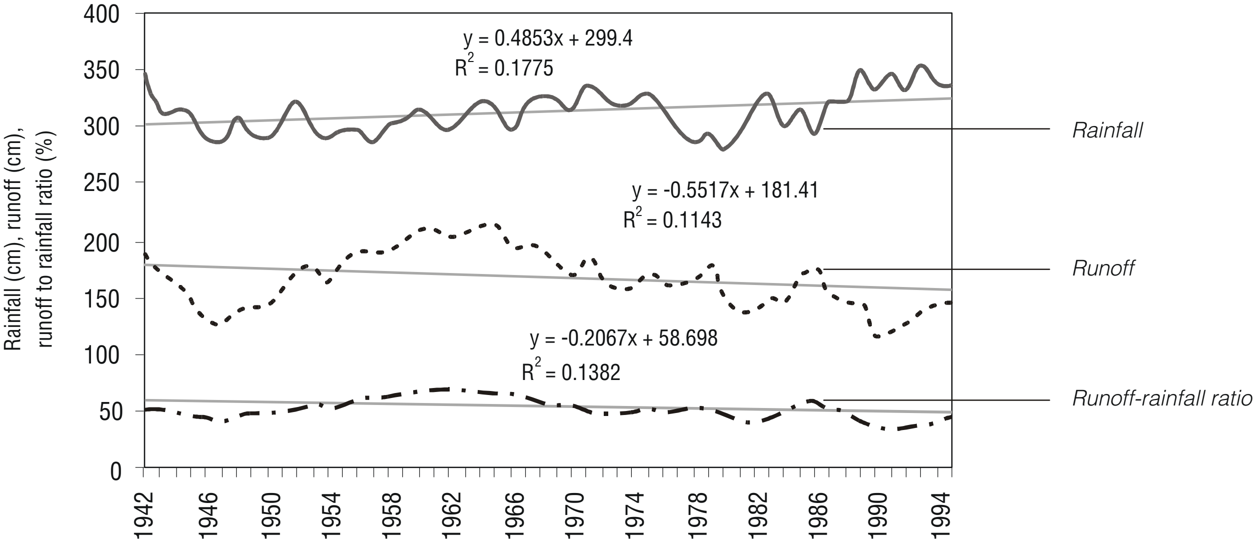
However, the management of smallholdings has progressed since 1956 and 11.5 percent of the area cleared in 1983 represent the land ready for replanting tea and forests cleared for other land uses. Though land use data are not available for the post-1983 period, there had been a substantial increase in tea smallholdings and also a further decline in forest cover but comparatively at a very low rate. At present, tea cultivation has become very attractive with competition among factories to buy green leaf from smallholders because of the establishment of the Tea Small Holdings Development Authority for provision of subsidies, extension services, etc., and the price escalation for low-elevation grown tea in the world market.

The rubber plantations that provide a good ground cover with cover crops was common in the middle section of the basin covering 8 percent of the total land area in 1956 but about half of that has gradually been replaced mostly by tea in 1983. Coconut and cinnamon plantations, which occupied about 0.1 percent of the total land area in 1953 had doubled by 1983. Scrub vegetation is found in the areas abandoned after cultivation and most of these areas are degraded. Such lands had increased from 0.5 percent in 1956 to 11.8 percent in 1972 but part of such lands has been converted to some uses and only 8.2 percent of the area was under scrublands in 1983. The major part of the grasslands that existed at 5 percent in 1956 has been converted to other uses. Rice lands, which occupy narrow poorly drained inland valleys along first order and second order streams and found as scattered patches, have almost doubled from 6 percent during 1956–1983. This increase should have been mostly at the expense of declining area under grasslands. In 1956, the area under home gardens was 16 percent of the total area. Despite the dramatic population expansion, mainly due to migration, the area under home gardens has increased by only 4 percent during 1956–1983. Most of the homesteads contain mixed species of tree crops such as coconut, jak, fruits, and timber, sometimes mixed with tea. The majority of households do not have such home gardens but have tea smallholdings and they are not reflected in the home garden category. However, part of the expanded population is reflected in area expansion under towns, villages, and other physical facilities from 0.04 percent in 1953 to 0.3 percent in 1983.

Changes in Total Annual Rainfall and Water Yield

The long-term trends of variations in annual runoff (water yield), rainfall, and their ratios based on 5-year moving averages during 1940–1997 are shown in figure 2. Linear regression models for the entire period show an increasing trend of rainfall while runoff and runoff to rainfall ratio are decreasing. However, these estimated annual changes are nonsignificant, explaining only 18 percent variation in rainfall, 11 percent variation in runoff, and 14 percent variation in

FIGURE 2.
Rainfall-runoff relations 1940–1997 (5-year moving averages).



runoff to rainfall ratio as indicated by the coefficient of determination (R^2) estimated for 5-year moving averages. However, there are substantial differences in rates and directions of short-term deviations. To discern these short-term trends, rainfall-runoff relations for these different time periods (i.e., 1940–1947; 1948–1964; 1965–1997), which showed distinct changes in hydrologic processes, were analyzed separately as shown in figures 3, 4, and 5.

The 1940–1947 Period

Figure 3 shows that during 1940–1947, rainfall, runoff, and runoff to rainfall ratio have decreased annually at 10.90 cm, 11.68 cm, and 2.05 percent, respectively. As the coefficient of determination (R^2) values indicate, the above estimated annual rates of changes are significant, explaining 87 percent variation in rainfall and 99 percent variation in both runoff

FIGURE 3.
Rainfall-runoff relations 1940–1947 (5-year moving averages).

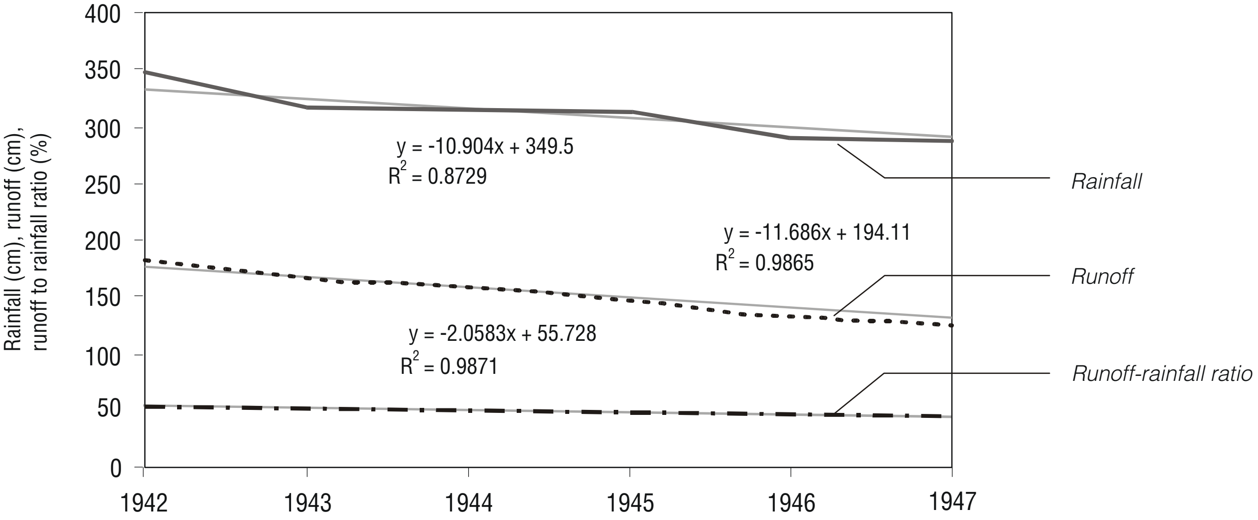


FIGURE 4.
Rainfall-runoff relations 1948–1964 (5-year moving averages).

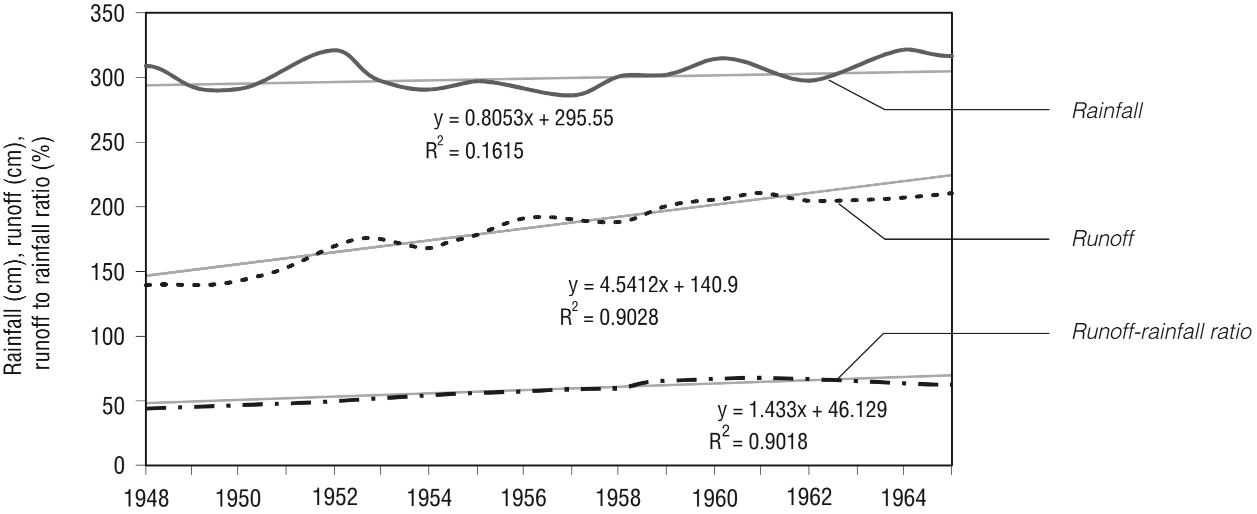
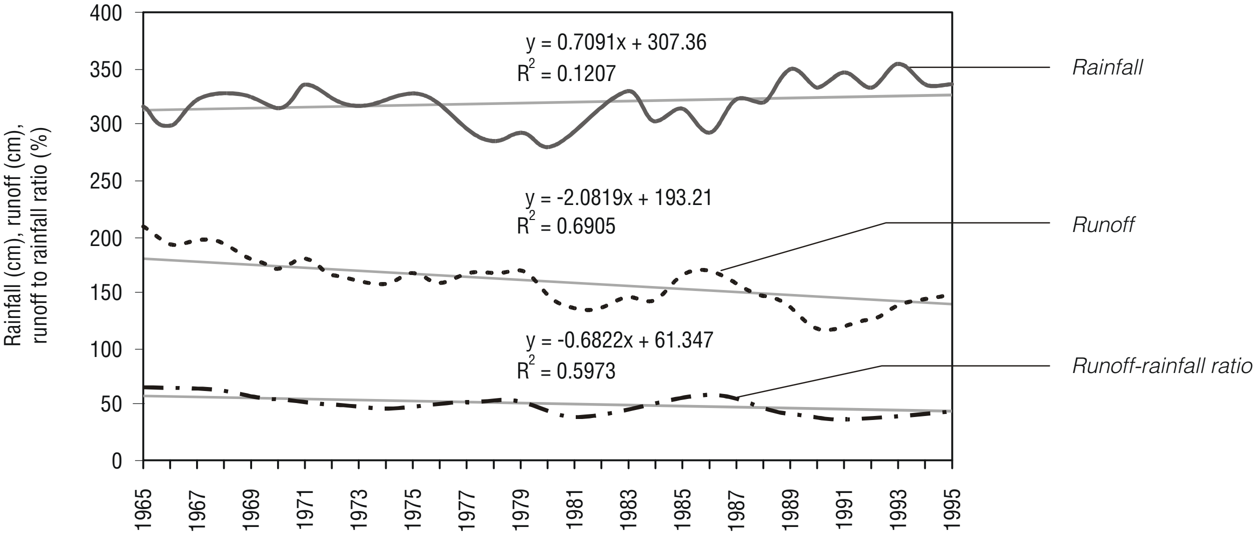


