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LOWER MEKONG BASIN:
WATER BALANCE STUDY

Phase 1 Report

INSTITUTE OF HYDROLOGY
Wallingford
Oxon
UK

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PHASE 1 REPORT

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The views expressed in this report
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1. INTRODUCTION

Background to the study

Over the past 30 years numerous developments have taken place in the upper and middle reaches of the Lower Mekong Basin. These developments include the clearing of forested land for agriculture, the introduction of irrigated agriculture and the construction of large storage reservoirs for hydropower and irrigation. Concern has been expressed that these developments may have significantly affected the hydrology of the Basin and reduced the volumes of water entering the delta during the dry season. Mainstream flows in some recent years have been lower than average and in the region of the delta, salt water has migrated upstream further than before and reduced the potential for using river water for irrigation.

It is possible that these low flows are a direct result of development in the riparian countries upstream. Alternatively they may merely represent the natural consequences of particularly low rainfall in the Basin upstream of the delta. The latter is almost certainly true because the hydropower schemes on the Nam Ngum in the Lao PDR and in northeast Thailand regulate the natural flow in the tributaries concerned, and will tend to increase the low flows downstream. However this situation is not likely to continue for long as the progressive development of irrigation, both in northeast Thailand and the Lao PDR, uses increasing volumes of the regulated flow in the tributaries.

In addition to the development of major irrigation schemes, many other changes in agriculture, cropping patterns and land use have also been taking place. On one hand numerous small tanks or reservoirs have been constructed for local small-scale irrigation and village water supplies. On the other, large areas of indigenous forest, particularly in northeast Thailand, have been cleared since the early 1950s and replaced with dry foot crops such as cassava and kenaf. At the same time more land has been brought under the bunded field system for paddy rice, involving the diversion of more of the flows early in the wet season.

Without a systematic review of the hydrology of the Basin it would be impossible to determine whether all these developments have had a significant impact on the water balance of the Basin, or on the seasonal distribution and volume of runoff. Consequently the objective of this study is to undertake such a review and to investigate the effects of the developments that have already taken place upstream. It will then be possible to assess more realistically what the consequences of future development are likely to be on the water regime in the lower part of the Basin.

The primary objectives of Phase 1 of the study were to undertake a comprehensive review of the available data, carry out water balance studies of selected tributary basins and investigate the variability of flows in the Mekong upstream of the delta. Having completed this essential ground work in Phase 1, it is now possible to define a detailed programme of work for Phase 2; a discussion of the work programme proposed for Phase 2 is given in the final chapter of this report.

The Study Area

The course of the Mekong river covers a distance of 4,200 km from its sources in the eastern part of the great plateau of Tibet to its delta south west of Ho Chi Minh City. The Mekong drains an area of about 795,000 km^2, of which some 606,000 km^2 is the Lower Mekong Basin that starts near Chiang Saen at the junction of the borders between Burma, the Lao PDR and Thailand (Figure 1).

In this study we are concerned with that part of the Lower Basin located between Chiang Saen and Paksé. This region can be split into two contrasting parts, namely the relatively flat Korat plateau of northeast Thailand, and the mountainous regions of the Lao PDR and northern Thailand. The mountains on the left bank form a number of separate drainage basins such as the Nam Ngum, the Se Bang Fai and the Se Bang Hieng. These contrast with the Mun-Chi river system which drains the largest part of the Korat Plateau.

Location map

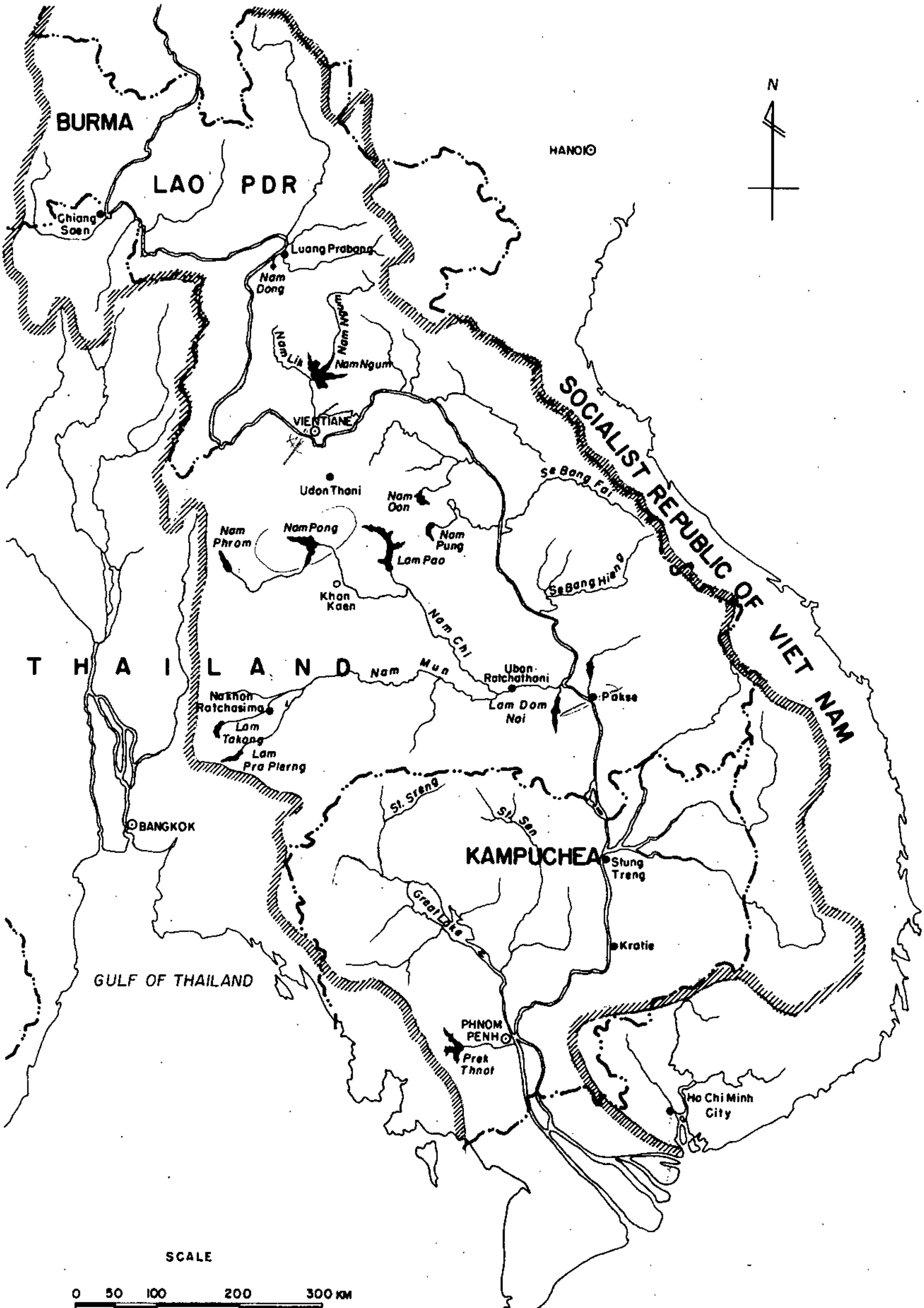


Figure 1

Climate

The climate of the Lower Mekong Basin is described in detail elsewhere (Mekong Secretariat, 1968 and 1978); a summary is given here for background information. The study area lies entirely within the tropical zone of the northern hemisphere, and its climate is controlled largely by the seasonal monsoon winds. The climate has two distinct seasons, separated by short transition periods. The southwest monsoon and the rainy season occur mainly between mid-May and mid-September or early October; the northeast monsoon or dry season occurs mainly between mid-October or early November and March.

The rainy season starts as the Intertropical Convergence Zone moves northwards in mid-May; by June a steady southwesterly airflow is established with regular local, occasionally torrential, showers occurring during the afternoon or early evening caused by convection or orographic lifting. Infrequently during August and September developing tropical storms enter the area and produce longer-lasting and heavy rainfall.

During the early part of the autumn transition period, the weather is quite similar to that of the southwest monsoon, but by mid-October in the north and late October in the south, the drier and cooler northeasterly airflow dominates the area. This airflow has generally dissipated by March, and during the transition period before the onset of the southwest monsoon temperatures reach their annual maximum, and rainfall begins to increase.

Hydrology

The mean annual rainfall of the study area ranges from about 1,000 mm in parts of northeast Thailand to as much as 3,000 mm over some of the mountains in the northeast of the Lao PDR. With the exception of the latter area, which has no clearly defined dry season, the rainfall that occurs between December and May is a very small percentage of the annual total. Estimates of annual potential evaporation range from 1,500 to 1,800 mm.

The climatic pattern of distinct wet and dry seasons is reflected in the streamflow records of the Mekong and its tributaries which show marked seasonal variations. Upstream of Chiang Saen however, the flow in the Mekong is influenced more by snowmelt than by rainfall associated with the monsoons; consequently the distribution of runoff is more uniform.

Generally the main river begins to rise following the start of the rains in May, and at upstream locations reaches its maximum level in August or September; further downstream the maximum occurs later in September or October. The recession during the autumn is rapid and the lowest discharges occur during March or April. This pattern of runoff is also characteristic of the tributaries, and in many catchments where groundwater storage is small, the rivers dry up completely soon after the end of the wet season.

Geology

The study area can be divided into three rather distinct physiographic units, namely the Northern Highlands, the Annamite Chain and the Korat plateau (Figure 2). The Northern Highlands comprise the north part of the Lao PDR, Loei province in northeast Thailand, and the mountains of Chiang Rai province in northern Thailand. This is a strongly folded mountainous area with complex and dissected relief; most of the rocks are sandstones and evaporites.

The Annamite chain is mostly steep and mountainous in the north and central parts, but forms dissected hills and rolling plateaux to the south. Sandstones and shales are common, and igneous rocks are found at the north and south ends of the chain. To the east of Thakhek there is a hilly area of karstic limestone, which forms the single most extensive area of limestone in the basin.

The Korat plateau is a large saucer-shaped basin tilted towards the southeast. The most common rocks are sandstones and shales, the more hilly regions being predominantly sandstone. Much of the plateau is underlain by thick deposits of salt formed in the Cretaceous period.

Physiographic units

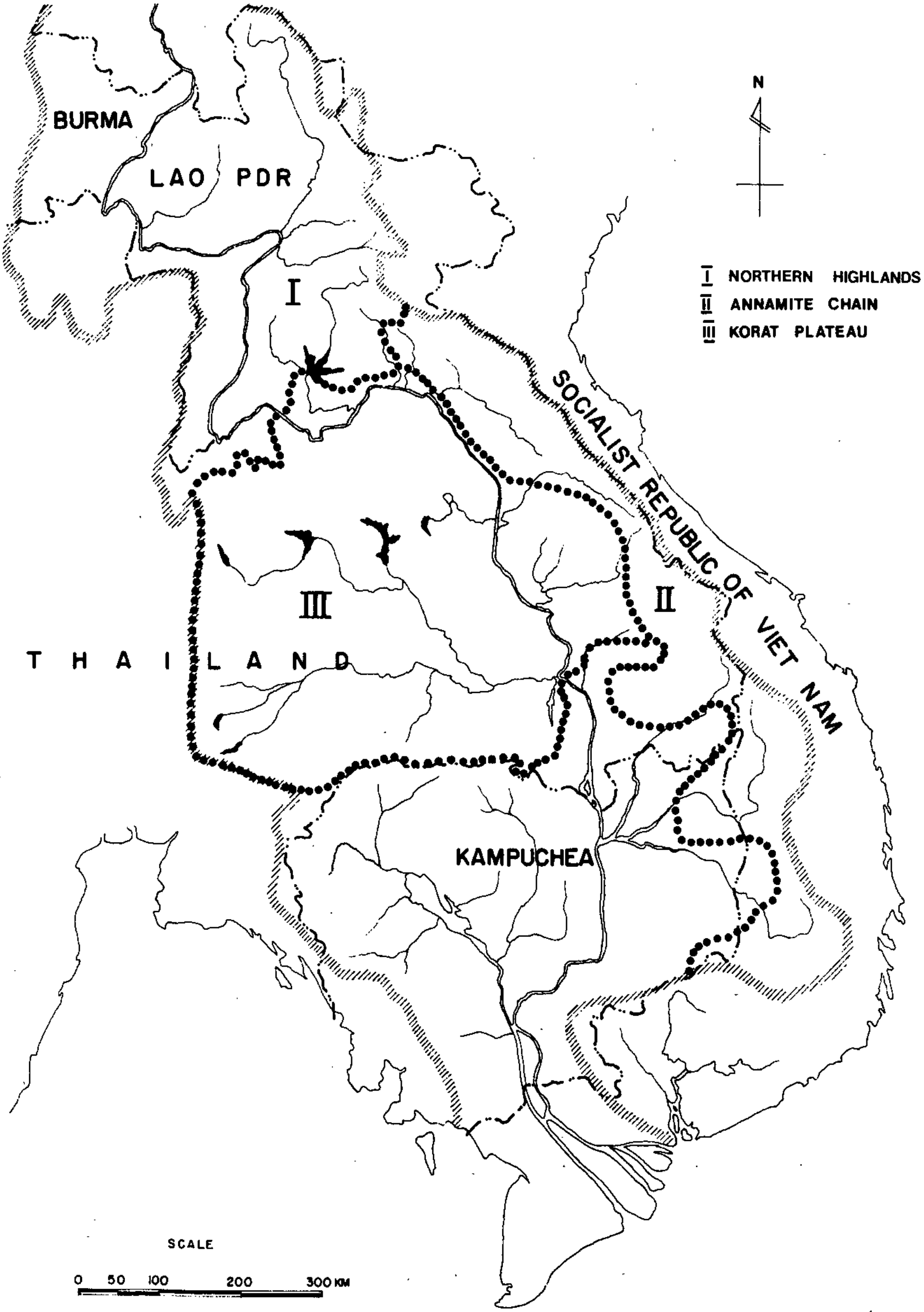


Figure 2

Soils

Detailed descriptions of the main soil types found in the study area are given elsewhere (Mekong Secretariat, 1968, 1977 and 1978). Briefly the soil types can be classified into three main categories which are determined by the parent material; alluvial soils comprise about 10 per cent of the area, soils on sandstone about 80 per cent, and soils on limestone and basalt the remaining 10 per cent (Mekong Secretariat, 1978).

The soils of the study area are generally considered to be poor, thin soils with low organic content and high acidity. The periods of high rainfall characteristic of the region cause progressive leaching of all soil types, resulting in nutrient-deficient podzolic soils. The annual wetting and drying of soils in this monsoon climate also encourages the process of laterization.

Vegetation

Natural rain-forest, the most likely climax vegetation of the study area, probably no longer exists in significant amounts anywhere in the Lower Mekong Basin. Swidden agriculture, also called 'slash-and-burn' or 'shifting' cultivation, has been a feature of the forests of southeast Asia for many generations; most forests will have been cleared to some extent at some time in history, and many may have been cleared several times. Spencer (1966) concluded that most of the mature forests are merely old forests that have reached a fairly stable equilibrium of ecological succession after some early clearing by man.

Large areas of degraded forest have arisen from the practice of replacing forest with temporary rainfed crops, which were abandoned once the soil fertility had fallen. In many areas the forest itself was not completely cleared, and isolated trees were left. Secondary formations, such as grasses, bamboos and shrubs, occupy more or less extensive areas depending on the cropping system used and its intensity.

The main features of the agricultural areas are the small, traditional bunded paddy fields located in the flat, low lying areas. As large irrigation schemes become more widespread the land in these areas is being cleared more thoroughly and bigger fields constructed. Significant expansion of agriculture into more of the upland regions has been taking place in recent years; dry foot crops such as cassava, kenaf and sugar cane are now common.

The main crop growing season is from May to November and corresponds to the wet season of the southwest monsoon. In general the growing season of rainfed rice starts with nursery and land preparation in May; transplanting follows in June and harvesting usually takes place in November. There will obviously be local variations on this pattern resulting from variations in the onset of the wet season among other factors. The irrigated cropping of rice during the dry season starts with nursery and land preparation in December; transplanting follows in January and harvesting in March or April.

2. AVAILABLE DATA

Rainfall

The raingauges in the Lower Mekong Basin are operated by a number of different agencies; much of the data from these stations is transmitted to the Mekong Secretariat and is published in the series of "Lower Mekong Hydrologic Yearbook" which started in 1962 (Mekong Secretariat, 1962 et seq.). In the Lao PDR and Vietnam national agencies perform the field operation and maintenance; the data are sent to the Secretariat for processing and publication. In Thailand the National Energy Administration (NEA), the Royal Irrigation Department (RID) and the Meteorological Department (MDT) all operate raingauges, and process and publish their rainfall records. Selected data from all three sources are included in the Mekong Yearbooks.

The rainfall data published by the Secretariat consist of monthly and annual data; the locations of the main stations in the present raingauge network are shown in Figure 3. This map is based on a map in the 1979 Mekong Yearbook but some gauges, mainly those recently installed, have been omitted. The parts of the Basin with the highest density of gauges are inevitably the low lying, more densely populated agricultural areas. There are few gauges in the mountainous, high rainfall, regions of the Lao PDR which provide the greatest proportion of the tributary inflows to the Mekong. At some stations, mostly those equipped with recording gauges, daily values are also published.

Monthly data for 11 stations in the northeast region of Thailand which lie in the Lower Mekong Basin have been published for the period 1911 to 1960 (Meteorological Department, 1964). These data are from meteorological stations operated by the MDT and were checked and verified before being included in their report.

In 1975 the Mekong Secretariat published summaries of monthly and yearly hydrometeorological data for the Thai part of the Lower Mekong Basin (Mekong Secretariat, 1975). During that study daily rainfall data for 18 stations, including Vientiane in the Lao PDR, were collected and written onto computer tape. The period covered by the

Location of main raingauges

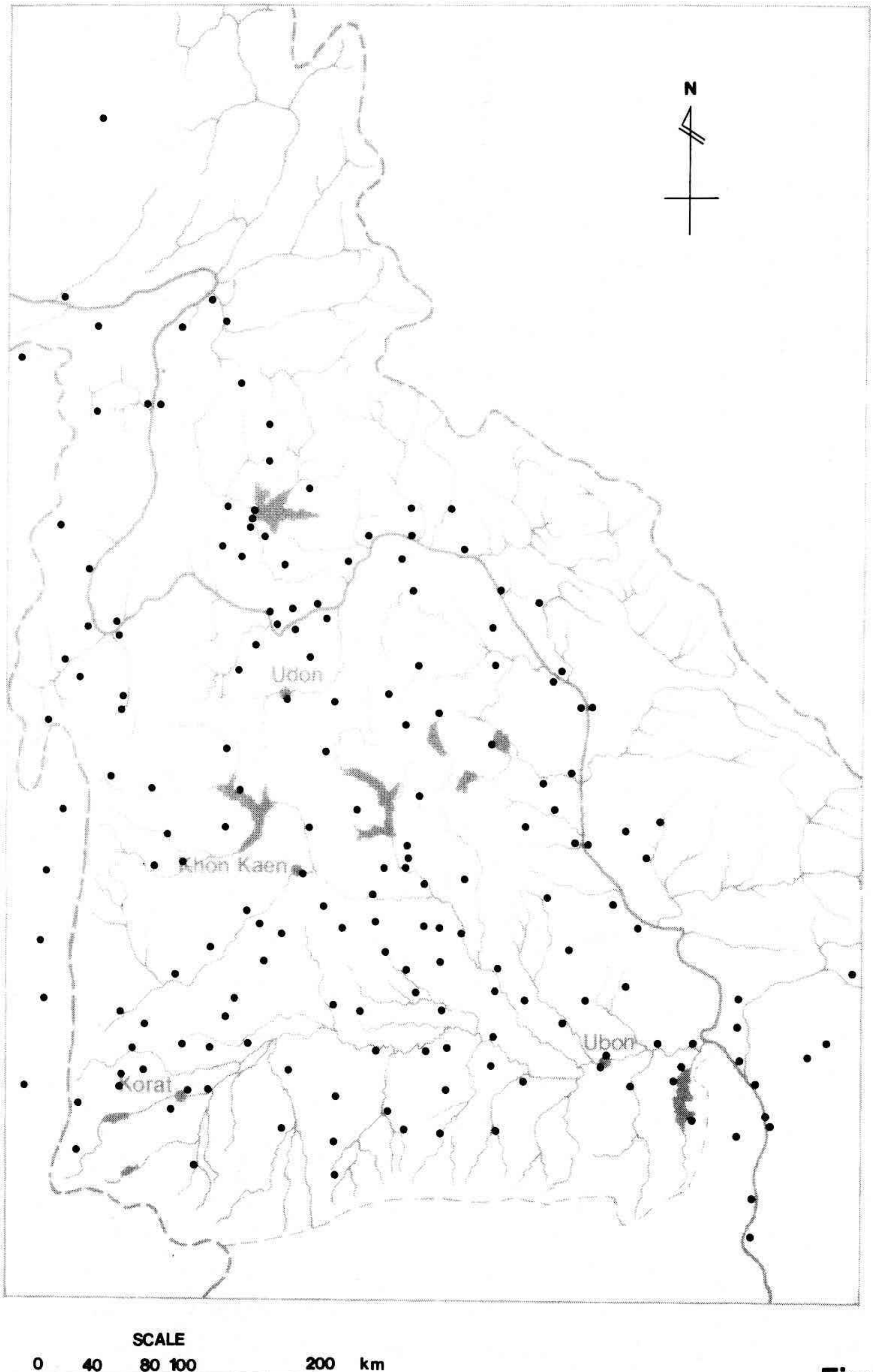


Figure 3

records on tape was originally between 1952 and 1972; at most of these stations records up to 1978 have now been included (Mekong Secretariat, 1981a). Additional daily data for raingauges in Thailand were also available from the Meteorological Department on request, but this was inconvenient because processing daily data by hand is extremely time consuming.

Recently two studies involving analyses of daily rainfall in Thailand have been completed at the Asian Institute of Technology (AIT). One of these (AIT, 1978a) used daily rainfall data for 58 stations in northeast Thailand covering the period from 1952 to 1977. Unfortunately these data are no longer held on computer tape or disc at AIT and could not be used directly. In the second of these studies (Apichart et al., 1980) daily data for the period 1952 to 1973 from stations covering the whole of Thailand were used; over 80 of the stations used are located in the northeast. The daily data for these stations are held on computer tape at AIT.

In addition to the regional studies of rainfall mentioned above, daily rainfall data have also been collected for specific water resource, irrigation or other engineering studies. The data used in some of these studies (i.e., NEDECO, 1982a, 1982b) were available on punched cards at the Mekong Secretariat.

Streamflow

River stage observations on the Mekong have been made for over 80 years. However it is only since the early 1960s that regular and systematic discharge measurements have been made, and the observation network extended to cover the major tributaries as well as the mainstream. The extent of the present network is shown in Figure 4; note that although this Figure is based on a map in the 1979 Yearbook the locations of some gauges, particularly those with short records, have been omitted.

These gauging stations are part of the overall network of stations operated by the national services of the riparian countries. selected data from these stations are now compiled and published in

Location of main gauging stations

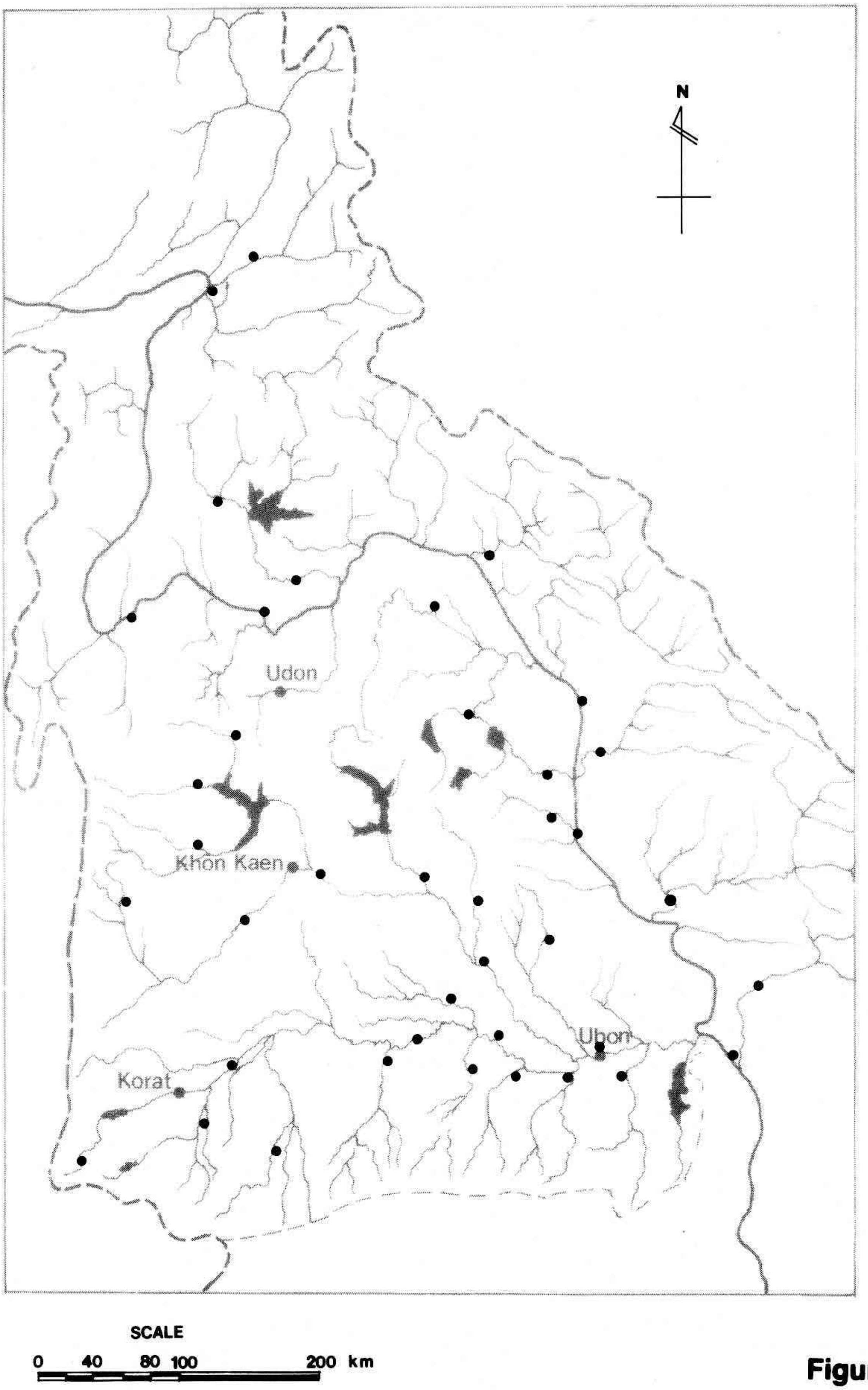


Figure 4

the "Lower Mekong Hydrologic Yearbooks" by the Mekong Secretariat (1962 et seq.).

For the period prior to 1960 streamflow observations were limited to the gauging stations on the main river and two stations in the Mun-Chi basin. Few discharge measurements had been made before 1960 when the Harza Engineering Company began a programme of regular and systematic discharge measurements (Harza, 1962); the discharge data published in their report are based on historic water level readings, and rating curves derived since 1960. A summary of the periods for which historic discharges were calculated is given in Table 1, which shows that the records for Vientiane, Mukdahan and Paksé are almost complete. However there are numerous instances in the data where footnotes indicate that the discharges had been computed on the basis of records up or downstream, because the gauge readings were missing or considered to be doubtful.

TABLE 1. Availability of discharge data prior to 1960

Station	Period
Mekong near Vientiane, Lao PDR	1923, 1925-45, 1947-59
Mekong at Thakhek, Lao PDR	1936-44, 1947-59
Mekong at Mukdahan, Thailand	1923, 1925-36, 1938-44, 1946-59
Mekong at Paksé, Lao PDR	1923, 1926-27, 1932, 1934-44, 1946-59
Mekong at Stung Treng, Kampuchea	1955-59
Mekong at Kratie, Kampuchea	1933-53
Nam Mun at Ubon, Thailand	1944-59
Nam Chi at Yasothon, Thailand	1951-59

Source: Harza (1962)

A comprehensive study of the Vientiane stream gauging station was completed by Berthelot in 1965 (Berthelot, 1965). He examined the historic water level records and adjusted them to a common datum, and corrected the rating curve derived by Harza for river stages higher than 5 metres. Daily discharges were then recalculated from the corrected water levels at Vientiane; the differences between these and the earlier data apply mainly to high discharges.

As part of the Mekong Systems Analysis Project additional work on the mainstream flow records was undertaken to develop a model of the Lower Mekong Basin using data collected during the period 1960 to 1964 (US Army Engineer Division, 1968). Because the gauging station at Vientiane has the longest record it was decided that it should be used as the key station from which the records at other locations could be infilled or corrected. Completed records of daily flows for the mainstream stations were thus obtained, and are available on punched card at the Mekong Secretariat.

These mainstream records are a vital source of information for the analysis of any long-term changes or trends in the hydrological behaviour of the Mekong. It is important therefore that these records should be unbiased. At first it was impossible to determine to what extent the original records had been corrected or infilled and whether the records really could be considered unbiased. However the Secretariat has now confirmed that not only were there few corrections made, but that the magnitude of the corrections was small; the daily flow records for the mainstream stations are therefore considered to be unbiased and independent.

Streamflow records for the tributary gauging stations cover much shorter periods of time than the mainstream stations; Table 2 gives a summary of the stations for which monthly data are available on punched cards at the Mekong Secretariat. Although some of the more recent daily data at these stations has been processed by computer, at few stations are the daily data kept in a form convenient for computer processing. Moreover at some of the stations, for the earlier part of the records, only monthly data exist at the Mekong Secretariat; the daily data for these stations is published in the relevant yearbooks (RID, 1966 et seq.; NEA, 1962 et seq.). In instances when the daily data had not been published, they were obtained from the agency concerned.

TABLE 2. Availability of monthly data for the Mekong tributaries

River	Station	Catchment area (km^2)	Period
Nam Khan	Ban Mixay	6,100	1961-79
Huai Mong	Ban Na Ang (kh-18)	1,307	1957-79
Nam Ngum	Tha Ngon	16,500	1960-79*
Nam Songkhram	Ban Tha Kok Daeng	4,650	1965-80+
Se Bang Fai	Se Bang Fai	8,560	1960-79
Nam Pung	Ban Tham Hai	1,070	1962-79*
Se Bang Hieng	Ban Keng Done	19,400	1960-79
Nam Chi	Ban Nong O (E-32, E-32A)	2,905	1961-79
Nam Chi	Ban Kok	28,500	1965-80*
Nam Chi	Yasothon	43,100	1951-80*[0]
Nam Yang	Ban Nong Saeng Thung (E-33A)	2,599	1961-80
Lam Se Bai	Phawaphuton Bridge (M-32)	1,654	1963-80
Nam Mun	Ban Tha Chang (M-2)	4,800	1950-80*
Lam Plai Mat	Railway Bridge, Buriram (M-8)	5,025	1963-80
Lam Chi	Ban Kho Kho (M-26)	2,927	1954-80
Nam Mun	Rasi Salai (M-5)	44,275	1955-80*
Huai Samran	Sisaket (M-9)	3,026	1954-80
Nam Mun	Ubon Ratchathani (M-7)	106,673	1950-80*
Lam Dom Yai	Det Udom (M-80)	3,340	1962-80

Notes:- *Rivers affected by reservoirs upstream

+Streamflow data up to 1975; from 1975 level data connected to discharge using a simple model (see NEDECO, 1982a)

[0]Composite record based on NEA and RID records

1) Stations with less than 15 years of record have been excluded.
2) There are some differences in the catchment areas measured by the various agencies: the areas given here are from the Mekong Secretariat Yearbooks, or the RID Yearbooks.
3) The numbers in brackets - (kh-18) - are RID station numbers.

Irrigation

Irrigation in the lower Mekong basin can be divided into three main types, namely gravity irrigation from storage reservoirs, pumped irrigation from flowing water courses and a variety of small-scale, highly localised methods. The latter include hand lifting of water from ponds and ditches, as well as some groundwater irrigation and gravity irrigation from tanks.

The areas that potentially could be irrigated from the existing major surface reservoirs in the basin are known (Mekong Secretariat, 1980a). However, for any given wet or dry season it is difficult to define accurately the areas that are actually being irrigated. Moreover it appears that no detailed inventory of the pump and small-scale local schemes is readily available except for the Thai part of the basin (AIT, 1978b and RID, 1979). Neither of these however gives any details of how the individual schemes are actually operated; this is a serious constraint in the data base.

Groundwater

With the exception of northeast Thailand few studies of the available groundwater resources appear to have been carried out in the Lower Mekong Basin; the availability of groundwater data is therefore limited to this part of the Basin (Ground Water Division, 1966). In general water from underground is only used locally for domestic suplies and irrigation on a very limited scale. Data concerning regional water level fluctuations and the availability of groundwater are therefore extremely limited. Some of the deep wells in northeast Thailand are equipped with water level recorders but the density of the observation network is very low; water level hydrographs for these wells cover a number of years and are available from the Ground Water Division.

