INTERIM
COMMITTEE FOR COORDINATION OF INVESTIGATIONS
OF THE LOWER MEKONG BASIN

LOWER MEKONG BASIN: WATER BALANCE STUDY

Phase 2 Report

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LOWER MEKONG BASIN - WATER BALANCE STUDY

SUMMARY

This report presents the work carried out in Phase 2 of the Water Balance Study; the background to the overall study and the conclusions of Phase 1 are given in the Phase 1 report (Institute of Hydrology, 1982). One of the underlying incentives to our work was the opportunity to provide fresh insights into the hydrological issues inherent in any coordinated development of the water resources of the region. Our approach has been to improve understanding of the hydrology of the region rather than satisfy the more practical and immediate requirements of engineering design. Consequently the outcome of the study could not have been predicted at the start of the project, so the Terms of Reference were written accordingly. Nevertheless the project has produced some important advances in understanding the hydrology of the region, as well providing a practical tool for the development and planning of its water resources. Moreover our work on the rainfall data base means that the Secretariat now has on their computer a comprehensive set of rainfall data for northeast Thailand that was hitherto unavailable. However because the outcome of this work is different from what had been anticipated in the original Terms of Reference it is useful to give at the beginning of this report a brief summary of the way in which the project progressed.

Over the past 30 years numerous developments have taken place in the upper and middle reaches of the Lower Mekong Basin; these 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 had been expressed that such developments might 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 had been lower than average, and in the delta there had been a tendency for salt water to migrate upstream further than before, thus reducing the potential for using river water for irrigation.

One of the primary objectives of Phase 1 of the study was therefore a systematic review of the hydrology of the Basin to determine whether upstream developments had had a significant effect on the water balance of the Basin as a whole. In Phase 1 we undertook a comprehensive review of the available data and carried out water balances on selected tributaries. The availability of suitable data limited the scope of the latter part of the work to areas of northeast Thailand.

The balance of the available evidence led us to the somewhat surprising conclusion that changes in land use did not appear to have had any appreciable effect on the water balances of individual catchments or on the overall hydrology of the Basin. At one time it had been hoped that a conceptual model capable of describing the hydrological effects of land use change and agricultural development would be produced at the end of the study. But the balance of evidence did not support the hypothesis that land use change had led to significant effects on hydrology. This meant that the emphasis of the work in Phase 2 moved away from conceptual modelling.

It followed that the factors that would affect flows in the downstream reaches of the Mekong were the man-made surface reservoirs used for hydropower, irrigation and flood control, and any major abstractions for, say, pumped irrigation schemes. Thus there appeared to be a need for a tool which could be used to assess the combined effects of such schemes.

Another problem raised by our early work was the difficulty of achieving reasonable water balances without having to adjust the rainfall component with hindsight. This would have potentially serious consequences in terms of the effectiveness of conceptual models unless more accurate estimates of catchment rainfall could be made objectively.

There were a number of other questions, such as the role of soil storage in catchment water balances, that merited further research. However given the resources available for Phase 2 it seemed more appropriate to limit the work to just two of the topics raised above.

Thus there were two primary objectives to Phase 2. The first was to develop a network-routing model of the Lower Mekong Basin containing elements to represent the major development schemes such as storage reservoirs for hydropower and irrigation as well as pumped and gravity irrigation schemes. The second was to study the problems inherent in estimating areal rainfall from point rainfall records, given the nature of the rainfall processes in the region and the extent of the existing raingauge network.

These two aspects of Phase 2 were tackled separately; the bulk of the modelling work was carried out in Bangkok, and the statistical analyses of rainfall in Wallingford. The reporting of the work is therefore divided up into two parts; in Part 1 we discuss the modelling work, and in Part 2 - presented as a separate report - we discuss the work on rainfall.

Two independent factors affected the progress of the study. The first was the upgrading of the Secretariat's computer with a new machine; the second was the amount of time that was needed to establish a reliable rainfall data base for the statistical analyses. As a result the project timetable was revised substantially, and the termination of the project delayed by several months.

Despite these problems the objectives of the study have to a large extent been met. The network model is a powerful tool with which the water resource development of the Basin can be planned and managed more effectively. The results of the rainfall studies provide basic statistical data, hitherto unavailable, from which other hydrological studies can now proceed.

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PART 1 - NETWORK MODEL

1. INTRODUCTION

The primary objective of these modelling studies was to provide the basis on which the combined effects of various developments on downstream flows could be assessed. To achieve this a network model of the Lower Mekong Basin containing elements which represent the major development schemes such as storage reservoirs for hydropower and irrigation as well as pumped and gravity irrigation schemes has been developed.

This report gives the general reader an overall description of the modelling work that has been completed and the problems that have arisen, and outlines how the model might be used in practice. Notes on the computer programs written for this study are described in more detail in a separate annexe.

A major influence on the progress of the study was the replacement of the Secretariat's CDC computer with a new VAX-11; this occurred towards the end of the work programme as originally scheduled. As a result the project timetable and contents were revised substantially, and the termination of the project put back by several months. This upgrade of computer system has also meant that some programming work, applicable only to the old machine, became redundant. However the improvements in performance and efficiency offered by the new machine more than outweighed this disadvantage. In particular it is now possible to run the suite of programs interactively from a terminal, rather than as batch jobs from a card deck. Moreover now that the Mekong Water Resources Database is being implemented, it will become possible to access hydrological data directly during program execution.

The network model, described in this report, now provides the framework within which the combined effects of various upstream developments on downstream flow conditions can be assessed. Unfortunately because of financial and time constraints it has not yet been possible to use the model for any detailed planning of water resource developments in the Lower Mekong Basin, and we have had to omit some aspects of the study that earlier we had hoped to cover. However now that this model has been completed, we look forward to the opportunity of being able to use it to help answer some of the hydrological problems being posed.

With any model of this type, the availability of suitable data for validating and then running the model can , as has been found in this study, be a major constraint. However, as far as validating the individual components of the network is concerned, we are satisfied that the submodels described later in this report are reasonable representations of what actually occurs.

The problems raised by the large areas of the basin with little or no coverage of streamflow or rainfall stations are perhaps rather more serious, but it is not necessary to dwell at any length on these. Clearly, when the network model is used in practice, it may well prove desirable to estimate streamflows at some ungauged points; but since the model is intended to demonstrate relative, rather than absolute effects, it should be possible to cope with this relatively easily.

Although the descriptions of the component parts of the model given in this report are drawn almost exclusively from northeast Thailand, the overall model and submodels could be used for any part of the Lower Mekong Basin. The model could be applied to a network of almost any size; the geographical boundaries can be easily changed for each study. Thus a network that covers the whole of the Lower Mekong could be made up from a number of smaller, tributary networks that could initially be modelled separately.

2. NETWORK ROUTING MODEL

Introduction

The purpose of this network routing model is not to simulate the behaviour of the river basin in real-time. Rather it is intended as a planning tool that can assist in medium and long-term management or development decisions.