FIGURE 5.
Rainfall-runoff relations 1965–1997 (5-year moving averages).



and runoff to rainfall ratio. It is important to note that runoff herein refers to the total stream flow which appears at the reference point in the surface stream. Therefore, this total runoff consists of both storm runoff (also referred to as direct runoff or surface runoff) and base flow (or groundwater flow). As a result, the runoff to rainfall ratio represents the total response of the watershed including dry season flow rather than the fraction of direct runoff of storm events (or storm runoff). For declining rainfall trends, the rate of deviation should be greater for stream runoff than for rainfall (Hudson and Hazen 1964). Therefore, the observed annual changes during 1940–1947, with a decline of runoff at a rate of only 1 cm less than that of rainfall, indicates there has been some interference affecting the runoff generation with disturbance to the natural forest cover. This may have resulted either from increased storm runoff or enhanced base flow or due to both processes. The land use transformations responsible for changing runoff, and their effect on storm runoff and base flow are discussed later in this report.

The 1948–1964 Period

Figure 4 shows that during 1948–1964 rainfall increased at 0.80 cm per year, runoff at 4.54 cm per year, and runoff to rainfall ratio at 1.43 percent per year. These rates of changes expressed by bivariate regression equations explain only 16 percent variation in rainfall, but explain 90 percent variation in both runoff and runoff to rainfall ratio. This is a clear indication that increase in runoff is not merely due to change in rainfall. This becomes obvious when the magnitude of runoff change is compared with that of rainfall. Therefore, the very conspicuous upward trend in runoff to rainfall ratio during 1948–1964 could be attributed to factors other than rainfall such as changes in land use. The acceleration of runoff generation during 1948–1964 is more compared to that of 1940–1947 in view of the significant increase in annual runoff to rainfall ratio. The cumulative effect is the increase of mean annual flow by 10.82 percent or 17.50 cm during 1948–1964 compared to the mean annual flow of 1940–1947.

The 1965–1997 Period

Figure 5 shows that during 1965–1997 rainfall increased annually by 0.70 cm, whereas runoff decreased at 2.08 cm due to annual decrease of runoff to rainfall ratio at 0.68 percent. The linear trend accounts for only 12 percent of the variation in rainfall, whereas the estimated trend explains 69 percent and 60 percent of the respective variations in runoff and runoff to rainfall ratio. The significant decreasing trend in runoff associated with increasing trend in rainfall is a clue for the influence of factors other than rainfall on reduction in runoff to rainfall ratio during this period. Also, it is important to note that despite the very high runoff to rainfall ratio observed at the beginning of 1965–1997, during the latter part it reached a rate less than that observed during the 1940–1947 initial period (table 2). As a result, mean annual runoff during 1965–1997 was the same as that observed during 1940–1947 but where the latest period of 1990–1997 is concerned it has been reduced below the 1940–1947 level by 15.53 percent or 25.13 cm.

TABLE 2.
Five-year moving averages of rainfall, runoff, and runoff to rainfall ratio.

Year	Runoff (cm)	Rainfall (cm)	Runoff to rainfall ratio (%)
1940			
1941			
1942	185.27	348.24	53.29
1943	168.21	315.98	52.24
1944	158.03	313.82	49.75
1945	148.35	311.75	46.93
1946	132.72	290.72	45.32
1947	126.70	287.48	43.60
1948	139.67	308.74	44.93
1949	141.18	292.56	48.35
1950	143.51	291.62	49.29
1951	154.30	305.44	50.58
1952	174.05	321.31	54.55
1953	178.76	296.90	56.43
1954	168.00	291.55	53.87
1955	181.64	297.13	57.02
1956	192.48	296.13	60.16
1957	192.36	285.42	62.94
1958	188.68	299.49	62.84
1959	203.50	303.54	67.53
1960	207.95	314.49	66.88
1961	211.48	307.05	69.38
1962	204.95	297.76	69.41
1963	208.08	309.88	68.10
1964	210.20	321.35	65.97
1965	211.97	317.25	67.15
1966	193.35	297.64	65.44
1967	198.33	321.27	62.12
1968	195.87	327.40	60.53
1969	183.58	324.41	57.22
1970	171.11	314.98	55.14
1971	182.53	334.98	53.57
1972	167.12	327.08	50.41
1973	163.72	317.46	51.22
1974	158.42	318.25	49.32
1975	169.86	327.53	51.35
1976	158.95	313.23	51.29
1977	167.79	297.44	54.44
1978	167.79	285.03	54.44
1979	172.63	292.38	54.21
1980	143.81	279.25	48.60
1981	137.82	298.62	41.47
1982	137.82	316.24	41.47
1983	147.29	329.20	44.65
1984	143.37	302.12	49.95
1985	169.30	313.80	55.69
1986	168.37	293.80	59.09
1987	157.47	320.97	52.21
1988	146.92	320.37	49.03
1989	140.91	349.50	42.00
1990	118.44	332.62	37.55
1991	123.45	346.46	36.88
1992	126.94	333.61	38.55
1993	138.78	354.44	39.46
1994	143.64	336.35	43.35
1995	149.55	336.35	45.59
1996			
1997			

Changes in Flow Regimes

In dealing with effects of land use transformations, it is important to distinguish between effects on water yield (i.e., total stream flow or total runoff) and on flow regimes (i.e., the seasonal distribution pattern of streamflow or runoff). Annual values of runoff and runoff to rainfall ratio give the combined effect of storm runoff and base flow and thereby they may conceal the actual changes that occurred in the runoff pattern during the relatively wet and dry periods. To discern such seasonal changes within the annual cycle, changes in flow regimes were first investigated. Figure 6 shows the variations in flow regimes, based on mean monthly runoff, during the time periods which showed different trends in annual total runoff. Mean monthly rainfall given in figure 7 shows that the distribution of rainfall is bimodal with southwestern monsoonal rains peaking in May and convectional cyclonic activities peaking in October-November. Table 3 gives the variations in mean monthly flow calculated for 1948–1964, 1965–1997, and also for 1990–1997 periods compared to those during the 1940–1947 period, in terms of both percentage of flow and depth (cm).

In the context of rainfall pattern shown in figure 7, it can be concluded that during the most prominent low flow periods of December–April, stream flow increased during 1948–1964 but it decreased during the 1965–1997 period compared to that of the 1940–1947 period. During the less prominent low flow period of July–August as well as during the two high flow periods of October–November and May, streamflow increased during both the 1948–1964 and the 1965–1997 periods in comparison to that of the 1940–1947 period. Compared to the 1940–1947 period, during the 1990–1997 period, despite the high rainfall, water yield decreased with changes in flow regimes. Moreover, high flow and low flow periods have shifted compared to those observed during the rest of the years (fig. 6). The changes compared to the 1940–1947 period are the reduction of November–March and June–July runoff by 31.86 cm and 10.57 cm, respectively, and the increase of April–May and August–October runoff by 6.91 cm and

FIGURE 6.
Changes in flow regimes.

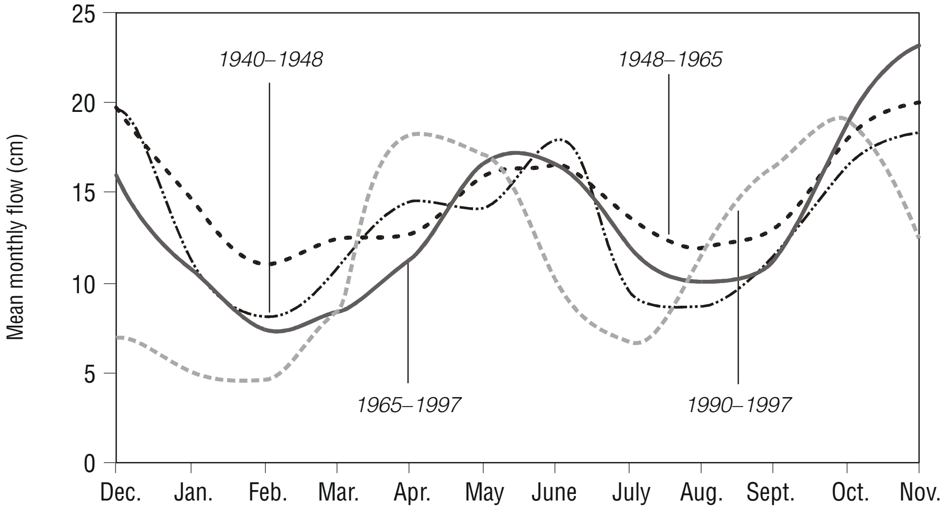
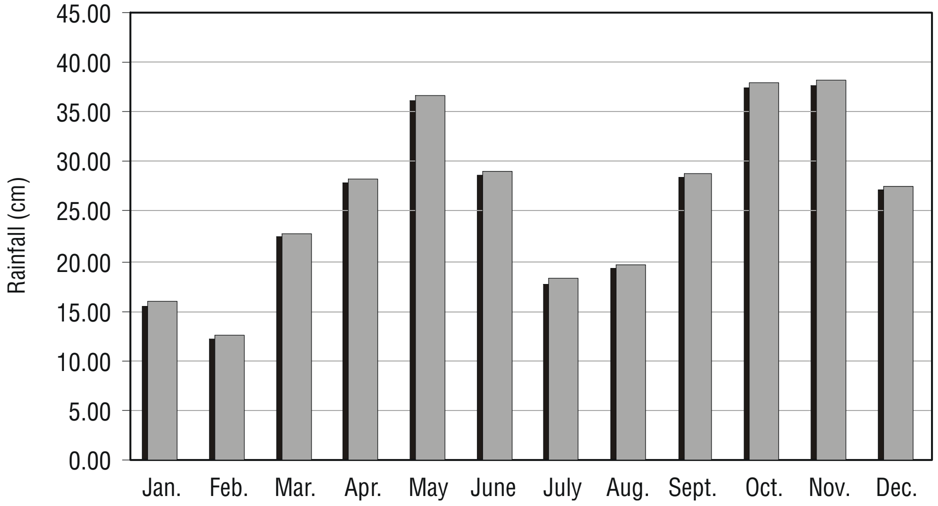


TABLE 3.
Variations in mean monthly flow.