Land use

Land use data can be derived from two independent sources, namely remote sensing and ground surveys of cropped areas and crop production. Until the early 1970s, remote sensing was limited to aerial photography. The interpretation of aerial photography to determine the land use of an area as large as the Lower Mekong Basin would have been highly impractical; it had therefore been limited to specific parts of the Basin.

Since the advent of satellite imagery it has been possible to investigate land use, and other land resources over more extensive areas. The Mekong Secretariat has used satellite imagery to produce land use, soils and land capability maps for the Lower Mekong Basin (Mekong Secretariat, 1977).

Satellite imagery has also been used by other agencies in Thailand. The Land Development Department (LDD) has produced land use maps of northeast Thailand (LDD, 1977). The extent of areas of forest and rates of deforestation have been investigated by the Royal Forestry Department (RFD) and Kasetsart University (RFD, 1981 and Wacharakitti et al., 1977).

From 1968 to 1974 the Mekong Secretariat (1968 to 1974) published an Annual Statistical Bulletin, which included data on land use and crop production. The Bulletins were compiled from data from various national and international publications and other sources, including primary data. In Thailand agricultural statistics are published annually (Ministry of Agriculture, Thailand, 1961 et seq.).

Water Quality

The first phase of a Basinwide Water Quality Study started in June 1981 and is now nearing completion (Mekong Secretariat, 1981b). The immediate objective of that study was to establish a pilot water quality monitoring system based on a comprehensive analysis of the data available, and to establish a programme of permanent and routine sampling in the Lower Mekong Basin. To date the sampling of water for water quality analysis has generally been restricted to gauging stations on the Mekong; measurements have also been made on samples taken from tributaries but generally these samples cover a period of only 1 or 2 years and were taken for specific projects.

Analyses of the samples include chemical parameters, some biological parameters, and suspended sediment concentrations. Data are published in the Mekong Secretariat Yearbooks (1962 et seq.).

A general conclusion from the study was that in the past insufficient samples for water quality analyses have been taken on a regular basis, and that the chemical and biological measurements made may sometimes vary from sample to sample. The lack of consistent sets of historic water quality data makes it impossible to identify any past trends in quality. However, with the exception of a few local sources of gross pollution, it appears that at present man-made influences on water quality are practically non-existent in the entire Basin.

3. ASPECTS OF CHANGE

Introduction

One of the main objectives of this study has been to determine whether any changes in the hydrology of the Lower Mekong Basin are evident from the available historic data. There are two reasons why such changes might have occurred. Firstly we might expect that any natural regional changes in climate such as an overall increase or decrease in mean annual rainfall and a change in its seasonal distribution, or a change in potential evaporation, would be reflected in catchment runoff. Such effects might superimpose a long-term trend on any random year by year fluctuations, which would show up in the time series of rainfall and runoff.

Secondly there have been major physical developments on the catchments themselves; such developments include the construction of surface resevoirs and storage tanks, and the replacement of forest by agriculture. Historically agriculture had been based on extensive systems of bunded fields for the cultivation of rice. More recently, however, the agricultural areas have increased, considerable areas have been planted to upland crops such as cassava and kenaf, and various forms of small and large-scale irrigation systems have been introduced into the region.

The hydrological behaviour of a catchment is controlled by numerous, highly interrelated physical processes which have been the subject of much fundamental theoretical and experimental research. No experimental work has been possible in this study, and our analysis of change had to be based on the routine measurements of hydrologial variables that have been made historically. It is therefore useful to consider a simple, qualitative representation of the regional hydrology in describing the background to our analysis.

One of the simplest representations of catchment behaviour is that of an input-output model, in which rainfall is the major input and runoff is the output; the mechanisms inside the system itself need not be described in detail. Our aim was to establish whether runoff, the output from the system, had changed with time, and if so why. A first priority was therefore to analyse the system input and output. If the historic time-series of rainfall were shown to be stationary - that is, there were no significant changes in mean or variance with time - then any changes in the system's output would have resulted from changes within the system itself.

The scope of the work that has been possible to examine the long-term effects was largely dictated by the ready availability of data. For example long-term rainfall records exist only for a small number of stations located mainly in northeast Thailand; the corresponding flow records exist only for some of the mainstream stations. Our analysis of these records concentrated on identifying the characteristics of the historic time-series and whether these characteristics had changed over time.

It is only in the past 20 to 30 years that flows on the smaller, tributary, catchments have been recorded; consequently more detailed analysis of the catchment, or system, behaviour was only possible for the short-term records.

Although we are unable to define the physical processes of the system in detail quantitatively, it is nevertheless useful to consider qualitatively the changes and developments that have taken place. The major change has been the steady degradation of forest and its substitution by agriculture. This change has taken place over a long period of time and it can be considered irreversible, because it is unlikely that forest will ever be re-established in anything like its original form and extent. In contrast changes in crops and cropping patterns will be dominated by short-term market forces and therefore will be more reversible. The general effect of these developments in agriculture and land use will be twofold. Firstly, plant species transpire different rates, so major changes in actual evaporation (and hence, runoff from the catchment) might be expected. Secondly the speed at which water is routed through the catchment will be influenced by factors such as the density of vegetation, and the extent and location of bunded fields and other surface storages, so we might expect this to affect the seasonal distribution of runoff.

A number of complementary approaches for evaluating these short-term changes can be identified. For example it should be possible to estimate the effect that a particular development such as a new irrigation scheme, or the widespread introduction of a new crop will have. The available data would then be examined for evidence that the anticipated effect had in fact occurred. The opposite approach would be to examine the observed data for any changes or trends; if such features were found they might then be related qualitatively to the developments that had taken place historically. Detailed water balances offer a third possible approach in which evaporation, the net loss of water to the catchment, is related to rainfall, runoff, and soil storage.

The description of the work that follows is divided up into two parts, namely analysis of long-term and short-term records. The first part describes the analysis of rainfall and mainstream flows to investigate any trends in the historic time-series. The flow records have also been analysed to identify any flow measures that might have changed with time, and whether the records for recent years are significantly different from the earlier records.

The second part is concerned with the effects that changes in agriculture and the introduction of irrigation might be expected to produce in the short-term. This part of the analysis has been restricted to northeast Thailand because few relevant data exist for catchments elsewhere in the Lower Mekong Basin. We discuss how crop water use can be estimated and how, in theory at least, regional evapotranspiration can be calculated from routine meteorological data. We then examine rainfall runoff relationships for some tributary catchments; the water balance analysis is discussed in detail in Chapter 4.

Analysis of long-term records

Rainfall

Rainfall records for a number of stations in the Basin extend back to the early 1900s. With the exception of a few stations located in northeast Thailand the records are far from complete, particularly in the early years, and their use in analysing long-term changes is limited.

However, the raingauges at Udon Thani, Ubon Ratchathani and Korat (Nakhon Ratchasima) give good geographical coverage of northeast Thailand, and their records from 1911 to 1980 are almost complete. Monthly data for these three stations were derived from the following sources, Meteorological Department (1964), Mekong Secretariat (1975), and the Lower Mekong Hydrologic Yearbooks. It should be mentioned that the data from the early part of these records may be less reliable than those from the later part. The stations at Udon and Korat were operated by the RID up to 1935, when they were established as synoptic stations by the Meteorological Department (MDT). The station at Ubon was initially operated by the RID before being transferred to a synoptic station of the MDT in 1942. In the rare instances when monthly data were missing - 1 month at Udon, 5 months at Ubon and 1 month at Korat - the records were completed by using the appropriate monthly mean for the missing data. The data were compiled in hydrological years, that is April to March.

A check on the relative reliability and consistency of the annual records was made by plotting double mass curves; such curves are plots of the cumulative data at a pair of stations and unless there are major inconsistencies or systematic errors in the data the points should plot as a straight line. Figure 5 shows curves of cumulative annual rainfall for Ubon plotted against the cumulative annual rainfall for Udon and Korat. There are no discontinuities or changes in the plotted points to suggest that there are errors or inconsistencies in the data.

These long-term rainfall records were analysed to determine whether any consistent trends over the period of record were evident. In this work we were not concerned with predicting rainfall in the future so no particular emphasis was put on isolating any long or short-term cyclical behaviour in the records. The 5 and 10-year moving averages of the annual data have been plotted in Figure 6; note that the points are plotted at the first year of the average. The graphs show no consistent trend with time, but they do indicate that rainfall has been higher in the second part of the record than in the first part. Table 3 is a summary of the rainfall statistics for the seven decades between 1911 and 1980, and reinforces the view of higher

Rainfall: double mass curve

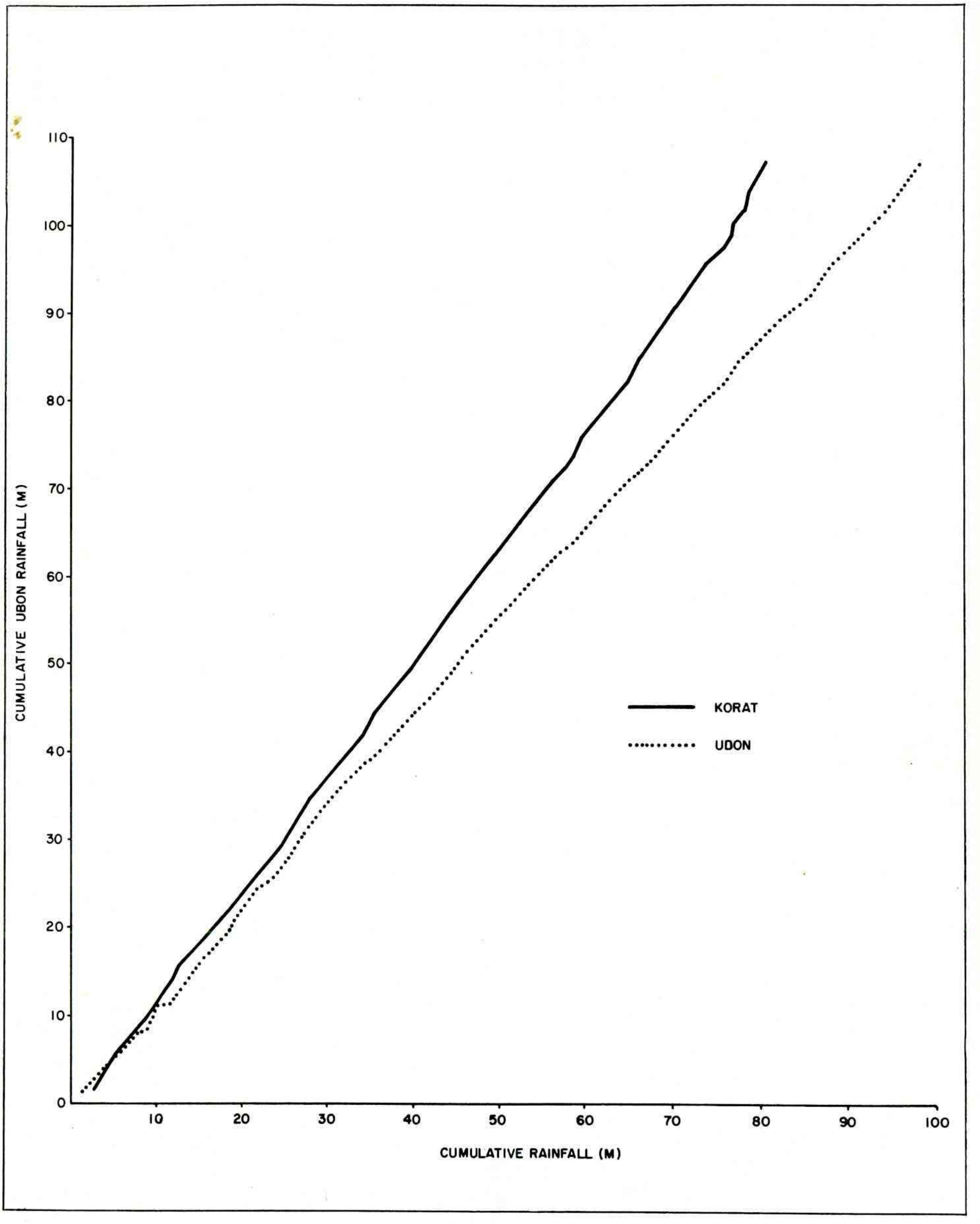


Figure 5

Rainfall: long term means

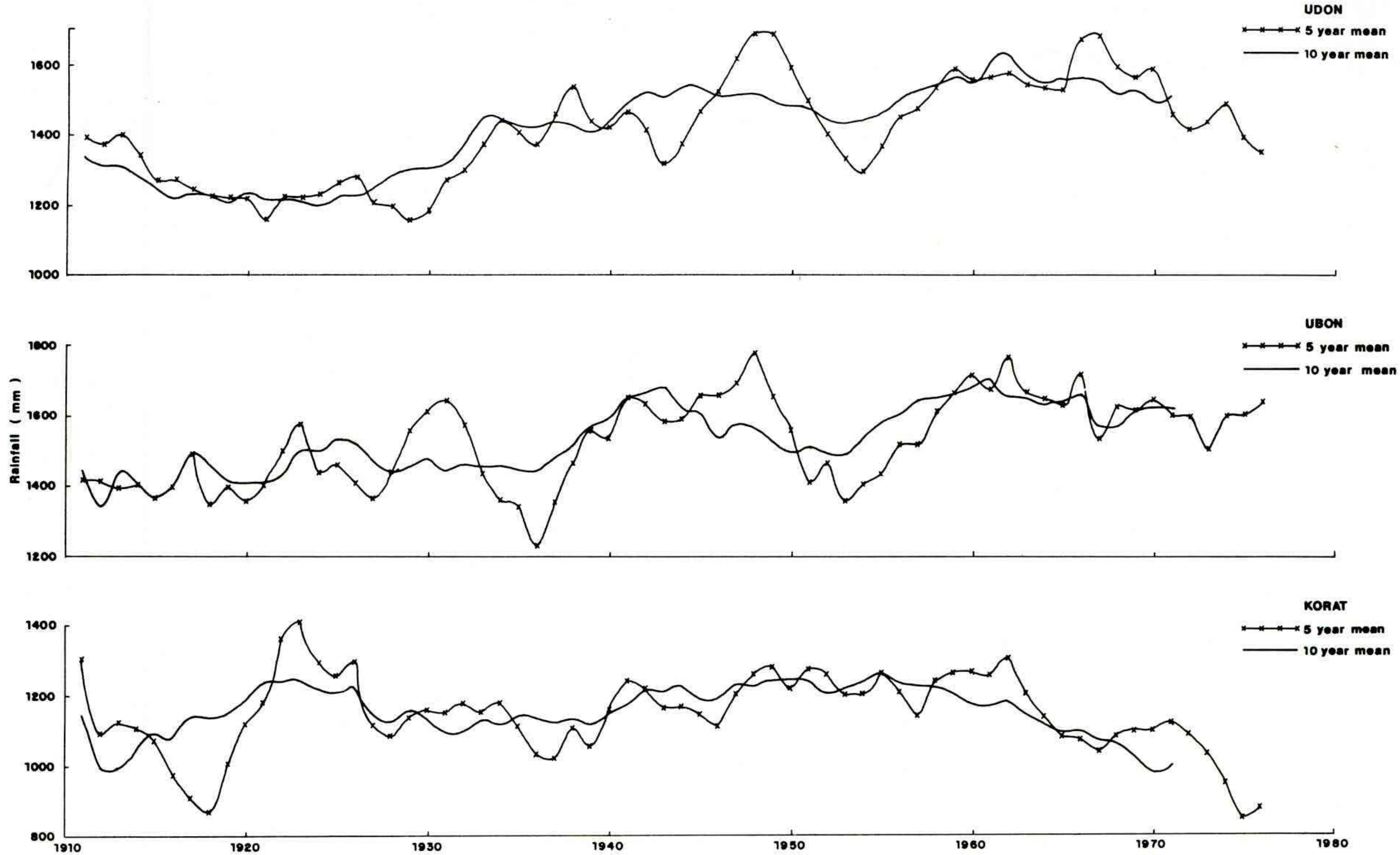


Figure 6

TABLE 3. Rainfall statistics

Decade	UDON Mean (mm)	UDON Std Dev (mm)	UDON C.V. (%)	UBON Mean (mm)	UBON Std Dev (mm)	UBON C.V. (%)	KORAT Mean (mm)	KORAT Std Dev (mm)	KORAT C.V. (%)
1911-20	1330	260	20	1413	328	23	1139	451	40
1921-30	1213	236	13	1406	324	23	1237	291	24
1931-40	1316	216	16	1437	287	20	1092	179	16
1941-50	1491	206	14	1649	156	9	1177	203	17
1951-60	1473	213	14	1464	296	20	1246	132	11
1961-70	1617	303	19	1694	326	19	1173	198	17
1971-80	1406	283	20	1618	194	12	1002	205	20
Overall	1407	268	19	1526	292	19	1152	257	22

Note: C.V. is the coefficient of variation defined as

$$\frac{\text{Std Dev}}{\text{Mean}} \times 100$$

rainfall in the later part of the record. There is however no evidence to suggest that the variability of the annual falls in each decade increases as the mean increases. The high variability in the first decade of the Korat record arises from an annual fall of over 2300 mm in 1911 when exceptional falls of over 600 mm were recorded both in August and October. We have already mentioned that the early records might be less reliable than the later records, so it is possible that these high recorded falls are erroneous.

Serial correlation is an important guide to the properties of a time-series, as it measures the correlation between observations at different intervals apart and can indicate whether there is any tendency for the magnitude of a given observation to be influenced by preceding observations. In this case the serial correlations, ρ_k, were calculated for the annual data. With the exception of Udon at lag 5, with $\rho_5 = 0.323 \pm 0.254$ the values of ρ_k were insignificant at the 95 per cent confidence level.

In some similar work (Mekong Secretariat, 1974) more instances of significant serial correlations were revealed. In the present study more data were available, but the main difference between the two pieces of work is in the definition of confidence limits for the ρ_k.

In preference to the t-test used in the previous work we have used an estimate of the 95 per cent confidence limits given by

$$\rho_k = \pm 1.96 \sqrt{\frac{1 + 2 \sum_i^{k-1} \rho_i^2}{n-k}}$$

where ρ_i is the serial correlation at lag i

n is the number of points in the sample

and k is the number of lags required (Freeman, 1981)

There is another measure called the Hurst coefficient (h) which can be used to quantify long-term fluctuations in a time series (Hurst, 1951 and 1956). Hurst examined a very large number of geophysical time series and found that the values of h ranged between 0.5 and 1.0, with a mean value of 0.73 and a standard deviation of 0.08. It can be shown that if a time-series consists of independently distributed observations then as the number of observations reaches infinity, h approaches 0.5. The discrepancy between the theoretical value of h for independent observations and that calculated from observed time-series is therefore a measure of long-term persistence.

In this study h was calculated for each of the long-term rainfall records as 0.76, 0.68 and 0.64 for Udon, Ubon and Korat respectively. A value of 0.74 for the corresponding record at Bangkok Metropolis was also calculated. The general conclusion from these values of h is that they are consistent with Hurst's own observations and that in this context there is nothing particularly unusual about the records.

The monthly data were then analysed to see whether there had been any change in the seasonal distribution of rainfall over the period of record, as there have been suggestions that deforestation has had the effect of decreasing the premonsoon rainfall of May and June (Mekong Secretariat, 1980b).

At each station the mean and standard deviation of the May and June rainfalls were calculated. Next the May and June mean rainfall was calculated for each of the 7 decades between 1911 to 1980; each mean was then tested to indicate whether it was significantly different from the long-term, or population, mean.

In this case the test statistic was given by:

$$z = \frac{x - \mu_o}{\sigma/\sqrt{n}}$$

where x is the mean of the sample of size n

μ_o is the population mean

and σ is the population standard deviation.

The calculated values of z are given in Table 4, and although there are a small number of significant results, the balance of evidence suggests that the means of the rainfall in May, June and the complete year for the seven decades between 1911 and 1980 are not significantly different from the long-term mean.

TABLE 4. Test statistics

	Period	May	June	Annual
Udon	1911-20	-0.50	-0.80	-0.90
	1921-30	-1.72	-0.26	-2.29*
	1931-40	0.57	-0.88	-1.07
	1941-50	0.85	-0.71	0.99
	1951-60	0.03	1.38	0.79
	1961-70	1.21	2.22*	2.48*
	1971-80	-0.43	-0.95	-0.01
Ubon	1911-20	-1.82	-1.16	-1.22
	1921-30	0.13	-0.54	-1.30
	1931-40	-1.10	-0.92	-0.96
	1941-50	0.67	-0.42	1.33
	1951-60	-0.81	-0.10	-0.68
	1961-70	3.00**	1.00	1.82
	1971-80	-0 07	2.15	1.00
Korat	1911-20	-0.21	1.04	-0.17
	1921-30	1.18	-0.05	1.04
	1931-40	0.10	0.27	-0.74
	1941-50	-0.30	-0.69	0.30
	1951-60	-0.21	-0.49	1.15
	1961-70	1.46	-0.50	0.25
	1971-80	-2.02*	0.42	-1.84

* result significant at the 95 per cent level

** result significant at the 99 per cent level

In northeast Thailand where many crops are grown under rainfed conditions any tendency for the mean annual rainfall to increase or decrease with time will have important implications for agriculture. However in the statistical context the changes in mean were found to be insignificant.

Another important characteristic of rainfall in northeast Thailand is the lack of correlation between rainfall at different stations; this is true not only for daily data but also for seasonal and annual data (NEDECO, 1982a). Clearly if it could be shown that in the long-term the rainfall over the region as a whole had increased, then the hydrological consequences would be considerable. We have examined three long-term records of point rainfall, but within the timetable allowed for Phase 1 it has not been possible to examine in any detail the problem of estimating regional rainfall from point rainfall records. The problem is particularly difficult when long-term estimates are required, because the majority of rainfall records do not start until the mid 1940s at the earliest; moreover the reliability of some early records is uncertain. At this stage of our work it is therefore impossible to say that there is conclusive evidence of an increase in rainfall over the region as a whole in recent years and we must infer that the rainfall regime is stable.

Flow records

Unfortunately there are no long-term runoff records available for tributaries in northeast Thailand which correspond to the rainfall records discussed in the previous section. Our analysis was therefore based on flow records for the Mekong at Vientiane, Mukdahan and Paksè. A summary of the main features of these records for the period 1934 to 1980 is given in Table 5; the statistics for the period 1951 to 1980 are also included together with the corresponding statistics for the Nam Mun at Ubon.

The annual data for the three mainstream stations are plotted as 5 and 10-year moving averages in Figure 7; note that the points are plotted at the first year of the average. There is no consistent upwards or downwards trend over the period of record, although there

TABLE 5. Summary of flow records (milliard m^3)

Station	Catchment Area (km^2)	Annual flows Mean	Annual flows Standard Deviation	Annual flows Mean as a percentage Paksé	Monthly flows Maximum	Monthly flows Minimum
Period 1934 to 1980						
Vientiane	299000	146	23	45	50	2
Mukdahan	391000	258	34	79	81	3
Paksé	545000	326	40	100	114	3
Period 1951 to 1980						
Vientiane		140	23	45	49	2
Mukdahan		245	34	78	77	3
Paksé		312	41	100	114	3
Nam Mun at Ubon	106798	19	7	6	15	0

Notes (1) milliard m^3 is defined as $m^3 \times 10^9$

(2) the minimum monthly flow at Ubon was 14 million m^3 which is rounded to 0 milliard m^3 in this summary

Mekong: long term means

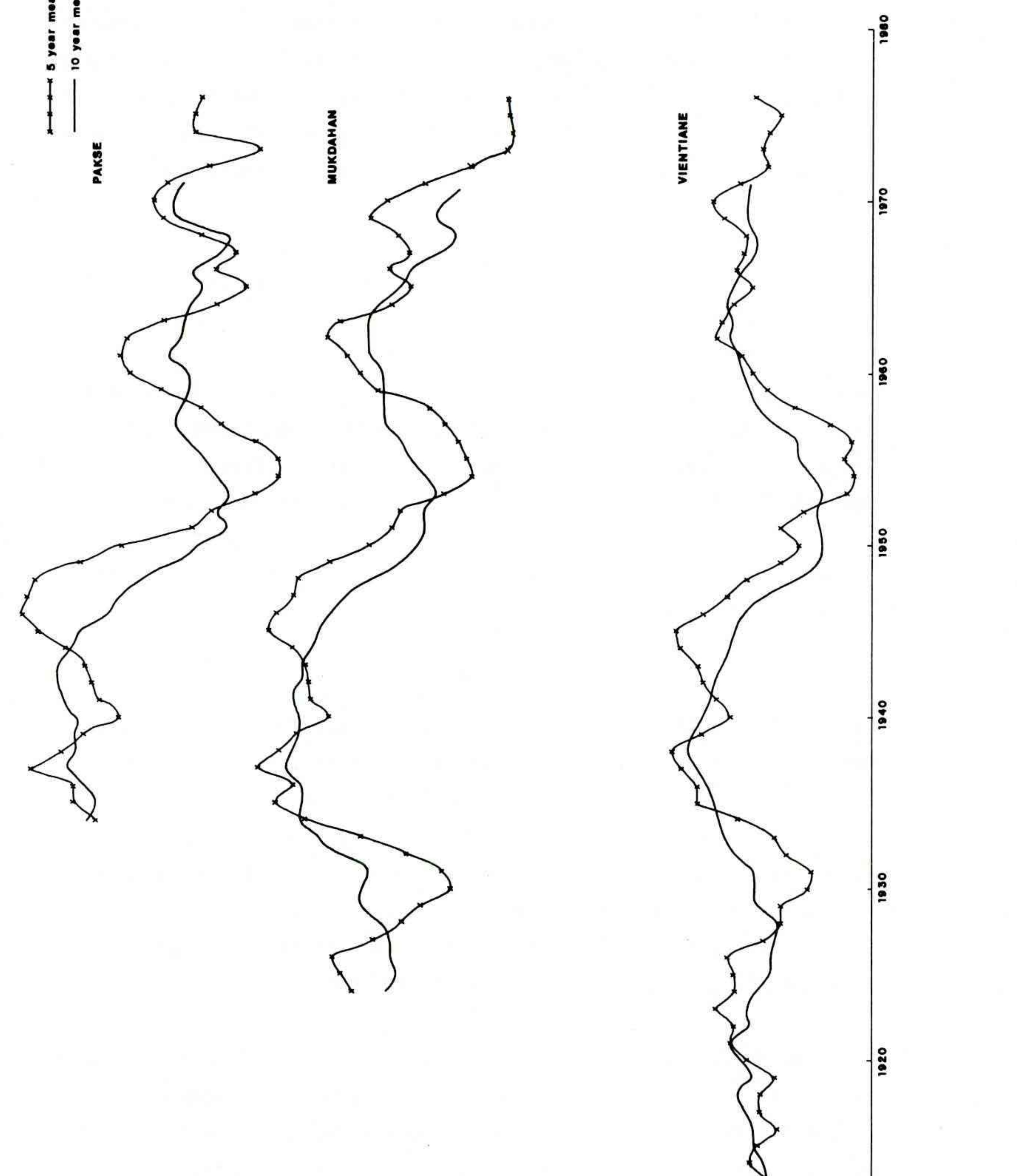


Figure 7

is a period of lower than average flows in the 1940s and 1950s at all the stations.

This effect occurs in all three of the records plotted which suggests that it has been caused by some phenomenon in the headwaters of the Mekong, and therefore outside the area included in this study. In recent years, however, the flows at Mukdahan appear to have fallen relative to the other two stations; this implies that there has been a reduction in inflow from the tributaries between Vientiane and Mukdahan.

There are two ways of looking at the relative contributions of tributaries to the mainstream flows. The first is to calculate the differences between the records at the mainstream gauging stations; these are the inflows from the intermediate catchments. When this method is used any errors in the flow data will be compounded by the process of differencing. The second is to use the flow records of the individual tributaries. In Table 6 the runoff for the Mekong, its intermediate catchments between Vientiane and Paksé and from the individual tributaries for which flow data exist, is tabulated for various periods of time.

One of the striking features of the Table is the variation in runoff between the various tributaries. In general the left-bank tributaries, with headwaters in the northern highlands or Annamite Chain (see Figure 2), have high runoff resulting from the high rainfall over the mountains. With the exception of the Nam Songkhram catchment where rainfall is higher than the rest of the Korat Plateau, the right-bank tributaries, have much lower runoff; these tend to be the largest catchments. Another important feature is the absence of data for the tributaries between 1930 and 1960.

The values of catchment runoff calculated for the period 1930-40 and the four decades from 1941 to 1980 confirm the inference from Figure 7 that the tributary inflows between Mukdahan and Vientiane have decreased in recent years. Only a third of the area of the intermediate tributaries is gauged so it is difficult to identify which regions are producing less runoff. Table 6 shows that the runoff from the Nam Songkhram has decreased, but the data cover a period of only 10 years and so these figures should be used cautiously. On the other right-bank tributary, the Huai Mong, runoff has inreased in the last decade.

Thus, it seems plausible that the left-bank tributaries have produced less runoff in recent years. It is impossible to state whether or not this is a result of development in the tributary catchments for a number of reasons. Firstly, as we have mentioned earlier, there are very few raingauges located in the mountainous, high-rainfall regions of the Lao PDR where the headwaters of many left-bank tributaries are located. The phenomenon could be merely the direct result of lower than average rainfall in these areas. Secondly only just over 40 per cent of the catchment area on the left-bank between Mukdahan and Vientiane is gauged. The catchment of the Nam Ngum has been affected by upstream regulation since 1971, so since then its runoff will not necessarily be representative of the surrounding catchments. Thirdly information on land-use and other agricultural changes in this region is extremely limited.

A different explanation of the recent decrease in runoff from the intermediate catchments is that the flows at Mukdahan have been systematically underestimated in the later part of the record. This would have contributed to the decrease in runoff between Mukdahan and Vientiane over the period 1971-80, and to the corresponding increase in runoff between Paksè and Mukdahan (Table 6). Also included in the Table are values of runoff for Thakhek, which is located some 90 km upstream of Mukdahan; the Thakhek runoff to some extent supports the hypothesis that the Mukdahan runoff had been underestimated.

However, we considered that on balance there was some evidence of a reduction in runoff from the left-bank tributaries in recent years. But without evidence to confirm that rainfall in the high-rainfall, headwater regions of these catchments had not been lower than average, it is impossible to relate this to agricutural or other developments.

Having examined the general features of the main Mekong flow records, the next step was to study the low flow regime of the river and to determine whether this had changed with time.

TABLE 6. Catchment runoff (mm)

Catchment	Area (thousand km²)	1934-40	1941-50	1951-60	1961-70	1971-80	Overall
Mekong at:							
Paksé	545	630	650	560	590	580	600
Mukdahan	391	710	720	620	670	590	660
Vientiane	299	520	530	420	490	490	490
Tributaries between Paksé and Mukdahan:							
Intermediate Catchment	154	410	460	390	390	550	440
Nam Mun at Ubon	104			173	188	208	193
Se Bang Hieng	19.4				885	775	850
Tributaries between Mukdahan and Vientiane:							
Intermediate Catchment	92	1350	1360	1270	1205	915	1205
Se Bang Fai at Se Bang Fai	8.6				1455	1255	1365
Nam Songkhram at Ban Tha Kok Daeng	4.7				745	675	720
Nam Ngum at Tha Ngon	16.5				1405	1270	1345
Huai Mong at Ban Na Ang	1.3				195	210	200
Tributaries between Paksé and Vientiane:							
Intermediate Catchment	246	760	795	720	695	690	730
Thakhek	373	695	700	610	645	600	645
Intermediate catchments:							
between Paksé and Thakhek	172	475	530	440	465	535	500
between Thakhek and Vientiane	74	1405	1390	1365	1270	1040	1270

Notes: (1) For clarity the tributary catchment areas have been rounded to the nearest 100 km², and runoff to the nearest 5 mm.

(2) Missing data:

Nam Mun	1951-55
Se Bang Hieng	1972-73, 1978-80
Se Bang Fai	1962, 1972, 1978, 1980
Nam Songkhram	1961-64, 1975-80
Nam Ngum	1961, 1980
Huai Mong	1979, 1980

One of the basic forms of data presentation used in the analysis of low flows is the flow duration curve (FDC). It shows graphically the relationship between any given discharge and the percentage of time that the discharge is exceeded. A detailed description of the derivation of FDCs is given in Annex I. FDC's for Paksé and Vientiane are shown in Figures 8 and 9 for the decades between 1940 and 1979 expressed as a percentage of the average daily flow (ADF). The curves at each station have the same general shape, although they diverge at the extremes of the flow range. There is however no consistent trend for the duration of periods of low flow to increase in recent years.

A flow frequency curve (FFC) shows the proportion of years or equivalently the average interval between years (return period) in which the river falls below a given discharge. A description of the method used to derive of FFCs is given in Annex II. In this work the analysis has been based on calendar year data, rather than hydrological year data. This is because the minimum flows usually occur during March or April, that is the beginning of the hydrological year.