It was considered that one of the most important requirements of the model was that it should be as simple as possible, yet flexible enough to be capable of representing the complex network of rivers, reservoirs and irrigation schemes that comprise the Lower Mekong Basin. The model is a water quantity mass balance model that accounts for the water used in the network under consideration. It comprises a number of submodels representing the individual components of the river system, that have been developed and tested separately; it is to be expected that the existing model representations of these components may change with time. Therefore it must be possible to alter any given component relatively easily, by changing the appropriate subroutine, without affecting the rest of the model.

What has been developed is a generalised flow model for the multi-tributary, multi-reach river system that is the Lower Mekong. It can accept inputs from tributary inflows, reservoir releases and irrigation returns, and also outputs or losses from the system such as gravity diversions or pumped abstractions.

The main elements of the model, whose interconnections are shown schematically in Figure 1, are:-

(1) flow assembly program
(2) routing program
(3) results program
(4) reservoir subprogram
(5) irrigation subprogram.

Note that both the reservoir and irrigation subprograms can be used on their own to simulate the behaviour of a given scheme.

Schematic Diagram of Network Routing Model

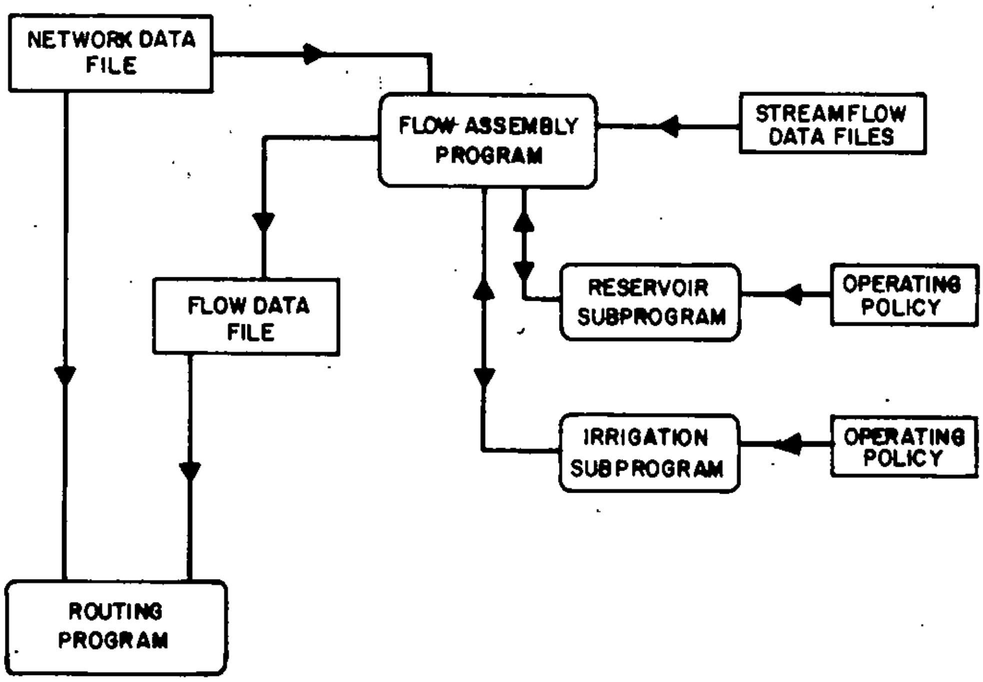


Figure 1

The data inputs to the model comprise a description of the river and tributary network, a basic set of hydrological data, and operating policies for the reservoir and irrigation schemes under consideration.

At the start of Phase 2, the plans for introducing a new computer to the Secretariat had yet to be finalised, so the programs developed had to be consistent with the machine that was then in operation. With that system all jobs had to be submitted in batch mode on cards. So a microcomputer was dedicated exclusively to the project for program development, thus bypassing some of the inefficiencies inherent in batch processing. This proved to be extremely useful in the initial development of small programs, but its capacity was too small to allow any testing of the model as a whole or to process any large sets of data.

Perhaps the most difficult and time consuming part of our work has been the need to provide a flexible scheme for handling input data. At an early stage it was decided that modelling on a monthly timestep would be too coarse. Hydrological data for any shorter timestep have to be calculated from daily data anyway, so the data input routines had to be able to read daily data and then calculate from these the data of the appropriate timestep.

Traditionally daily streamflow data at the Secretariat had been stored on cards in the 6-D format used by the SSARR model. It was decided that the most efficient way of using data already existing as card images would be to maintain this input format. The purpose of the flow assembly program was therefore to read the relevant card images and rewrite the data to disc file for subsequent use by the program itself.

The flow assembly program therefore had to be extensively rewritten for the new VAX computer, and will undoubtedly have to be modified further as and when the Mekong Water Resources Data Base is further developed and implemented. The flow data file written by this program, and subsequently input to the routing program may remain substantially unchanged.

The reservoir and irrigation subprograms have also been modified for compatibility with the improved file handling capability of the VAX.

Network

The first step in preparing a model run is to describe the geographical structure and features of the river system under consideration in schematic form; from this, a network data file is built up. This data file contains all the information necessary to define the extent and main features of the network, as well as the relevant channel routing parameters.

By way of illustration we have used the Mun-Chi Basin in northeast Thailand to show how this is achieved. The main geographic features of this basin which comprises the Nam Mun and its tributary basins, the Nam Chi, the Nam Pong and Lam Pao, are shown in Figure 2. A schematic representation of the corresponding tributary and reach structure necessary is shown in Figure 3. The reach boundaries themselves are determined according to the various inflow points and the locations of releases, abstractions and returns of the major schemes. Following the work described in the Mekong Systems Analysis Project (US Army Engineer Division, 1968) a reach length of 10 km is often used. For reaches of this length the routing parameters are considered to be constant.

Each tributary is considered in turn and the channel divided up into reaches. The occurrence of any inflow or abstraction point within any reach is indicated by a flag in the input data file; see Table 1 for a description of the available flags. When the model program is executed, the value of the flag determines which of the various subprograms is called.

The great advantage of this representation of the river network is its flexibility. The number and type of development schemes can easily be modified in the modelling process just by altering the values of the flags and the reaches in which they occur; the actual reach structure stays substantially the same.