Period	Dec.-April (prominent low flow)	May (high flow)	July-Sept. (low flow)	Oct.-Nov. (high flow)	Annual total
1948–1964	+ 7.75 % (5.04 cm)	+ 13.10 % (1.84 cm)	+ 29.51 % (8.79 cm)	+ 8.74 % (3.04 cm)	+10.82 % (17.50 cm)
1965–1997	- 17.87 % (- 11.64 cm)	+ 18.33 % (2.58 cm)	+ 11.54 % (3.43 cm)	+ 20.46 % (7.13 cm)	+ 00.11 % (0.18 cm)
1990–1997	- 34.04 % (- 22.17 cm)	+ 22.44 % (3.15 cm)	+ 16.09 % (4.79 cm)	- 9.42 % (- 3.28 cm)	- 15.53 % (25.13 cm)

FIGURE 7.
Mean monthly rainfall during 1940–1997.



10.40 cm, respectively. The shifts in flow regimes during 1990–1997 have resulted from changes in rainfall regimes as shown in figure 8.

To understand the underlying causes of changing flow regimes, monthly rainfall runoff relations, based on 5-year moving averages, were analyzed separately and subsequently, consecutive months with a similar pattern of change were plotted taking the cumulative values of rainfall and runoff for such consecutive months.

December to April—Prominent Low Flow Period

Figures 9, 10, and 11 depict the rainfall runoff variations observed during December–April, the most prominent low flow period of the stream flow. Figure 9 shows that during 1940–1947, total rainfall of the December–April period decreased at 2.60 cm annually whereas runoff to rainfall ratio decreased at 4.64 percent resulting in an annual decrease of 4.34 cm of runoff. As R^2

FIGURE 8.
Changes in mean monthly rainfall during 1990–1997.

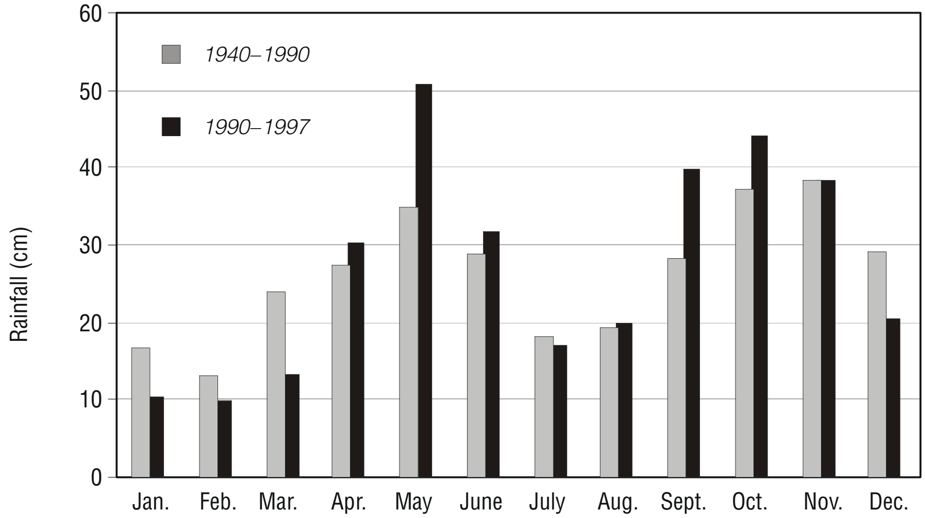
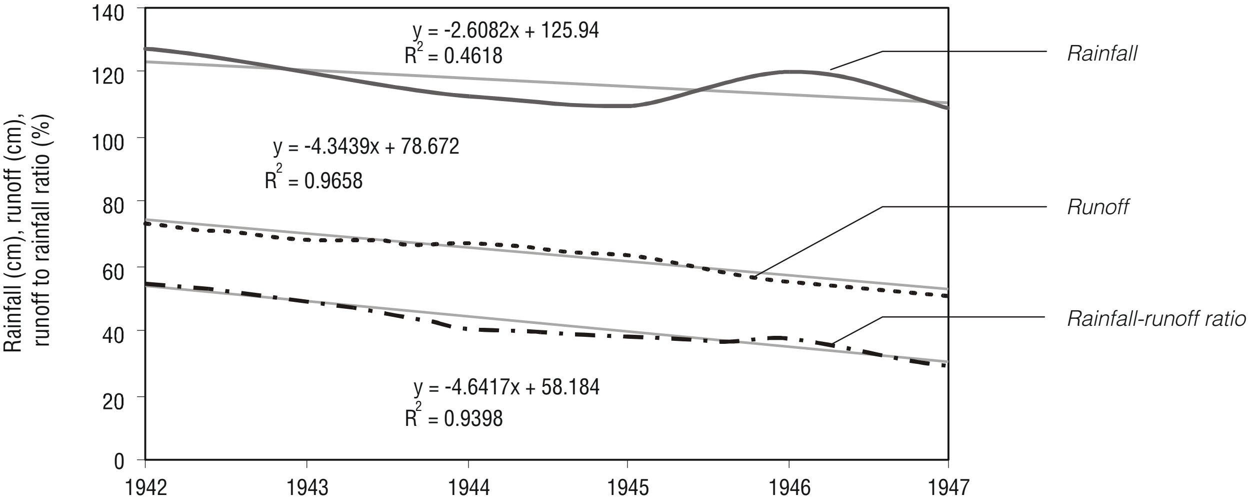


FIGURE 9.
Rainfall-runoff relations during December-April (1940–1947).



values indicate, the trend of decreasing runoff and its ratio is more significant than that of rainfall. During the 1948–1964 period, despite the 1.00 cm decrease in annual rainfall, runoff increased by 1.11 cm (fig. 10). Here only the trend in runoff is significant indicating a relatively greater contribution by the base flow compared to 1940–1947. The runoff to rainfall ratio had initially increased till 1955, then it remained above 60 percent for a few years, and again it decreased. This variation has resulted in the lack of any significant linear trend in runoff to rainfall ratio during 1948–1964. During the 1965–1997 period, though rainfall decreased at 1.07 cm per

FIGURE 10.
Rainfall-runoff relations during December-April (1948–1964).

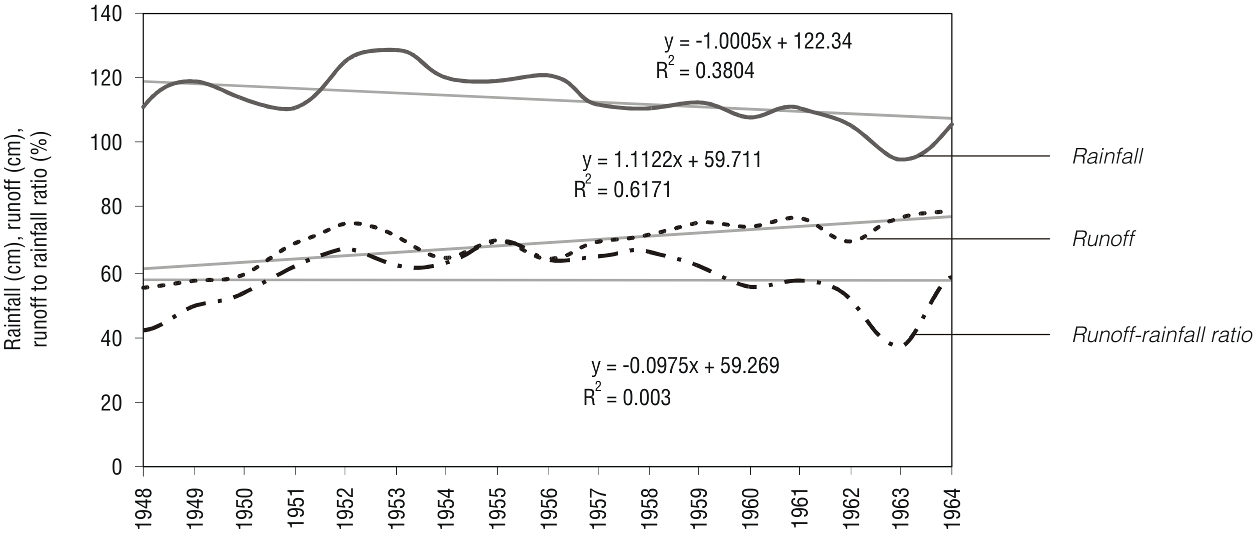
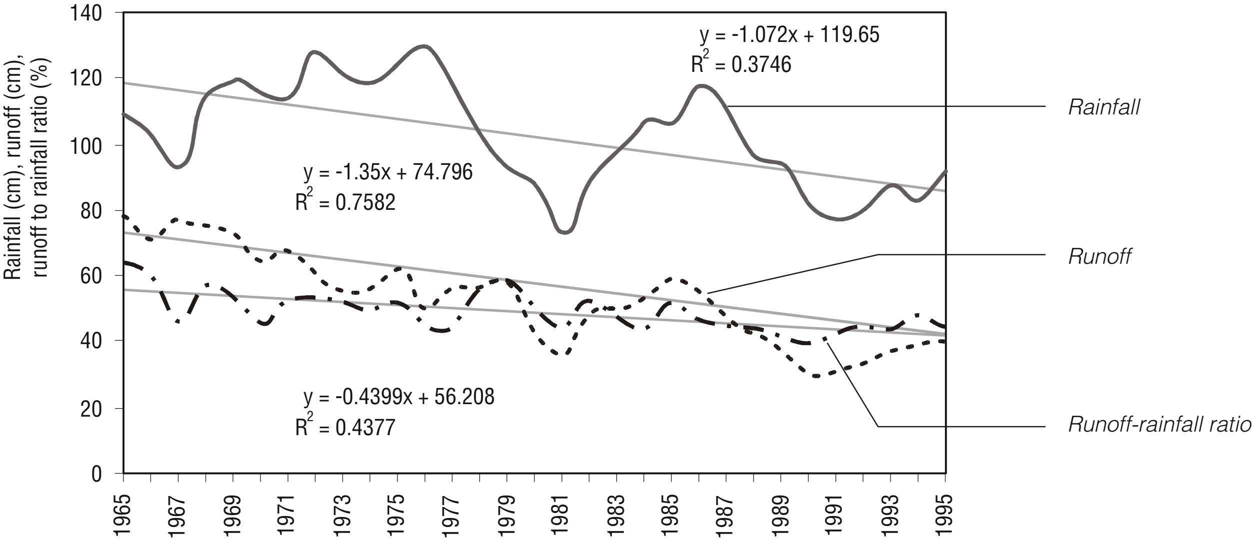


FIGURE 11.
Rainfall-runoff relations during December-April (1965–1997).



year, runoff decreased at 1.35 cm due to annual decline of runoff to rainfall ratio at 0.44 percent (fig. 11). The trend in runoff is more significant indicating a declining contribution from the base flow.