In Figures 10 and 11 FFCs for Paksé are shown for various durations. The results are tabulated in Table 7 which indicates that, except for annual durations, the flows in the late 1970s have not been unusually low. This result was rather surprising so an alternative way of presenting the data was used. In Figure 12 flows for 2, 10 and 50 year return periods are plotted against duration; the flows for 1977 and 1979 as well as the average minimum flows are also included. The graph shows that in 1977 the short duration flows were not particularly extreme events, and illustrates that the problems experienced in the delta in 1977 were not the result of extreme low flows of short duration. Implicitly these occur during the dry season, so the problems experienced in 1977 arose from lower than average flows during the wet season and the subsequent recession.

In 1979 the minimum flows of up to 180 days duration were higher than average; however Table 7 shows that the annual flow in 1979 was ranked 33 giving a return period of about 3.5 years. This is a possible explanation for the belief that 1979 was a year of particularly low flows in the delta.

Mekong at Pakse: Flow duration curve

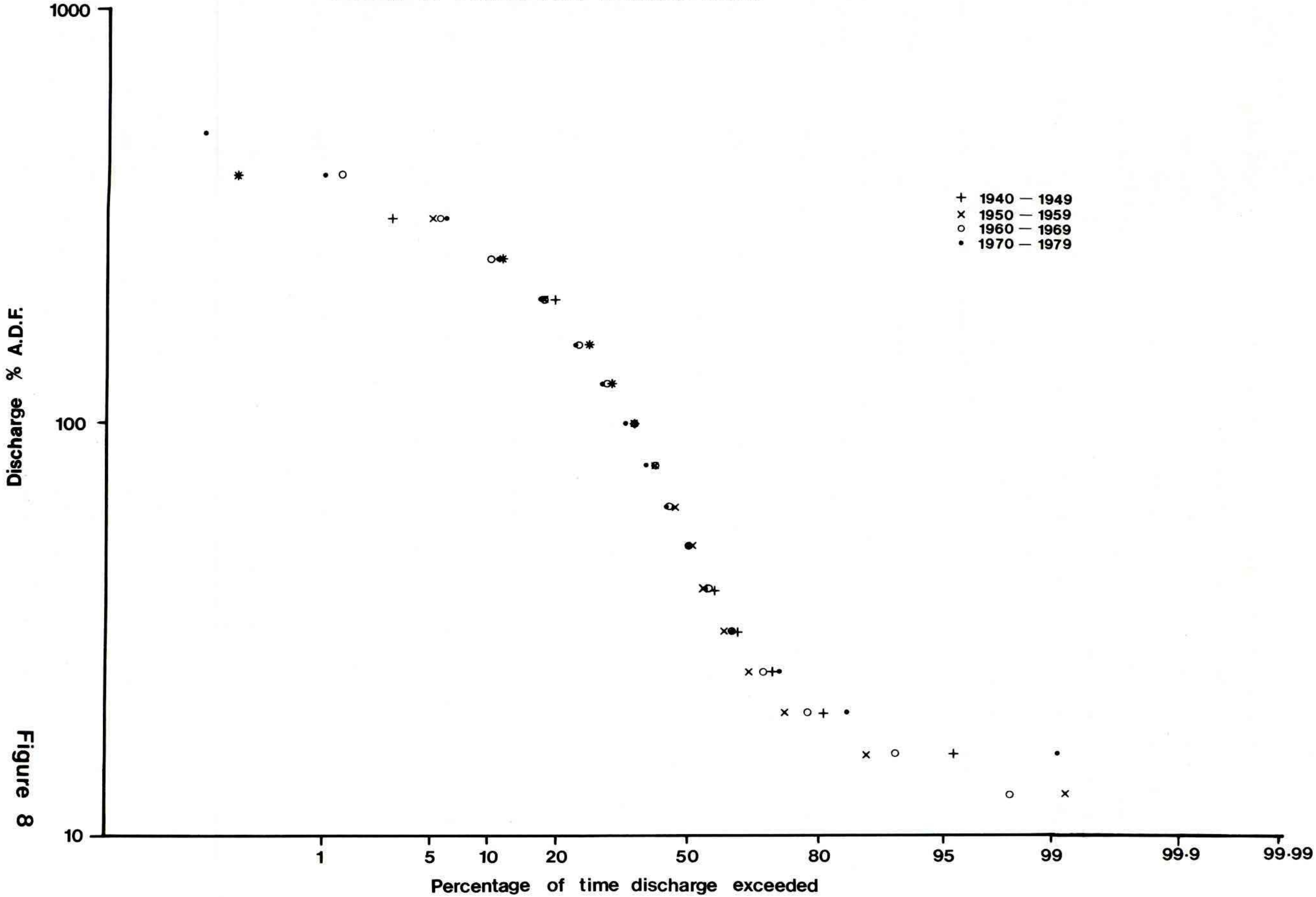


Figure 8

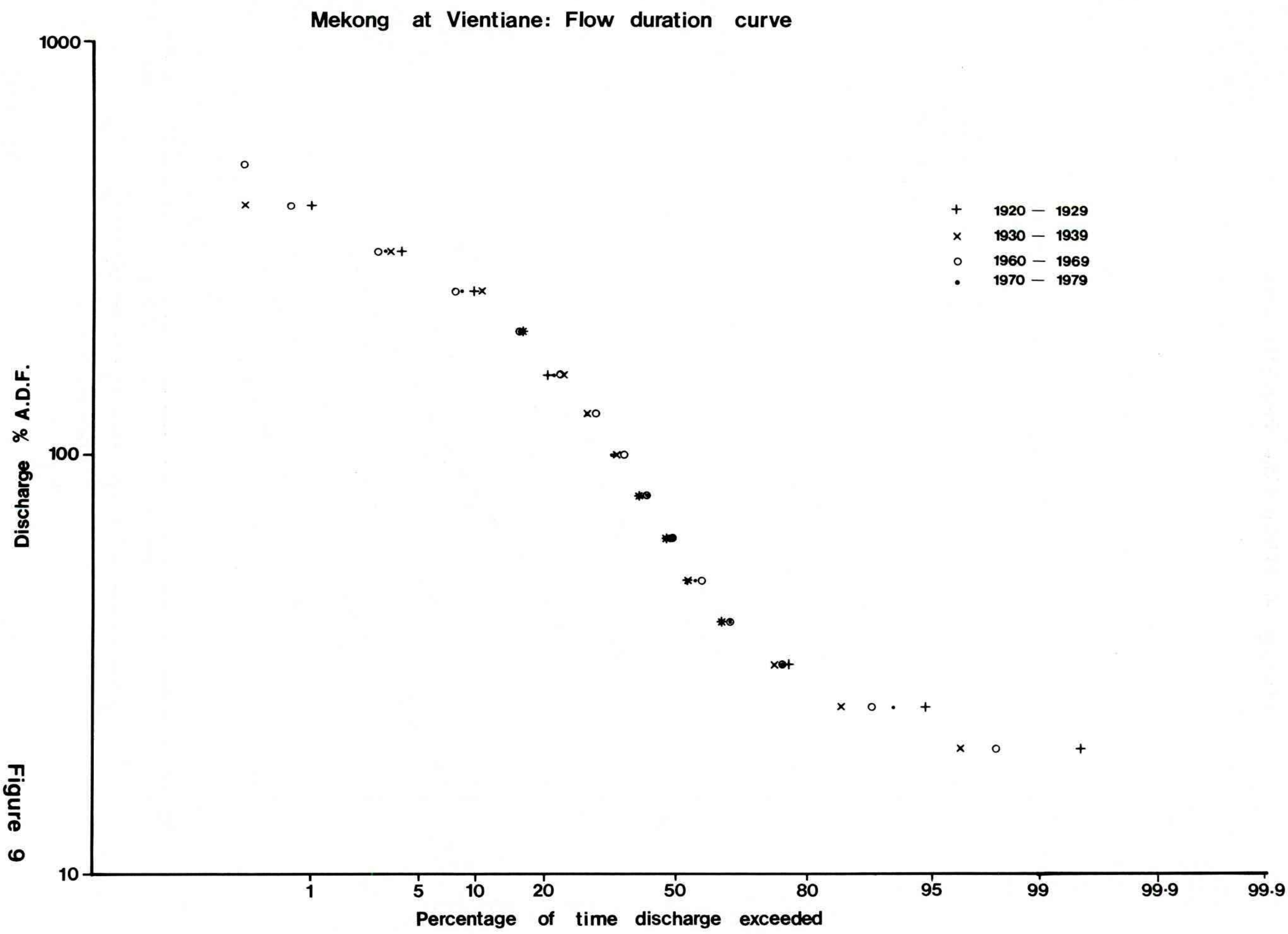

Mekong at Vientiane: Flow duration curve
+ 1920 — 1929
× 1930 — 1939
○ 1960 — 1969
• 1970 — 1979
Discharge % A.D.F.
1000
100
10
1
5
10
20
50
80
95
99
99·9
99·9
Percentage of time discharge exceeded

Figure 9

Mekong at Pakse: Flow frequency curve

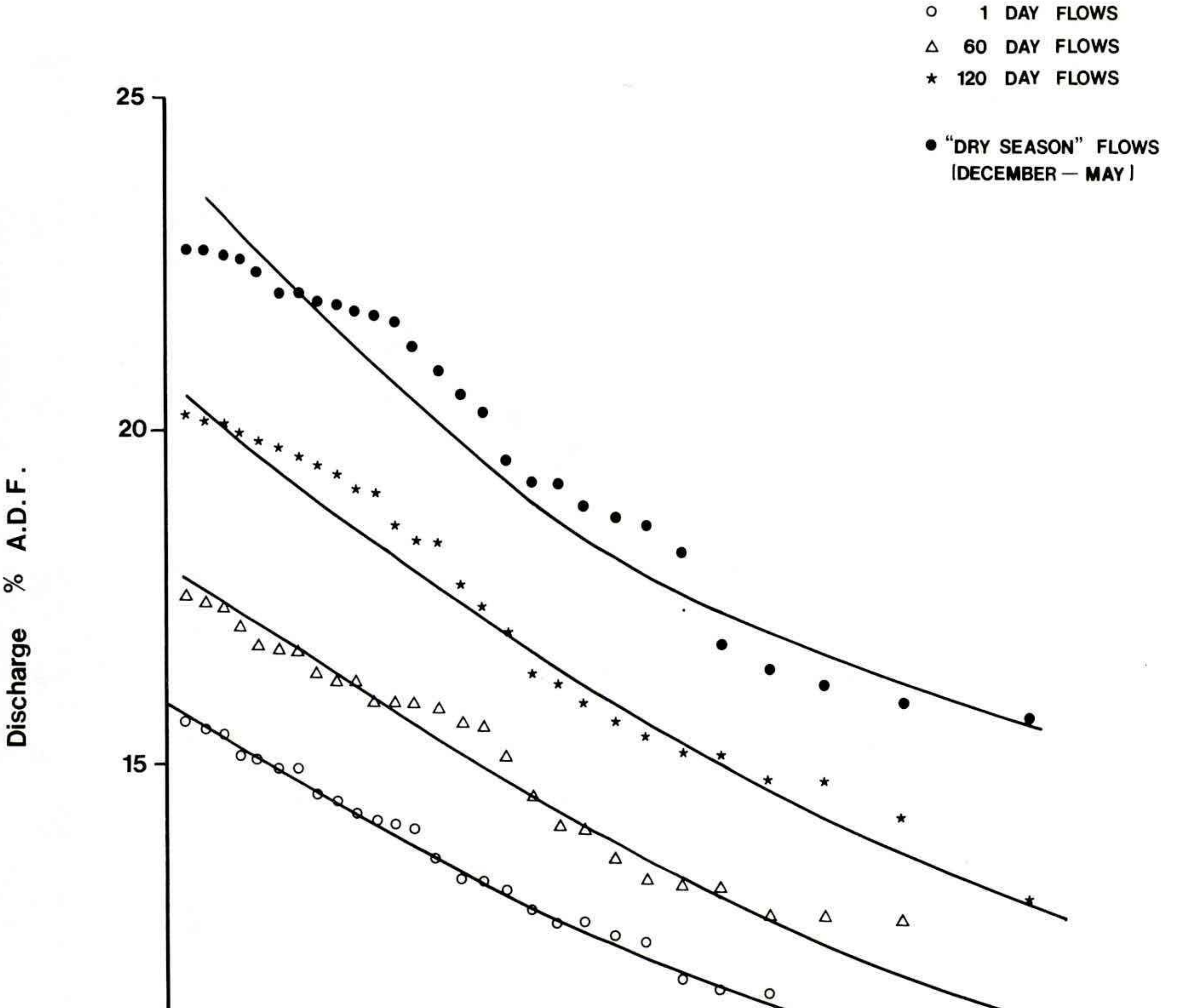


Figure 10

Mekong at Pakse: Annual flow frequency curve

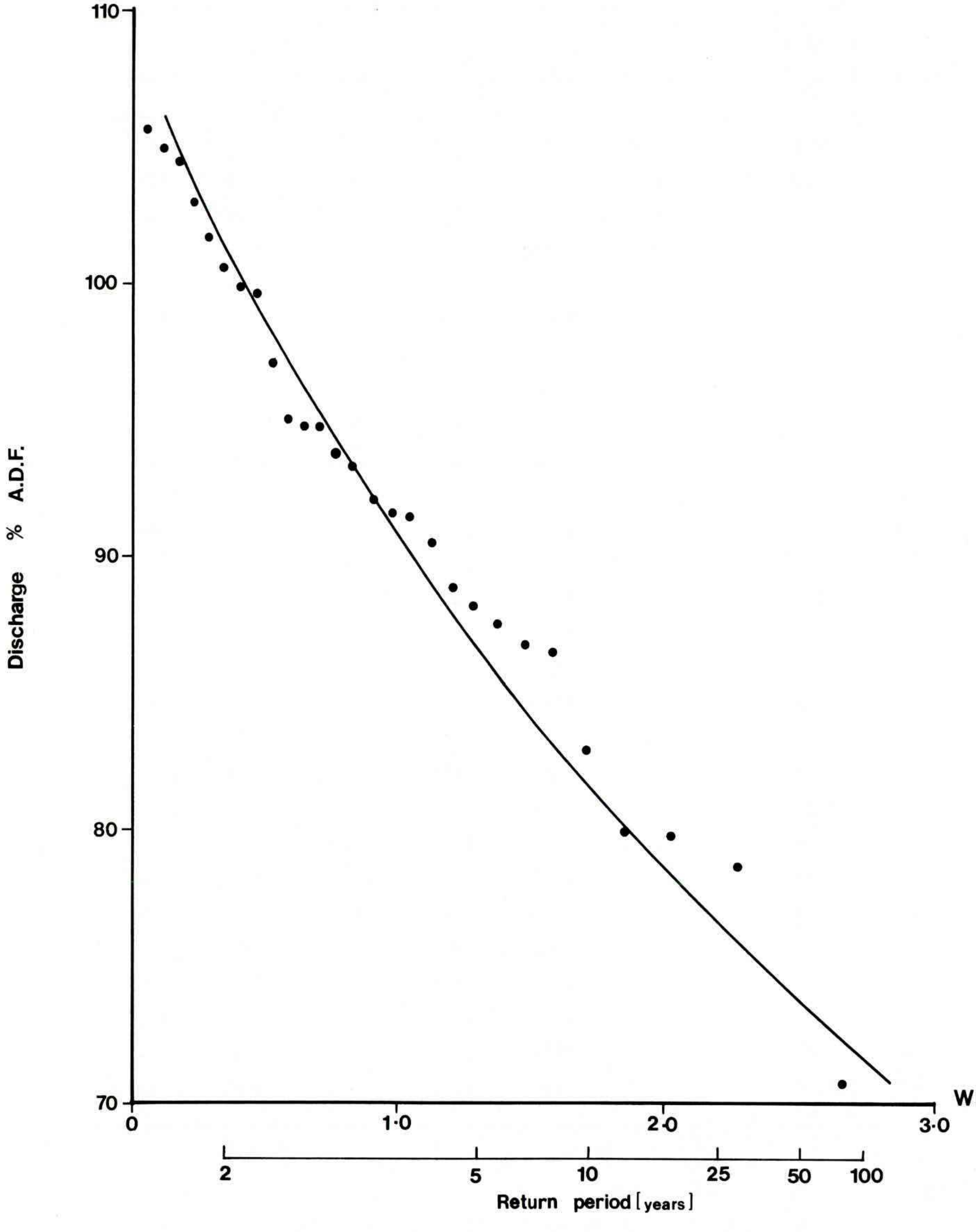


Figure 11

TABLE 7. Derivation of flow frequency curves for Paksé
(ranks 1 to 17 omitted for clarity)

Rank	Plotting position W_i	1-day flow Q_i (m^3/s)	1-day flow Year	60-day flow Q_i (m^3/s)	60-day flow Year	120-day flow Q_i (m^3/s)	120-day flow Year
18	0.06	1624	1948	1817	1947	2104	1977
19	0.12	1610	1975	1807	1978	2090	1972
20	0.18	1600	1980	1801	1964	2089	1941
21	0.23	1570	1965	1772	1966	2070	1975
22	0.29	1566	1950	1741	1980	2057	1944
23	0.35	1550	1978	1733	1975	2050	1964
24	0.41	1550	1967	1732	1965	2031	1940
25	0.47	1511	1966	1699	1946	2022	1946
26	0.53	1500	1944	1683	1944	2005	1950
27	0.59	1480	1968	1682	1950	1986	1965
28	0.65	1470	1971	1656	1971	1977	1962
29	0.71	1463	1951	1654	1962	1923	1968
30	0.77	1457	1946	1649	1968	1906	1971
31	0.84	1410	1957	1644	1951	1898	1980
32	0.91	1380	1962	1621	1957	1834	1957
33	0.98	1377	1952	1612	1961	1798	1961
34	1.05	1360	1961	1568	1955	1763	1955
35	1.13	1330	1959	1507	1952	1698	1956
36	1.21	1310	1955	1458	1959	1680	1952
37	1.29	1310	1969	1453	1970	1650	1970
38	1.38	1290	1956	1410	1969	1622	1937
39	1.48	1280	1970	1374	1956	1600	1954
40	1.59	1223	1953	1368	1953	1573	1959
41	1.71	1204	1937	1365	1937	1569	1969
42	1.86	1200	1958	1318	1958	1533	1958
43	2.03	1160	1963	1316	1963	1526	1953
44	2.27	1126	1954	1313	1954	1471	1963
45	2.66	1060	1960	1157	1960	1448	1960

Note: (1) ADF = 10374 m^3/sec

(2) These analyses are based on calendar year data

(3) Annex II gives details of the method.

TABLE 7 (continued) Derivation of flow frequency curves for Paksé

Rank	Plotting position W_i	Annual flows Q_i (m^3/s)	Annual flows Year	"Dry season flows" (Jan to May) Q_i (m^3/s)	"Dry season flows" (Jan to May) Year
18	0.06	10957	1971	2426	1943
19	0.12	10887	1945	2354	1951
20	0.18	10838	1943	2339	1944
21	0.23	10683	1975	2326	1940
22	0.29	10544	1956	2322	1941
23	0.35	10432	1964	2289	1975
24	0.41	10363	1980	2272	1950
25	0.47	10326	1963	2269	1972
26	0.53	10067	1962	2259	1962
27	0.59	9851	1944	2258	1968
28	0.65	9833	1973	2243	1977
29	0.71	9824	1940	2235	1956
30	0.77	9717	1972	2205	1965
31	0.84	9672	1965	2166	1971
32	0.91	9544	1953	2117	1980
33	0.98	9500	1979	2101	1953
34	1.05	9492	1974	2024	1961
35	1.13	9379	1960	1992	1957
36	1.21	9163	1976	1990	1970
37	1.29	9146	1954	1945	1952
38	1.38	9078	1969	1940	1937
39	1.48	9000	1957	1930	1955
40	1.59	8973	1959	1885	1954
41	1.71	8596	1958	1742	1969
42	1.86	8293	1967	1702	1959
43	2.03	8280	1955	1668	1960
44	2.27	8159	1968	1654	1958
45	2.66	7336	1977	1628	1963

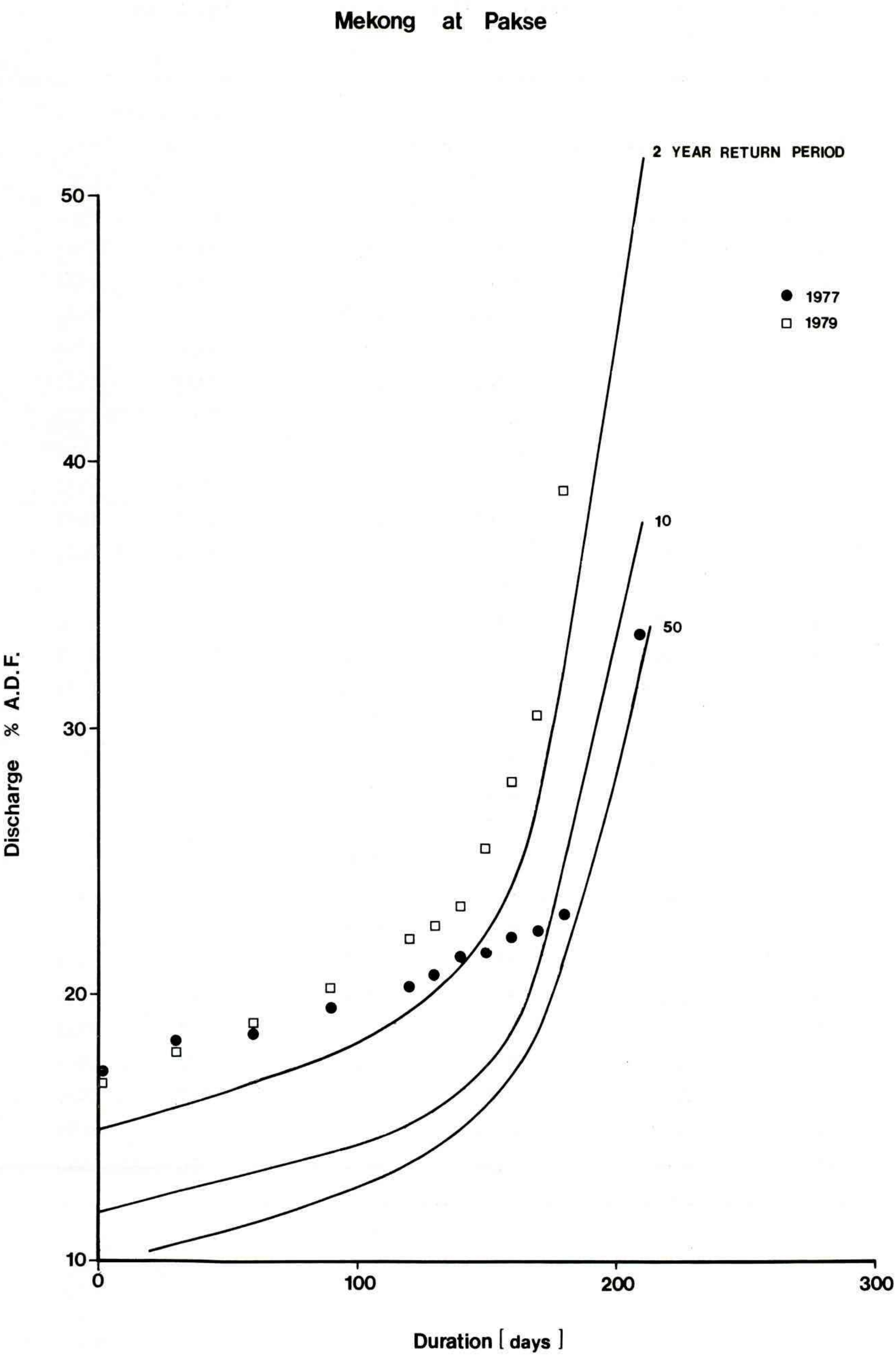

Mekong at Pakse
2 YEAR RETURN PERIOD
10
50
1977
1979
Discharge % A.D.F.
50
40
30
20
10
0
100
200
300
Duration [days]

Figure 12

Analysis of short-term records

In the previous section we have examined long-term rainfall and mainstream flow records; it now remains to study the short-term data that exist for individual catchments in the northeast of Thailand. Here the main land use developments include the degradation of natural forest and transfer of the cleared land to agriculture, and the construction of large irrigation schemes. Such developments have been widespread over most of the region and it would be surprising if their effects were not reflected in changes in the hydrological regimes of the catchments thus cleared.

Flow records

The scope of our work on the tributary basins has been limited by the ready availability of data. In the Mun-Chi Basin of northeast Thailand daily flow records were available on punched cards for the Nam Mun at Rasi Salai and the Nam Chi at Yasothon. On the other smaller catchments our analyses were initially based on the monthly data provided by the Secretariat.

The flow in the Nam Chi has been regulated by reservoirs upstream since 1966 when the dam at Nam Pong came into operation; the dam at Lam Pao was completed shortly afterwards in 1968. The effect of river regulation is shown clearly in the flow duration curves for the Nam Chi at Yasothon (Figure 13); here the high flows have been reduced marginally, but proportionally the increase in low flows is more apparent. The combined volume of the reservoirs upstream of Rasi Salai on the Nam Mun (435 million m^3) is much smaller than the combined volume of the Nam Pong and Lam Pao reservoirs (2,910 million m^3). Consequently the effect of upstream regulation on the flow duration curve for the Nam Mun at Rasi Salai shown in Figure 14 is less apparent.

The effects of upstream regulation are also well illustrated by the mean monthly flows for the periods before and after 1967. The statistics of monthly flows for the Nam Chi at Yasothon, and the Nam

Nam Chi at Yasotl n: Flow duration curve

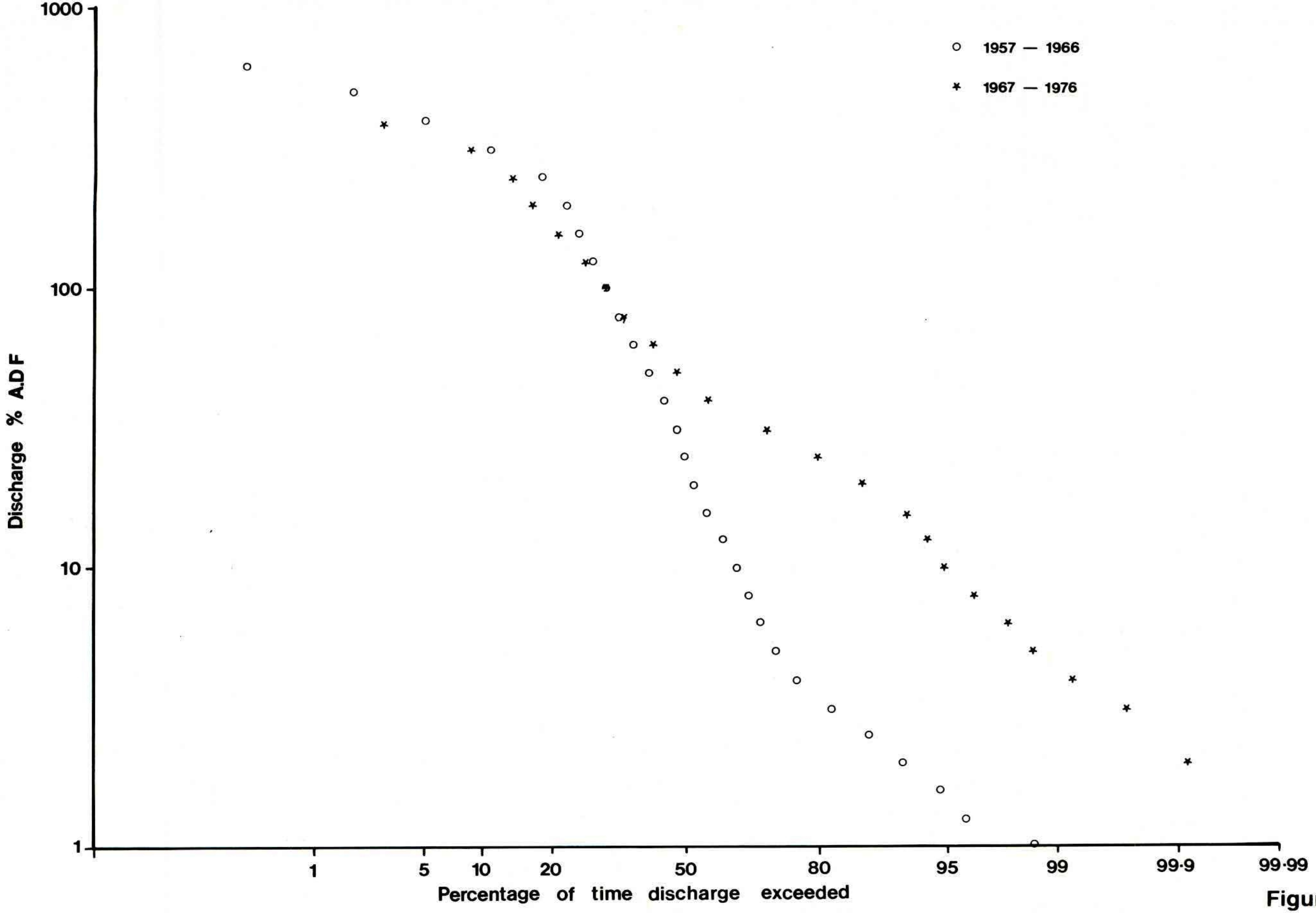


Figure 13

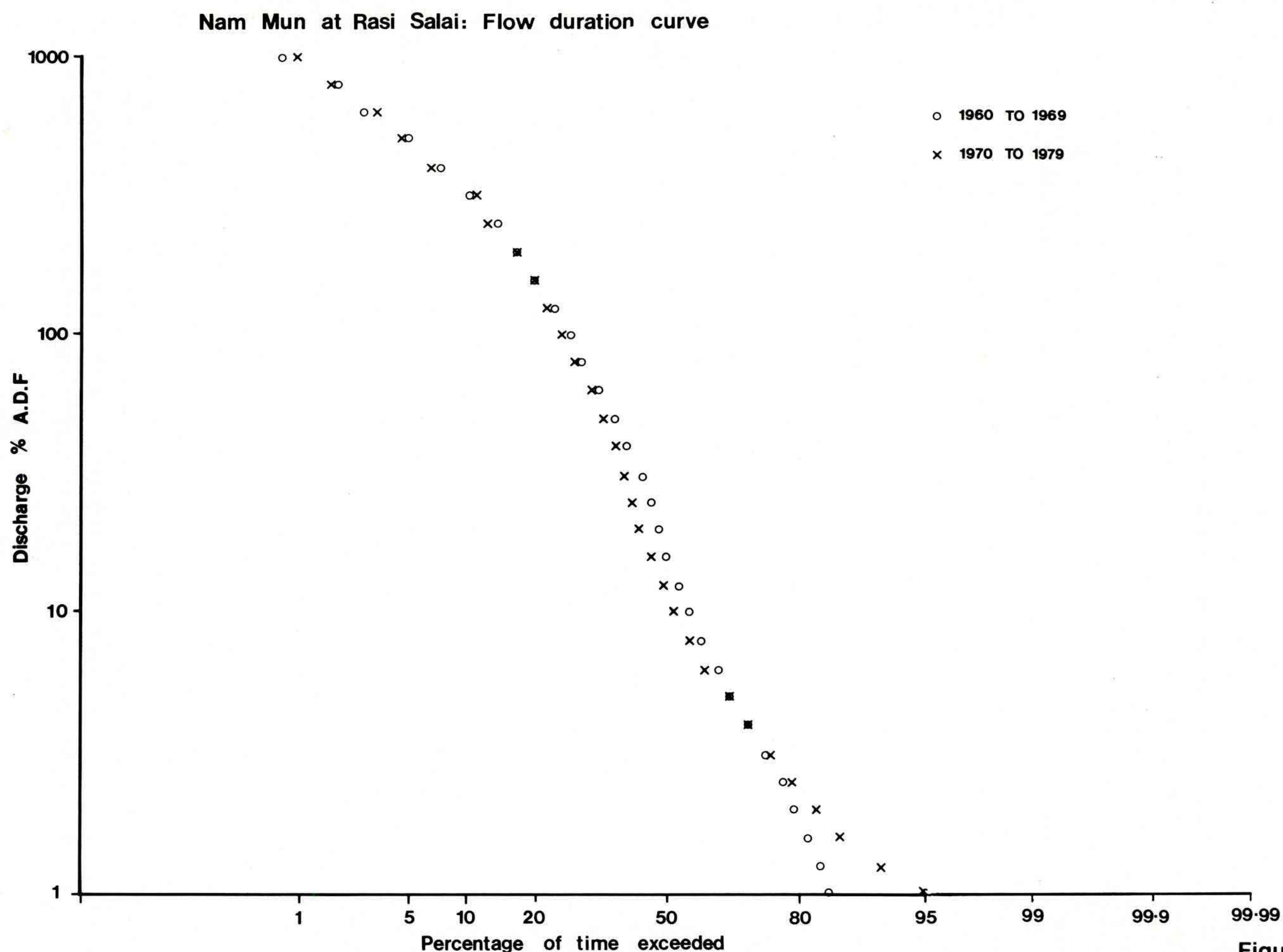

Nam Mun at Rasi Salai: Flow duration curve
1000
100
10
1
Discharge % A.D.F
1
5
10
20
50
80
95
99
99·9
99·99
Percentage of time exceeded
o 1960 TO 1969
x 1970 TO 1979

Figure 14

Mun at Rasi Salai and Ubon are given in Table 8. The distribution of monthly flows for the Nam Chi at Yasothon and the Nam Mun at Rasi Salai are shown in Figures 15 and 16 respectively. Since 1967 at Yasothon there is a marked increase in flow from December to March, and a decrease from September to November. This decrease, about 14 per cent of the mean annual flow, is some 1000 million m^3 and can therefore be accounted for by storage of flood flows at Nam Pong which are subsequently released for hydropower during the dry season.