Mun Chi Basin

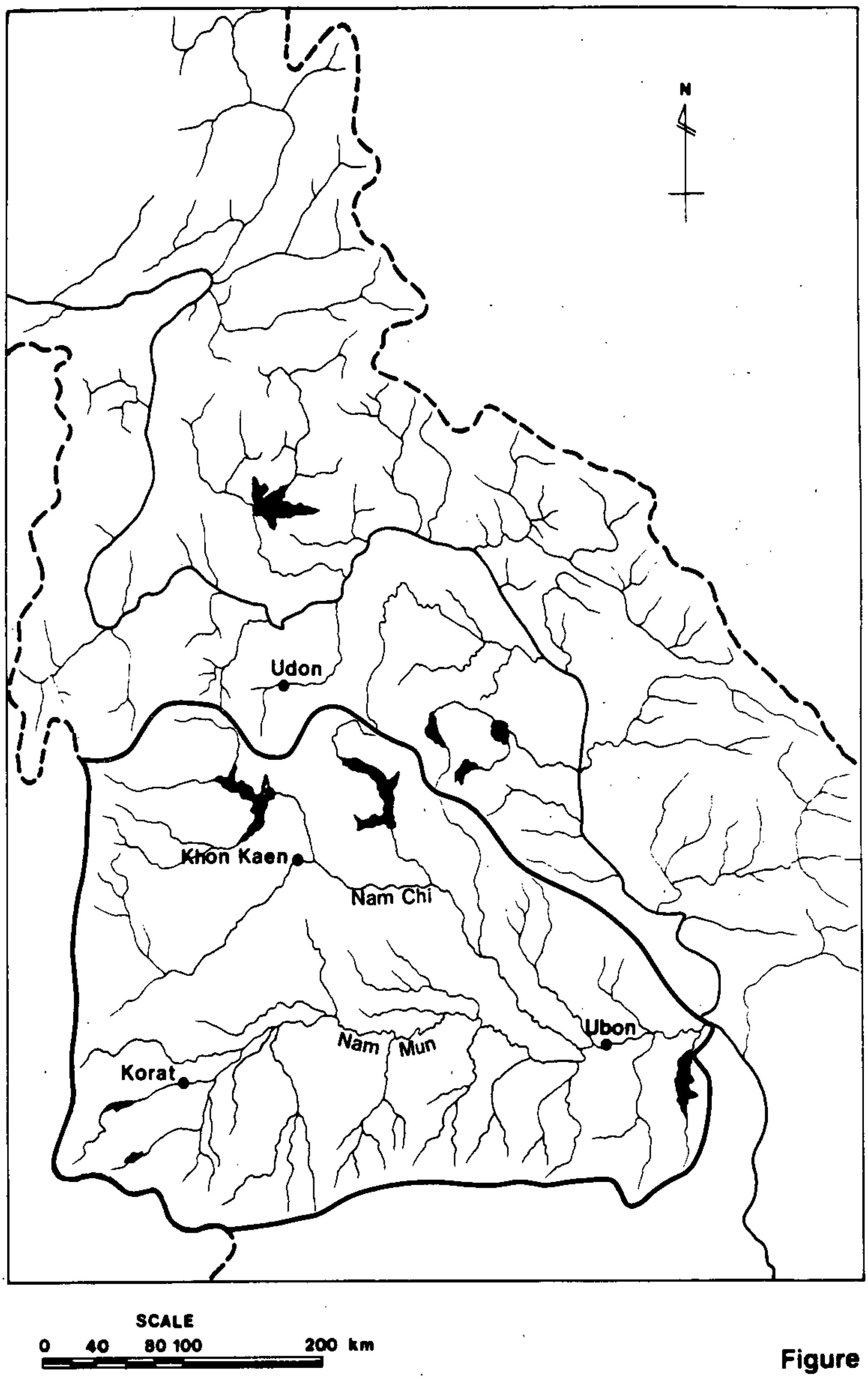


Figure 2

Mun Chi basin-schematic

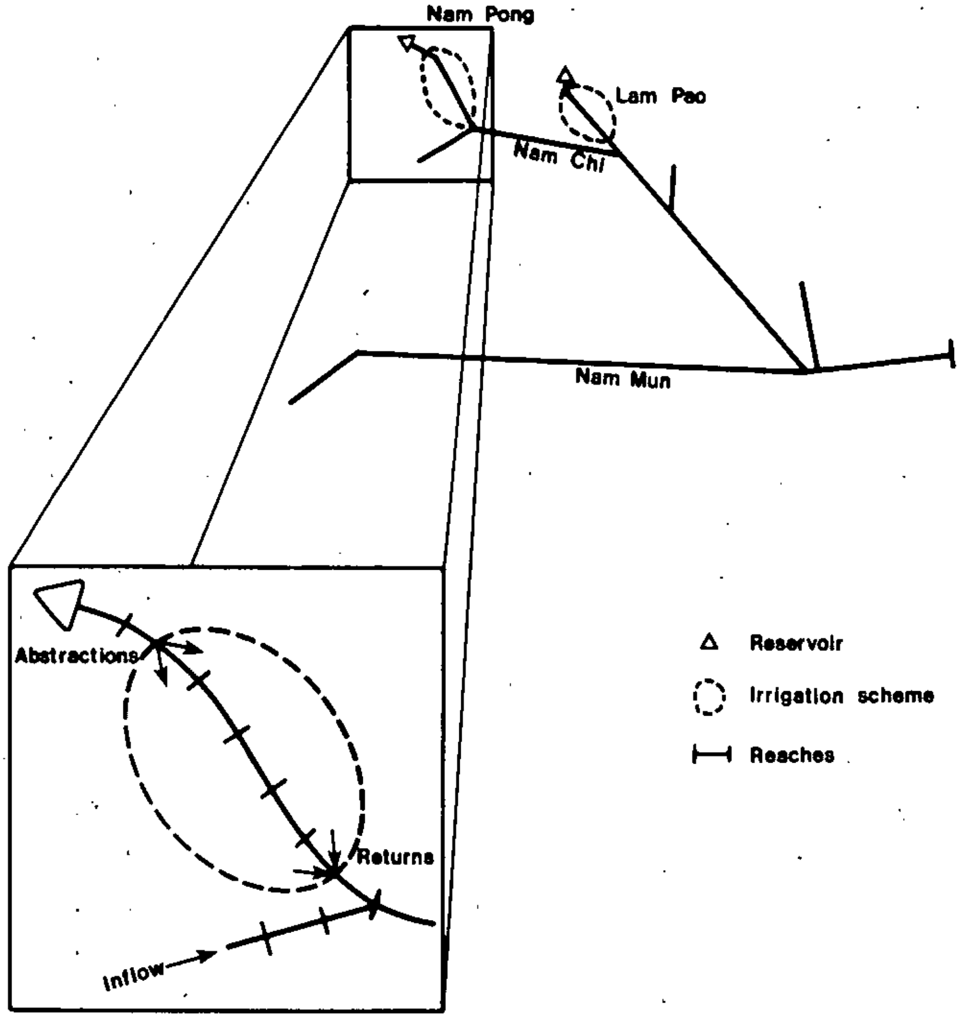


Figure 3

Reservoirs

The operation of storage reservoirs, particularly for hydropower generation, is one of the most obvious ways in which regulation can be imposed on a river basin. In general the effect of reservoirs is to smooth out the annual hydrograph by storing peak discharges and releasing water for hydropower generation and other demands downstream. In some tributary catchments of the Lower Mekong Basin, releases from storage reservoirs are a particularly important component of the dry season flows.

The purpose of the reservoir subprogram is to simulate the performance of a given reservoir under different operating strategies and produce a sequence of releases to be used subsequently as input data to the network model. Reservoir operation programs of varying complexity are available, but because the main purpose of this part of our work is to provide inflows to the network model, rather than provide a detailed description of the performance of the reservoir itself, this program has deliberately been kept simple. The program is a straightforward simulation of the reservoir water balance, given an initial set of starting conditions, a sequence of inflows and demands.

Initially the timestep of the simulation was a month, but a modification has now been made to accept a 5 day or pentad time step. The program does however compute an average daily release over the time step. The simulation is based on average values derived from conditions at the start and end of each timestep. These end conditions are not known until the balance is complete, so the procedure is iterative with the average conditions for reservoir area, water level and so on being successively re-estimated until the balance becomes consistent.