The changes in cumulative runoff during the December-April period can be summarized as: a decrease of runoff from 78.67 cm to 57 cm from 1940 to 1947 with an annual decrease at 4.34 cm; then an increase to 77.5 cm in 1964 with an annual increase of 1.11 cm during 1948–1964; and again a decrease to 34.29 cm in 1997 with an annual decrease of 1.35 cm during 1965–1997. The accompanied changes in runoff to rainfall ratio include its decrease from 58.18 percent to 34.97 percent at 4.64 percent per annum during the 1940–1947 period; then an increase to about 70 percent in 1955 and a decrease to 56.2 percent in 1965; and a further reduction to 43 percent in 1977 at 0.44 percent per annum during 1965–1997.

May—High-Flow Period

Trends in rainfall runoff relations for May during different time periods are shown in figures 12, 13, and 14. During May, the southwestern monsoonal rains peak and therefore, a major portion of runoff can be expected from storm runoff rather than from the base flow. During 1940–1947, rainfall of May decreased annually at 8.36 cm whereas, runoff decreased at a lesser rate of 2.02 cm due to the increase in runoff to rainfall ratio at 3.15 percent (fig. 12). All the trends were highly significant. Therefore, the increase in runoff to rainfall ratio can mostly be attributed to the increasing storm runoff from individual storm events. During 1948–1964, both rainfall and runoff have shown increasing trends (fig. 13). Runoff to rainfall ratio has increased annually at 0.46 percent but it has not shown a consistent increase mostly due to its dependence on rainfall and high fluctuations in rainfall during this period. During the 1965–1997 period, runoff to rainfall ratio showed a decreasing trend but it is not significant due to its interannual fluctuations. However, runoff has shown a slightly increasing trend (fig. 14).

The changes in runoff during May over time is the reduction from 19.82 cm to 9.69 cm at 2.03 cm per year during 1940–1947; then an increase to 18.68 cm in 1964 with an annual increase of 0.36 cm during 1948–1964; and remaining almost constant at 16.5 during 1965–1997. The accompanied variation in runoff to rainfall ratio includes an increase from 33.54 percent to 49.31 percent at 3.15 percent per annum during 1940–1947; then hovering around 50 percent during 1948–1965; and a decrease to 48.17 percent in 1997 at 0.54 percent per annum during 1965–1997.

FIGURE 12.
Rainfall-runoff relations in May (1940–1947).

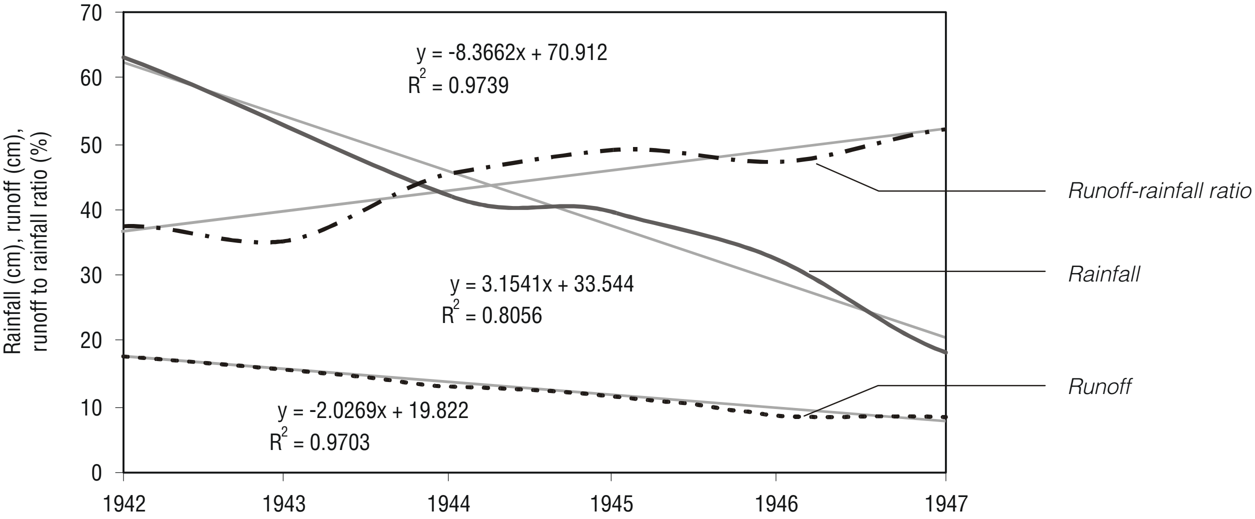


FIGURE 13.
Rainfall-runoff relations in May (1948–1964).

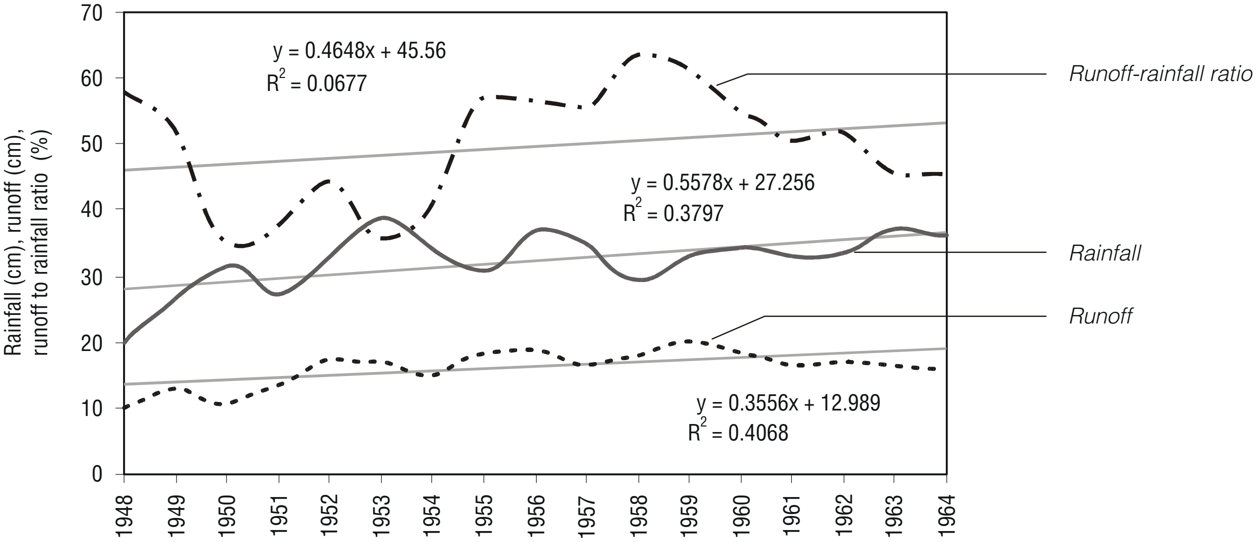
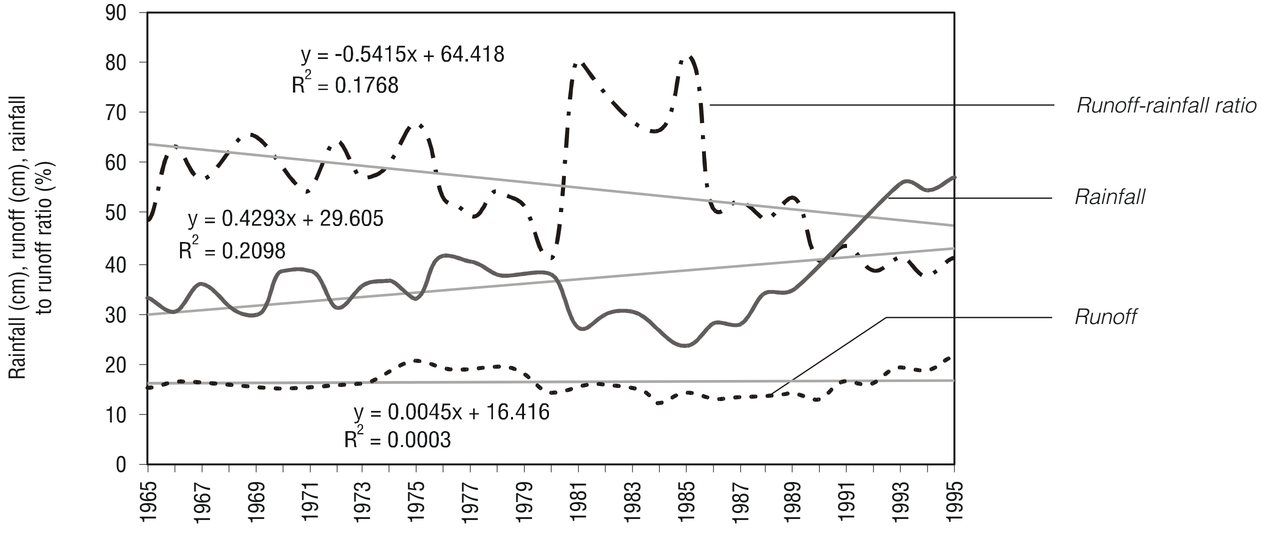


FIGURE 14.
Rainfall-runoff relations in May (1965–1997).