Rainfall-runoff relationships

On the tributary basins where only monthly data were available, our analysis has centred on examining the basic rainfall-runoff relationship and the relationship between rainfall and catchment losses. The results from just two basins are given here as examples.

The basic rainfall-runoff relationship for the Lam Se Bai at Phawaphutanon Bridge is shown in Figure 17; catchment rainfall has been calculated as the arithmetic mean of the records from two raingauges. There are few outliers in the data, and there is no indication that the early part of the record is any different from the later part. A graph of catchment losses or the implied evaporation is given in Figure 18; here the relationship between losses and rainfall is reasonably consistent, the losses ranging from 850 mm to 1200 mm.

The second example is the Huai Samran at Sisaket; again rainfall has been calculated as the mean of two records. There is considerable scatter in the points of the rainfall-runoff relationship shown in Figure 19, and Figure 20 implies that the catchment losses range from 750 mm to over 1400 mm.

These results, and similar results from other basins, indicate that the general rainfall-runoff relationships show no obvious change with time. The values of implied evaporation are reasonable, but in some cases the year to year variability is very high. While the accuracy of runoff measurement is probably lower than that of rainfall measurement at a point, the estimation of areal rainfall is affected strongly by the

TABLE 8. Mun-Chi Basin, Statistics of monthly flows (million m^3)

	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
Nam Chi at Yasothon: 1952 to 1966													
mean	26	106	508	656	1008	1973	2267	1144	170	48	31	28	7965
standard deviation	22	110	418	505	506	544	915	746	131	22	22	26	1799
maximum	81	406	1390	1640	1950	2920	4090	2550	509	104	95	115	11706
minimum	7	14	47	136	284	1020	705	101	34	20	13	11	4834
Nam Chi at Yasothon: 1967 to 1980													
mean	191	271	467	916	1119	1718	1873	802	257	164	152	184	8113
standard deviation	85	122	252	646	554	756	965	618	177	82	63	98	3406
maximum	387	457	1070	1910	2370	3000	4050	2000	715	291	289	444	14907
minimum	42	25	177	163	231	690	500	178	74	58	44	26	3883
Nam Mun at Rasi Salai: 1957 to 1966													
mean	7	58	218	254	467	1624	3164	1424	302	54	17	16	7604
standard deviation	8	113	470	267	426	1120	1122	583	223	28	11	29	2688
maximum	21	371	1540	893	1430	4040	4990	2390	692	106	31	98	11928
minimum	0	3	5	10	35	493	1320	512	99	24	5	2	3278
Nam Mun at Rasi Salai: 1967 to 1980													
mean	9	20	126	473	562	1364	2655	971	239	52	18	11	6502
standard deviation	6	14	165	547	449	672	1713	995	248	32	11	8	3241
maximum	21	50	608	1715	1743	2682	6483	3632	911	118	47	34	12933
minimum	2	6	9	16	73	225	779	106	38	14	5	4	1832
Nam Mun at Ubon: 1951 to 1966													
mean	44	231	852	1352	2431	4337	5469	3458	826	120	60	52	19233
standard deviation	31	340	827	871	1418	1867	2423	1800	738	43	27	28	5356
maximum	135	1420	3530	2670	5410	9200	9500	6120	2790	219	134	138	30171
minimum	14	22	92	272	524	2100	500	569	175	67	32	22	10437
Nam Mun at Ubon: 1967 to 1980													
mean	224	330	798	1915	2678	4426	5115	2461	614	262	203	222	19248
standard deviation	78	120	496	1475	1423	1578	2028	2162	496	93	65	83	6753
maximum	400	549	2200	4670	5810	7210	9910	7070	2030	398	317	435	32109
minimum	103	153	252	322	909	1390	2400	428	176	97	83	114	7882

Nam Chi at Yasothon: Distribution of monthly flows

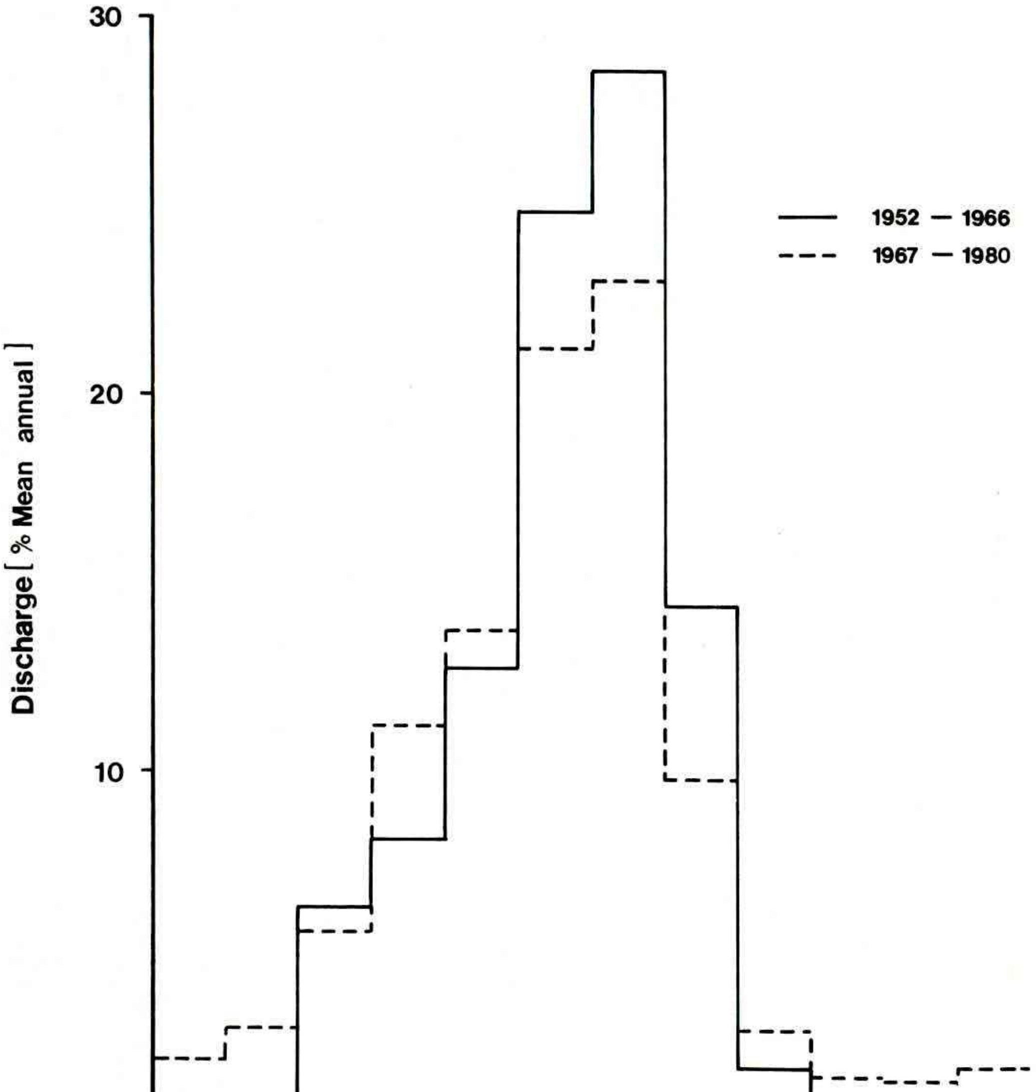


Figure 15

Nam Mun at Rasi Salai: Distribution of monthly flows

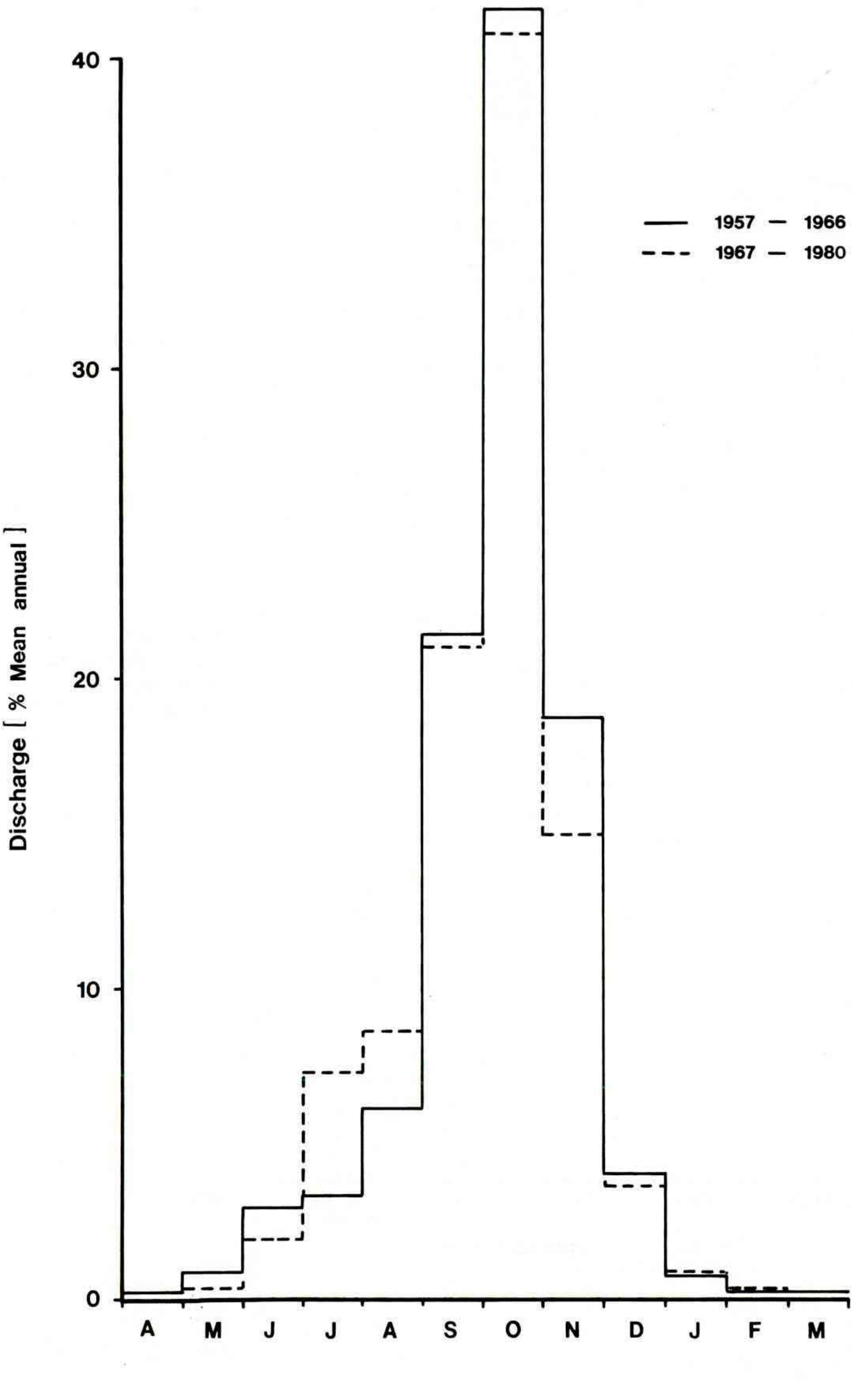


Figure 16

Lam Se Bai: Rainfall Runoff relationship

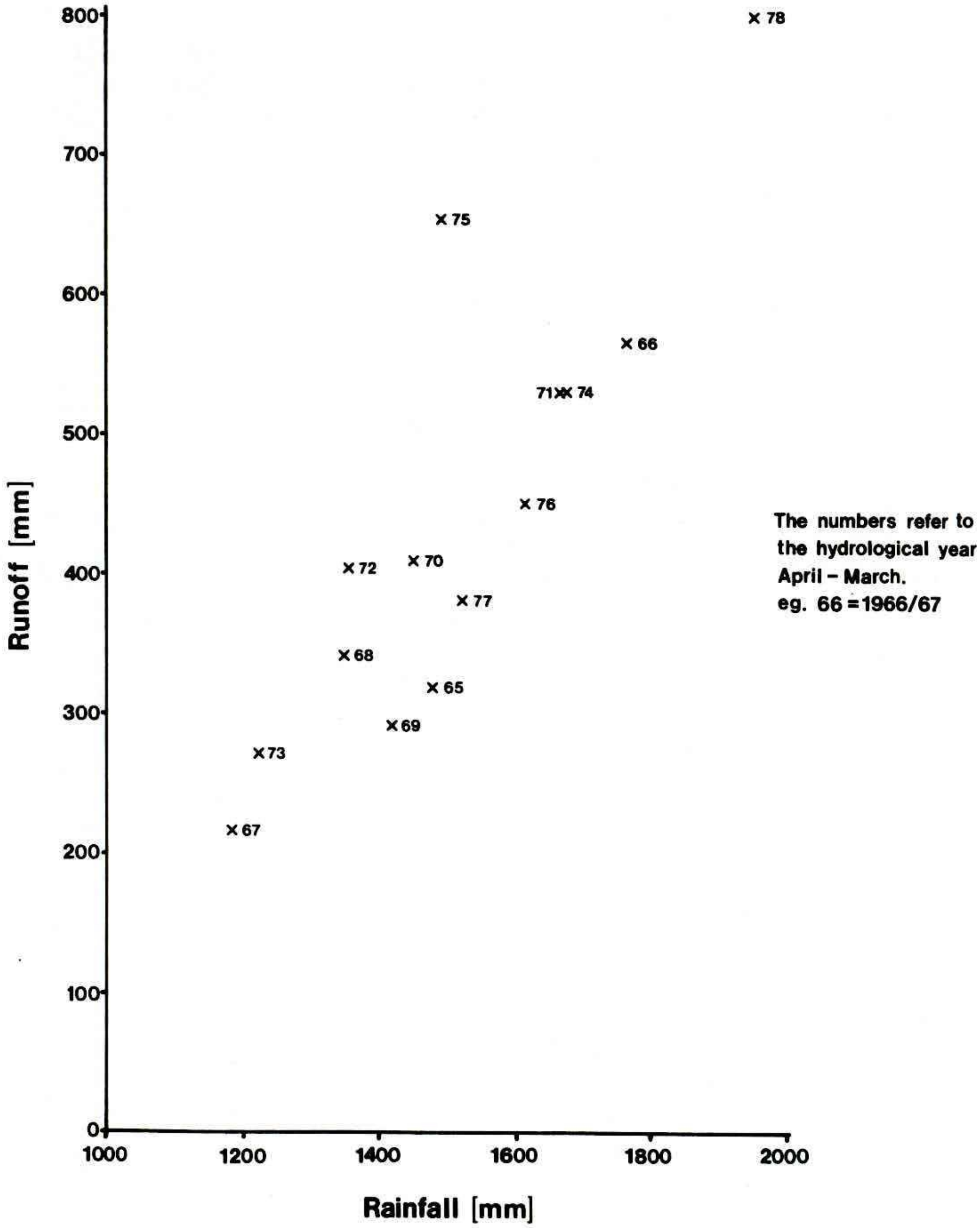


Figure 17

Lam Se Bai: Implied losses
(Rainfall - Runoff)

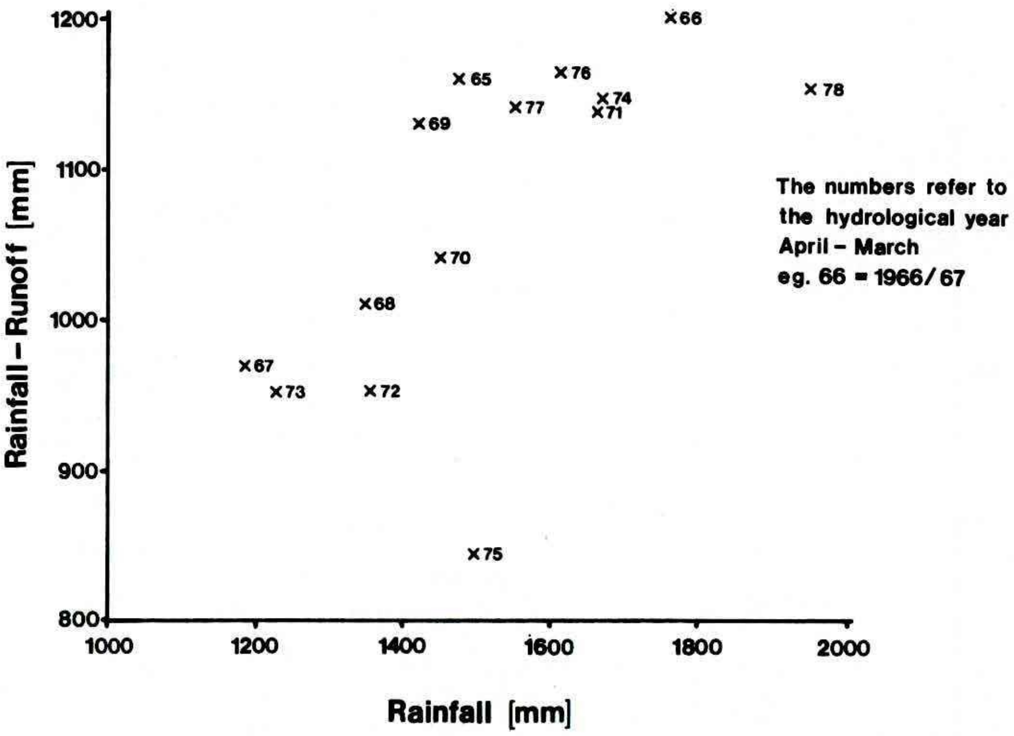


Figure 18

Huai Samran: Rainfall Runoff relationship

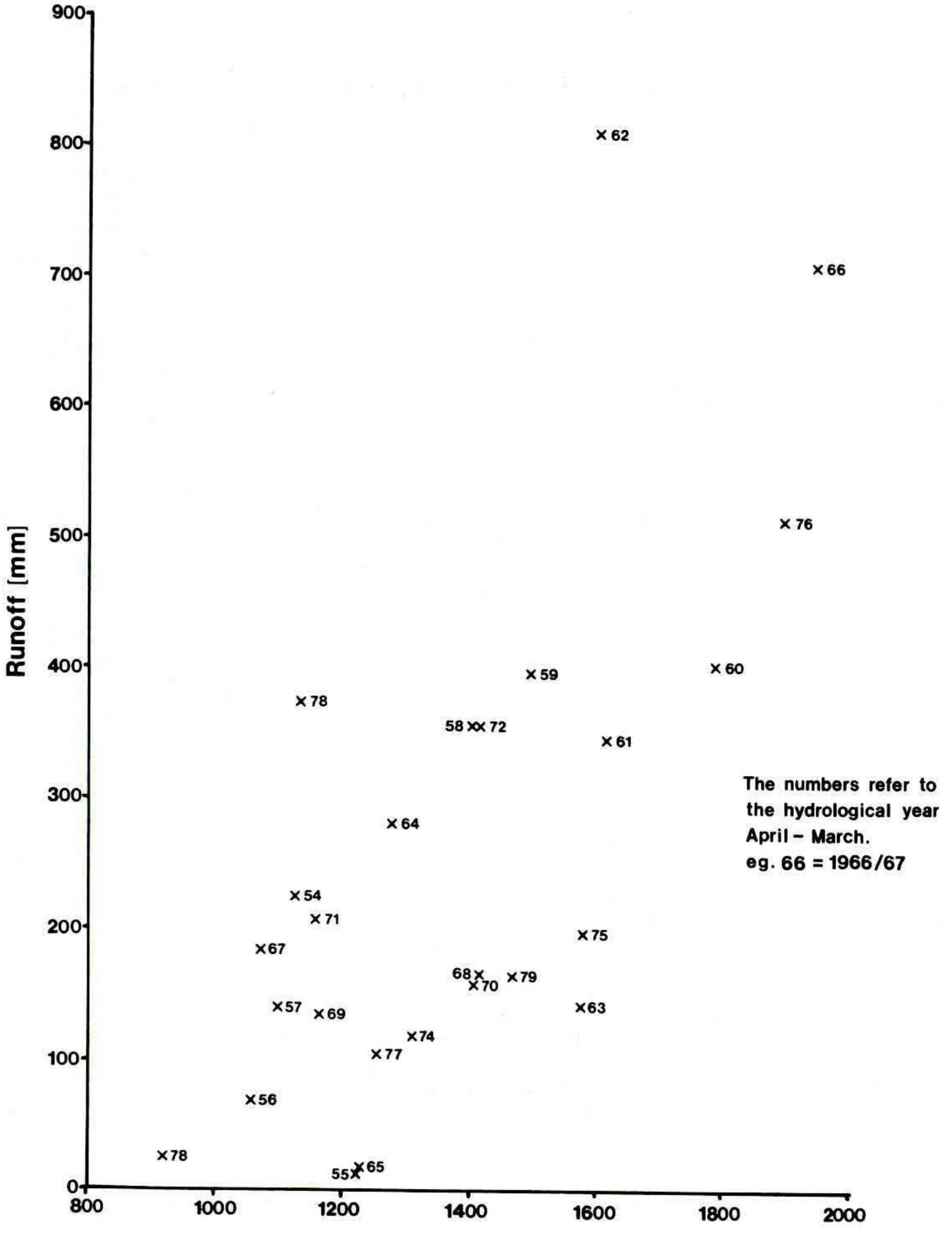


Figure 19

Huai Samram: Implied losses
(Rainfall - Runoff)

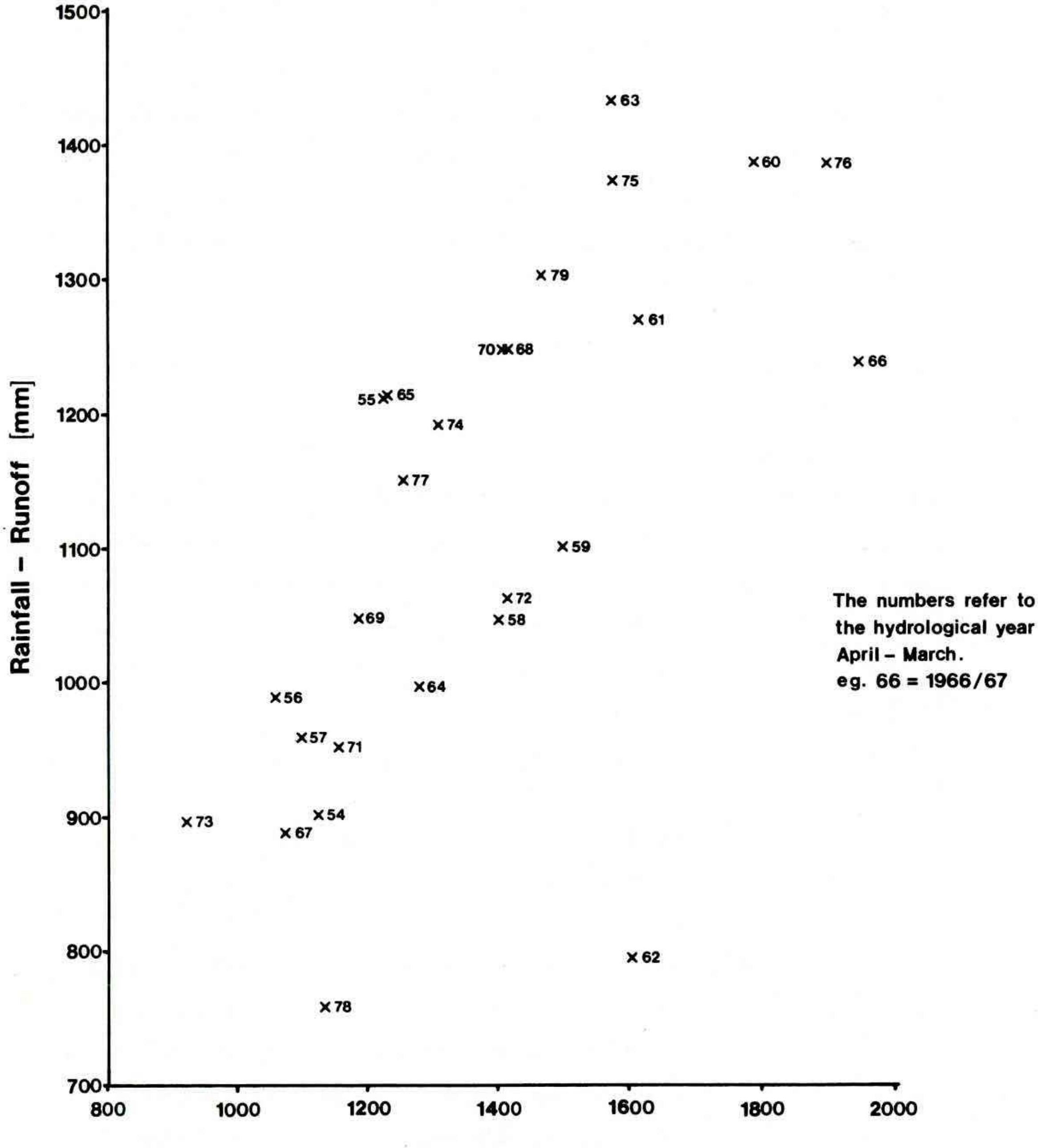


Figure 20

problems of sampling. Rainfall exhibits poor areal coherence in NE Thailand and records from many gauges are needed to ensure accurate areal estimates. We can reasonably infer that it is poor estimation of areal rainfall from the sparse raingauge network that causes this scatter in the rainfall-runoff relationship and the variability in the implied catchment losses.

The low flow measures and the rainfall-runoff relationships discussed above reveal no strong evidence to suggest that changes in runoff regime have occurred other than from river regulation by storage reservoirs upstream. The next approach attempted centred on a study of evaporation and crop water use.

Evaporation and crop water use

For much of the wet season in northeast Thailand rainfall exceeds potential evaporation, so once any residual soil moisture deficit from the dry season has been made up by the early rains, transpiration generally proceeds at the potential rate. There will be periods of consecutive dry days which will cause some moisture stress and a reduction in transpiration, but for this general discussion they can be disregarded. The main difference between the water use of different vegetation types will then occur during the dry season.

The soils of northeast Thailand are poor with low moisture-holding capacities; consequently we would expect all the soil moisture stored at the end of the wet season to have been abstracted by the end of the dry season, whatever the local vegetation. Groundwater levels are quite near the ground surface even at the end of the dry season so it is likely that the deep rooted trees of the virgin and disturbed forest, and crops such as sugar cane, will be able to abstract groundwater at any time during the year. Sugar cane in particular is susceptible to drought, but in many areas we observed healthy unirrigated crops during the dry season amongst otherwise parched vegetation, which suggested that this deep rooted crop is able to use groundwater.

Cassava, an increasingly widespread crop in the region, has a thin open canopy and is well adapted to surviving long periods of drought. Its water use is likely to be low, but no detailed work on its soil water relations has been carried out to confirm this. Other upland crops such as kenaf or maize do not survive the dry season without irrigation, and it is doubtful that their roots reach the water table. Transpiration of these crops during the dry season therefore relies entirely on stored soil moisture.

The total evaporation from a crop has two main components; transpiration from the canopy of the crop itself and evaporation from the soil surface or, in the case of paddy rice, from water standing in the fields. The predominant land use in the Lower Mekong Basin is the unirrigated cropping of rice, and upland crops such as cassava, kenaf and sugar cane. A knowledge of the water use of these crops is fundamental to the understanding of the hydrology of both the areas of unirrigated agriculture, and the much smaller areas where irrigation is practiced. The rate at which water is used by a particular crop is in general dependent on climate; however a number of other factors which include age, variety, soil, pest or weed infestation and cultivation practices, are also important. Consequently the water use of a crop will vary from region to region and often from field to field.

The standard method of estimating crop water use is to calculate reference crop evapotranspiration (potential evaporation) from climatological data and then to relate this reference value to the crop in question by means of a crop factor (Doorenbos and Pruitt, 1977). If the relevant crop factors and areas planted to specific crops are known then in principle it should be possible to determine reasonable estimates of the net loss of water due to evapotranspiration; any changes in these losses over time as a direct result of land use changes could then be calculated.

This method is widely used, but for it to work well the crop factors should be determined by local experiments. In the Lower Mekong Basin few experimental studies of crop water use have been carried out, and locally derived crop factors are unavailable except for irrigated rice. An additional obstacle to this method of estimating changes in evapotranspiration from a catchment was the problem of obtaining reliable estimates of the areas planted to individual crops; see Annex IV for a detailed description of our study of land use changes. As a result of this work we concluded that a realistic assessment of land use and cropped areas was impossible given the often conflicting sources of data presently available. It was therefore impossible to estimate changes in evapotranspiration due to different land uses and this approach was abandoned.

Consumptive use of irrigated crops

Since the mid 1960s seven major reservoirs have been constructed in northeast Thailand wholly or partly for the provision of irrigation water. Table 9 gives brief details of the schemes and the areas that could potentially be irrigated once these projects are fully implemented and operational. It has been extremely difficult to obtain reliable statistics on the actual operation of these schemes, and it is generally thought that attempts to introduce irrigated agriculture into the region have proved disappointing (KKU-Ford, 1981); the report also estimates that of the potentially irrigable area less than one third is actually irrigated in the wet season and less than 5 per cent in the dry season.

Even if reliable statistics on cropped areas in the irrigation schemes did exist, it would be extremely difficult to estimate crop water use directly. The lack of control structures and the poor state of some of the canals means that more water may be lost in conveyance and in flooding fallow land than would be lost by evapotranspiration from the crops. Moreover it appears that irrigation issues are not recorded regularly.

The overall water use in pumped irrigation schemes is impossible to determine without detailed surveys at individual sites of pump ratings, pumping schedules and returns of irrigation water to the river.

None of the conventional methods of estimating the net loss of water from a catchment by evaporation was successful. Consequently we

TABLE 9. Irrigable areas from existing large reservoirs in northeast Thailand

Reservoir	Effective storage (million m^3)	Irrigable area (ha)
Nam Pong	1650	47000
Lam Pao	1260	48600
Lam Dom Noi	900	24000
Lam Nam Oon	475	29728
Lam Takhong	290	19700
Lam Phra Plerng	145	9100
Huai Luang	113	12800
Total	4833	190928

Source: AIT, 1978b

then used a recently developed method in an attempt to estimate actual evaporation regionally.

Estimates of actual evaporation

In the past it has not been possible to estimate actual evaporation other than by difference from a water balance or experimentally by very sophisticated micro-meteorological instrumentation at a particular site. Recent advances in understanding of the physics of the evaporation process have produced a method which, at least in theory, allows actual evaporation to be estimated from meteorological data without the use of empirically derived factors. The Brutsaert and Stricker method (B & S) and its application to this study is discussed in more detail in Annex III.

In this project the B & S method has been used with the meteorological data from most of the synoptic stations in northeast Thailand (Meteorological Department, 1961 et seq.); the locations of the stations used are shown in Figure 21. These stations give reasonably good geographical coverage of the region, but they are generally situated in the middle of towns and not in agricultural areas where most of the evapotranspiration is taking place. The regional validity of evaporation estimates for agricultural land using these data therefore needs to be assessed by field experiment.

Many of these meteorological stations were visited during field visits. The standard of maintenance of the instruments, the records, and the stations themselves appeared to be high. However, it has proved to be extremely difficult to derive good estimates of incoming radiation from the data currently available. Few sites are equipped with instruments for measuring radiation, and at these sites the radiation data appear to be unreliable. Consequently the Angstrom equation had to be used to estimate radiation from sunshine hours. Sunshine hours are measured at most of the meteorological stations, but it is only at Khon Kaen that a relatively long continuous record is available. At other stations only cloud amount data are published, so an empirical relationship between sunshine hours and cloud amount had to be derived.