The structure of the program has been developed from a multipurpose reservoir simulation program that has been widely used at the Institute of Hydrology. The program carries out a water balance of the reservoir, having determined the required release from storage according to a preselected set of priorities and

TABLE 1. Network data file - Scheme flags

Flag	Explanation
A	A(bstraction) from an irrigation scheme - initiates a call to the irrigation subprogram.
E	(r)E(turn) from an irrigation scheme - associated with A above.
R	R(eservoir) releases water into the network - initiates a call to the reservoir subprogram.
B	B(asin) transfer by routing reservoir releases to another basin - initiates a call to the reservoir subprogram.
T	T(ributary) inflow - initiates a call to abstract flow data from a streamflow data file.
M	M(ain) stem - initiates a call to abstract flow data from a streamflow data file.
P	P(ump) scheme - initiates a call to the irrigation subprogram.
I	I(nflow) from previous model run of an upstream network - calls the appropriate data file.
O	O(bserved) releases or abstractions - calls the appropriate data file.

demands for hydropower generation or downstream release. For completeness a subroutine to allow for rationing has also been included.

Only two demands - irrigation and hydropower - are considered. These are expressed as an irrigation release, and a demand for firm energy; the release necessary to generate this energy is calculated in the program. The user is able to specify which demand should be given priority, should shortfalls occur. Irrigation releases can be routed either through the turbines or directly to the downstream channel.

Reservoir characteristics, downstream channel conditions (tailwater rating curve) and turbine characteristics are all represented by a series of points which can usually be obtained from published graphs. Linear interpolations between these points are assumed to be acceptable approximations to the true curve. There are three sets of points:

(1) reservoir contents (million m^3) and surface area (km^2) are all related to the same list of reservoir water levels (m).
(2) downstream flow (m^3/sec) is related to tailwater level (m).
(3) turbine efficiency (%) at average power, and peaking capability (MW) are all related to the same list of net head (m) across the turbine.

A constant head loss across the turbines is assumed, and its value is input to the program at the start of the simulation. Minimum release levels are defined for irrigation and hydropower independently.

At the start of each timestep, the average reservoir conditions - water level, surface area and tailwater water level - are set to the values held at the end of the previous timestep. The net evaporation loss is calculated, as is the release required to meet the demand for firm energy generation. Conditions at the end of the timestep are calculated from the trial water balance.

Operating decisions are then based on these conditions and the balance modified if necessary. At the end of the iteration revised estimates of average reservoir level and area are made and the process repeated. Four iterations are used as standard, but this number is reduced if successive estimates of the end contents differ by less than 0.1 per cent.

The operating decisions referred to above are made by comparing the end of timestep reservoir contents with the appropriate rule curve. In this simulation two rule curves are defined, namely, a design flood curve that specifies the reservoir contents that must not be exceeded to ensure the safety of the dam, and an operating curve, that specifies the lowest reservoir contents that can be tolerated be fore rationing is initiated.

A simple rationing procedure is allowed for, and either hydropower or irrigation can be allocated the highest priority. If rationing is initiated, the demand with the lowest priority is reduced by 5 per cent of the original value and a new balance attempted. This procedure is repeated until a satisfactory outcome is achieved, or until the demand has been reduced to zero. Rationing of the demand with the next highest priority is then initiated.

A simplified method for calculating hydropower releases has been used here. The basic demand for hydropower is expressed as a firm energy in gigawatthours (gwh) per timestep. The basic equation relating the required discharge to the average net head and demand is

$$Q = \frac{\text{Den} \times \text{Days} \times K}{\text{Nethead} \times \text{Eff}}$$

where Q is the required release in $m^3 \times 10^6$
Den is the demand for energy in gwh over the timestep,
Days is the duration of the timestep,
K is a constant equal to (24 x 3600)/(9.81 x 1000),
Nethead is the net head across the turbines in m, and
Eff is the overall turbine efficiency.

For completeness, an estimate of secondary energy is also calculated when the releases available to the turbines - either from irrigation, flood control release, or spill - are greater than the release required to satisfy the firm energy alone. For simplicity it has been assumed that all secondary energy is generated at peak power.

As far as the network model itself is concerned the important output data are the releases from the reservoir into the river system. Much of the other output information discussed above has been used to verify the way in which the program works, to keep a record of the operating conditions used in a particular run and to allow the performance of the reservoir to be monitored.

Irrigation schemes

There are three types of irrigation scheme found in the Lower Mekong Basin: gravity, pumped and village schemes. The gravity-fed schemes are large areas of land (~ 50,000 ha) situated in the valleys of the major rivers, often on both banks, supplied by a network of canals drawing water either directly from one or more upstream reservoirs, or from a diversion structure situated on the river channel below the reservoir. The pumped schemes are smaller (~ 350 ha), situated on a bank of one of the major rivers, and supplied by water pumped from the river by centrifugal or axial pumps up the steep river banks, and then flowing by gravity through a network of small canals away from the river.

The village schemes are much smaller, generally made up of individual plots of less than 10 ha, and situated downstream of simple earth embankments impounding water in the minor tributaries. These minor tributaries normally stop flowing in the dry season and the impoundments merely reduce flows in the wet season. Because the stored water is consumed locally by the irrigation schemes in the dry season, it was considered that the village schemes, though numerous, would have negligible effect on the low flows in the major rivers. Consequently attention was concentrated on modelling the gravity and pumped schemes which abstract irrigation water directly from the major rivers.

The general style of irrigated farming, in terms of bunded fields and crops grown, appears similar regardless of the type of water supply; it was possible, therefore, to use a single submodel, with minor modification to the input data, to simulate both gravity-fed and pumped irrigation schemes. For certain of the surface schemes, however, the irrigation duty may be abstracted from a reservoir, but the drainage from the scheme back into the river will occur downstream of the reservoir, or even, on account of the scheme's large size, downstream of a major tributary. The output information from the submodel must therefore be separate estimates of both the irrigation duty at the abstraction point and the drainage back to the river, rather than just their difference, in order to allow proper integration of the submodel into the complete network of reservoirs, tributaries and irrigation schemes.

Because the network model is to be used for medium to long-term planning, the irrigation submodel must use as input data only that cropping, climatological, soil and design information which is easily available to the engineer prior to commissioning a scheme. It does not therefore accept the type of data that might be needed for real-time operation.

A water balance model similar to one used by Joshua (1977) to estimate irrigation duty of paddy rice in Sri Lanka was chosen for this study. This model, which could be used for any crop, uses estimates of all the most important inputs and outputs of a typical irrigation scheme such as rainfall, evaporation, percolation and conveyance losses. From the balance, estimates of the irrigation duty and surface drainages are made (Figure 4).