July to September—Less-Prominent Low-Flow Period

Variations in runoff in the July-September period over years are shown in figures 15, 16, and 17. Figure 15 shows that during the 1940–1947 period rainfall decreased at 2.91 cm per year but runoff declined only at 0.72 cm as the runoff to rainfall ratio increased at 1.46 percent. During 1948–1964, runoff to rainfall ratio shows an increasing trend at 1.48 percent per annum while runoff increased at 1.95 cm which is significant (fig. 16). Despite the decreasing rainfall from 1949 to 1956, the increase in runoff to rainfall

FIGURE 15.
Rainfall-runoff relations during July-September (1940–1947).

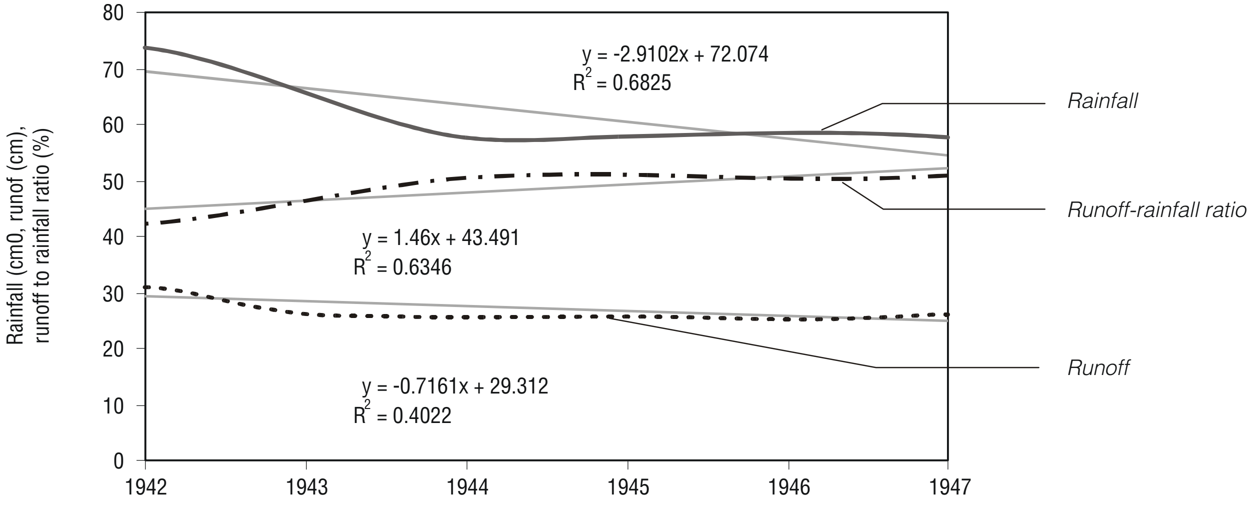
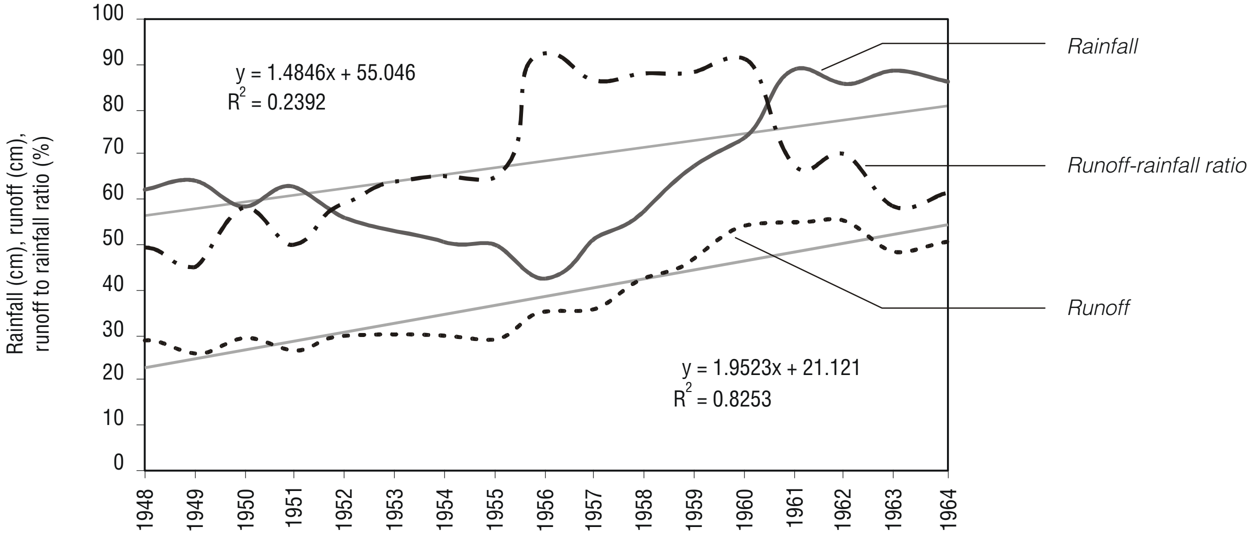


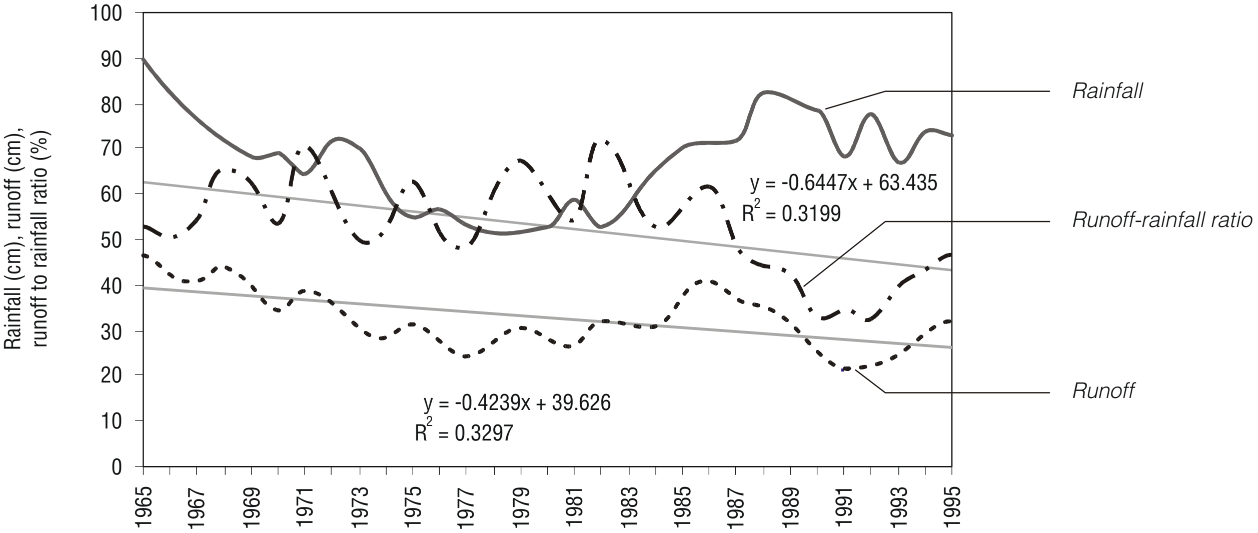
FIGURE 16.
Rainfall-runoff relations during July-September (1948–1964).



ratio is indicative of the important contribution of storm runoff. Therefore, it is reasonable to assume that both storm runoff and base flow are important during the July-September period. During the 1965–1997 period, rainfall and runoff fluctuated substantially; however, runoff and runoff to rainfall ratio showed decreasing trends (fig. 17).

The changes in cumulative runoff during the July-September period are the decrease from 29.31 cm to 25.73 cm during 1940–1947 at 0.72 cm a year; then an increase to 52.36 cm in 1964 at 1.95 cm per year during 1948–1964; and a reduction to 26.91 cm in 1997 at 0.42 cm a year during 1965–1997. The runoff to rainfall ratio increased from 43.49 percent to 50.79 percent at

FIGURE 17.
Rainfall-runoff relations during July-September (1965–1997).



1.46 percent a year during 1940–1947; then it hovered mostly around 60 percent during 1948–1997.

October to November—High-Flow Period

Rainfall is high in October and November, particularly with cyclonic activities bringing high-intensity rains. Therefore, a large contribution of storm runoff can be expected compared to that of base flow. Figure 18 shows that during 1940–1947, rainfall decreased annually at 3.56 cm whereas runoff decreased at 2.73 cm. The runoff ratio also decreased at 1.3 percent with declining rainfall. Trends of rainfall and runoff are highly significant. The relatively less reduction in runoff compared to that in rainfall may have been brought about by increased storm runoff. Figure 19 shows that during 1948-1964 rainfall increased but with a nonsignificant trend whereas the runoff to rainfall ratio increased at 1.64 percent increasing the annual runoff by 1.52 cm. Figure 20 shows that during 1965–1997 rainfall and runoff had a slightly decreasing trend but runoff to rainfall ratio had remained almost constant.

The cumulative runoff during October-November decreased from 42.97 cm to 29.31 cm at 2.73 cm a year during 1940–1947; then it increased to 48.01 cm in 1964 with an annual increase of 1.52 cm during 1948–1964; and decreased to 40.16 cm in 1997 with an annual reduction of 0.22 cm during 1965–1997. The runoff to rainfall ratio decreased from 48.79 percent to 42.29 percent during 1940–1947 with an annual decrease of 1.3 percent; then increased to 68.13 percent in 1964 with an annual increase of 1.64 percent during 1948–1964; and remained almost constant at 52.5 percent during 1965–1997.

Impacts of Land Use Transformations on the Hydrologic Response

In 1940, about 50 percent of the watershed area was under natural forest cover. Due to continued deforestation, forest cover decreased to 43 percent in 1948 and to 30 percent in 1965. The deforested area was replaced mainly by shifting cultivation, home gardens, and large-scale tea plantations during 1940–1947. During the 1948–1964 period, tea smallholdings comprised the major land use which replaced natural forests, particularly those at steep headwater areas. Tea smallholdings further expanded during this period at the expense of other land uses such as shifting cultivation. These land use changes, particularly the conversion of natural forests, must be responsible for the increased runoff generation process during 1940–1964 as revealed by an analysis of annual runoff-rainfall relations.