Location of met. sites

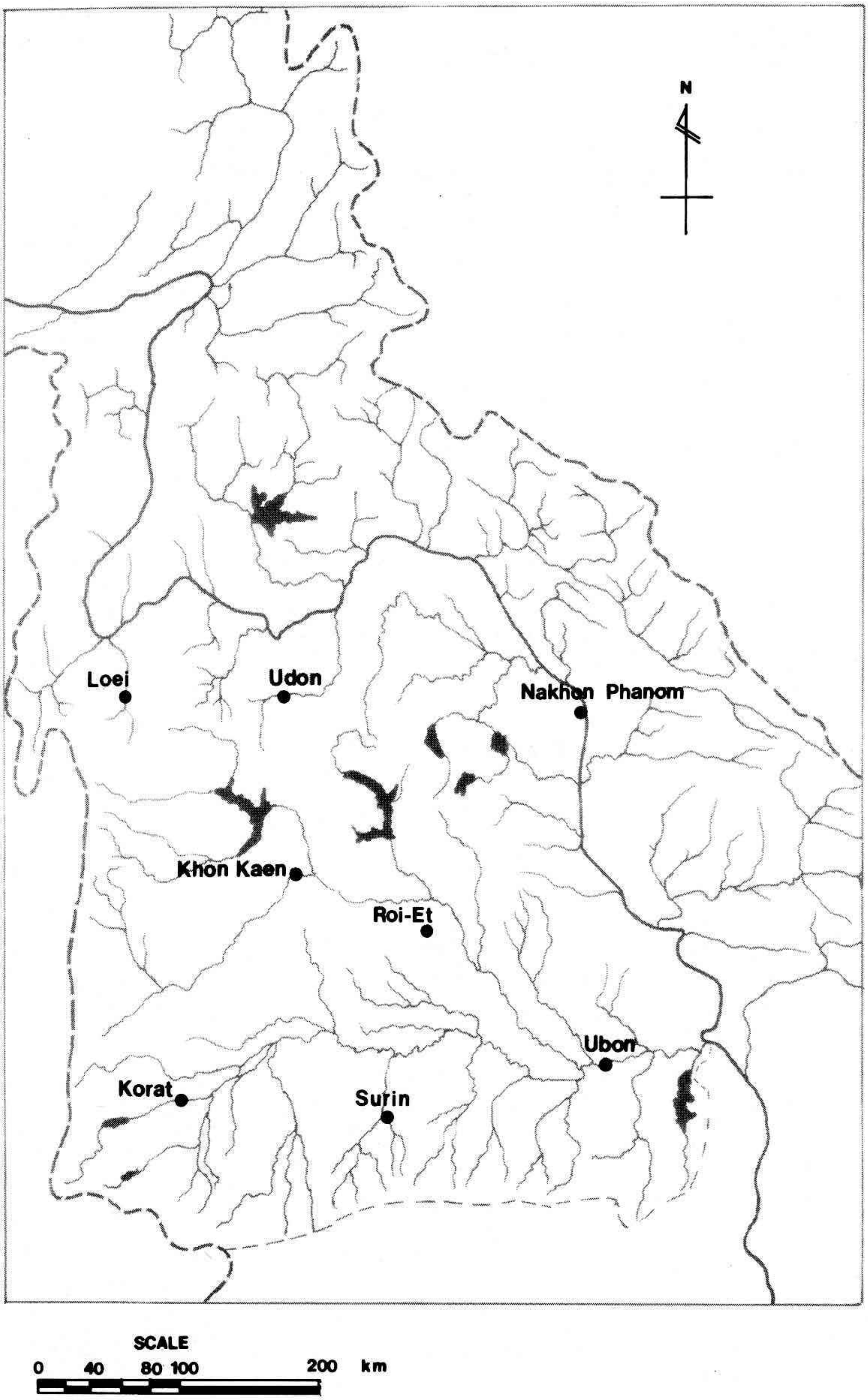
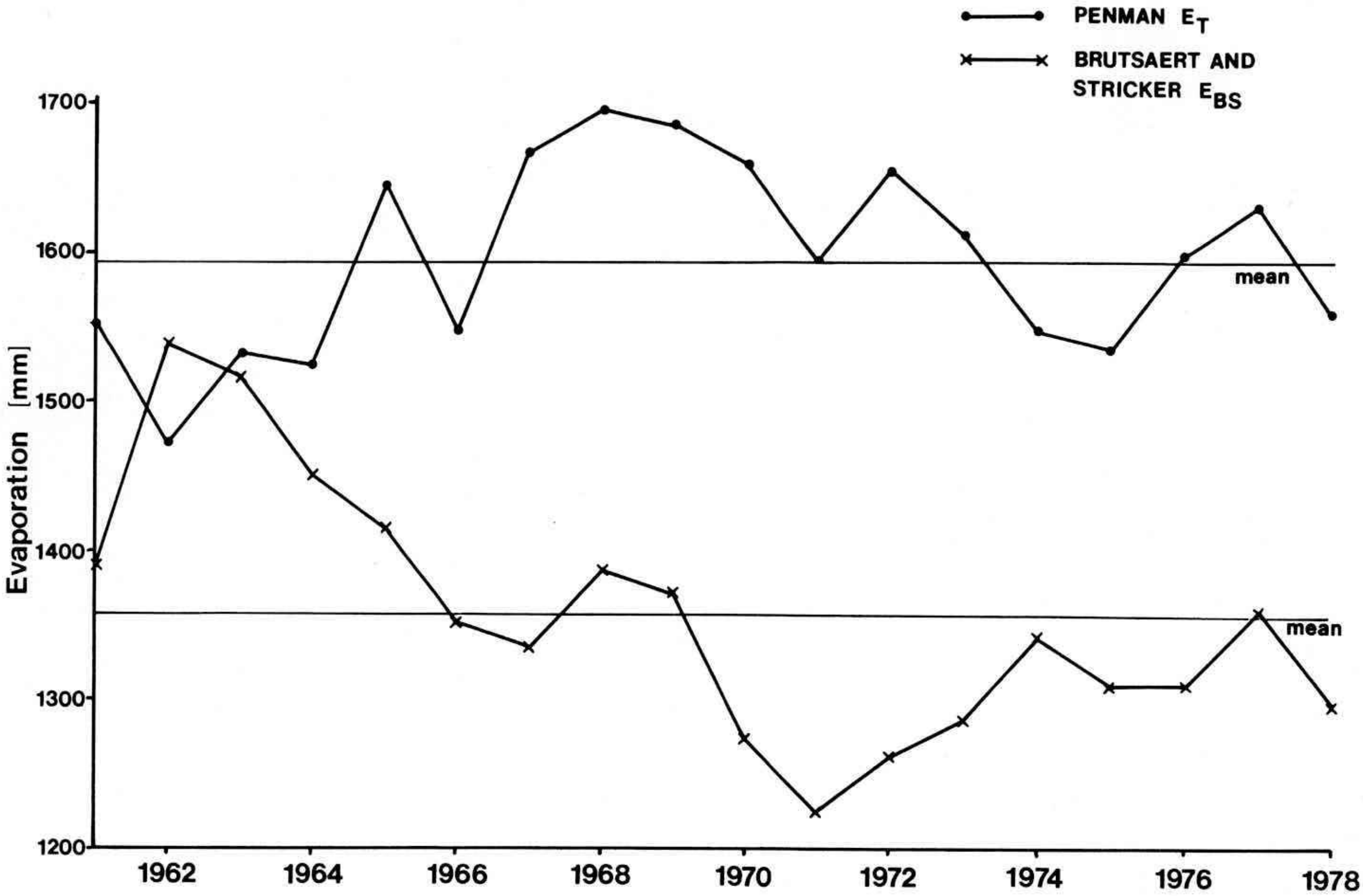


Figure 21

Evaporation at Khon Kaen



Evaporation at Surin

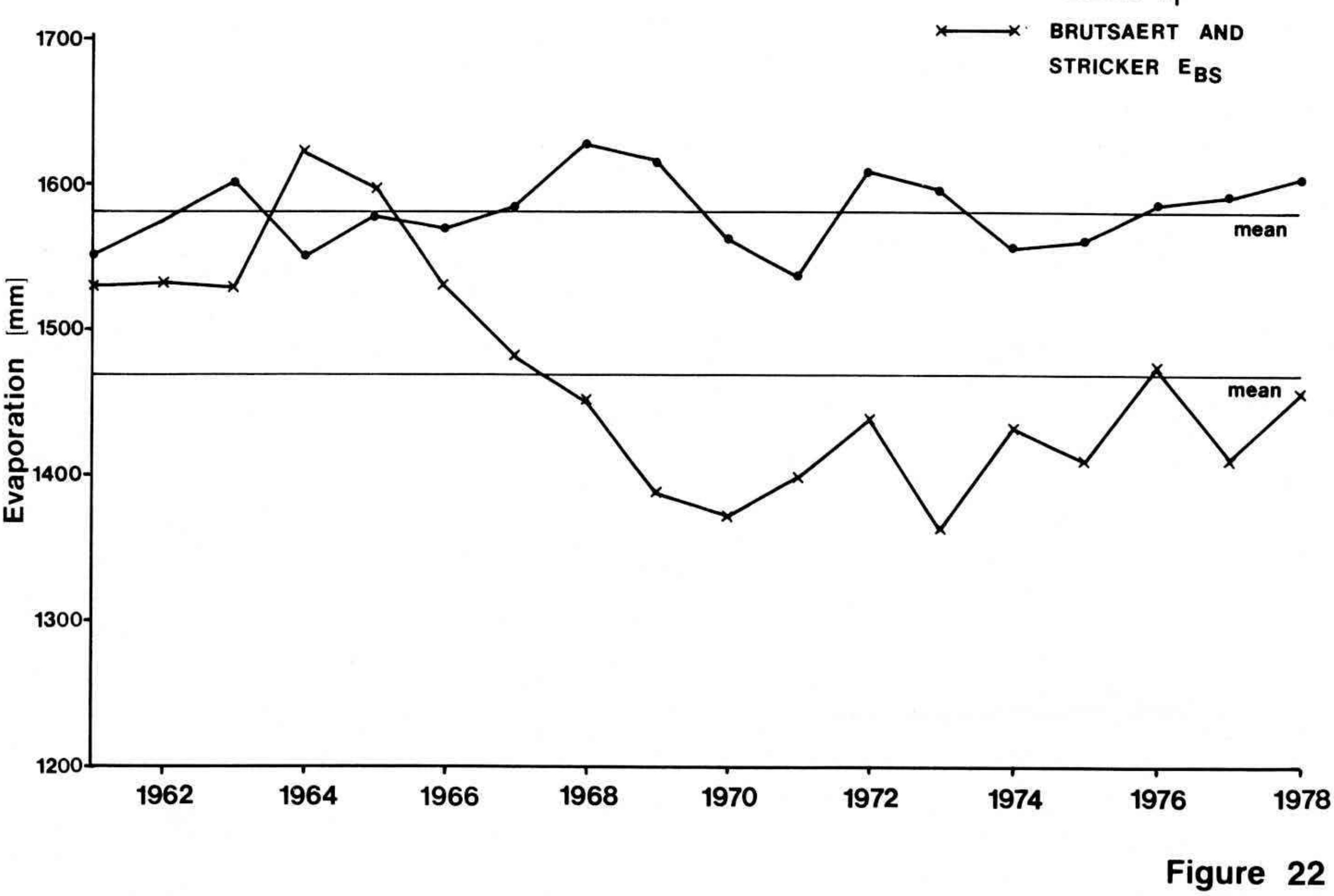


Figure 22

Potential evaporation and actual evaporation (calculated using the B & S equation) were estimated from these data for the period from 1960 to 1978. The results suggested that in some areas there have been some significant changes in actual evaporation over the period. Figure 22 shows the variations in annual evaporation at Khon Kaen and Surin which have been chosen as examples.

At both sites the main feature is the fall in actual evaporation (E_{BS}) during the 1960's; at Surin the decrease is less pronounced than at Khon Kaen.

In Figure 23 the mean monthly actual evaporation for two periods (1961-64 and 1974-77) are plotted and indicate some interesting differences between the results for each site. At Khon Kaen for example reductions in evaporation have taken place in the early part of the wet season and most of the dry season. At Surin the decrease has occurred during the wet season and the beginning of the dry season.

There is no obvious explanation for these dry season results which are a little surprising, particularly for Khon Kaen; here there has been an increase in dry season irrigated cropping within the Nong Wai irrigation scheme and we would have expected to see actual evaporation in the dry season increase. The dry season results at the two sites might themselves be inconsistent because radiation for Khon Kaen was estimated using sunshine hours whereas for Surin it was estimated from cloud amount data.

There are three possible explanations for the decrease in wet season evaporation; firstly, the interception of rainfall by forests is higher than by upland crops. Secondly, as some crops are only planted at or immediately before the beginning of the wet season they do not make use of the early season rainfall. Thirdly, the albedo is lower for forests than for upland crops as a result the potential evaporation of forests is higher than for crops and if water is not limited actual evaporation is correspondingly higher.

The main conclusion to be reached from the discussion above is that given present understanding of the soil-crop-water relations in

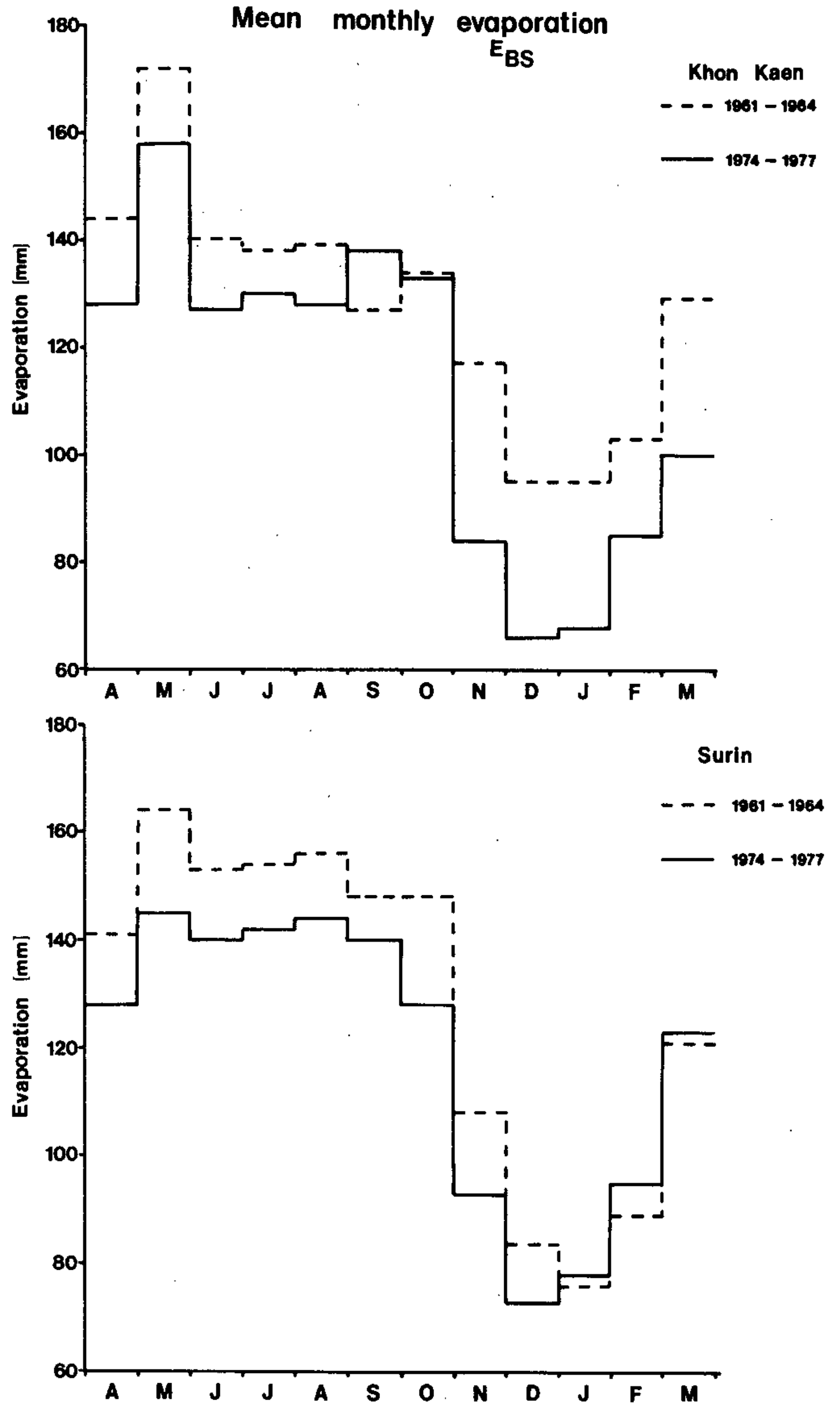

Mean monthly evaporation
E_{BS}
Khon Kaen
1961 – 1964
1974 – 1977
Evaporation [mm]
180
160
140
120
100
80
60
A M J J A S O N D J F M
Surin
1961 – 1964
1974 – 1977
Evaporation [mm]
180
160
140
120
100
80
60
A M J J A S O N D J F M

Figure 23

northeast Thailand, it is impossible to estimate actual evaporation from various crops accurately enough to determine whether any differences exist between them. The results of the Brutsaert and Stricker method for calculating actual evaporation has also proved inconclusive; at this stage it is not possible to say whether this is due to shortcomings in the method, or to inadequacies in the basic hydrometeorological data themselves.

4. WATER BALANCES

Changes in the land use of a catchment such as widespread deforestation, the extension of bunded field agriculture or changes in crops and cropping patterns might result in a change in actual evaporation with a corresponding change in runoff. A water balance analysis attempts to quantify the relationships between rainfall, runoff and catchment losses. These losses represent the evaporation from vegetation, and the direct evaporation from standing or flowing water. Thus any changes over time in the loss component might indicate that changes in actual evaporation had occurred as a direct result of changes in land use.

The Brutsaert and Stricker method has been used in Chapter 3 to analyse the available climatological data for northeast Thailand. Taken at face value one implication of the results is that there has been a modest 20 per cent decrease in actual evaporation; this would have resulted in an increase in runoff of the order of 100 per cent. The available streamflow records do not demonstrate any evidence of such an increase; and these estimates of actual evaporation must be regarded with some scepticism.

The simple rainfall-runoff relationships also discussed in Chapter 3 showed no obvious change with time. The values of catchment losses, or implied actual evaporation were reasonable, but in some of the catchments studied the year to year variability was very high. If we assume that the runoff estimates are reasonably accurate, then there are strong reasons to believe that in some years the estimates of catchment rainfall were particularly poor.

The next step was to calculate a water balance on a shorter time interval to see how the seasonal distribution of rainfall affects catchment storage and hence runoff.

Trial water balance analysis

The first trial water balance used pentad, or 5-day, data for the Lam Chi at Ban Kho Kho (Figure 24). The three years 1967, 1974 and 1976 were chosen to represent years of average, low and high runoff.

Location of water balance catchments

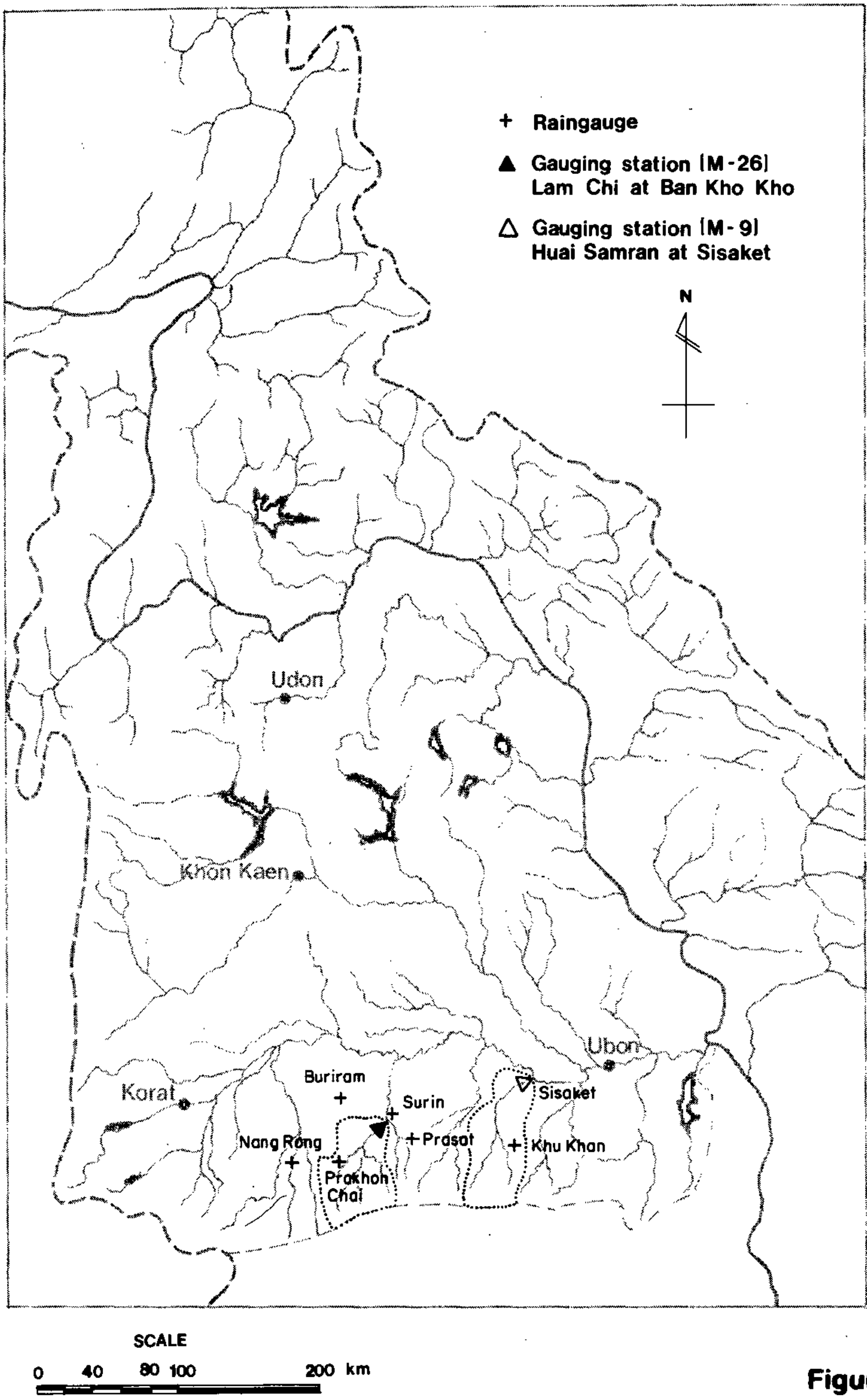


Figure 24

Initially rainfall data from Surin only was used; the evaporation data were based on the Penman potential evaporation data for Khon Kaen for the relevant years. In Figure 25 the build up of rainfall and runoff from the start of the hydrological year (April) is shown. The graph shows broad consistency between the pattern and quantity of rainfall and runoff, but it is surprising that 1967, which had the same rainfall total as 1974, should have produced so much more runoff. The extra rainfall at the end of the wet season in 1976 is clearly able to produce substantially more runoff than in the other years.

As might be expected these results confirm that the catchment rainfall is not sufficiently well estimated by a single gauge. In an attempt to improve the rainfall estimate, a regional approach using the arithmetic mean of the records for Surin, Prasat Surin, Buriram, Prakhon Chai and Nang Rong was adopted. Due to problems in obtaining daily records for calculating pentad rainfall, the following analysis was based on monthly data.

For the three selected years the monthly average rainfall, its standard deviation and relationship with Surin rainfall were calculated. In this case the standard deviation is a measure of the spatial sampling error associated with the use of a single gauge to estimate mean areal rainfall; a summary of the results is given in Table 10, and the revised estimate of cumulative areal rainfall is shown in Figure 26.

The 5 station average rainfall now looks more consistent with the pattern of runoff shown in Figure 25 than the Surin rainfall alone. There is a clear distinction between the rainfall totals for 1967 and 1974; the 1976 rainfall is now not so high in view of the more modest difference between the runoff in 1967 and 1976. The rainfall growth curves also seem to be concave upwards for most of the wet season so that rainfall exceeds potential evaporation only towards the end of the season thereby delaying the start of significant runoff until September or even October.

Lam Chi: Cumulative rainfall and runoff

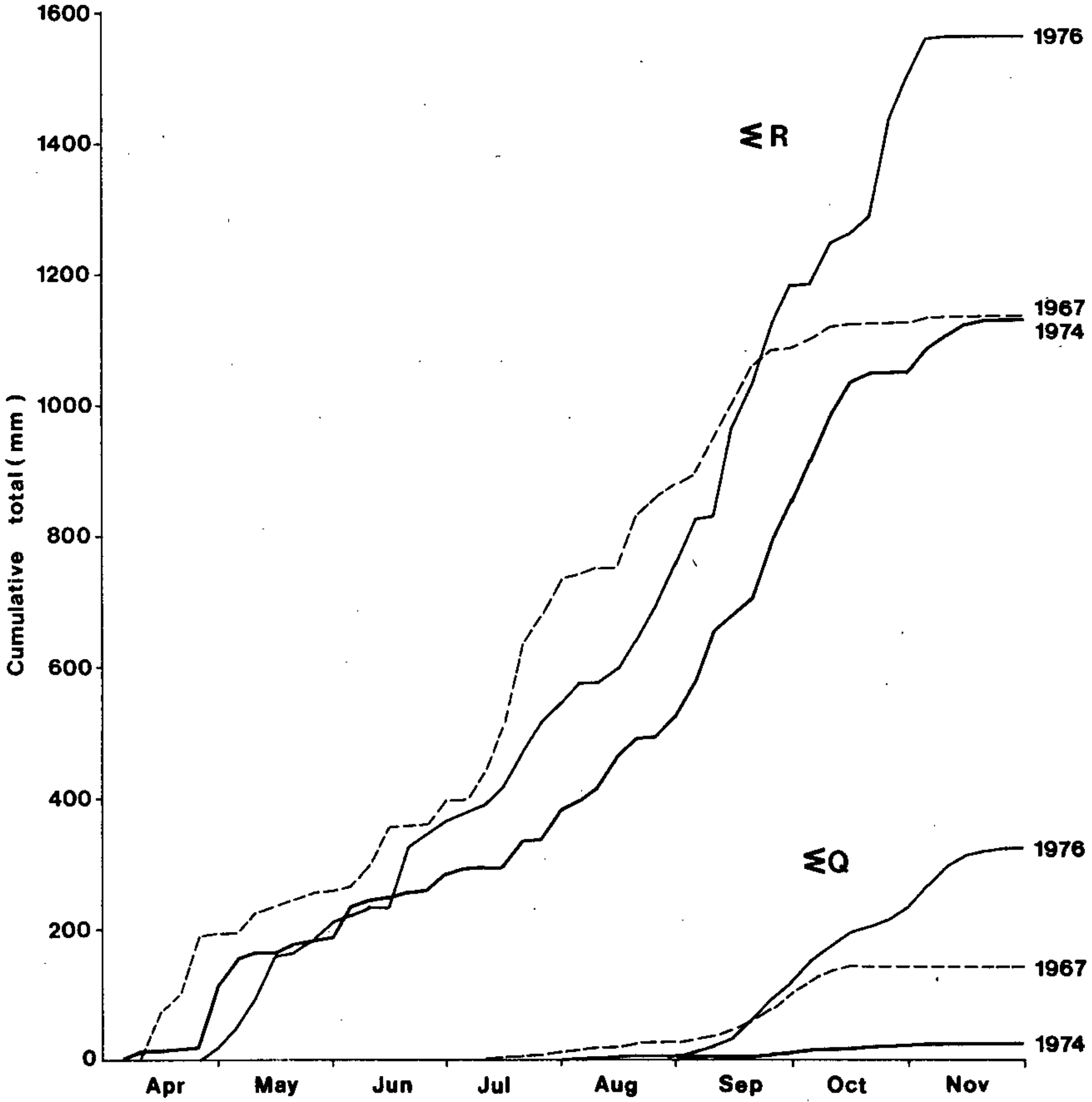


Figure 25

TABLE 10. Estimation of catchment rainfall (mm)

Station	Apr	May	June	July	Aug	Sep	Oct	Nov	Total (Apr-Nov)
1967									
Surin	192	60	137	343	144	213	36	9	1134
Prasat	131	81	150	364	153	218	12	21	1130
Buriram	130	146	15	79	125	438	67	60	1060
Prakhon Chi	121	171	242	138	141	293	112	0	1218
Nang Rong	122	155	79	210	146	315	118	34	1179
Average	139	123	125	227	142	295	69	25	1144
SD	30	49	85	125	10	92	46	23	59
Surin/Average	1.38	0.49	1.10	1.51	1.01	0.72	0.52	0.36	0.99
1974									
Surin	113	75	93	98	149	326	197	57	1108
Prasat	39	145	91	175	136	164	124	87	961
Buriram	137	38	99	117	143	80	88	57	759
Prakhon Chai	72	62	99	275	105	218	100	109	1040
Nang Rong	69	142	149	195	83	175	138	88	1039
Average	86	92	106	172	123	193	129	80	981
SD	39	48	24	70	28	90	42	22	135
Surin/Average	1.31	0.82	0.88	0.57	1.21	1.69	1.53	0.71	1.13
1976									
Surin	23	187	153	177	213	428	319	60	1560
Prasat	96	184	144	190	276	381	322	12	1605
Buriram	24	104	108	257	184	301	128	0	1106
Prakhon Chai	68	214	242	221	125	283	309	6	1468
Nang Rong	48	123	163	124	163	263	307	28	1219
Average	52	162	162	194	192	331	277	21	1392
SD	31	47	49	50	57	70	83	24	219
Surin/Average	0.44	1.15	0.94	0.91	1.11	1.29	1.15	2.86	1.12

Lam Chi: Comparison of cumulative rainfall

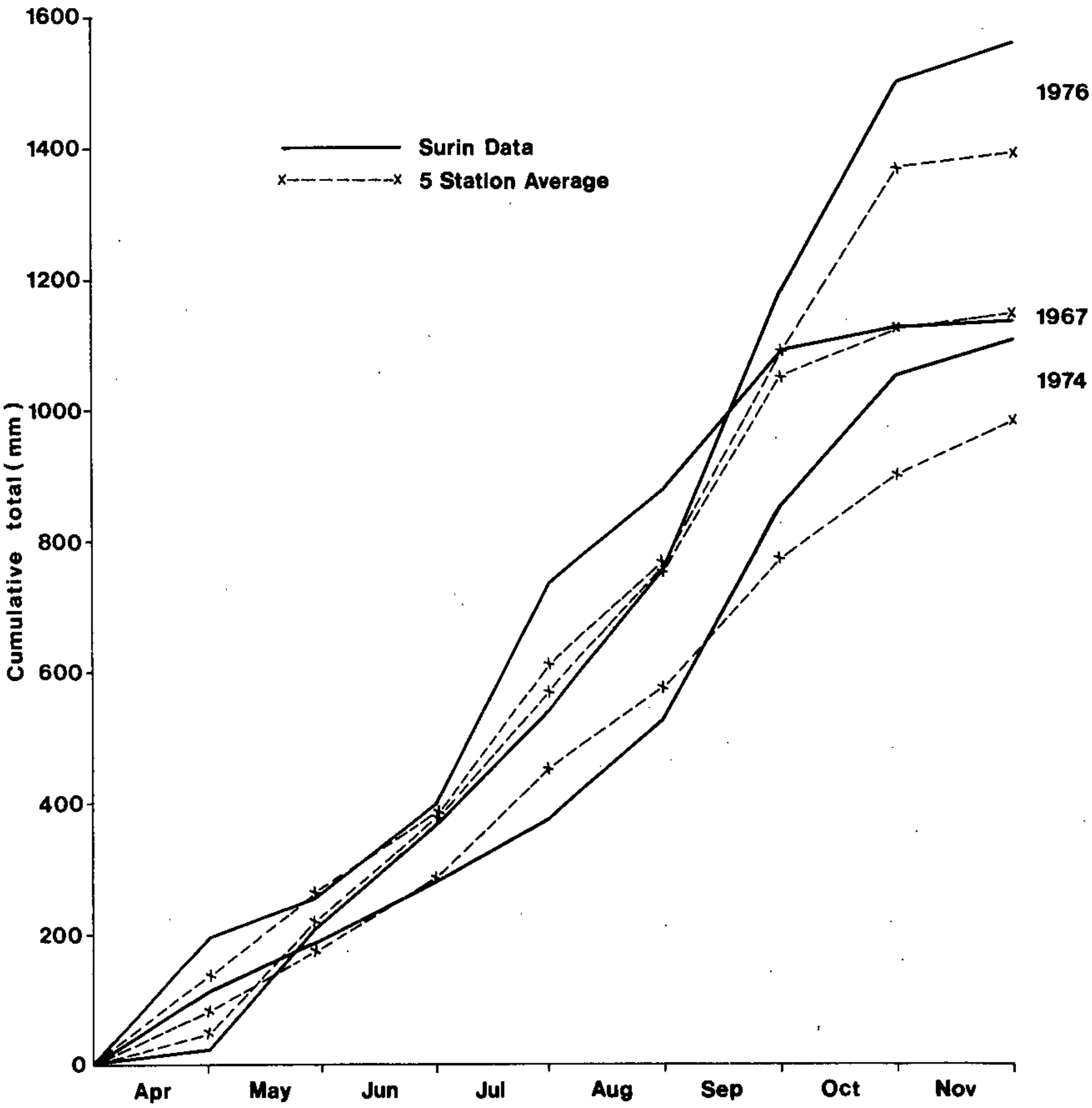


Figure 26

Water balance modelling of the Huai Samran

The choice of river basin for the next step in the water balance analysis was influenced by the need for a relatively long flow record and the easy availability of daily rainfall data for a number of gauges. The basin chosen was the Huai Samran above Sisaket which has a record from 1954 to date; the location of the catchment and nearby raingauges is shown in Figure 24.

The analysis was carried out on a 5-day or pentad time interval, a subjective compromise between using either monthly or daily data. The monthly time interval is too long and the accurate estimation of areal rainfall becomes increasingly difficult as the duration of the data decreases.