There are a number of criticisms that can be levelled at the chosen model: for example, it makes no allowance for the time taken for the water to pass through the irrigation scheme; it does not include a contribution to the drainage from outflow due to groundwater; it takes no account of that proportion of the scheme's area that is out of command or used for fish farming. If the objective of this part of the study had been to model the distribution of water within a single scheme, then detailed information on such items could be collected and a more complicated

Irrigation submodel - schematic

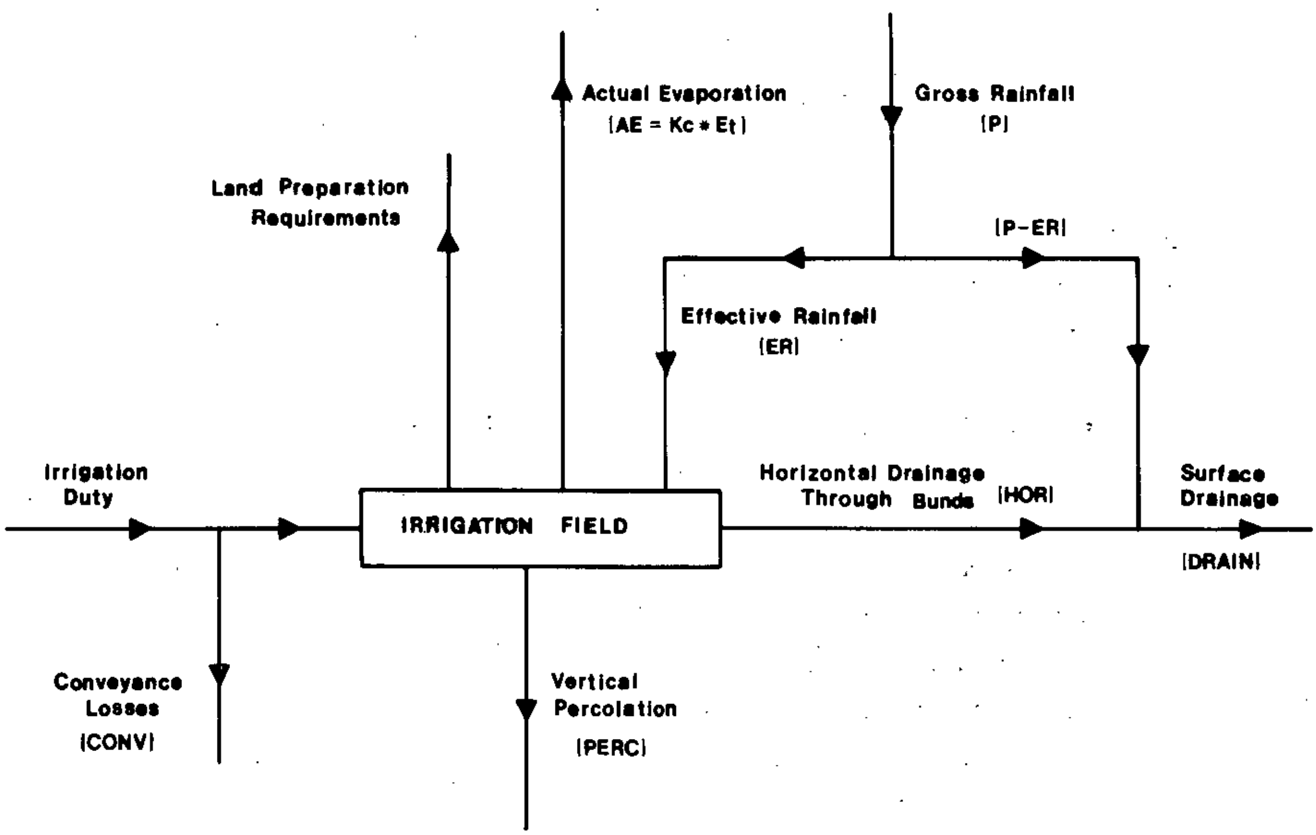


Figure 4

model applied. A model of this type has been developed by Holmes (1983) and applied successfully to data observed on the Kaudulla irrigation scheme in Sri Lanka. However here the objective is to obtain reasonable estimates of irrigation duty and surface drainage, and, provided that not too fine a time interval is chosen, a simple water balance approach was considered adequate. A basic interval of 5 days length was used, and each month's data was split into 6 equal parts.

The main inputs and outputs considered in the model are shown in Figure 4. The actual evaporation (AE) from the fields is found from the product of a crop factor (k_C) appropriate to that period of the cropping calendar and the reference crop evaporation (RCE), taken as the Penman estimate of evapotranspiration (E_T) from a short well watered crop at the nearest station in the network of climatological stations (Institute of Hydrology, 1982). At other times of the season the fields may lie fallow, when no evaporative demand is assumed, or may be under land preparation, when a fixed volume of water is applied over a short period of time.

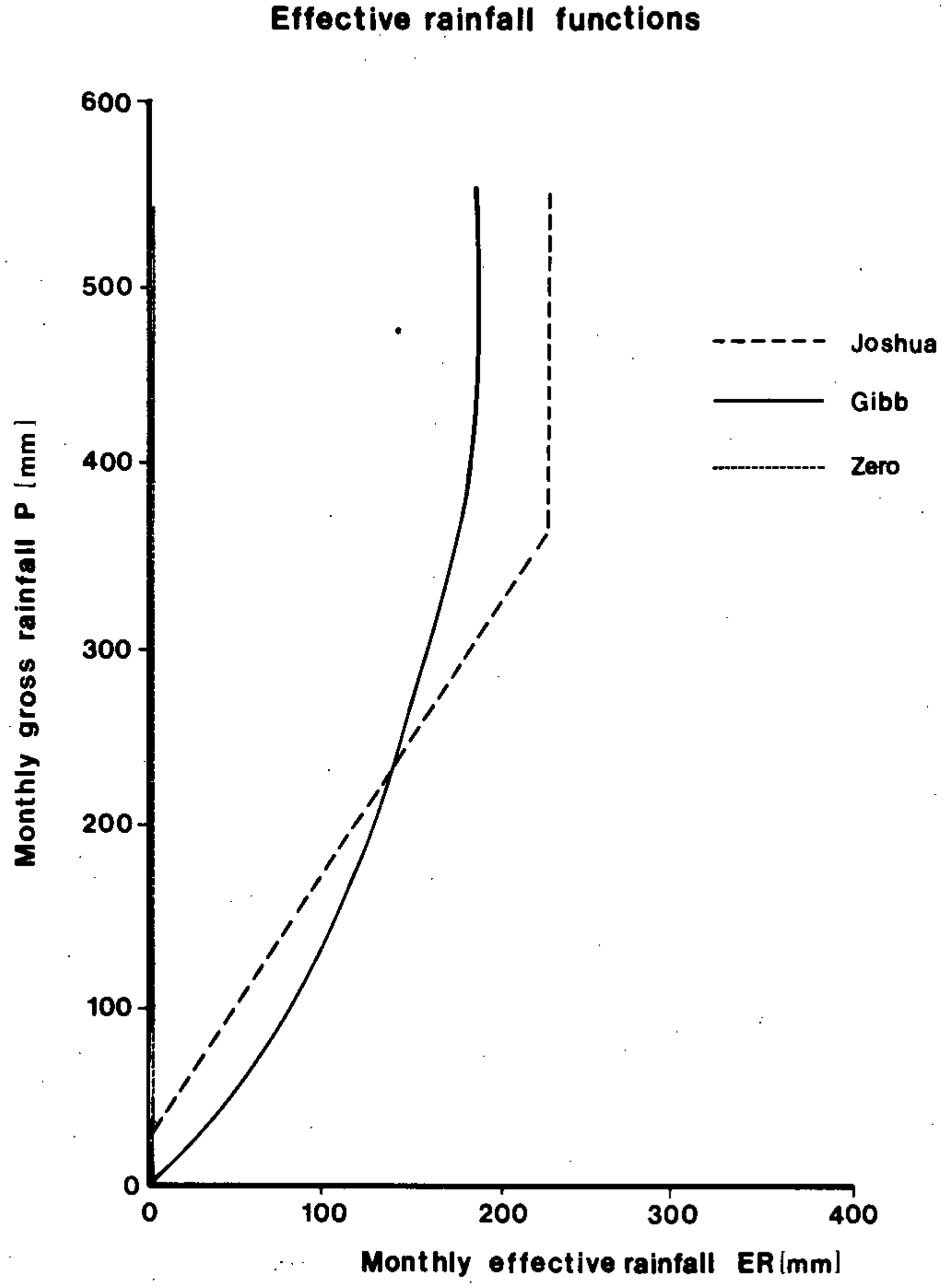
The gross rainfall input (P) to the scheme was estimated from the nearest reliable daily rainfall record, with a second gauge used to fill in any missing gaps. This rainfall (P) was split into the effective rainfall (ER) which contributed to reducing the field water requirement, and the remainder (P-ER) which contributed directly to surface drainage. ER was expressed as a function of P, and for validating the submodel three different functions were considered, referred to as Joshua, Gibb and Zero, illustrated in Figure 5.