However, the increased runoff generation is not reflected in annual runoff (water yield) during 1940–1947 due to declining rainfall though the runoff to rainfall ratio increased in May and during July-September. This decreasing rainfall was accompanied with a substantial reduction in base flow during the December-April low-flow period. An increase in runoff generation has, therefore, taken place with the reduction of natural forest cover from 50 percent to 30 percent of the watershed area. An analysis of seasonal runoff revealed that during the 1948–1964 period, both base flow and storm runoff had increased. This has been brought about by a higher runoff to rainfall ratio during the prominent low-flow period of December to April compared to that of 1940–1947; and a further increasing runoff ratio from 1948 to 1964 during the July-September less-prominent low flow period as well as in the high rainfall months of May and October-November. The cumulative effect of these changes is the increase in mean annual runoff by 10.82 percent or 17.50 cm during 1948–1964 in comparison to the 1940–1947 period. About 80 percent of this increase in annual runoff (water yield) is due to increased flow during periods with substantial base flow (i.e., December-April and July-September). Increase in base flow with reduction of forest

FIGURE 18.
Rainfall-runoff relations during October-November (1940–1947).

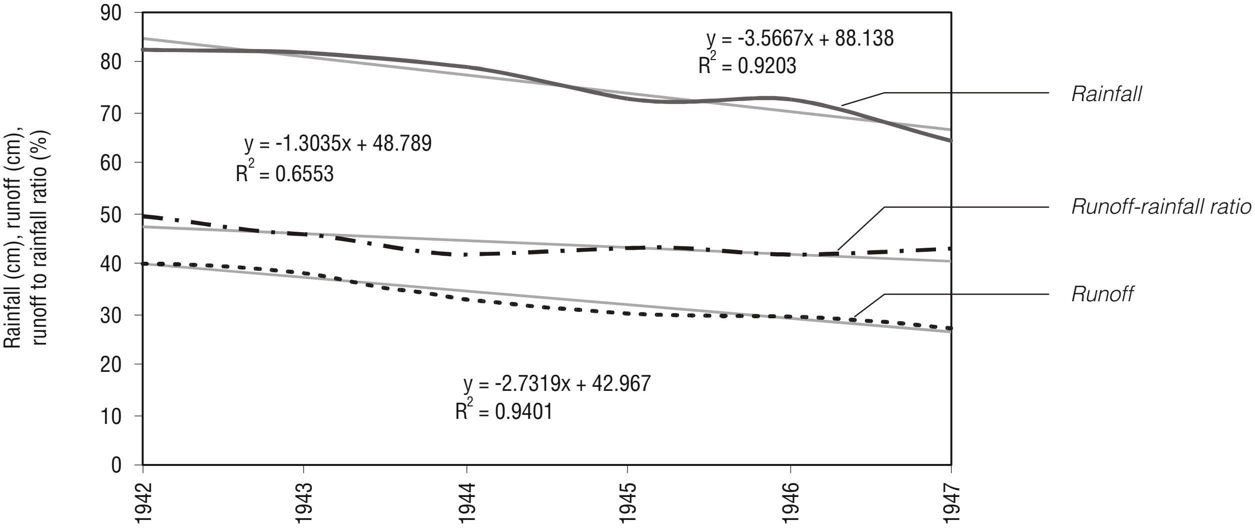


FIGURE 19.
Rainfall-runoff relations during October-November (1948–1964).

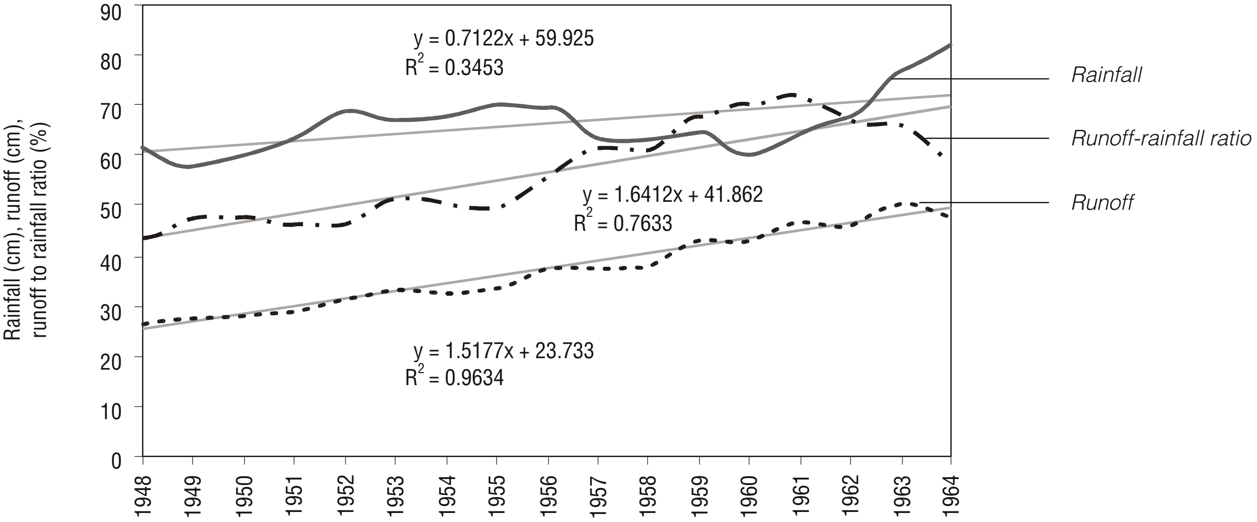
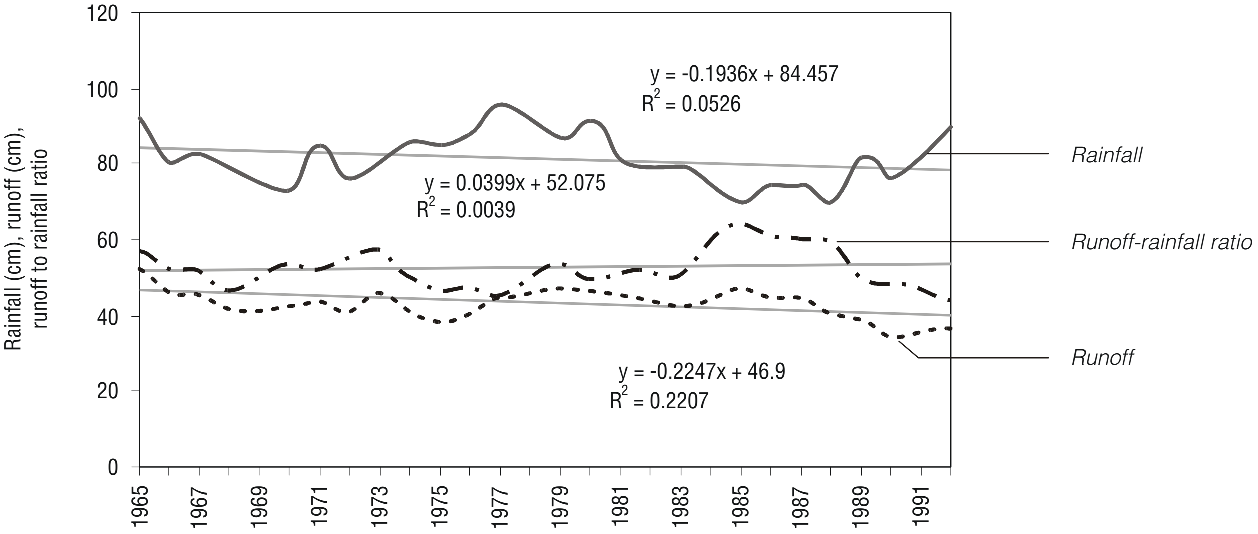


FIGURE 20.
Rainfall-runoff relations during October-November (1965–1997).



cover should be due to the reduction of transpiration during low flow periods. Increase in storm runoff is mainly due to the reduced infiltration rate when forest is converted to other land uses.

These changes in the runoff generation pattern are in agreement with the state of knowledge on the prospective role of tropical forests, that reducing forest cover in forested catchments increases the water yield from the catchment with the majority of the increase occurring in the base flow component. A more conspicuous increase in water yield during 1948–1964 compared to that of 1940–1947 has resulted mainly from the impact of decreased rainfall during 1940–1947, but it may be partly due to differences in slope and soil conditions, and topographic, edaphic, and vegetation cover types of the cleared forests because the latter period coincides with clearance of forest cover from 43 percent to 30 percent in most of the steep headwater areas.

The major land use transformations during 1965–1997 include a further reduction of natural forest cover till about the late 1980s at half the rate of the 1940–1964 period. The clearance of forests was mainly for tea smallholdings. During this period, tea smallholdings further expanded at the expense of other land uses like rubber plantations and scrublands. As a result, by the end of 1977, of the total watershed area, less than 15 percent was under natural forests, about 50 percent under tea, and about 20 percent under home gardens and the balance under agricultural land uses, which were mostly plantation crops.

Although disturbances to the natural forest cover continued, there is a significantly decreasing trend in annual runoff (water yield) during the 1965–1997 period. As a result, despite the very high annual runoff to rainfall ratios observed at the beginning of the 1965–1997 period, during the latter part it reached the initial rates observed during the 1940–1947 period and even below. An important feature, which can be responsible for this hydrologic response during the 1964–1997 period, is the development of a ground cover by most of the already established main crop, tea, as well as the establishment of a vertical canopy structure in home gardens and other plantations, which mimic natural forests to some extent in the already converted natural forests.

Though mean annual runoff during 1965–1997 reached the same level as that of 1940–1947, there were variations in flow regimes compared to those before 1965. The major changes include the reduction of contribution to runoff by base flow (i.e., December-April and July-September) and a further maintenance of the increased storm runoff during high rainfall months (i.e., May and October-November). These changes were accompanied by a decreasing runoff to rainfall ratio during December-April and July-September from 1965 through 1997; and maintenance of runoff to rainfall ratios almost at the same high levels as those of 1948–1964 during the high rainfall months of October-November and May. Therefore, the changes in flow regimes have exacerbated after 1965 with a further declining of forest cover from 30 percent of the watershed area, particularly due to continued reduction in low flow.

Nortcliff, Ross, and Thornes (1990) have demonstrated that it is evident the major changes in runoff occur between 0 percent and 30 percent cover, with changes of cover above this having a relatively small impact. Observations in the study catchment, particularly flow regimes, agree very closely with such a behavior. The increase in base flow during 1948–1964 with clearance of forests cover from 43 percent to 30 percent and the subsequent decline of base flow after that (i.e., during 1965–1997) can be attributed to the establishment of home gardens and tea in a substantial area of deforested lands because these perennials could extract groundwater for transpiration during low flow periods.