The raingauge at Sisaket and Khu Khan lie within the catchment boundary; Surin and Ubon are the nearest other gauges for which daily data are readily available. Daily records at Sisaket, Surin and Ubon are held on tape at the Mekong Secretariat; however only monthly data for Khu Khan were available.

The pentad rainfall on the catchment was calculated as the arithmetic mean of the pentad rainfalls at Sisaket, Surin and Ubon. To reduce bias in this mean, a weighting factor (W_i) for each year i was derived from the annual data as:

$$W_i = \frac{(\text{Sisaket} + \text{Khu Khan})}{(\text{Sisaket} + \text{Surin} + \text{Ubon})} \times \frac{3}{2}$$

The mean value of the weighting factors, W is 0.95 with a standard deviation of 0.10; this suggests that the estimate of annual areal rainfall could be biased by more than 10 per cent in 1 year out of every 3 on average.

A simple computer programme for the water balance was written which calculates the cumulative totals of rainfall (R), runoff (Q) and catchment losses (R-Q). Once R exceeds the potential evaporation (E_t), ΣE_t is also calculated. The storage in pentad i is given by:

$$S_i = S_{i-1} + R_i - Q_i - E_{t_i}$$

and if any S_i becomes negative it is set to zero.

A graph of ΣR, ΣQ, and ΣE_t (for $S > 0$) for the years of high runoff in 1962 and 1976 is given as Figure 27. Note that the higher rainfall in 1976 should have produced more runoff (or 1962 less), and that this either illustrates severe bias in the rainfall estimate or an illustration of change in land use.

Some of the key variables from the water balance are summarised in Table 11. All the measures of storage show a wide variation, and the storage (S) approaches zero in several years when runoff has not yet ceased. In other years when the end of November storage is high runoff had already ceased. The relationship between rainfall and runoff on an annual basis is poor, and there is little suggestion of a systematic or consistent response from the catchment. But we have seen that a small error in the estimation of areal rainfall would upset the balance markedly, and we can conclude that this is happening.

As there is no other relevant information on rainfall, any attempt to improve the rainfall estimate must use information contained in the runoff record. Two sets of derived weighting factors were estimated which ensure that for each year:

(1) the maximum storage is ≈ 350 mm W_1.

(2) the end of November storage is ≈ 150 mm, W_2.

These limits, whose values were chosen subjectively, can be considered as general measures of the physical characteristics of the catchment. The first limit represents the surface and soil storage, and the second the storage available to vegetation for evapotranspiration once seepage to ground and surface water ceases.

The adjusted weighting factors are shown in Table 12; these factors taken simply as a time-series appear little different to the original series in terms of mean and standard deviation. This suggests a large random component in the estimation of rainfall

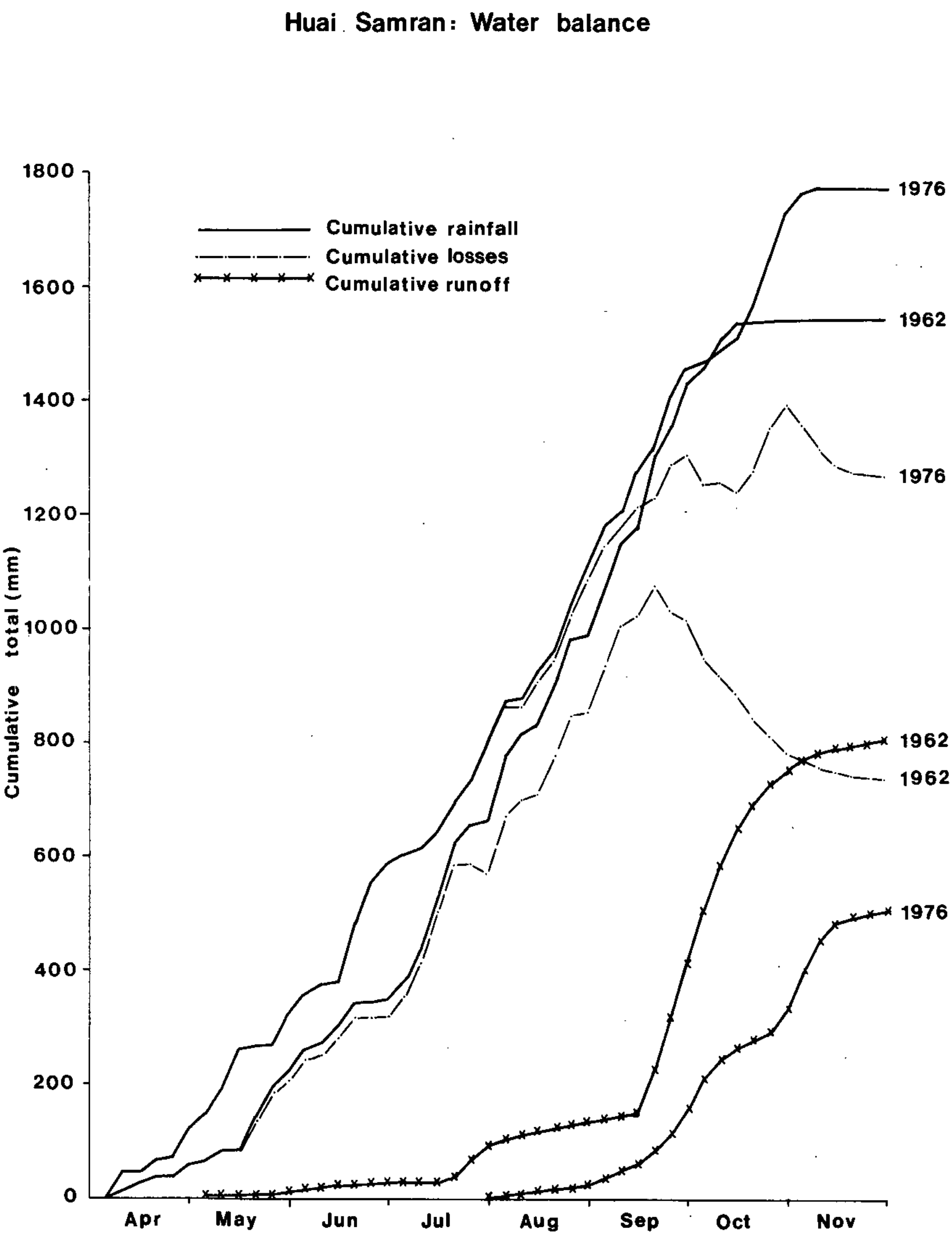

Huai Samran: Water balance
Cumulative rainfall
Cumulative losses
Cumulative runoff
Cumulative total (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
1976
1962
1976
1962
1962
1976

Figure 27

Huai Samran: Rainfall weighting factors

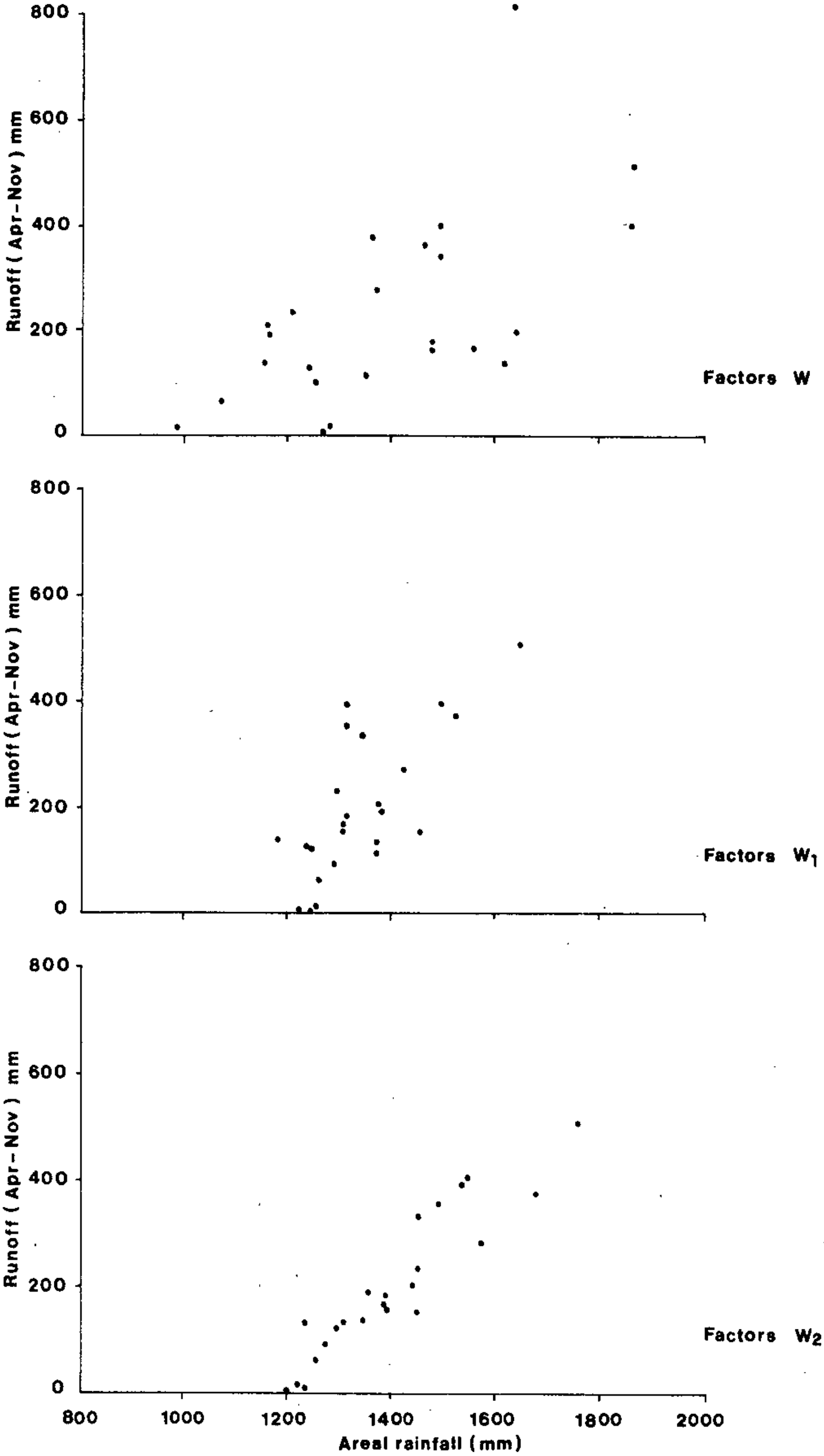


Figure 28

TABLE 11. Pentad water balance for the Huai Samran at Sisaket (mm)

Year	April to November ΣQ	ΣR	S_{start}	S_{max}	S_{end}	Q_{max} (pentad value)
1954	230	1107	217	296	0	41
1955	9	1173	299	367	222	2
1956	66	973	96	187	0	7
1957	137	1053	245	311	75	30
1958	357	1368	377	472	126	44
1959	395	1399	149	347	114	54
1960	398	1763	93/543	864	469	74
1961						
1962	803	1541	97	418	0	93
1963	139	1524	266	580	435	18
1964	273	1254	197	292	0	36
1965	13	1184	375	375	193	2
1966	713	1923	335/611	801	212	105
1967	183	1067	159	268	0	28
1968	159	1381	160	380	178	30
1969	128	1144	259/302	355	109	32
1970	168	1385	305	489	234	53
1971	205	1069	66	167	0	18
1972	336	1397	132	492	192	26
1973	18	888	141	157	0	4
1974	114	1257	142	340	157	18
1975	191	1548	169	585	430	21
1976	504	1772	236	525	254	67
1977	97	1151	51	315	129	14
1978	371	1262	81	238	0	90
1979	159	1467	170	612	317	22
Mean	247	1322		409	154	
Std dev	202	259		180	148	

Note: (1) in 1960, 1966 and 1969 there were two periods in which runoff occurred

(2) incomplete runoff records were available for 1961.

(3) S_{start}: storage when runoff starts

S_{max} : maximum storage

S_{end} : end of November storage

TABLE 12. Rainfall weighting factors for the Huai Samran at Sisaket

Year	Original Factor W	W_1: for S_{max} = 350	W_2: for S_{end} = 150
1954	.98	1.06	1.20
1955	.96	.94	.90
1956	.81	.97	.95
1957	.86	.89	.93
1958	.97	.86	.99
1959	1.02	1.02	1.05
1960	1.16	.80	.95
1961			
1962	.94	.88	1.15
1963	1.10	.92	.88
1964	.91	.96	1.07
1965	.93	.91	.89
1966	.96	.69	.93
1967	.91	1.04	1.10
1968	1.00	.98	.98
1969	.89	.89	.93
1970	.87	.76	.81
1971	.81	.97	1.02
1972	.92	.82	.89
1973	.81	1.03	1.00
1974	.92	.93	.91
1975	1.06	.88	.86
1976	1.13	.99	1.06
1977	1.03	1.07	1.05
1978	.78	.88	.96
1979	1.00	.82	.88
Mean	.95	.92	.97
Std dev	.10	.10	.10

weights as one might expect from few gauges over a large area subject to local intense storms. In some years the factors calculated by each of the three methods are consistent; in other years marked differences are apparent. Moreover there is no obvious relationship to suggest that the factors are larger for years in which runoff is high.

In Figure 28 the rainfall calculated using each set of factors is plotted against runoff. The correlation between the original series is poor; using the series, W_1, the correlation is better, but the slope of the line is unacceptably high which indicates that either runoff is forced to ensure that the storage does not exceed 350 mm or rainfall is reduced excessively to achieve the same effect.

Only the correlation using W_2 is satisfactory, but this is not surprising. Wet season evaporation varies relatively little from year to year as rainfall generally exceeds potential evaporation; actual evaporation therefore proceeds at the potential rate. Fixing the end of November storage effectively fixes the dry season evaporation; the total evaporation is therefore fixed and a linear relationship between rainfall and runoff results.

Table 13 summarises some of the main features of the revised balance using factors W_2. In years when runoff is high S_{max} is generally higher than in other years and illustrates that a component of storage, attributable to channel routing, becomes increasingly important. There is also an indication that the time at which runoff starts and the corresponding storage seem to be related; when runoff starts early in the wet season the total storage is lower than usual. This suggests an upper 'surface' or 'retention' storage which fills first and allows runoff to occur before a lower 'soil' storage is fully replenished. When the start of runoff occurs only later in the wet season it can be assumed that both storages are already full.

This concept of a two-part storage is supported by field observations on catchments in northeast Thailand as well as some soil water profiles measured as part of the Tung Kula Ronghai Project (McGowan International, 1981). These profiles for soils in the Nam Mun catchment around Rasi Salai showed that the soil becomes saturated

TABLE 13. Huai Samran - revised pentad balance using W_2 (mm)

Year	ΣR	ΣQ	Start of runoff SA	Start of runoff Pentad	SA_{max}	S_{end}	S > 0 continuously from
1954	1356	230	409	4 Sep	473	138	5 May
55	1100	9	-	-	307	158	6 May
56	1141	66	324	4 Sep	332	155	3 May
57	1138	137	352	1 Oct	376	143	4 Jun
58	1396	357	472	4 Sep	496	153	4 May
59	1441	395	258	3 Aug	369	148	5 May
60	1444	398	415	5 Sep	565	157	3 May
61							
62	1885	803	272	4 Jul	682	150	4 May
63	1219	139	317	2 Sep	324	157	5 May
64	1474	273	422	4 Sep	469	141	3 Apr
65	1133	13	-	-	334	148	4 May
66	1863	713	363	6 May	750	155	1 May
67	1290	183	328	2 Sep	401	155	3 Jun
68	1353	159	325	2 Sep	357	151	3 Apr
69	1195	128	395	5 Sep	395	155	6 May
70	1290	168	365	4 Aug	420	147	3 May
71	1346	205	195	4 Jul	402	151	3 May
72	1352	336	399	2 Sep	452	149	6 May
73	1096	18	-	-	319	156	1 Jun
74	1243	114	265	3 Sep	330	146	3 Jul
75	1256	191	297	3 Sep	326	146	2 May
76	1662	504	246	2 Aug	441	149	6 Apr
77	1173	97	285	2 Sep	331	147	5 May
78	1586	371	207	6 Jul	491	156	3 Apr
79	1291	159	228	6 Jun	441	144	5 Apr

Notes: (1) Start of runoff is defined by the first pentad that runoff exceeds 5 mm.

(2) 4 Sep refers to the 4th pentad in September

(3) SA is the average storage between pentads.

(4) SA_{max} is the maximum storage between periods.

(5) S_{end} is the storage at the end of November.

in September, the month in which runoff often begins. The importance of the surface storage is that unless there has been moderate antecedent rainfall at the beginning of the wet season to completely or partially fill it, exceptionally heavy rainfall of over 100 mm/pentad does not necessarily cause runoff.

The implications of the water balance analysis described above are twofold. Firstly a constant evaporation and soil storage has been imposed on the water balance; we can infer that any physical or land use changes in the catchment which might have influenced the time-series of runoff would have been reflected in a drift in the time-series of rainfall weighting factors. The results in Table 13 show no consistent drift and therefore no indication of a change in response to rainfall. This implies that there has been no change in annual actual evaporation because the soil storage will return to zero at some time each year and there is little evidence to suggest that groundwater storage is an important part of the balance.

The second implication concerns the role of catchment storage. The water balances discussed above used the concept of total storage; however field observations and inferences discussed above suggested that a two-part representation of catchment storage would be more appropriate. The logical extension of the work was therefore to use some form of conceptual modelling.

Simple conceptual model

A simple lumped catchment model was developed that treats the catchment as a homogeneous unit. The model has 3 parameters to control runoff and a maximum of 3 involved in routing; the structure of the model is shown in Figure 29, whose storage parameters are:

SUM : the size of the upper 'surface' storage
SLM : the size of the lower 'soil' storage
FR : a constant maximum infiltration rate between SUM and SLM.

It is assumed that evaporation takes place at the potential rate

Simple model

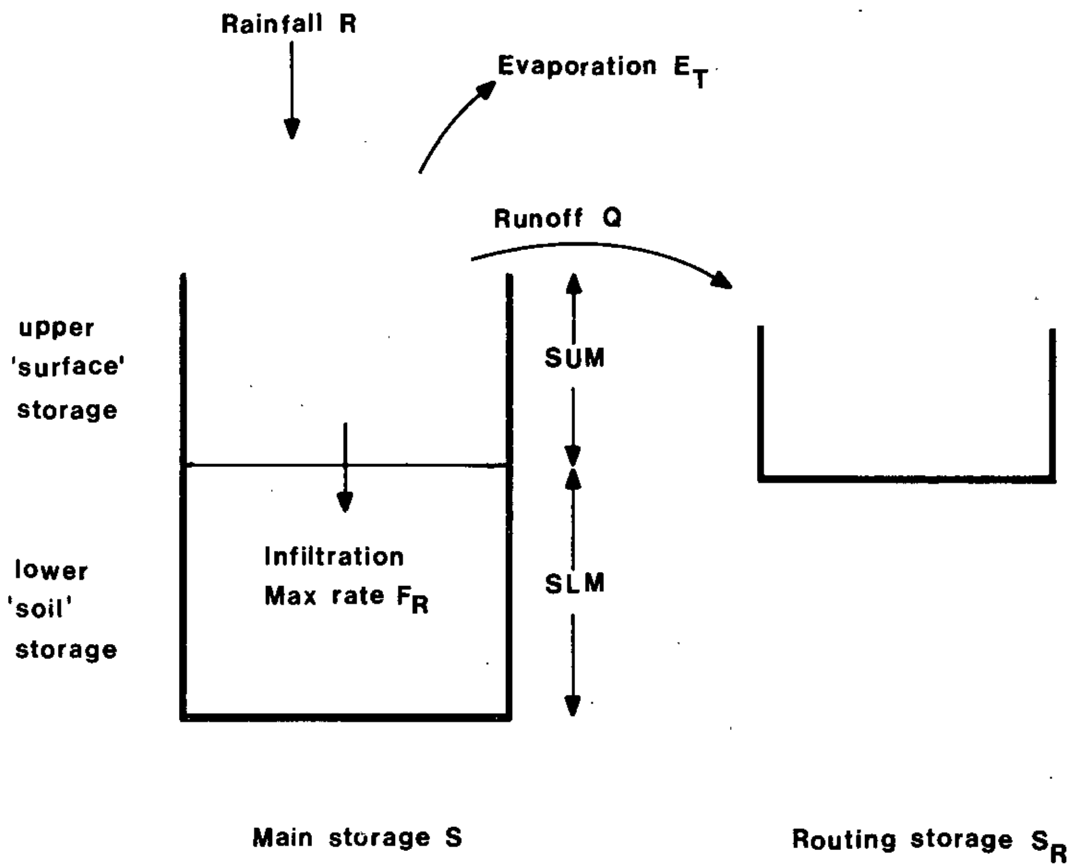


Figure 29

preferentially from rainfall, or either storage; it falls below this rate only when the catchment is completely dry. Once the upper storage is full, runoff is estimated simply as the excess net rainfall and then passed through a routing element.

Two types of routing were tried namely Muskingum and a simple non-linear routing given respectively by:

$$Sr = Pk\ (Px \cdot Inflow + (1 - Px) \cdot Outflow)$$

$$Sr = Pk\ (Inflow)^{1/2}$$

In both cases a third parameter NDEL was also included; this parameter is a linear delay parameter which has the value of an integer number of pentads. Sr is the routing storage component of the total storage calculated in the original water balance.

The simple conceptual model was used on data for the Huai Samran and 3 other basins in northeast Thailand; the locations of the catchments, the gauging stations and the raingauges used in the analysis are given in Figure 30. A summary of the data used is given in Table 14. In the model runs evaporation has been based on a regional estimate; no direct estimates of actual evaporation are available. Also no direct measurements of soil storage or groundwater fluctuations were available for the 4 basins studied.

In the water balance analyses discussed above an unreasonable pattern of rainfall and runoff was revealed (see Table 11); in some years runoff still occurs long after the storage is totally depleted whereas in others there is excessive end of November storage but no runoff. We believe that these inconsistencies arise principally from poor estimates of areal rainfall due in part to the sparse network of raingauges, but also as a result of inaccuracies in the flow and evaporation measurements.

We therefore decided to calculate annual values of rainfall weighting factors (RWF) instead of using the objective estimates based

Location of catchments used for simple model

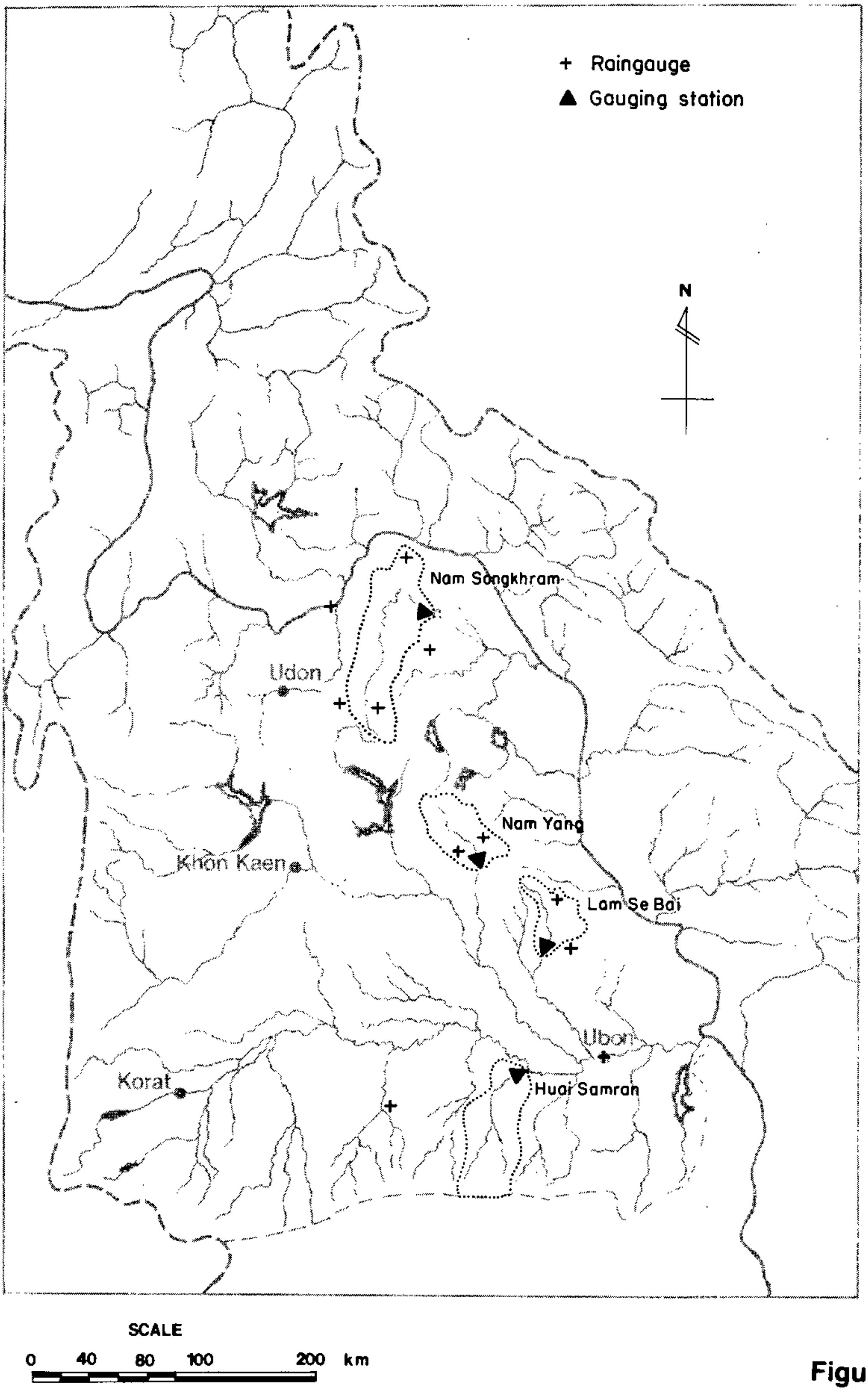


Figure 30

TABLE 14 Data used in simple model

Catchment	Flow Records	Rainfall records		
Huai Samran at Sisaket	1954-79	Surin	1954-79	
		Sisaket	1954-79	
		Ubon	1954-79	
		Khu Khan	1954-79	missing 1960
Lam Se Bai at Phawaphutanon Bridge	1966-80	Amnat Charoen	1966-78	
		Long Nok Tha	1966-80	
Nam Yang at Ban Nong Saeng Thung	1966-80	Khuchinarai	1966-79	
		Phon Thong	1966-80	
Nam Songkhram at Ban Tha Kok Daeng	1965-80+	Phon Phisai	1965-80	
		Nong Han	1965-80	missing some of 1979
		Sawang Daen Din	1965-80	
		Wanon Wiwat	1965-75	
		Bung Kan	1965, 1970-80	
		Ban Tha Kok Daeng	1966-80	

Notes: (1) At Khu Khan only monthly data were available

(2) Flow records for the Nam Songkhram are fom 1965 to 1975; since then they were calculated from river stage using a simple model (NEDECO 1982b)

on the arithmetic mean of the gauges in or near each basin. On the basis of the water balances for the Huai Samran it was decided to choose values of RWF that ensured that the end of November storage was 150 mm. The RWFs thus derived are tabulated in Table 15.

The parameters that generate runoff - SUM, SLM and FR - were fitted by minimising the sum of squares of differences in seasonal runoff; the routing parameters - Px, Pk and NDEL - were fitted by minimising the sum of squares of differences in pentad runoff. When optimising these parameter values, FR was not effective except for the Huai Samran; and then it was the least sensitive of the runoff generating parameters. Of the routing parameters Px was always zero and NDEL was effective only on the Huai Samran. So in most applications the model has only three sensitive parameters. Table 16 gives a summary of the optimum parameter values obtained using the variable RWFs discussed above.

The RWFs were then fixed at the appropriate mean value and then at 1.0 to give comparative results; for the Huai Samran it was found that the parameter values did not shift significantly for the new rainfall inputs.

The values of SUM and SLM appear to be reasonable; the differences between the catchments may not be significant because it has been assumed that the end of November storage should be 150 mm for each basin. If it was, say, 100 mm on one of the catchments, perhaps because rainfall on average ended earlier, then the RWF would be lower and less storage would be needed to delay runoff to the correct time, and thereby constrain it overall. Pk varies, but this is likely to be a result of different physical characteristics such as area, slope and drainage network between the catchments.

There are two main sources of error in the model, namely that it is an imperfect representation of physical reality and that there are errors in the hydrological data. The relative importance of these errors depends to some extent on the objectives of modelling. The values of explained variance in Table 16 indicate that for the prediction of annual runoff the most important factor is to adjust the rainfall.

TABLE 15. Rainfall weighting factors

	Huai Samran	Lam Se Bai	Nam Songkhram	Nam Yang
1954	1.20			
55	0.90			
56	0.95			
57	0.93			
58	0.99			
59	1.05			
1960	0.95			
61	-			
62	1.15			1.11
63	0.88			0.99
64	1.07			0.98
65	0.89		1.27	1.08
66	0.93	1.06	1.10	0.99
67	1.10	1.11	1.60	1.11
68	0.98	1.09	1.04	0.86
69	0.93	1.06	1.49	1.15
1970	0.81	1.07	1.00	0.95
71	1.02	1.00	0.99	0.82
72	0.89	1.32	0.98	-
73	1.00	1.15	1.09	0.98
74	0.91	1.12	1.39	1.37
75	0.86	1.09	1.13	1.02
76	1.06	0.93	1.49	2.29
77	1.05	0.98	1.01	0.94
78	0.96	1.05	1.06	1.00
79	0.88	-	0.99	1.45
1980		1.00	1.05	1.67
Mean	0.97	1.07	1.17	1.15
SD	0.10	0.09	0.21	0.35

TABLE 16. Optimum parameter values

		Huai Samran	Lam Se Bai	Nam Songkhram	Nam Yang
SUM (mm)		150	170	170	180
SLM (mm)		160	170	170	180
FR (mm/pentad)		10	16	8	16
Pk		3.6	1.8	5.8	2.6
Px		0	0	0	0
NDEL		1	0	0	0
Initial variance	annual	978845	315405	998202	165002
	pentad	182039	189949	231780	78608
Unexplained variance					
RWF variable	annual	27133	16180	26022	32809
	pentad	62075	67869	40689	52829
RWF = mean	annual	368106	201239	1388926	1062388
	pentad	81618	76480	85368	121978
RWF = 1	annual	413158	261563	1733821	563634
	pentad	82955	70718	104355	84948
Explained variance (%)					
RWF variable	annual	97	95	97	80
	pentad	66	64	82	33
RWF = mean	annual	62	36	negative	negative
	pentad	55	60	63	negative
RWF = 1	annual	58	17	negative	negative
	pentad	54	63	55	negative

The variability of the annually derived RWFs is high for the Nam Songkhram and the Nam Yang; the results show the benefits of using these variable factors rather than the mean RWF or a factor of 1.0. The implication of these results is that the model need not be very good or sophisticated at all to produce an acceptable annual result, if the rainfall has been fixed in some way. For the pentad statistics it is less easy to achieve acceptable results. Clearly there might be an additional source of error introduced when the true RWF for a given pentad does not coincide with the annually, or seasonally derived factor.

Discussion of modelling results

The main conclusion of the modelling work is that it seems impossible to achieve good prediction of annual or pentad runoff unless catchment rainfall is better known or alternatively adjusted in some way as part of an overall water balance. Thus it is unrealistic to consider that the effects of land use changes or other agricultural developments can be modelled realistically, unless better estimates of catchment rainfall can be made.

One of the criticisms that could be levelled at this simple modelling exercise is that the catchments studied all lie on the eastern part of the Korat plateau (see Figure 30). This bias arises from the criteria used to select catchments for the modelling work; these were that there should be a relatively long period of rainfall and runoff records, there should be at least two raingauges within or near the catchment itself, and there should be no large reservoirs upstream. A large number of catchments were ruled out because of inadequate rainfall data. These included the Nam Loei, the upper reaches of the Nam Chi and the Huai Mong. The main finding of our modelling work, namely that good estimation of catchment rainfall is a key factor in obtaining good rainfall-runoff models and even simple water balances, clearly vindicates our earlier decision to select catchments for further study partly on the basis of rainfall data availability.

Another criticism might be that we have not identified whether or not land use changes have occurred in any of the catchments modelled above. A detailed discussion of the available land use data is given in Annex IV, which identifies the main sources of data as agricultural crop statistics and mapping using aerial photography or remote sensing imagery; it was found that the reliability of both sets of data was suspect.

Of these the crop use statistics were considered to be the least reliable. Also their potential for estimating land use changes in individual catchments is restricted because the statistics are published for the local government administrative units or changwats. It is rare for catchment boundaries to coincide with the administrative boundaries; indeed there are instances when a river marks these boundaries. It was found that there are many catchments which cover two or more changwats; others may occupy only part of a changwat, sharing it with one or more other tributaries for which hydrological data are unavailable. Clearly it would be impossible to use these agricultural statistics directly to estimate what land use changes had occurred in individual catchments.

In 1974-75 the Mekong Secretariat produced a land use map based on interpretation of images from the LANDSAT I (1972-73) satellite. The methods employed made it possible to distinguish the main structural vegetation units of the Lower Mekong Basin, however, it was concluded that "the map cannot pretend to yield an accurate picture of the forest cover of the Basin" (Mekong Secretariat, 1979a).