The Joshua method was that proposed in Joshua's original model; the Gibb method is that used by the consultants Sir Alexander Gibb and Partners in their design study of 5 irrigation schemes in Thailand for the Royal Irrigation Department (Sir Alexander Gibb and Partners, 1981), and based on daily observations of rainfall for Thailand drawn from a report from the Mekong Secretariat (1979); the Zero method is when the effective rainfall remains zero for all values of gross rainfall P, and represents the irrigation management system in which no reduction of duty occurs even when substantial input occurs to the fields from gross rainfall. Clearly there are a number of other effective rainfall functions that could be used, but for the purposes of this study, the three functions described above were considered to be adequate.

Continuous losses from the fields occur either as vertical percolation PERC or horizontal drainage through the bunds (HOR): overflow through the orifices in the bunds due to heavy rainfall is accounted for by the function used for the effective rainfall calculation. Losses from the distribution canals, (CONV), is taken as a constant proportion of the irrigation duty which Holmes et al. (1981) have demonstrated from observation to be a reasonable assumption.

On any irrigation scheme, particularly those with substantial areas under cultivation, the main events in the crop calendar, such as nursery planting, land preparation, transplanting, and draining down before harvesting, do not occur simultaneously throughout the scheme. Instead such an event may be spread out over a month or more, ensuring that any abrupt changes in total irrigation duty are smoothed out. In the model allowance is made for this practice by dividing the area of the scheme into 3 equal subareas, and introducing a time stagger. This means that in the second subarea, events in the crop calendar always occur at a fixed number of 5 day intervals behind those on the first subarea; events on the third subarea are further delayed by the same amount.

A typical set of input data required for the model is shown in Table 2; the various items in the table are self explanatory, but note that a crop factor of -1.0 is used to indicate land preparation. The output data from the model consist of daily values of irrigation duty and surface water drainage calculated from individual 5 day periods. These are also summed to give monthly totals on the computer printout, as well as details of the cropping pattern, crop factors, climatological data and other scheme parameters.



Effective rainfall functions
600
500
400
300
200
100
0
0
100
200
300
400
Monthly gross rainfall P [mm]
Monthly effective rainfall ER [mm]
Joshua
Gibb
Zero

Figure 5

TABLE 2 Irrigation submodel - typical input data

NONG WAI - Wet season 49%, Dry season 12.9%

DESIGN AREA	40480.0	HECTARES
MAIN INTAKE CHANNEL CAPACITY	50.000	CUMECS
CONVEYANCE LOSSES	20.0	PER CENT OF INTAKE FLOW
PERIOD OVER WHICH NO IRRIGATION APPLIED AT END OF GROWING SEASON	3	FIVE DAY PERIODS
LENGTH OF LAND PREPARATION PHASE	4	FIVE DAY PERIODS
DEPTH OF WATER REQUIRED FOR LAND PREPARATION	220.0	MM
STAGGERED TIME DELAY FOR EACH 1/3 AREA INITIAL CULTIVATION	2	FIVE DAY PERIODS

	MONTH											
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
REFERENCE CROP EVAPORATION IN MM	170.0	157.0	135.0	136.0	126.0	122.0	134.0	116.0	109.0	113.0	125.0	166.0
VERTICAL PERCOLATION IN MM	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
DRAINAGE RATE THROUGH BUNDS	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

CROP FACTORS APPLICABLE FOR EACH FIVE DAY PERIOD

PERIOD	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
1	1.20	0.00	0.00	1.00	1.15	1.15	1.20	1.20	0.00	0.00	1.00	1.15
2	1.20	0.00	0.00	1.00	1.15	1.15	1.20	1.20	0.00	0.00	1.00	1.15
3	1.20	0.00	-1.00	1.00	1.15	1.15	1.20	1.20	0.00	-1.00	1.00	1.15
4	1.20	0.00	-1.00	1.00	1.15	1.20	1.20	0.90	0.00	-1.00	1.00	1.15
5	0.90	0.00	-1.00	1.00	1.15	1.20	1.20	0.90	0.00	-1.00	1.15	1.20
6	0.90	0.00	-1.00	1.00	1.15	1.20	1.20	0.00	0.00	-1.00	1.15	1.20

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
PERCENTAGE OF DESIGN AREA CROPPED DURING EACH MONTH	12.9	12.9	49.0	49.0	49.0	49.0	49.0	49.0	49.0	12.9	12.9	12.9
RAINFALL IN MM	46.7	211.1	358.4	97.3	161.4	335.0	97.6	0.0	0.0	0.0	8.3	14.0

Routing

Many channel routing methods are currently available; these include hydrological or storage methods, methods based on a convection-diffusion equation, and methods that use a numerical solution of the full Saint-Venant equations for gradually varying flow in open channels. The hydrological or storage methods are the most popular, and in general the simplest of all flow routing methods (NERC, 1975).

For this work it was decided that a hydrological or storage method would be the most appropriate, and also have the added advantage of similarity with that used in the SSARR model (Surin, 1980). In this class of method the flow routing in a given reach of the river is based on the continuity equation. This equates the rate of change of storage in the reach to the difference between the inflow at the upstream section and the outflow at the downstream section. A relationship between channel storage and both the inflow and outflow is also derived, either from physical characteristics or by calibration using existing streamflow data. The two equations are then solved to give the outflow from the reach once the inflow is given.