Observations of Anderson and Spencer (1991) have clearly demonstrated that hydrologic impacts of forest cover changes are likely to be much more short-lived due to rapid regeneration of tropical vegetation. However, in the study catchment, this recovery of change is true only for the increased base flow during 1948–1964 (with forest cover declining from 43 percent to 30 percent) because it has declined after 1965. Nevertheless, this decline in low flows has continued to levels below those of 1948 and high flows have maintained their increased levels from 1965 through 1997 with further clearance of forests even at a low rate together with the establishment of a new cover in deforested areas. As a result, in the 1990–1997 period, where forest cover was in less than 15 percent of the watershed area, changes in flow regimes were at its peak, compared to the 1940–1947 initial conditions. The observed reduction in base flow after 1965 during low flow periods is accompanied by increased storm runoff during high rainfall months compared to that observed with a high percentage of forest cover. Such a variation may not have resulted from evapotranspiration of new growth in excess of natural forests but due to reduced infiltration opportunities.

Under such situations reduced low flow is well-explained by Bruijnzeel (1990) that if infiltration opportunities after forest removal have decreased to the extent that the increase in amounts of water leaving the area as storm runoff exceeds the gain in base flow associated with decreased evapotrans-piration, then the result is diminished dry season flow. However, in the study catchment, the evapotranspiration of the new growth dominated by tea and home gardens cannot be expected to be much less than that of the forest cover. Such high evapotranspiration rates combined with rapid storm runoff generation (i.e., less infiltration opportunities) must have brought about the decline in base flow after 1995. This change in flow regimes implies that the new cover dominated by tea and home gardens may not be as effective as natural forest in maintaining high infiltration rates as asserted by Wiersum (1985) and Brandt (1986) and others that it is the clearance of the under-storey and litter that is more important than the clearance of the canopy.

The period 1940–1947 is characterized by declining forest cover from 50 percent to 43 percent with an accelerated surface runoff generation. Though the base flow has declined during this period, mostly due to declining rainfall, the base flow may have been above that of steady state conditions with a higher percentage of forest cover as this period falls within the time where increase in base flow is evident. Therefore, the comparative reduction in total water yield during 1990–1997 by 25.13 cm or 15.53 percent, brought about mostly by reduced base flow, may be an exaggeration of the actual deviation from the steady state conditions. Nevertheless, during the 1990–1997 period, the rapidity of surface runoff has further increased with reduced infiltration and, in turn, it is partly responsible for reduction in base flow. Therefore, in comparison to the 1940–1947 period with a substantial forest cover, significant deviation of flow regimes during 1990–1997 (as well as during 1965–1997) is a clear indication that the present management of agricultural land uses has failed to attain the flow regimes closer to its steady state conditions or even to that which existed with substantial forest cover.

The 1990–1997 period with less than 15 percent forest cover and more than 70 percent of the area under agricultural land uses, had mainly tea in about 50 percent of the area, home gardens in about 20 percent of the area, and other plantation crops. There is experimental evidence that agricultural land uses such as tea and home gardens could simulate forest conditions when well-managed. For instance, a 4-year measurement of surface runoff in well-managed vegetatively propagated tea plantation in 30 percent-40 percent slope in the mid-country wet zone has shown that surface runoff was less than 1 percent of the rainfall. Measured annual surface runoff was between 0.38 percent and 0.53 percent of rainfall, which increased from 1,773 mm to 2,134 mm and the annual soil loss was between 0.025 t/ha and 0.33 t/ha (Krishnarajah 1985a). In a mid-country typical home garden with mixed plantings of various tree species, the maximum storm runoff recorded was only 8 percent of the rainfall and the annual soil loss recorded was only 0.05 metric tons per hectare (Krishnarajah 1985b).

Similar trends in flow regimes have been observed by Madduma Bandara (1997) at Peradeniya in the flow of Mahaweli Ganga, the longest river of Sri Lanka. He has observed that during the 1940–1980 period, wet season flows increased rapidly over the years while dry season flows slightly declined. However, in this case increase in wet season flows was more than decrease in dry season flows bringing an increase in annual discharge. The major land use changes during the study period were the reduction of tea, which occupied over 60 percent of the basin to less than 40 percent and forest cover from 17 percent to 15 percent. Much of the land lost from tea and forest was taken up by homesteads and other crops. Also the built-up area under settlements has expanded significantly.

Implications of Changed Flow Regimes

Consequent to the modification of natural forests, the changes in the time distribution of runoff with the attendant reduction of low flows and increase in high flows have brought about many adverse environmental consequences. Such adverse impacts were obvious according to the experience of the local residents as well as to what was revealed by intensive field observations conducted during 1995–1997. As a result of the conversion of forest lands into other agricultural land uses, soil erosion has been accelerated by increased surface runoff generation during heavy rains when combined with various degrees of soil exposure depending on the management conditions adopted. Both splash erosion caused by rainfall and scour erosion caused by surface runoff must have been exacerbated under such conditions. This is of great importance because the deforestation for tea planting was mainly on sloping terrain and the big share of steep lands was a distinct feature of the study catchment.

The impacts have become detrimental to the long-term productivity of the land resources, particularly those on steep terrain of the study catchment. The observable results, especially in tea lands, are the loss of top soil and depleting soil fertility while making the users, over time, more and more dependent on chemical fertilizers. The frequency of fertilizer application has also been increased to cope with increased washdown of applied fertilizer by rapid runoff and reduced adsorption due to deteriorated soil structure and depleted organic matter. Severe limitations to agricultural land uses, due to limited rooting depth resulting from reduced water-holding capacity as well as the stoniness and acidity of exposed sub-horizons, can be observed in lands where erosion has taken place consistently at high rates without adequate protection. On the extreme, failure to protect soils adequately from erosion has led to the emergence of some wastelands and unproductive lands, particularly in the steep terrain.

Besides the agricultural land uses, development of infrastructure such as roads and buildings with heavy disturbance to the land forms, without appropriate soil conservation measures, seems to have aggravated the sediment supply into streams, sometimes with landslides resulting from the indiscriminate removal of the toe-support. The aggradation of stream channels due to high sediment supply from the watershed has further aggravated the likelihood of economic damages of flash floods that have become more frequent with rapid runoff. The local residents have observed such changes in streams like Milla Ela and Demodara Dola in the course of time. Besides the damage to properties located along streams, inundation of rice fields in inland valleys causes crop damages and decline in land productivity with the removal of the less-dense surface layer of boggy soils.

Part of the eroded material, mostly sand and large particles, has finally settled in irrigation canals necessitating frequent dredging operations to maintain their functions. When such coarse particles are deposited in rice fields, land productivity is reduced. Eroded particles carried in streams as suspended sediment may transport pesticides and nutrients by adsorption, particularly from tea lands where agrochemicals are used abundantly, and pollute fresh water resources.

The reduction in groundwater recharge and the consequent lowering of the water table have resulted in relative droughts after periods of dry spells due to lowered well levels and diminishing flow in perennial rivulets, springs, and some of the first-order and second-order streams. As a result of this, domestic water supply during dry spells has become a crucial issue and in the recent past many domestic water supply schemes have been implemented to overcome this problem. Rice fields within the study area occupy the inland valleys and depend on the tree cover of the slopes for a steady supply of water from first-order and second-order streams during dry spells within a season. As the stream flows during dry periods have gradually diminished, farmers have experienced shortages of water during dry spells occurring within both dry and wet seasons.

A major portion of the downstream part of the river is just a few tenths of a meter above sea level resulting in temporary storage of quickly drained out water from the upper catchment to lower portions and therefore, frequent flooding has been reported during rainy periods in these areas. Moreover, the upper part of the river basin (i.e., study area) has more of a compact circular shape which leads to a larger concentrated floods downstream. Vast areas of the floodplains are submerged with the slightest increase of the water level of the river as the natural levees have not been formed on the banks of the Nilwala river. As a result, in the course of time, damages to crops and property with interruption to communication and transport by flooding have increased considerably in the downstream floodplains. In fact, the analysis of flow data has revealed increased high flows with forest modification.[2]

The reduced low flows are reflected in reduced dependency on a reliable supply of good quality water downstream during periods of less rainfall. Further, the river bed is below the sea level at the outlet and the diffusion of ocean salinity because of tidal intrusion into the river estuary must have increased with reduced low flow regimes due to less fresh water pressure to repel sea water intrusion. This has actually threatened the quality of water supply to downstream areas. For instance, relocation of the intake for the Matara Water Supply Scheme several kilometers upstream was effected in the mid-1980s to ameliorate the salinity intrusion. On completion of the Nilwala Flood Protection Scheme in the lowest section of the river, excessive drainage has resulted in the development of acid sulfate conditions in the coastal rice fields. One sound alternative to ameliorate the problem is to irrigate affected fields using the river as the source. However, this option remains questionable due to inadequate low flows now observed in the river.

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[2] It was realized that at the end of this study, overbank flood flows had occurred in the Bopagoda gauging site for a few extreme flood events and the extrapolation of peak floods in gauge-calibrated chart had underestimated these events. Therefore, the results for this watershed have to be used cautiously, although the methodology is robust and is applicable anywhere.

Historical Data as a Decision Support Tool in Watershed Management

Analysis of historical hydrologic data in the context of land use transformations has clearly demonstrated that most of the adverse impacts, both upstream and downstream, have resulted from the conversion of natural forest to other land uses where cause-effect relations are concerned. The major cause underlying all such identified adverse impacts was the changes in the water cycle brought about by changes in the physical processes of runoff generation. Such changing hydrologic regimes caused by both rapid storm runoff generation and decreased dry weather flow have triggered a chain of reactions in other processes such as soil erosion, sediment transport, downstream water quality, flooding, biomass production, etc. Therefore, all the adverse impacts identified in this study will respond to the same conservation treatments aimed at remedying the rapid runoff generation in all land uses as well as maintaining a balanced dry weather flow. Nevertheless, in agricultural land uses, without special attention to erosion control, the soil erosion rate could not be brought closer to the limits that existed under natural forests. Therefore, the conservation must aim at both soil and water. As such, the analysis of historical data gives the clue that soil and water conservation must be the prime objective in the development of sustainable agricultural systems and land uses in the study catchment of the upper Nilwala river basin.

As the current status of various land use management conditions and the involved resource users are concerned, the conservation strategy must involve a package of conservation measures that is economically beneficial to the landholders, and include the type of vegetation/ crop suitable for the given location, appropriate land and water saving and conservation practices, as well as user rights to benefit from conservation of natural resources. Under such circumstances, the aggregated impact of such initiatives as a whole can be expected to have a role upon the quality and quantity of water including its temporal and spatial distribution so that the water cycle could be changed to be closer to that which existed with a higher percentage of land area under natural forests.