Subsequently it was hoped that a comparative study of the LANDSAT I and LANDSAT II (1975-76) imagery would make it possible to assess the impact of forest degradation over a three-year period. However it was apparent that considerable differences existed in subjective interpretation of the distinction between areas of dense and degraded forest. Consequently aerial photography taken 1954 was compared with the land use map derived from LANDSAT I data. Over the 20-year period it was found that degradation showed up more clearly and that differences in subjective interpretation were less important, generally being confined to the limits of the forests. This study led to the publication of a map titled "Korat Plateau - Degradation of

Forests between 1954 and 1973" (Mekong Secretariat, 1979a). It was estimated that about 60 per cent of the 1954 forest cover had been degraded by 1973.

Table 17 gives the proportion of each catchment that falls within a given classification. The interesting feature of the Table is that with the exception of the Nam Songkhram a large proportion of each catchment was already in the classification of cultivated land as early as 1954. Most of this land is in lowland regions. In contrast over 50 per cent of the Nam Songkhram is classified as degraded forest,but only about 20 per cent of the catchment was cultivated in 1954.

The Land Development Department (LDD) have also studied the available remote sensing imagery (LDD, 1977 and 1980). Land use maps based on these two sources are shown as Figures 31 and 32. Comparison of the two maps suggests that there had been extensive substitution of forest by upland crops between 1977 and 1980. Much of this deforestation is almost certain to be imaginary because in the earlier map the extent of the forested areas had been interpreted from satellite imagery, whereas the later map used additional information from the Royal Forestry Department. It is therefore likely that much of the area designated as forest in 1977 is really degraded forest or scrubland.

Both methods of estimating land use changes therefore present some serious difficulties so it has not been possible to identify reliably the land use changes in the catchments studied above over the periods for which hydrological data are available.

TABLE 17. Land use classification (%)

Catchment	Forest in 1973	Forest degraded between 1954-73	Cultivated Land in 1954
Huai Samran	13	35	52
Lam Se Bai	25	19	56
Nam Yang	19	41	40
Nam Songkhram	24	55	21

Note: These are rough estimates taken from the map in Section II of Mekong Secretariat, 1979.

1980 Land use map of N.E.Thailand

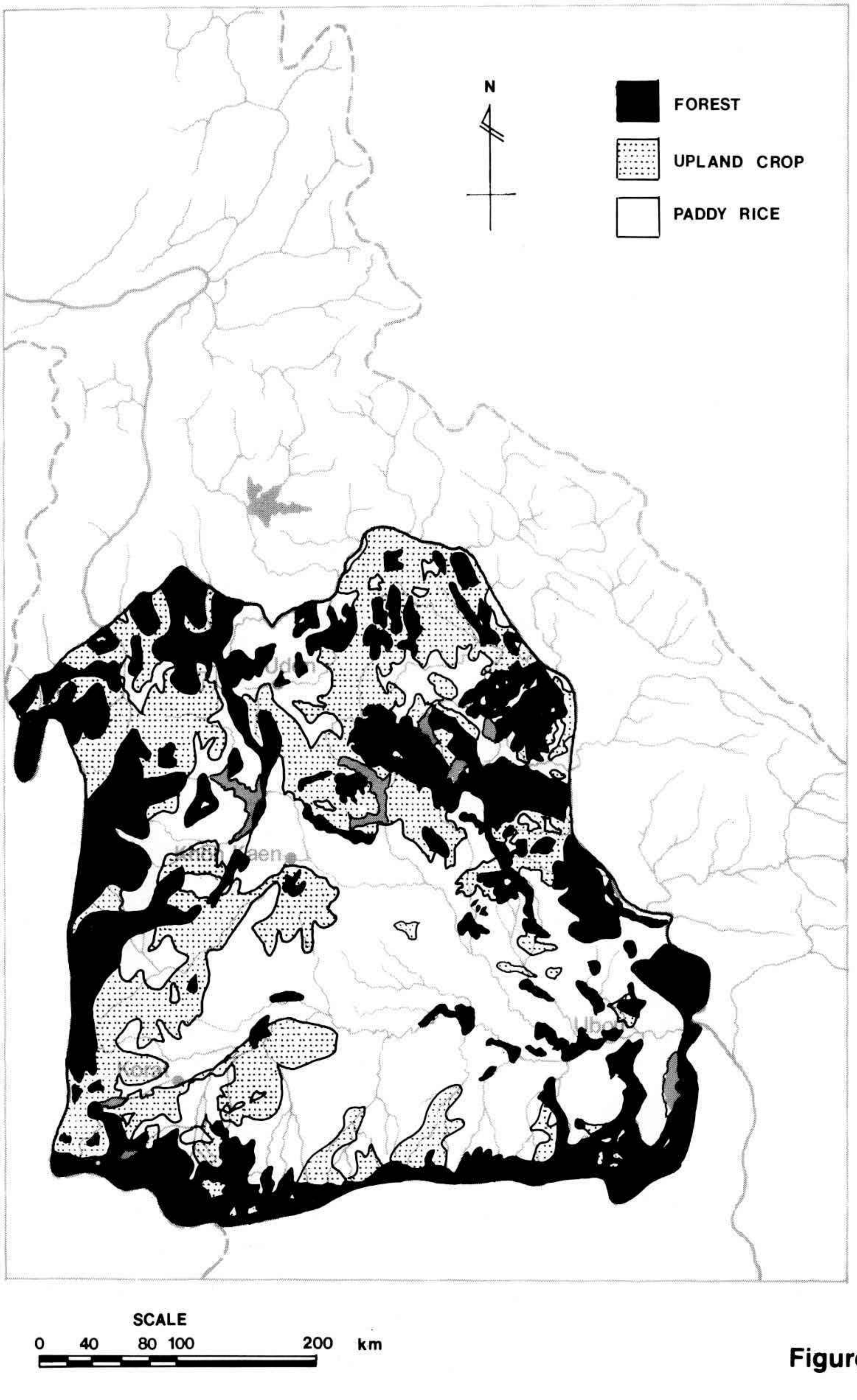


Figure 32

Our analysis of the hydrology of individual catchments showed that in general a reasonable water balance between rainfall-runoff and catchment losses or evaporation could be achieved. There was no evidence to suggest that evaporation had changed with time, but it was clear that the accurate estimation of catchment rainfall is a key factor that determines whether a realistic balance can be achieved. This became particularly noticeable when the duration of the analysis was reduced from a monthly to a pentad (5-day) basis. The subsequent work on more detailed water balance and simple conceptual modelling confirmed this.

It was found that reasonable water balances, that fitted our understanding of the regional hydrology, could only be achieved by fitting catchment rainfall to ensure a fixed level of soil storage at the end of the wet season. A constant soil storage and evaporation was imposed on the water balance, so any change or trend in runoff over the period of analysis would have been reflected by a trend in the rainfall factors; no such effect was observed so this helped confirm that there has been no noticeable change in the response of individual catchments to rainfall.

An alternative approach centred on estimating evaporation and seeing whether this had changed over time. Although the standard of the meteorological stations from which climatological data are available is high, it was found that there were no good records of solar radiation. This hampered attempts to obtain reliable estimates of potential evaporation. In theory, a recently developed method should have enabled direct estimates of actual evaporation to be made, but the results obtained in this study were unconvincing. At this stage it is not clear whether it is inaccuracies in the data that have caused this or whether there are some shortcomings in the theory itself.

The implication of these results is that if changes in the hydrology of the region have occurred, as a direct result of land use changes and agricultural development, then these effects appear to be small given the data available for the study and the methods of analysis used. Moreover it has been found that provided good estimates of areal rainfall can be made, even a very simple conceptual model will produce good estimates of runoff from rainfall. Therefore there are likely to be few advantages in using a complex catchment model rather than a simple model of the type described above, unless areal rainfall can be realistically, and objectively estimated.

The terms of reference for Phase 1 of this study called for a review of the performance of the SSARR model and information on the adequacy of the data collection networks. From our studies it is clear that the estimation of areal rainfall is the dominant problem affecting both issues.

The performance of any hydrological model depends both on the accuracy of the input data and the degree to which the model represents the complicated hydrological processes at work in the catchments. It is shown in our analysis in Chapter 4 that unless areal rainfall is adjusted, given hindsight, at least on a seasonal basis, a straightforward water balance cannot be achieved. It follows that without such adjustment no realistic model can be expected to produce reliable results. The SSARR model which uses an objectively derived estimate of areal rainfall must suffer from this problem and whether or not it can produce a better result than the simpler model used in Chapter 4 becomes an academic issue when neither model can perform well without substantial adjustment of the rainfall input.

In the circumstances the best solution for flow forecasting may well be the use of one of the statistical models of the CLS or ARIMA type. These models contain terms which represent the uncertainty in the relationship between rainfall and runoff and this uncertainty is large if the rainfall (or indeed the runoff) estimates are poor. The value of these models lies in their ability to put confidence limits on the forecast flows.

In terms of the data collection networks a substantial increase in the density of raingauges is the most urgent need. But the scale of the task may well be impractical even in NE Thailand alone. A selective approach is more realistic but further detailed statistical

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work and detailed discussion with the Mekong Secretariat is necessary to produce a rational design. The objectives and required accuracy of modelling need to be defined and representative basins chosen. Given the need for intensive statistical analysis we have had to defer completion of this work to Phase 2 of this study.

One of the objectives of the study as a whole was to produce a model that could describe the hydrological effects of land use and agricultural developments, and be used to predict the effects of further developments. One conclusion from Phase 1 is, perhaps surprisingly, that the effects of land use changes on the hydrology of the Mekong's right bank tributaries are insignificant. The available land use maps show that much of the low-lying land in the Korat Plateau was classified as agricultural land as early as 1954. This implies that the land use changes that have taken place, will have been on higher ground of the periphery of individual catchments, a long way from the points where flows are measured. By the time runoff generated in these remote areas appears at a gauging station it may have passed through the storages created by bunded fields in the low-lying areas. It is therefore possible that the hydrological effects of land use changes will have been masked by this process of routing through areas that have long since been under agriculture. Consequently these effects have not been observed in the records of gauging stations downstream.

This and the difficulties associated with the estimation of areal rainfall has caused the emphasis of the work programme being proposed for Phase 2 to shift away from the concept of developing an hydrological model capable of predicting the effects of future land use developments. It is clear that factors that will have a marked effect on the whole river system are the operation of man-made storages, and the implementation of the pumped irrigation schemes that are currently proposed. There is therefore an urgent need to develop a network model so that the combined effects of all these schemes on flows in the lower reaches of the Mekong can be assessed in years of average and lower than average runoff.

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In Phase 2 it is envisaged that a network model would be built containing elements to represent all the major schemes; these include storage reservoirs for hydropower, irrigation and flood control as well as pumped and gravity irrigation schemes. The model would represent the network of river reaches, reservoirs and irrigation schemes, account for the net use of water in each component and then route the resulting flows to a point downstream. Because rainfall-runoff modelling is not to be attempted, this network model will be a tool for medium to long term planning, rather than for short term operational purposes.

Without reliable data concerning the actual operation of gravity and pumped irrigation schemes, the usefulness would in practice be severely limited. We therefore consider that a study of 'operational agriculture', to determine the net use of water in various schemes, should be carried out in parallel with the modelling study.

Our Phase 1 work has also highlighted a weakness in the rainfall data base and it appears that one of the major constraints to conceptual modelling is the problem of estimating areal rainfall. Clearly it is impossible to improve the data base retrospectively, but it should be possible to rationalize, or, if necessary, redesign the raingauge network to give areal rainfall estimates of a chosen precision. Good rainfall estimates are required not only for conceptual modelling, but also for more basic water resources work, the assessment of design floods and irrigation requirements. This problem will also be addressed in Phase 2.

Our current studies have suggested that a good knowledge of the components of surface and soil storage is an important ingredient in the understanding of the hydrology of the region. Whilst the concept of storage used in our water balances appears consistent and reasonable in the context of the limited quantitative information available and our own field observations, the precise behaviour of the storage components is still far from clear. Moreover, it is very likely that the role of these storages will be different in the upland regions, cultivated predominantly with dry foot or field crops, and the lowland regions where rice is grown.

Although we would therefore like to see a major effort in soil water investigations to provide experimental data to substantiate the conceptual ideas we are currently using, such studies would require a large budget and are not crucial to the development of the network model envisaged. Arguably some studies along these lines will be necessary in future years when the broad performance of the network model is assessed and the requirement for fine calibration becomes clearer. Such studies are not being included in Phase 2 of this project.

In summary the work we are proposing for Phase 2 consists of two parts namely:

(1) the development of a network routing model
(2) a study of the estimation of areal rainfall from point rainfall records.

ANNEX I

Derivation of flow duration curves

A flow duration curve shows the relationship between any discharge and the percentage of time that the discharge is exceeded. The curve can be drawn for daily or monthly flow data or for any consecutive D-day period. Data for a duration D days are easily derived from daily data by calculating the D-day moving average.

Flow duration curves can be derived from a sample of data of the chosen duration by assigning each point in the sample to a class interval and then counting the number of points within each interval. The proportion of the total number of points above the lower limit of any given class interval is then calculated and plotted against the lower limit of the interval.

It is convenient to express the flow data as a percentage of the average daily flow (ADF) over the recorded period. The purpose of this is that it allows comparison between catchments, by reducing the effect on the slope and location of the flow duration curve or differences in catchment area and higher or lower than average flows during the recorded period.

Following the procedure outlined in the Low Flow Study Report (Institute of Hydrology, 1980), a logarithmic division of class interval was used in this study. The procedure used was to divide the range of discharge into 30 class intervals on a logarithmic basis from 1 per cent ADF to 1000 per cent ADF. However, other equally valid class interval boundaries could be used to detail particular flow ranges or to simplify the numerical calculation.

A normal probability scale is used for the frequency axis. If, in a sample of N, there are n instances when the discharge is above a given level q, then the plotting position on the frequency axis is given by t where:

$$P(Q > q) = n/N = 1 - \Phi(t)$$

and Φ is the normal probability integral given by:

$$\Phi = \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$$

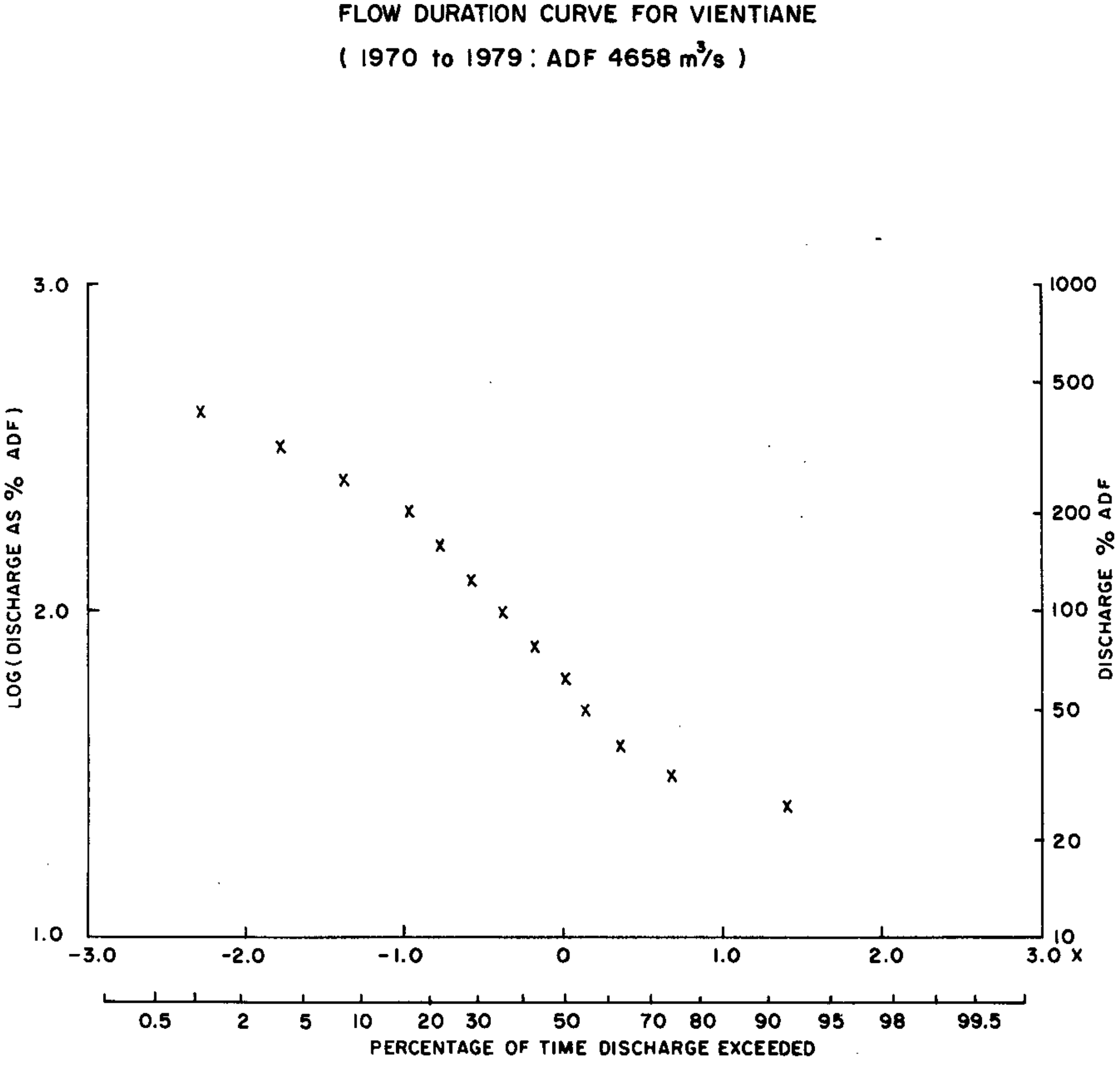
If graph paper with an appropriate frequency axis is not available, then the following equations can be used to construct it with adequate accuracy. If the normal variate is x and the exceedence probability p is expressed as a proportion then:

$$x = \text{signum}\ (p - 1/2)\ \{1.238t\ (1 + 0.0262t)\}$$

where signum $(p - 1/2) = +1$ where $p > 1/2$, -1 where $p < 1/2$ and

$$t = \{-\ln 4p(1 - p)\}^{1/2}.$$

Figure A1 shows a graph that has been constructed in this way.



FLOW DURATION CURVE FOR VIENTIANE
(1970 to 1979 : ADF 4658 m³/s)
LOG (DISCHARGE AS % ADF)
3.0
2.0
1.0
DISCHARGE % ADF
1000
500
200
100
50
20
10
-3.0
-2.0
-1.0
0
1.0
2.0
3.0 X
0.5
2
5
10
20
30
50
70
80
90
95
98
99.5
PERCENTAGE OF TIME DISCHARGE EXCEEDED

Figure A1

ANNEX II

Derivation of flow frequency curves

The flow frequency curve provides a graphical technique for estimating the probability that a year will contain an annual minima less than a given discharge. The probability is commonly expressed in terms of a return period, that is, the average interval in years between the occurrence of an event of a specified or more extreme severity. The curve can be drawn from daily or monthly flow data or from minima of any consecutive D-day period.

The method of drawing the flow frequency curve is to find the lowest flow of the chosen duration in each year of data; these minima are then ranked from highest to lowest. Each minima is then assigned a plotting position, against which the magnitude of the discharge is plotted.

In the Low Flow Study (Institute of Hydrology, 1980) flow frequency curves were drawn adopting the Weibull distribution for convenience; the same procedure has been used in this study, and the relevant equations are given below:

$$f(x) = (\gamma/\theta)\, x^{\gamma-1} \exp(-x^{\ell}/\theta)$$

$$0 < x < \infty$$

$$F(x) = 1 - \exp(-x^{\ell}/\theta)$$

where f(x) and F(x) are the probability density and distribution functions; θ and γ are parameters of the Weibull distribution.

If x is replaced by -x it can be shown that this is identical to the Extreme Value Type III (EV3) distribution (NERC, 1975 (I)). This means that if a variable is distributed as EV3 then its negative is distributed as Weibull, and is identical to Gumbel's 'limited distribution of the smallest value' (Gumbel, 1958). The relevant formulae for the plotting position for the ith largest point in a sample of N are:

$$P_i = (i - 0.44)/(N + 0.12)$$
$$Y_i = - \ln (- \ln P_i)$$
$$W_i = 4(1 - e^{-.25y_i})$$
$$T_i = (1 - P_i)^{-1} .$$

where Y_i is the EV1 reduced variate

P_i is the corresponding exceedence probability

W_i is the plotting position for the case of $\gamma = 4.0$

T_i is the corresponding return period.

In the calculation of plotting positions a value of $\gamma = 4.0$ was chosen. Note that whilst data that are drawn from the Weibull distribution with $\gamma = 4.0$ will plot on a straight line, it has not been assumed that annual minima necessarily conform to this distribution. The value of γ was chosen purely to provide a convenient plotting scale.

It was not intended that the frequency curves should be used to predict more extreme events then occurred in the historic record. The intention was to examine the extreme low flow events of recent years in the context of the long-term records; hence the choice of formulae for calculating plotting positions is unimportant.

The discharge axis of the curve shown in Figure A2 is expressed in terms of the average daily flow (ADF) during the period of record; standardization of the curves in this way allows comparisons between different catchments to be made. A return period axis has also been drawn on the graph; the return period, T, is calculated by:

$$T_i = \left[1 - \exp\left[-\{1-W/4\}^4\right]\right]^{-1}$$

The application of the flow frequency curve is similar to the flow duration curve but it is better equipped to describe rarer events. Note that the 90 per cent exceedence on the flow duration curve is a more common event than the 90 per cent or 10-year return period low flow from the flow frequency curve.

FLOW FREQUENCY CURVE FOR VIENTIANE
(1934 to 1980 – Season December to May – ADF 1625 m^3/s)

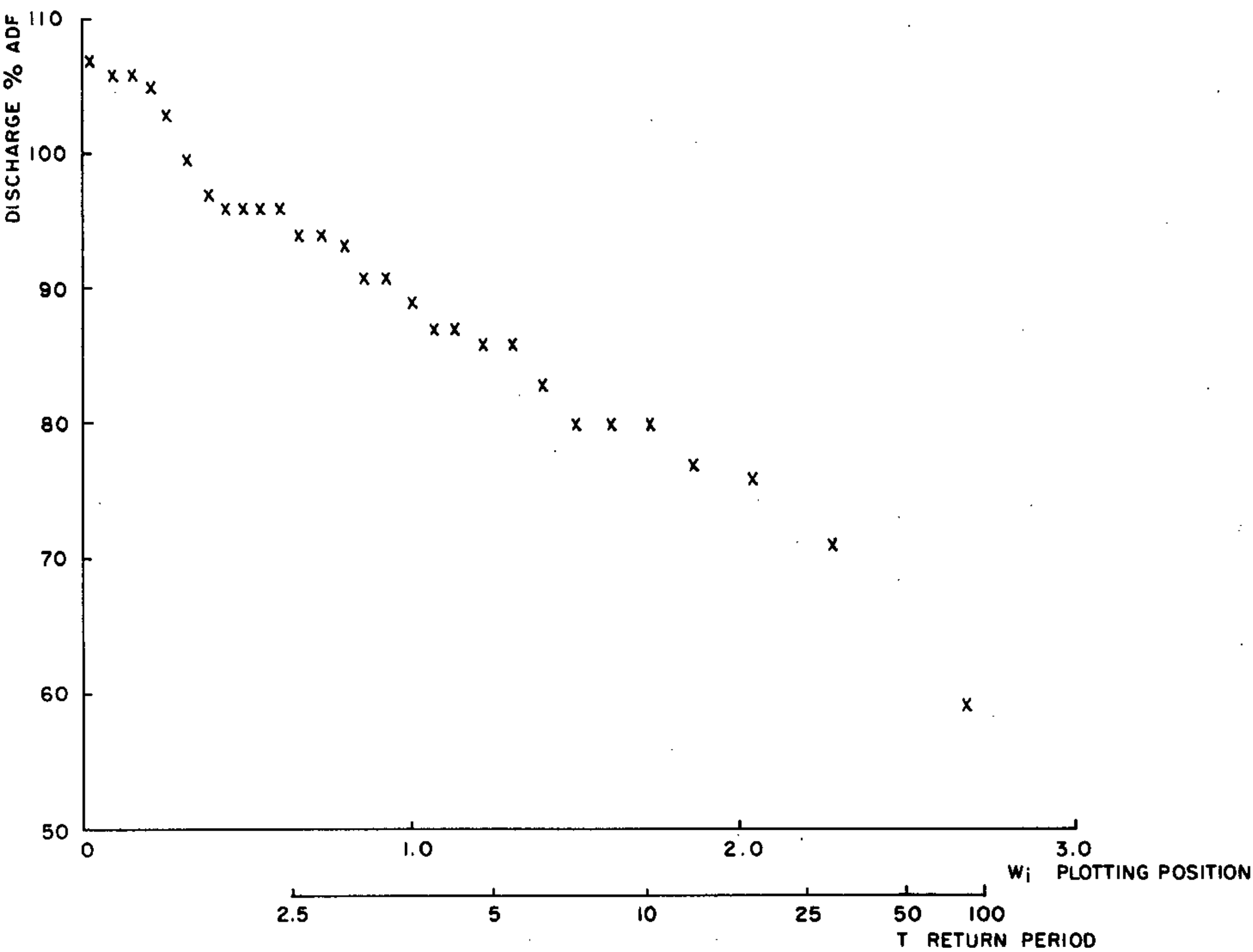


Figure A2

ANNEX III

Calculation of evaporation

Conventionally routine meteorological data are used to estimate potential evaporation or transpiration by a variety of methods; that originally proposed by Penman being widely used (see Shuttleworth, 1979 for a discussion of estimating evaporation). The Penman equation is a physically-based method of estimating potential evaporation using climatological data. The form of the equation used in this study is given by:

$$ET = \frac{\Delta}{\Delta+\gamma}\left[Ra(1-\alpha)(0.25 + 0.50\ n/N)\right]$$
$$- \frac{\Delta}{\Delta+\gamma}\left[\sigma T_a^4\ (0.1 + 0.9\ n/N)(0.34 - 0.044\sqrt{e})\right]$$
$$+ \frac{\gamma}{\Delta+\gamma}\left[0.26\ (1 + U_2/160)(e_s - e)\right]$$

where

- ET - potential evaporation (mm/day)
- Δ - slope of s.v.p. curve at mean air temperature (mb $^0K^{-1}$)
- σ - psychrometric constant (mb $^0K^{-1}$)
- Ra - radiation at the top of the earth's atmosphere (mm day^{-1})
- α - albedo (0.25 for most field crops, 0.10 for forests, 0.05 for open water)
- n - observed number of hours of bright sunshine
- N - maximum possible hourse of bright sunshine
- σ - Stefan's const (mm day^{-1} $^0K^{-4}$)
- T_a - mean air temp (^0K)
- U_2 - wind run at a height of 2 metres (Km/day)
- e_s - s.v.p. at the mean air temperature (mb)
- e - actual v.p. (mb)

This method however is reliable only when the solar radiation and the vapour pressure deficit are the factors limiting evaporation. In other words they assume that the crop or natural vegetation has available an unlimited supply of water. In conditions when the supply of water is limited the vegetation cannot transpire at the potential rate and the energy available for transpiration cannot be fully used. Thus temperatures rise and the vapour pressure deficit increases; the meteorological data are then no longer consistent with those which would have been recorded over a freely transpiring surface.

It has been thought for some time that there should be a relationship between actual evaporation, the true potential evaporation and the potential evaporation which would result from meteorological data from an area suffering a shortage of water. In 1979 Brutsaert and Stricker proposed a method for defining this relationship (Brutsaert and Stricker, 1979).

Their equation enables us to estimate actual regional evaporation from the same input data that is required for the Penman equation. The approach is based on a conceptual model involving, first, the effect of regional advection on potential evaporation, and second, an assumed symmetry between potential and actual evaporation. As the evaporation is estimated solely from meteorological data no information is required on cropped areas or soil moisture.

Consider the potential evaporation $(EP)_A$, defined as the evaporation from a complete cover of short green vegetation having access to a plentiful supply of water, for a location A. This location is at the centre of a large area (of say radius 50 km) which has a high rainfall so that actual evaporation $(EA)_A$ is not limited by the supply of water and is only limited by the supply of energy. In this case the potential and actual evaporation will be equal; Bouchet (1963) denoted the rate of potential evaporation under these conditions as EP_o and defined it by:-

$$EP_o = (EP)_A = (EA)_A \qquad (2)$$

Now consider a dry area (called location B), situated at the same latitude, where the actual evaporation $(EA)_B$ is limited by the supply of water rather than by the supply of energy, then:-

$$(EA)_B < EP_o \qquad (3)$$

$$EP_o - (EA)_B = q \quad \text{(say)} \qquad (4)$$

Now consider the energy balance of the two locations. For the wet location:-

$$(Rn)_A = (EA)_A + (H)_A + (G)_A + (Q)_A \qquad (5)$$

and for the dry location:-

$$(Rn)_B = (EA)_B + (H)_B + (G)_B + (Q)_B \qquad (6)$$

where

Rn - net radiation
EA - actual evaporation
H - sensible heat flux
G - soil heat flux
Q - advected energy

These energy terms will differ between the two locations even though the energy input at the top of the atmosphere above the two locations is the same. The most significant differences occur to the actual evaporation and sensible heat flux terms. The decrease in actual evaporation at location B due to limited water supply results in lower absolute humidities and higher air temperatures. Thus the potential evaporation at location B will be higher than at location A:-

$$(EP)_B > (EP)_A = EP_o \qquad (7)$$

The concept of complimentary evaporation proposes that the difference between the potential evaporation at the dry location (B) and the evaporation at the wet location (A) is equal to q, the same as the difference between the evaporation at the wet location and the actual evaporation at the dry location, that is:

$$(EP)_B - EP_o = q \qquad (8)$$

rearranging Eqn (4):

$$(EA)_B - EP_o = - q \qquad (9)$$

combining with Eqn (8)

$$(EA)_B = 2EP_o - (EP)_B \qquad (10)$$

Brutsaert and Stricker proposed that EP_o the true potential evaporation, could be estimated using the Priestley-Taylor equation (Priestley and Taylor, 1972). This equation was developed to estimate evaporation from land sites in the absence of advection. They also proposed that the Penman formula should be used for estimating EP, the local potential evaporation. For this work the Thom and Oliver version of the Penman equation was used (Thom and Oliver, 1977) following studies at the Institute of Hydrology of the performance of the B & S equation. Preliminary findings suggest that the modified Penman equation gives better results than using the more standard version.

The form of the Priestly-Taylor equation used here is given by:

$$EP_o = 1.26 \left\{ \frac{\Delta}{\Delta+\gamma} \left[Ra(1-\alpha)(0.25 + 0.50\, n/N)\right] - \frac{\Delta}{\Delta+\gamma} \left[\sigma T_a^4 (0.1 + 0.9\, ^n/N)(0.34 - 0.044 \sqrt{e}\right]\right\} \qquad (11)$$

and the Thom and Oliver equation by:

$$EP = \frac{1}{\Delta+\gamma(1+r_s/100)0.65(1+U_2/160)} \quad \Delta Ra(1-\alpha)(0.25 + 0.50\, n/N) - \Delta\, \sigma T_a^4 (0.1+0.9\, n/N)(0.34-0.044\sqrt{e}) + \gamma 0.65(1 + U_2/160)(e_s-e) \qquad (12)$$

where

Δ - slope of the s.v.p. curve at mean air temp (mb $^0K^{-1}$)

γ - psychrometric constant (mb $^0K^{-1}$)

Ra - radiation at top of the earth's atmosphere (mm day^{-1})

r_s - surface resistance (s m^{-1})

α - albedo

n - observed hours of bright sunshine

N - maximum possible hours of bright sunshine

σ - Stefan's constant (mm day^{-1} $^0K^{-4}$)

T_a - mean air temperature (^0K)

U_2 - wind run at a height of 2 metres (Km/day)

e_s - s.v.p. at mean air temperature (mb)

e - actual v.p. (mb)

ANNEX IV

Recent changes in land use in Northeast Thailand

The current picture

The northeast region covers an area of over 17 million ha, about one third of the total area of Thailand. Although the soils and climate are not ideal for intensive farming, the areas under agriculture have increased significantly in recent years at the expense of forest.

The assessment of land use in the northeast is confusing, for not only do the various agencies use different definitions of land classification, the classification used by any one agency may itself change from survey to survey. Moreover the data from some sources is sometimes conflicting. As an example Table A1 gives independent estimates of land use which are all derived from the 1977 Landsat imagery.

TABLE A1. Land use and suitability (million ha)

	A.I.T. (1978b)	Wacharakitti et al. (KU) (1977)	Sudchoochait et al. (1980)
Total area	16.73	17.41	17
Arable area	10.00	9.95	8
Suited to paddy	3.62		
Suited to upland crops	6.39		
Forest and woodland area		4.32	

In 1973 when Landsat imagery first became available, van Liere described 6.35 million has of the northeast as being 'topographically arable'; in this category 3.49 million ha were 'suited to paddy' and 2.67 million ha were 'suited to upland crops' giving an area of 6.16 million ha in total. The corresponding figures gives by AIT in 1978 (see Table 1) are 3.62, 6.39 and 10.00 million ha respectively.