The relationship between inflow (I), outflow (Q), and storage (S) in each cell or compartment of a reach is represented by the differential equation:

$$\frac{dS}{dt} = \frac{1}{\tau} (I - Q) \tag{1}$$

where τ is a travel time or residence parameter . τ must be allowed to vary with flow Q and can be expressed as

$$\tau_Q = \frac{L}{un} \tag{2}$$

where L is the length of the reach, u is the mean flow velocity in the reach and n is the number of cells in the reach. The velocity itself is related to discharge through

$$u = a\ Q^b \tag{3}$$

where a and b are coefficients to be estimated. The amount of dispersion in a reach is controlled by n; the values of all these parameters can be obtained through calibration on an observed record of downstream flow.

Thus the travel time τ defined above is analogous to the time of storage T_s defined in the SSARR model as follows:

$$T_s = \frac{KTS}{Q^n} \tag{4}$$

If the upstream and tributary inputs are known, then simulations of the downstream flow can be derived by solving the differential equation (1), with the travel time calculated through equations (2) and (3), or equation (4).

These equations can be solved either by numerical integration or by approximation. For this work it was decided for consistency to adopt the approximate solution currently used in the SSARR model. At a later stage some numerical integration technique could be substituted if it was felt to be worthwhile, and a suitable integration package was implemented at the Secretariat.

The approximate solution used in the SSARR model is given by

$$Q_{t+1} = \frac{(I_m - Q_t)}{T_s + \frac{dt}{2}} \cdot (dt) + Q_t$$

where Q_t and Q_{t+1}	are the outflows at the beginning and end of period t respectively
Im	is the mean inflow defined as
$Im = (I_t + I_{t+1})/2$	where
I_t and I_{t+1}	are the inflows at the beginning and end of period t respectively
T_s	is the time of storage
dt	is the length of the period t

It is important to remember when using this flow routing procedure that the solution is only approximate. In some circumstances these approximations can lead to the generation of flow within a reach because the continuity equation is not completely satisfied. However, storage routing procedures assume that the flow has been steady prior to the beginning of each hydrograph at the flow rate of its first ordinate. So provided the changes in flow caused by reservoir releases or irrigation abstractions are kept relatively smooth, then this should not cause too much of a problem.

Output

Two types of output information are available at the end of the model run: the first is an output hydrograph at the downstream point of the network, and the second is information relating to the performance of the individual schemes in the network.

A number of subroutines have already been written to help interpret the outcome of a given model run by calculating certain characteristics of the hydrograph or by producing graphical plots. At present the available options include lineprinter plots at the downstream output point as well as other points selected in the network, lineprinter plots of the downstream flow duration curve, and the calculation of various error criteria.

Obviously every individual user may have their own preference for the most appropriate form of output information, so it is to be expected that these subroutines will be modified. Moreover only lineprinter plots can be produced at present; the relevant subroutines will have to be updated when on-line graph plotting facilities become available.

The other type of output, such as the detailed summary of reservoir releases, spills and electricity generation, is more useful for understanding how an individual scheme has performed, and for achieving effective use of the available water. For example it may be important to check whether there is excess water held in storage at the end of a year's simulation. If that is the case, then there might be an argument for releasing more water during the year. During each run lineprinter output of the main details of the input data files is produced so that a proper record of each run is kept.

3. AVAILABILITY OF DATA

Hydrological data

The availability of hydrological data for the Lower Mekong basin was discussed in some detail in our Phase 1 report. The interested reader is referred to that report for more details. However it is worth restating some of our previous comments on the hydrological data base.

The Mekong itself is equipped with a reasonable number of gauging stations. The quality of the flow records from these stations appears to be good, although there must be some doubt about some of the data early on in the period of record which were corrected, or filled in, by modelling, (US Army Engineering Division, 1968). Daily flow records for the mainstream stations were kept on punched cards at the Mekong Secretariat, and are now being transferred to the main data base.

The situation on the tributaries, especially those outside northeast Thailand is far less satisfactory. Not only are the records relatively short, but the geographical coverage is far from adequate (Figure 6). This is particularly true for the left bank tributaries in the Lao PDR where the rainfall and runoff are higher than in other parts of the basin.

The locations of raingauges whose records are published in the Secretariat Yearbooks are shown in Figure 7; as for the streamflow records the geographical coverage is poor outside northeast Thailand.