Population density of the study catchment is high and it varied from 300 to more than 600 per square kilometer in different locations. Land use is quite intensive with the characteristic pattern of dwindling natural forests on the upper ridges, tea on the steep slopes, home gardens on less-steep lower slopes, and rice fields in the narrow inland valleys at the bottom. More than 70 percent of the entire study catchment is now under agricultural use. To ensure the sustainability of production systems in parallel with assured environmental quality, basin management approaches must focus on the management practices that would facilitate bringing the hydrologic regimes closer to that which existed in a forest ecosystem. Considering the present status of various land uses, the following guidelines can be considered as prerequisites for such an approach.

Some patches of the existing forests are degraded and, therefore, the forest management should involve both conservation of existing forests and enrichment of degraded forests including stream reservations. Home gardens could be improved to mimic forest ecosystems, particularly by the development of a multi-storeyd vertical canopy structure through agro-forestry interventions and various other conservation practices. The soil and water conservation techniques for other arable lands should be an integrated package including physical works such as drains and stone terraces; vegetation techniques like ground cover by crops, residue management, and vegetative hedgerows; and cultivation techniques such as agronomic measures. To make use of the mutual reinforcement, concurrent application of biological and physical measures should be promoted depending on the validation of such combinations under given circumstances from engineering, agronomic, and socioeconomic points of view. Therefore, the suggested techniques of soil and water conservation include only those well known to the farmers in the area and accepted by them, though they are not extensively practiced by all. These selected techniques have been validated by various government agencies for their effectiveness and incorporated into the package of practices recommended for different land uses.

One of the most effective single soil and water conservation measures under tropical conditions is the ground cover that intercepts the energy of rain drops, retards the speed of surface water flow, and acts as a miniature reservoir for surface water infiltration. This can be achieved in tea lands, which represent the current major land use of the catchment covering more than 50 percent of the area, through management of the crop cover by vacancy filling either directly with tea plants when land is well-managed and manured, or else with *mana* grass (Cymbopogon confertiflorus) in degraded soils for improving soil prior to planting tea plants in vacancies.

Another important measure is the maintenance of lock-and-spill drains constructed along the contours, which retain most of the storm runoff and eroded soil particles. This temporary storage of storm runoff for gradual infiltration is of great importance because the agricultural land uses generate much high storm runoff than forests as revealed by the analysis of historical data.

Experience and experiments have shown that if well-managed with lock-and-spill drains, the tea crop could maintain 100 percent ground cover with surface runoff and soil erosion conditions being closer to those of a natural forest (Krishnarajah 1985a). Maintaining a multi-storeyd vertical structure in home gardens can be promoted to have a similar effect (Krishnarajah 1985b).

Residue management or mulching, introduced to newly planted tea, etc., works on the same principle as that of ground cover but with further advantages of conservation of moisture owing to improved soil structure and reduced evaporation, and enhanced soil fertility. In the case of senile seedling tea plantations, it is also important either to replant tea or to diversify with other tree species if a good ground cover is to be achieved. The periods most critical for erosion in tea lands are the planting time, early growth (first 18 months), and pruning times. Therefore, during such vulnerable periods careful farm-level measures, particularly those related to mulching, must be adopted. Other important cultural practices to minimize soil loss are the proper bush management through pruning; practice of selective weeding and hand weeding instead of mechanical weeding; and proper management of high- and low-shade trees.

Besides increase in soil fertility, addition of organic mater would improve the soil structure and reduce soil erodibility resulting in a better crop growth that provides protection to the soil. Trash bunding or vegetative barriers such as closely grown vetiver grass (Vetiveriaziz savendara) slips on contours (on the lip of contour drains) that work by intercepting the overland flow on the slope to cause deposition of sediments can also be promoted. These practices further benefit by converting sloping surfaces into a terraced form while enhancing infiltration of water.

Sloping Agricultural Land Technology (SALT) with double hedgerow planting of leguminous trees has its benefits similar to those of grass hedgerows while providing biomass for mulching. The SALT technology provides a viable system to sustain agricultural production on marginal and steeply sloping farm lands. These hedgerows provide a variety of other benefits such as fixing of atmospheric nitrogen for soil replenishment and together with leaf manure, fertilizer application is reduced while response to fertilizers is increased. The species selected for SALT are multipurpose, being capable of supporting economically important vines like pepper and providing fuelwood and fodder. Also, the continued maintenance of lock-and-spill drains dug out at regular interval at tea lands should be promoted since it traps at least a part of the eroded soil particles and surface runoff till such time that other vegetative conservation measures become effective.

Wastelands and marginal lands have resulted mainly from the consistently high erosion rates that have occurred with poorly managed previous agricultural land uses. Such lands could be rehabilitated with the introduction of agro-forests, wood lots, etc. In the case of transforming degraded lands, it is of great importance to consider the land use capabilities of the landscape to preclude environmental hazards while rehabilitating such lands. The selection of species for such plantations could be based on demand for timber, fodder, fuelwood, fruits, biomass for organic manure, biodiversity needs, etc. It is of great importance to stabilize the slopes and protect the exposed land surface from rain drop impact and scouring runoff in case of house building and road construction, to reduce heavy sediment supply to the streams.

Literature Cited

Anderson, J. M., and T. Spencer. 1991. Carbon, nutrient and water balance of tropical ecosystems subject to disturbance: Management implications and research proposals. *MAB Digest* 7. Paris: UNESCO.

Beven, K. 1989. Changing ideas in hydrology- the case of physically based models. *Journal of Hydrology* 105.

Brandt, J. 1986. Transformations of the kinetic energy of rainfall with variable tree canopies. Ph.D. diss. University of London. Duplicated.

Bruijnzeel, L. A. 1990. *Hydrology of moist tropical forests and effects of conversion: A state of knowledge review* . UNESCO International Hydrologic Programme, Amsterdam: Humid Tropics Programme, Free University.

Burnham, C. P. 1989. Pedological processes in temperate and tropical soils. In *Mineral nutrients in tropical and savanna ecosystems*, ed. J. Proctor. Oxford: Blackwell Scientific Press.

Dano, A. M. 1990. *Effects of burning and reforestation on grassland watersheds in the Philippines* . Publication 192. International Association of Hydrologic Sciences. Wallingford, UK.

Dyhr-Nielsen, M. 1986. Hydrologic effects of deforestation in the Chao Phraya basin in Thailand. Paper presented at the International Symposium on Tropical Forest Hydrology and Application. Chiang Mai, Thailand, 11-14 June, 1986.

Frissel, C. A., and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. *Water Resources Bulletin* 32(2).

Fritsch, J. M. 1987. *Ecoulements et erosion sous prairies artifielles apres defrichement de la forest tropicale humide* . Publication 167. International Association of Hydrologic Sciences. Wallingford, UK.

Gumbricht, T., H. Lindholm, A. Akre, R. Szczepanek, M. Hessling, and J. McCarthy. 1997. GIS integrated modelling of a Himalayan landscape. *International Journal of Water Resources Development* 13 (1). (March)

Hay, L. E., and L. K. Knapp. 1996. Integrating a geographic information system, a scientific visualization system, and a precipitation model. *Water Resources Bulletin, Journal of the American Water Resources Association* 32 (2). (April)

Hewlett, J. D., and J. C. Fortson. 1983. The paired catchment experiment. In *Forest water quality,* ed. J. D. Hewlett. Athens, Georgia, USA: School of Forest Resources, University of Georgia.

Hsia, Y. A., and C. C. Koh. 1983. *Water yield resulting from clear cutting a small hardwood basin in Central Taiwan*. Publication 140. International Association of Hydrologic Sciences. Wallingford, UK.

Hudson Jr., H. E., and R. Hazen. 1964. Droughts and low streamflow. In *Handbook of applied hydrology*, ed. Van Te Chow. New York: MaGrow-Hill Book Company.

Institute of Hydrology. 1990. Eucalyptus: Forest friend or foe ? In *Report of the Institute of Hydrology for 1988/89*. Wallingford, UK.

Jensen, M. K., P. Bourgeron, R. Everett, and I. Goodman. 1996. Ecosystem management: A landscape ecology perspective. *Water Resources Bulletin, J. of the American Water Resources Association* 32 (2). (April.)

Kraijenhoff Van De Leur, D. A. 1973. Rainfall runoff relations and computational models. In *Drainage principles and applications.* Publication 16, Vol. II, ed. Institute for Land Reclamation and Improvement. Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement.

Krishnarajah, P. 1985a. Soil erosion control measures for tea land in Sri Lanka. *Sri Lanka J. Tea Sci*. 54(2).

Krishnarajah, P. 1985b. A national scheme of soil conservation for the peasant sector lands. Memorandum submitted to the Land Commission.

Madduma Bandara, C. M. 1997. Land-use changes and tropical stream hydrology: Some observations from the upper Mahaweli Basin of Sri Lanka. In *Process and forms in geomorphology*, ed. D. R. Stoddart. London and New York: Routledge.

Montgomery, D. R., G. E. Grant, and K. Sullivan. 1995. Watershed analysis as a framework for implementing ecosystem management. *Water Resources Journal*, December 1995. Economic and Social Council for Asia and the Pacific, UN.

Nortcliff, S., S. M. Ross, and J. B. Thornes. 1990. Soil moisture, runoff and sediment yield from differentially cleared tropical rainforest plots. In *Vegetation and erosion*, ed. J. B. Thornes. London: John Wiley & Sons Ltd.

Qian, W. E. 1983. *Effects of deforestation on flood characteristics with particular reference to Hainan island, China*. Publication 140. International Association of Hydrologic Sciences. Wallingford, UK.

Richardson, J. H. 1982. Some implications of tropical forest replacement in Jamaica. *Zeitschrift fur Geomorphologie Neue Folge, Supplement Band 44.*

Roche, M. A. 1981. Watershed investigations for development of forest resources of the Amazon region in French Guyana. *Tropical Agricultural Hydrology. J*., ed. R. Lal and E. W. Russell, 75-82. New York: Wiley.

Shuttleworth, W. J., J. H. C. Gash, J. Roberts, C. A. Nobre, and L. C. L. Molion. 1990. Post-deforestation Amazonian climate: Anglo-Brazilian research to improve prediction. Paper presented at the International Seminar on Hydrology and Water Management of the Amazon Basin, Manaus, 5-9 August 1990, 13 pp.

Wiersum, K. F. 1985. Effects of various vegetation layers of an Acacia auriculiformis forest plantations on surface erosion in Java, Indonesia. In *Soil erosion and conservation,* ed. S. A. El Swaify, W.C. Moldenhaur, and A. Lo. USA: Soil Conservation Society of America.

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