The objective of the work described in this Annex was to examine the information available on land use in an attempt to examine these changes. We discuss the areas planted to major crops, and then consider forestry. Statistics provided by the Ministry of Agriculture are examined for trends in land use; these are related to rising population in the region.

Crop production - areas planted to major crops

Whilst the agricultural area has increased steadily, there has been simultaneous rapid change of crops in the northeast. The crops which occupy the greatest areas are: rice, maize, kenaf and cassava. Table A2 is derived from the annual Agricultural Statistics Report and gives the areas recorded as planted to these crops over the past 30 years; these data are shown in graphical form in Figure A3.

Rice

Rice is by far the most important crop grown in the northeast, occupying between one-third and one-half of total area (see Table A6); the northeast regularly produces about one-third of all Thai rice. The amount of effort required to level and bund a paddy field, and then to develop an impervious sub-soil layer, should ensure that a paddy field remains under rice being replaced only by a new crop which has extremely attractive cultivation characteristics (crop calendar, reliability, marketability, and yields). The marginal land now being reclaimed from forest may be suitable for conversion to irrigated paddy, but upland rice, with its lower yields, is an alternative that entails less land preparation but greater risk; it has been estimated that upland rice in the northeast will yield a crop in only 3 years out of 10 (Johnson et al., 1981). After a rapid expansion of rice production in Thailand during the years 1872 - 1908 (4.7 per cent increase in area annually) the rate of increase slowed over the period to 1961 to an average of 0.4 per cent annually. Since then, the average annual rate of expansion has risen again, to almost 4 per cent.

Although published statistics appear to differentiate between 'paddy' and 'upland' rice, it is likely that a large area of rice included under 'paddy' is not in fact grown in irrigated conditions.

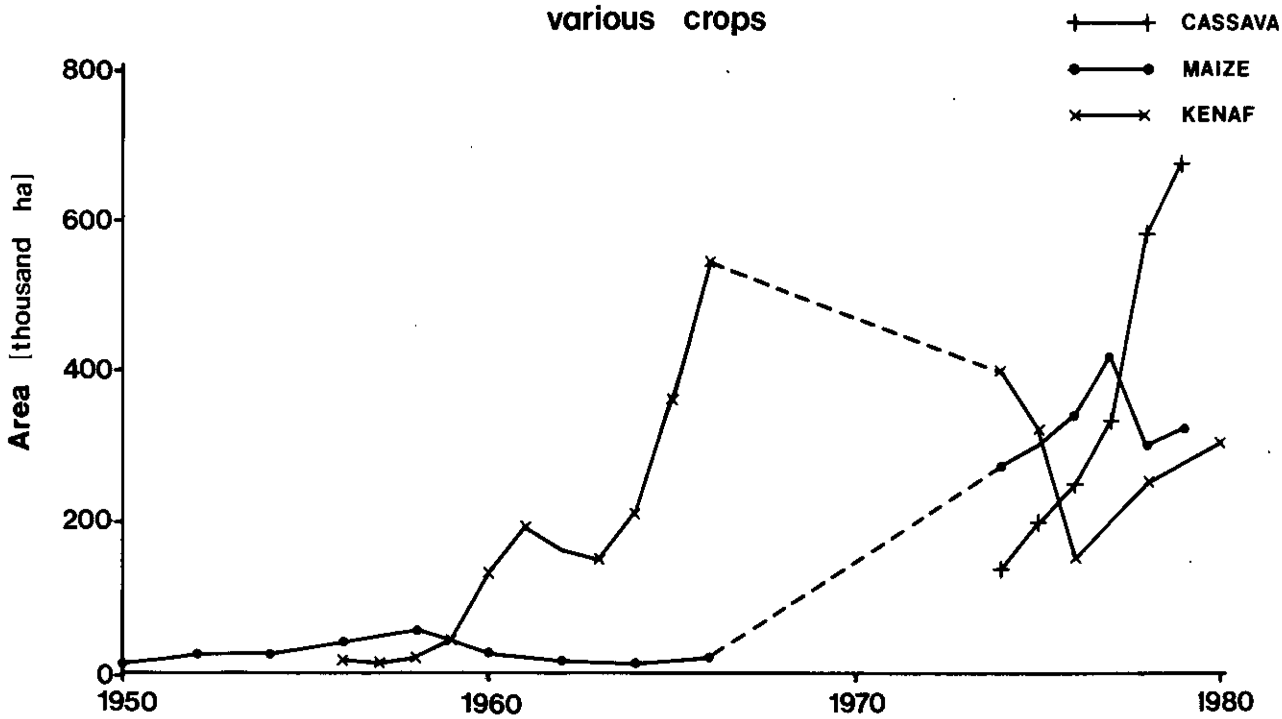
TABLE A2. Crop areas in northeast Thailand, 1950-80 (thousand ha)

	Rice		Maize		Cassava		Kenaf	
Year	Min. of Ag.	Other	Min. of Ag.	Other	Min. of Ag.	Other	Min. of Ag.	Other
1950	2031		13				5	
1952	2364		25				11	
1954	2538		24				6	
1956	2323		37				17	
1958	1838		52		1		20	
1960	2506		25		5		136	
1962	2364		11		6		111	114+++
1964	2707		10		8		214	153+++
1966	2429		18		11		519	384+++
								441+
1968	2255		na	82+		13+		348+++
								332+
1970	3238	3245+	na	139+		16+		377+++
1972	3435	3555+	na					466+++
		3100+				160++		
1974	3552	3500+++	275	275+++	131	129+++	423	550+++
1976	3999		343		254	252	321	326+++
						581		210**
								256+++

Sources: *Ministry of Agriculture, 1961 et seq.
+Mekong Secretariat, 1968 et seq.
++Mekong Secretariat, 1978
**Ministry of Agriculture, 1978
+++Mekong Secretariat, 1979

Notes: (na not available)

Northeast Thailand: Areas planted to various crops



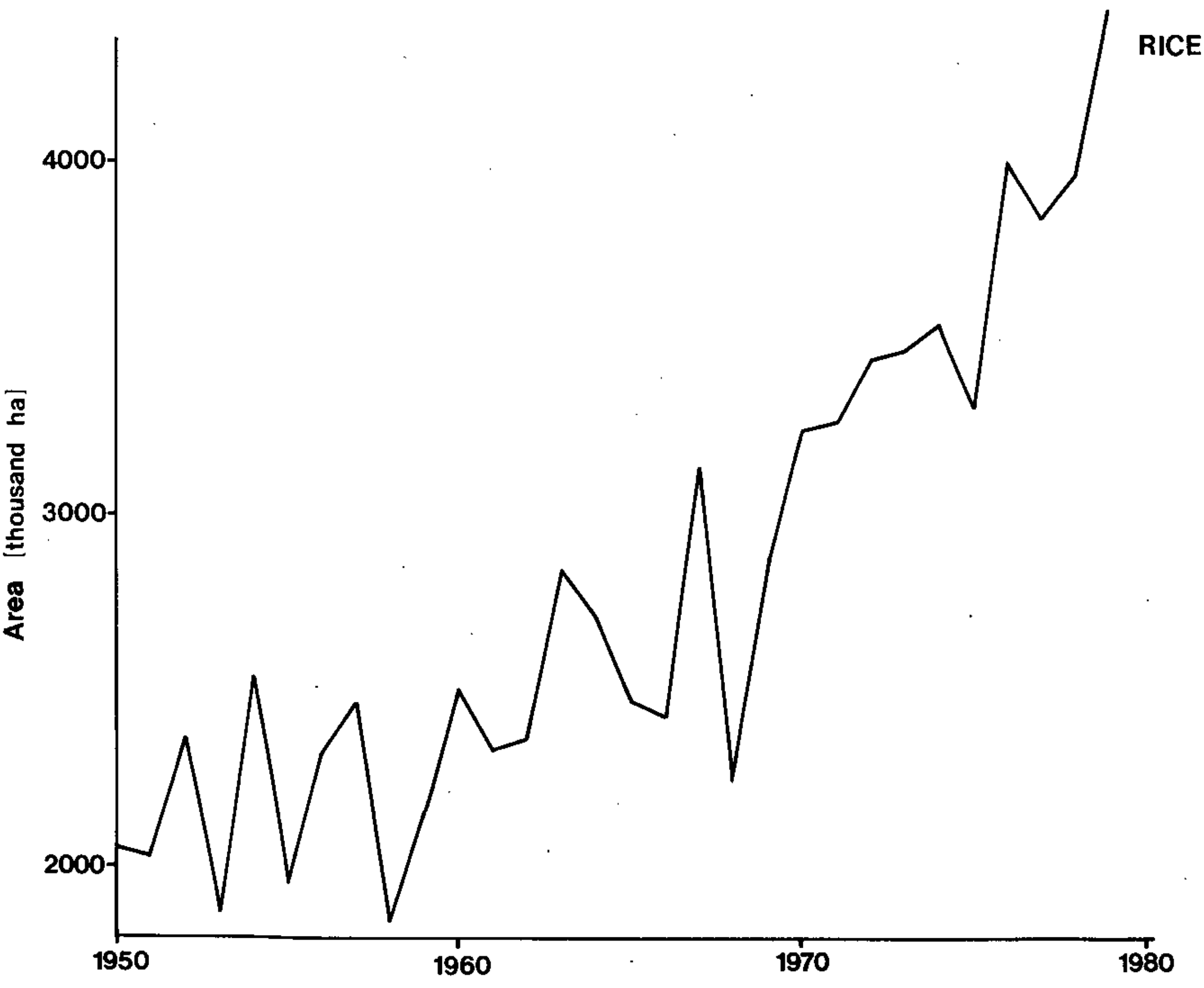


Figure A3

The average yield of rice in Thailand is 1.8 tons/ha, though potential yield is put as high as 6.0 tons/ha. The overall yield in the northeast is about 0.9 tons/ha, a maximum of 3.34 tons/ha was achieved in 1979 (Tantigate, 197?). Under traditional, 'swidden', farming methods yields up to 4 tons/ha with an average of 1.6 tons/ha are achieved (Mekong Secretariat, 1978).

Cassava

Cassava planting in the northeast has risen very rapidly during the 1970s: as shown in Table A2 the area under cassava quadrupled between 1974 and 1978.

Cassava is known to be exhaustive of soil potash (Purseglove, 1972) and declining yields have been noted in Thailand where cassava has been grown constantly for 4-5 years without fertilization. Land producing its first cassava crop may yield about 9.4 - 12.5 tons/ha (as at Khon Kaen), but land which has been under cassava for over 5 years may yield only 6.25 tons/ha; 7.5 - 9.4 tons/ha is thought to be a 'realistic average' which can be improved with fertilizers to a stable 9.4 - 12.5 tons/ha (Mekong Secretariat, 1979).

In the face of declining cassava yields and the need to purchase fertilizers, farmers may reclaim new land for cassava production, or may rotate land between cassava and other dryland field crops. Consequently cassava production may be affecting more land than the statistics indicate: some land may have been taken out of cassava production and been replaced by either newly reclaimed land or land previously under other field crops. The Mekong Secretariat is looking at alternative uses for land during a soil-restorative fallow. The methods under study are based on livestock; small-scale dairying is also being investigated (Brereton, pers. comm.).

Recent work on intercropping cassava with legumes (Johnson, 1981) could lead to better returns per ha from cassava plus the intercrop, enabling the farmer to purchase fertilizers. This could eventually mean stabilization or even further expansion of cassava production.

Maize, other grains

Maize occupied a total of 254,700 ha of northeast Thailand in 1978 (Mekong Secretariat, 1978). No wheat was grown then, but small areas of sorghum (1,170 ha) and sweet corn (1,035 ha) were planted.

Kenaf

Until cassava production exploded in the mid 1970s, kenaf was the most important upland crop in Thailand (Mekong Secretariat, 1979b), and it continues to be a major Thai export.

Table A2 shows the area planted to kenaf. Planting rose throughout the sixties and early seventies reaching a peak of 549,760 ha in 1973/1974. An earlier peak (500,000 ha planted in 1966/1967) was followed by a rapid decline of planted area in the following years. Average fibre yields in the region have fluctuated between 906 kg/ha (1970/1971) and 1,388 kg/ha (1964/1965) but for the 17 years 1962-1979, average yield has been over 1,000 kg/ha. In consequence, total production of fibre rose from 134,000 tons in 1962/1963 to 594,000 tons in 1973/1974, since when it has fallen back to 165,000 tons; this is equal to about 1,030,000 tons of whole kenaf.

Kenaf is considered to be less damaging to soils than cassava and some farmers in the northeast are anxious to return to kenaf production (Mekong Secretariat, 1979b). This crop is being promoted to help diversify agricultural production.

A large pulp mill has been established at Khon Kaen (Phoenix Pulp and Paper Co) which uses the whole dried kenaf stalk. When in full operation this mill will require 200,000 tons of kenaf (whole plant) annually - the product of 40,000 ha at present yield rates. Whilst it is an important market for kenaf in the northeast it appears to be insufficiently strong to influence prices greatly or to increase the area planted to kenaf to the levels reached in the mid-sixties or mid-seventies.

Sugar cane

A far smaller area is planted to sugar cane than to the four crops discussed above. Nevertheless as the crop appears to be able to compete with kenaf where milling facilities are available, it is also worth mentioning. A sugar mill has been opened in Khon Kaen - also the location of the kenaf pulp mill - but sugar cane is a popular crop in the area (Brereton, pers. comm.). Sugar cane covered 13,000 ha in 1950, rising to 45,300 ha by 1960. The most recent figures available are for 1978, from the Agricultural Census, which quotes 40,600 ha for the northeast. Around Khon Kaen at least, the area under sugar cane has probably been increased since 1978.

Vegetables and field fruit crops

Vegetable crops grown in the northeast include brassicas, umbelliferae and cucurbits. Water melons occuped 42 per cent of the total northeast vegetable crop area, sweet corn coming next with only 7 per cent of all vegetable crops. Amounting in total to only 13,884 ha in 1978, vegetable crops are obviously a very minor form of land use, i.e. less than 0.1 per cent of all land in the northeast, though they do represent a significant proportion of dry season crops. Obviously their market value and the cost of inputs used (fertilizers, herbicides, etc.) belie this small share.

Vegetable crops are being strongly promoted in Thailand as part of the crop diversification strategy, but conditions in the northeast are such that vegetables are restricted to good land within easy reach of water, so significant expansion is unlikely until larger areas can be reliably irrigated. Even then they may be grown only as an adjunct to paddy rice, particularly in the dry season.

Forests

Three research agencies have made major studies of the changes in forest area in recent years, using Landsat imagery and aerial photography. Each of these studies uses a slightly different definition of forest in view of its particular objectives; a summary of the definitions is given below:

Land Development Department: (LDD, 1977)	Forest, depleted woodland and scrub are treated together. This group is sometimes included in the category 'other land use'.

Royal Forestry Department: (RFD, 1981)	Forest areas, are those with 'good' canopy cover.
Kasetsart University (KU): (Wacharakitti et al. 1977)	Commercial forest, i.e. productive areas.

Thus, the definition used by the LDD is the widest interpretation of 'forested land', and that of KU is the most restrictive. Unfortunately, it has not been possible to identify exactly what constitutes a 'good' canopy cover as defined by the RFD but this interpretation includes all areas with a continuous or near continuous forest canopy. Forest types included are: tropical evergreen, mixed deciduous, pine, dry dipterocarp, bamboo and plantation areas. The interpretations of forest areas made by the LDD, the RFD and KU for the 1970s are given in Table A3.

TABLE A3. Forested areas 1973-78 (million ha)

Year	1973	1976	1977	1978
Agency				
LDD			6.39	
RFU	5.07	4.15		3.12
KU	4.75		2.75	

The RFD figures show that 2.95 million ha of forest were lost beteen 1973 and 1978; thus about 38 per cent of the 1973 area was lost by 1978 at an average rate of about 8 per cent per annum. This represents a decrease in forested area from 30 to around 18 per cent of the total area of the region. In each year of the period 1973 to 1978 some 2 per cent of the region was affected by deforestation.

With reference to Table A3, it should be noted that using the 1977 Landsat data, KU identified a further 1.57 million ha of disturbed, unproductive forests which leads to the figure of 4.32 million ha of productive and unproductive forest in Table A1. If we assume a steady rate of depletion from 1976 to 1978, then the RFD figures would give an area of 3.64 million ha for 1977 in Table A3, some 0.6 million ha less than the KU figure. This difference in area can be interpreted as woodland areas with interrupted forest canopies.

Ministry of Agriculture estimates of land use

At irregular intervals, the Ministry of Agriculture publishes some information on the pattern of land use in the regions of Thailand in its annual report (Ministry of Agriculture, 1961 et seq.). The categories of land use are changed frequently but nevertheless, some trends are clearly visible in the statistics. Table A4 reproduces the Ministry's figures (converted to hectares) for the years 1955, 1961 and 1964 and crop years 1973-1974 and 1977-1978.

In the four years 1961 to 1964 the area of 'forests and grazings' was reduced by 34 per cent and the area of 'unclassified' land increased by a compensatory amount (the total area of the northeast region was reassessed at this time). The categories 'forest and grazing' and 'swamps and lakes' disappear from the classification in 1973-1974. Increase in 'land in farm' accounts for 62 per cent of the reclassified 'forest and grazings' area - the remainder (2.62 million ha) is added to the 'unclassified' category.

Between 1961 and 1973-1974 the area of 'land in farm' more than doubled. This increase is largely accounted for by the increase in paddy rice (an extra 3.22 million ha, or 136 per cent of 1961 area) and by the increase in field or upland crops (0.73 million ha). Over the same period the area under fruit and rubber trees was halved (from 248,000 ha to 121,000 ha).

Surprisingly, the 1977-1978 figures indicate a decrease in the amount of paddy. It seems likely, however, that this is because of the introduction of the category 'idleland' - presumably the 1973-1974 area for paddy includes a similar area of land. The area under tree crops continued to decline sharply over this period, whilst field crops increased. There are a series of other minor readjustments between categories. More interesting is the disappearance of the 'farm woodland' category which covered 406,000 ha in 1973-1974. This area appears to have been subtracted from the 'land in farm' group, and transferred to 'unclassified', together with a further 40,000 ha from other sources.

It is worth mentioning that the statistics for paddy quoted in Table A4 for 1977-1978 (5.38 million ha) are markedly different to the

TABLE A4. Land utilization for selected years. (thousand ha)

	1955	1961	1964
Rice	2323	2364	2475
Fruit trees	170	6	145
Rubber		242	56
Upland crops	558	593	525
Farm woodland	402	292	267
Miscellaneous	692	116	134
(Land in farm)	(4144)	(3613)	(3602)
Forests and grazing	10267	10266	6794
Swamps and lakes	48	63	63
Unclassified	2247	2763	6563
Total	16707	16705	17022

	1973-74	1977-78
Paddy	5584	5378
Tree crops	121	50
Field crops	1321	1408
Fruit & vegetables	36	10
Idleland*	*	290
Grassland*	*	29
Others	196	112
Housing	131	152
Farm woodland**	446	**
(Land in farm)	(7835)	(7429)
Unclassified	9187	9593
Total	17022	17022

Source: Ministry of Agriculture, 1961 et seq.

Notes: * These categories introduced in 1977-1978

** This category not used in 1977-1978

statistics given elsewhere in the same publication for rice area planted in that year: 3.96 million ha (Ministry of Agriculture, 1961 et seq.). The rice area estimate provided by the 1978 Agricultural Census (Ministry of Agriculture, 1978) falls between these two, at 4.7 million ha. As paddy area accounted for almost three-quarters of 'land in farm' in this year, these discrepancies are of major importance. Brereton (pers. comm.) suggests that areas under increasingly intensified forms of swidden agriculture accounts for at least part of the difference. He also notes the steady exploitation of standing timber for charcoal from the 'no man's land' subject to swidden farming in the northeast.

The main conclusions to be drawn from the data presented above are that there has been a steady growth of farmed area, particularly in the area planted to rice, and rapid destruction of forest and impoverishment of tree cover.

Remote sensing (landsat imagery) has been used during the 1970s, to record changes in land use, and has been particularly useful in assessing loss of forest cover. The Landsat maps have been studied by the Land Development Department (LDD); in Table A5 their estimates are compared with those of the Ministry of Agriculture taken from Table A4. In Table A5 the categories are regrouped (as indicated), to provide more direct comparisons; note that the dates of the two surveys are within one year of each other.

Thus, two major sources of land use data disagree over interpretation. The land uses of greatest importance in the area are paddy, forest and field crops. The proportions of land allocated to each by the two sources are those shown in Table A6.

If the LDD's figures are correct, the Ministry of Agriculture underestimated the 1978 paddy area by about one third (2.7 million ha).

Population and land use

The increase in population of the northeast is shown in Table A7. It appears from available statistics that the area of arable land per head in the northeast has increased slightly over the period 1954

TABLE A5. Comparison of land classification (thousand ha)

Min. of Agr./LDD category	Min. of Agr. 1978	LDD 1977
Paddy land	5,378	8,131
Tree crops/Perennial crops	50	8
Field crops & fruit & veg./field crops	1,418	1,811
Grassland/Pasture & rangeland	29	24
Housing/Urban land	152	14
Idleland & others/Misc. plus airfields	402	363
Unclassified* minus water/Forest	9,454	6,394
(Water)/Water body	(139)**	139
Total	17,022	16,884

Source: Ministry of Agriculture, 1961 et seq., and Land Development Department, 1977.

Notes: * includes 446,000 ha farm woodland

** assumed

TABLE A6. Comparison of land classification 1977-78

	Min. of Agr. (%)	LDD (%)
Paddy	32	48
Unclassified*/Forest	55	38
Field crops	8	11
Various	5	3
Total	100	100

Source: Table A5

Note: *This category may include some non-forest uses

TABLE A7. Population statistics (1000 persons)

Year	1947	1960	1970	1980
Northeast Thailand				
Population	6210	8992	12003	15975
Growth rate (%)	2.9	2.9	2.9	
Thailand				
Population			36210	44160*

Sources: Van Liere, 1973
Thailand Population Census

Note: *1977 data

to 1980, though it must be remembered that these statistics are not totally reliable.

This increase of 0.14 ha/head of arable land fits in with the assumption that the land recently cleared for agriculture is relatively poor, but may also be the result of families attempting to lay claim to larger areas than they can farm - see below.

A contradictory trend, the intensification of production on unsuitable land, may also be expected to exist but is not visible in these data. The existence of such a trend depends on how freely available is land for clearing - if land tenure regulations restrict land clearing then intensification of effort on existing land must be expected. If land for clearing can be obtained without difficulty, then the farmed area will expand at approximately the same rate as population (in this case, 2.9 per cent). This may be compared with about 3.9 per cent per annum increase in arable area (Table A8).

Assuming an average household size of 6, and a population growth rate from 1970 to 1977, of 2.9 per cent, then the number of households appearing over the period 1973 to 1977 would be 264,000. Past research (Mekong Secretariat, 1978) indicates that upland farmers require approximately 30 ha/family whilst bunded field farming calls for 1.5 - 3.0 ha per family. The 2.6 million ha cleared between 1973 and 1977, distributed between these 264,000 households, would provide an average of 9.8 ha per household of marginal land. Researchers at AIT (AIT, 1978) have noted that the northeast is an area of undulating topography, about 40 per cent of most farms is left uncultivated. This suggests that cultivated area per household reclaimed in the 1973-1977 period, averages 5.9 ha (N.B. The figure of 2.6 million has cleared is a minimum estimate, see Table A2 for explanation). An explanation for this larger area has been suggested by Brereton (pers. comm.). He believes that in the past, farm families have attempted to farm too much land in order to lay claim to it whilst it is still available and as an insurance policy against partial crop failure. In consequence, the standard of cultural operations and possibly yields may be lower than would have been achieved on smaller holdings. Land is no longer available for claim and although population growth has now slowed down, pressure on holding size will continue and probably increase; in 1978 it was stated that intensive agriculture in the northeast was able to absorb labour productively (Mekong Secretariat, 1978)

Conclusions

Discrepancies between the estimates given by different land-related bodies for the total area of the northeast under each use make the calculation of the rates of land use change impossible and inadvisable. However, it is clear that forest cover has been considerably depleted and agricultural use of land has increased.

It seems likely that the creaming of typical high forest to extract a few valuable stems per ha, especially when this is carried out by elephant power as is often the case in northeast Thailand will not greatly alter the hydrological characteristics of the area. The runoff from a depleted, unproductive forest area may be expected to return rapidly to the pre-logging levels. Only if forest is removed wholesale, the soil exposed to the sun and a crop then a crop planted, will significant differences be apparent. For this reason, the maximum estimate of 'forest cover' is used below, rather than the Royal Forestry Department's 'productive forest' of 2.7 million ha.

Table A9 gives suggested estimates of changes in land-use for the 25 year period from 1955 to 1980; it also indicates a steady fall in land under 'other' vegetation. Presumably this is urban land (road, airports, towns, etc.), scrub and rough grazing and bare rock or soil, but it could include some illegal agricultural land (i.e. not sanctioned by the Ministry of Agriculture). The amount of land classified as 'arable' and 'forest' over the 25 year period has increased; whereas 16 per cent of the area was classified as 'other' in 1955, only 4 per cent was so classified in 1980, i.e. 12 per cent of the total area has been reclassified. The decrease in forest has caused reclassification of a further 24 per cent of the area. Overall, it appears that over the 25 year period, the use of about 37 per cent of the area has changed from either forest or 'other' to agricultural use.

TABLE A8. Population and land use

	Arable area (thousand ha)	Population (thousand persons)	Area/Land
1954	3,700	7,500	0.49
1980	10,000	15,975	0.63
Increase	6,300	8,465	0.14
% per annum	3.9	2.9	

Sources: Ministry of Agriculture, 1955
Tables A4 and A7

TABLE A9. Changes in land use (thousand ha)

	Arable	Forest	Other	Total
1955	3,700	10,300	2,700	16,700
1980	10,000	6,400	600	17,000
Average annual change	+ 240	- 156	- 84	
(%)	3.9	1.7	- 1.2	

Note: the change of base area 300 000 ha is less than 0.1 per cent/year over 25 years

7. REFERENCES

Apichart Anukularmphai et. al., 1980. Rainfall and Evaporation Analyses of Thailand, AIT.

AIT, 1978a. Water for the Northeast: Drought Analysis - Part I: Rainfall Analysis.

AIT, 1978b. Water for the Northeast: a Strategy for the Development of Small-scale Water Resources.

Berthelot, R., 1965. Monography of the Vientiane stream gauging station. Mekong Committee Publication, WRO/MKG/INF/L. 167.

Bouchet, R.J., 1963. Evapotranspiration reele et potentielle, signification climatique. Publication 62, 134-142, General Assembly IASH, Genbrugge, Belgium, 1963.

Brutsaert, W. and Stricker, H., 1979. An advection-aridity approach to estimate actual regional evapotranspiration, Water Resources Research, 15, 443-450, 1979.

Doorenbos, J. and Pruitt, W.O., 1977. Crop Water Requirements. Irrigation and Drainage Paper No. 24, FAO, Rome, 1977.

Freeman, T.G. 1981. Introduction to the use of CAPTAIN for time-series analysis. Computing Note 43, CSIRO division of computing research.

Ground Water Division, 1966. Groundwater Resources Development of Northeastern Thailand: Ground Water Bulletin No.2.

Gumbel, E.J., 1958. Statistics of extremes. Columbia University Press, New York and London.

Harza Engineering Company, 1962. Lower Mekong River Basin Discharge Data Prior to 1960.

Hurst, H.E., 1951. Long-term storage capacity of reservoirs, Trans. Am. Soc. Civ. Engrs. 116, 770-808.

Hurst, H.E., 1956. Methods of using long-term storage in reservoirs, Proc. Inst. Civ. Engrs., 1, 519-543.

Institute of Hydrology, 1980. Low flow studies report. Institute of Hydrology, Wallingford.

Johnson, S., Charoenwatana, T., 1981. Economics of rainfed cropping systems.

Khon Kaen University - Ford 1981. An Agroecosystem Analysis of Northeast of Thailand: Draft Report of a Workshop held in Khon Kaen December 1980, KKU-Ford Cropping Systems Project.

Land Development Department, 1977. Land use map of northeast Thailand using Landsat Imagery.

Land Development Department, 1980. Land use map of northeast Thailand.

McGowan International, 1981. Field data from Thai-Australian Tung Kula Ronghai Project.

Mekong Secretariat, 1962 et seq. Lower Mekong Hydrologic Yearbook. Mekong Committee Publication.

Mekong Secretariat, 1968. Atlas of Physical Economic and Social Resources of the Lower Mekong Basin. Mekong Committee Publication.

Mekong Secretariat, 1968 to 1974. Annual Statistical Bulletin. Mekong Committee Publications WRD/MKG/INF/L. 295, 382, 425, 488, 570, 584, 592.

Mekong Secretariat, 1974. Analysis of rainfall in Northeast Thailand as a basis for the planning of irrigated agriculture. Mekong Committee Publication MKG/13.

Mekong Secretariat, 1975. Summary of Monthly and Yearly Hydro-meteorological Data in the Thai part of the Lower Mekong Basins. Mekong Committee Publication MKG/29.

Mekong Secretariat, 1977. Explanatory Note to the Atlas of Thematic Maps of the Lower Mekong Basin. Mekong Committee Publication MKG/49 Rev 1.

Mekong Secretariat 1978. Agriculture in the Lower Mekong Basin. Mekong Committee Publication MKG/60.

Mekong Secretariat, 1979a. Interpretation of Remote Sensing Imagery (Activity for 1979) Mekong Committee Publication MKG/R. 231.

Mekong Secretariat, 1979b. Kenaf Pioneer Project. Mekong Committee Publication MKG/R 225.

Mekong Secretariat, 1980a. Annual Report 1980. Mekong Committee Publication MKG/87 Rev. 2.

Mekong Secretariat, 1980b. Continuous Review of the Water Balance in the Lower Mekong Basin. Mekong Committee Publication MKG/R 283.

Mekong Secretariat, 1981a. Agroclimatology in the Lower Mekong Basin. Mekong Committee Publication MKG/R 338/INF.

Mekong Secretariat, 1981b. Basinwide Water Quality Studies, Phase 1. Mekong Committee Project, Document MKG/R. 247 Rev. 3.

Meteorological Department, 1961 et seq., Annual Meteorological Bulletin, Meteorological Department of Thailand, Bangkok.

Meteorological Department, 1964. Monthly and Annual Rainfall of Thailand with Departure from normal (for the Period from 1911 to 1960), Meteorological Department, Bangkok.

Ministry of Agriculture, 1955. Statistical Review of Thai Agriculture. Ministry of Agriculture, Bangkok.

Ministry of Agriculture, 1961 et seq. Agricultural Statistics of Thailand, Ministry of Agriculture, Bangkok.

Ministry of Agriculture, 1978. Agricultural Census, Ministry of Agriculture, Bangkok.

National Energy Administration, 1962 to 1977. Hydrologic Data.

Natural Environment Reseach Council (NERC), 1975. Flood Studies Report (5 volumes), Institute of Hydrology, Wallingford.

NEDECO, 1982a. Feasibility study of the lower Mun-Chi Basin, March 1982.

NEDECO, 1982b. Mathematical Hydraulic Model of the Lower Nam Songkhram Basin, May 1982.

Priestley, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review, 100, 81-92, 1972.

Purseglove, J.W., 1972. Tropical Crops: Dicotyledons. Longman, London.

Royal Forestry Department, 1981. Using Landsat Imagery to Investigate the Change of Forest Land Use (in Thai), Royal Forestry Department, Bangkok.

Royal Irrigation Department, 1966 to 1978. Thailand Hydrological Yearbook volumes 1 to 11. Royal Irrigation Department, Bangkok.

Royal Irrigation Department, 1979. Table showing Water Resources Development in Thailand Completed to the end of 1978 and under construction in 1979. Royal Irrigation Department, Bangkok.

Spencer, J.E., 1966. Shifting Cultivation in Southeast Asia, University of California Publication in Geography 19. University of California Press, Berkeley.

Shuttleworth, W.J., 1979. Evaporation. Institute of Hydrology Report No. 56.

Sudchoochait, P., Juntharasri, S., Early, A. 1980. Engineering Performance Evaluation of 3 Tank Irrigation Systems in northeast Thailand.

Tantigate, K. 197? Conflict between rice and sugarcane farmers over irrigation water - a case study in Thailand.

Thom, A.S. and Oliver, H.R, 1977. On Penman's equation for estimating regional evaporation. Quarterly Journal Royal Meteorological Society, 103, 345-357, 1977.

US Army Engineer Division, 1968. Mekong Systems Analysis Project: Final Report on Training.

van Liere, W.J., 1973. Topography, population and actual land use in the Northeast in relation to its present and future land capability. Discussion paper for the Agriculture working Group of the Development Assistance Group, Thailand, Khon Kaen.

Wacharakitti, S. et al., 1977. The Assessment of Forest Areas from Landsat Imagery. (in Thai), Kasetsart University.