Location of main gauging stations

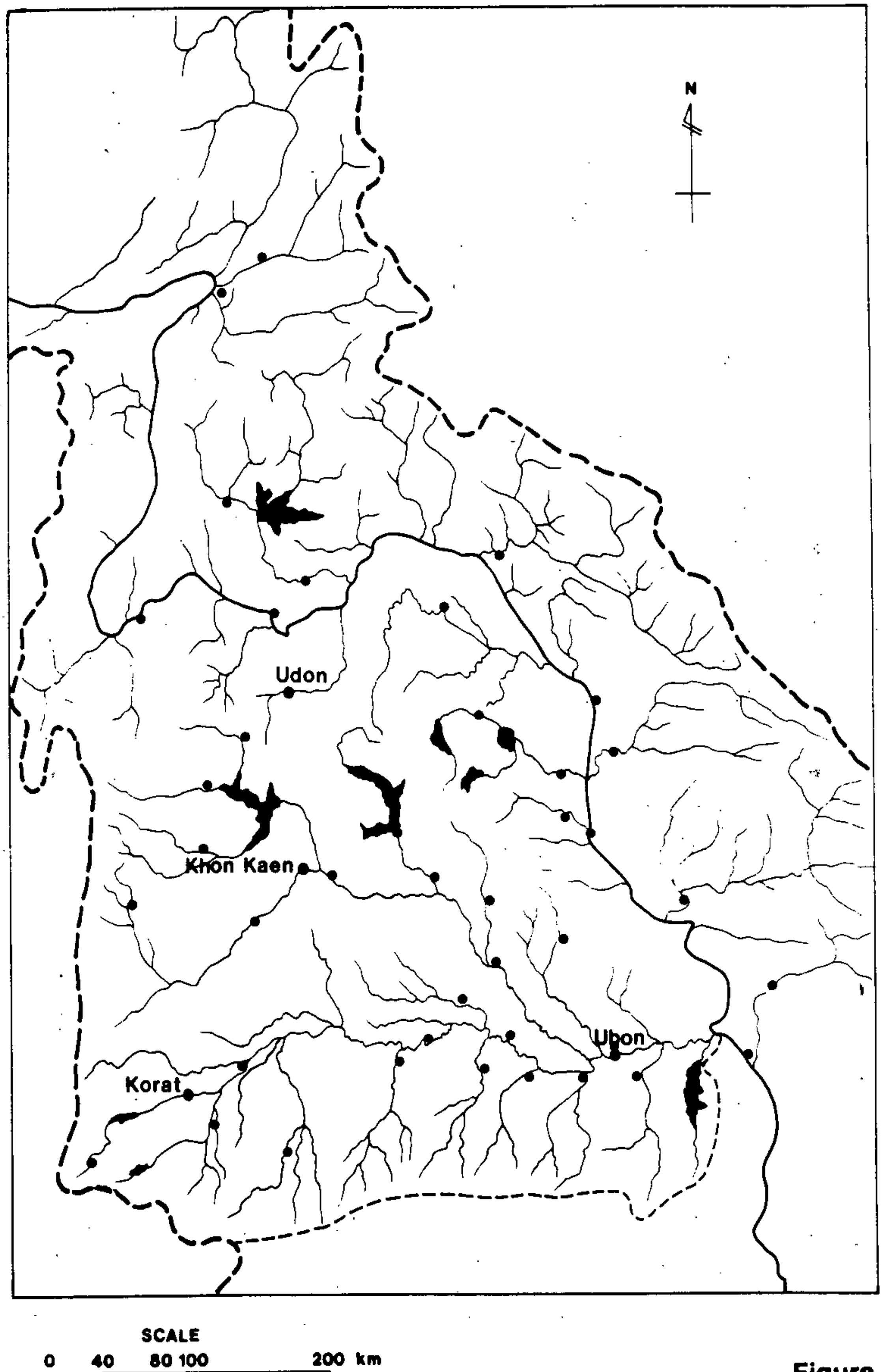


Figure 6

Location of main raingauges

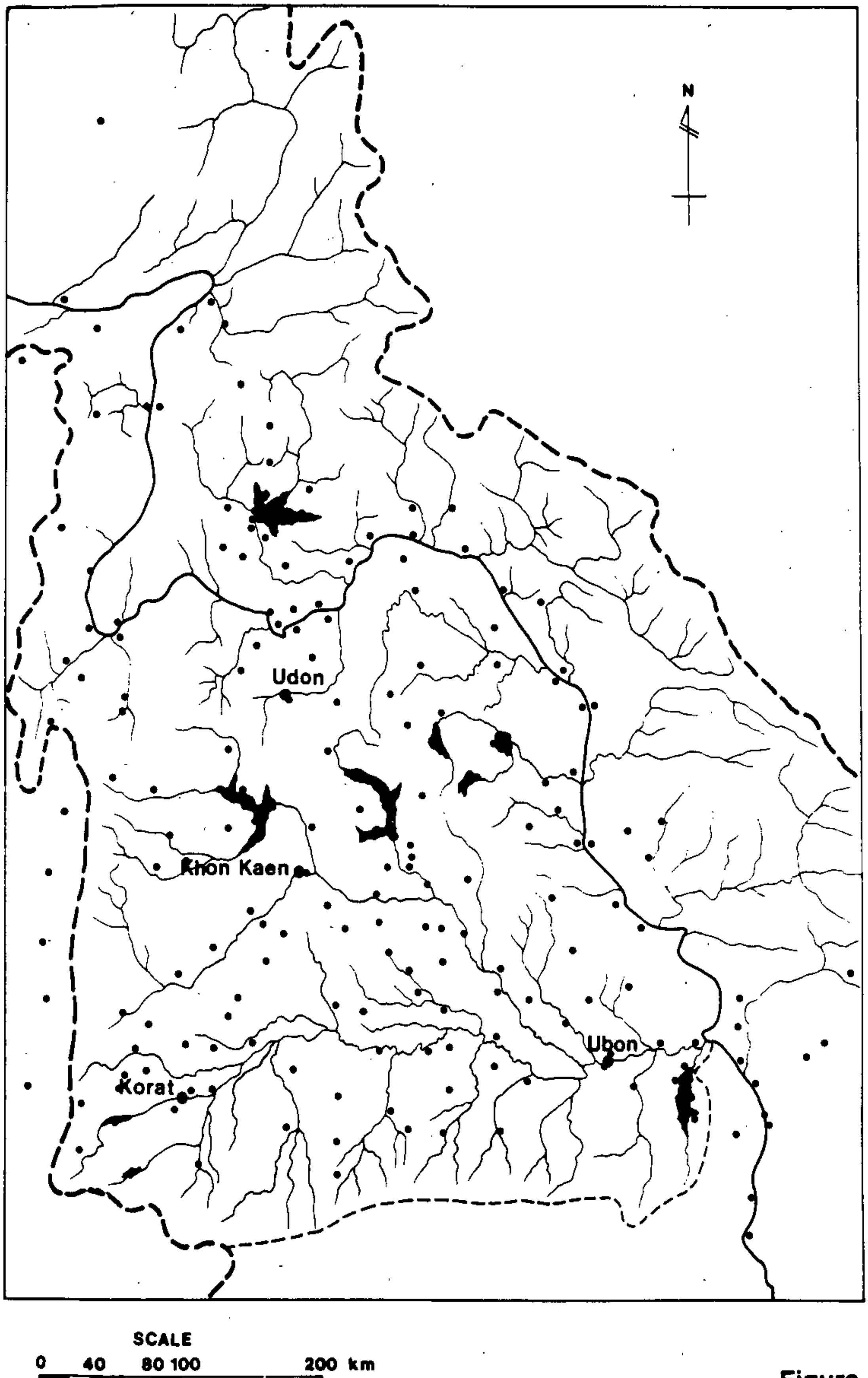


Figure 7

It turned out that the most extensive source of rainfall data was the archive of daily rainfall for Thailand kept by EGAT on magnetic tape; a detailed account of this source of data is given in Part 2 of this report. For the irrigation and reservoir submodels we have simply used the appropriate data from raingauges in or near the project areas. Estimation of potential evaporation at 8 sites in northeast Thailand is discussed in our Phase 1 report. Table 3 summarises those results.

For the purposes of this study we are more concerned with demonstrating that the network model does work, and is capable of simulating the combined effects of the various water resource developments in the Basin. Consequently the absence of continuous flow records over the whole basin for a common period of several years was not a major set back; we selected typical years of hydrological data to represent "wet", "dry" and "average" conditions to be used as baseline examples. These data have been compiled from observed records wherever possible; the recent acquisition of the later volumes of the RID Yearbooks (RID 1979 et seq.) has been particularly useful. For the examples described later in this report we have chosen the years 1973, 1975 and 1980 as "dry", "average" and "wet" years respectively. This choice of years is perhaps somewhat arbitrary, but in future management studies a rather more formal choice would have to be made.

Reservoir data

The characteristics of the major surface water reservoirs in the Lower Mekong Basin are given in Table 4; the locations of the reservoirs are shown in Figure 8. The Nam Ngum and Lam Dom Noi dams are operated for hydropower, whereas Nam Oon and Lam Pao are purely for irrigation. The operation of Ubol Ratana (Nam Pong) has been the subject of much study in recent years (Saltzgitter, 1982), but it appears that it is now operated primarily for irrigation downstream at Nong Wai. This situation is only likely to change when the major structural alterations to the dam have been implemented.

TABLE 3. Estimates of Penman evaporation (mm)

STATION	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
LOEI	106	121	161	168	156	138	141	132	126	130	109	100	1588
KHON KAEN	113	125	166	170	157	135	136	126	122	134	116	109	1609
SURIN	118	127	163	160	146	126	125	115	111	126	114	111	1542
ROI ET	115	124	161	163	155	140	143	134	120	132	117	110	1614
KORAT	111	127	163	166	155	140	140	133	122	130	116	110	1613
UBON	121	129	162	162	152	137	140	133	124	131	120	115	1626
NAKHON PHANOM	110	120	157	160	150	129	134	127	125	131	115	105	1563
UDON THANI	108	122	162	168	154	130	135	125	124	136	115	104	1583

Note: These mean values are calculated from data for the period 1961 to 1979

TABLE 4. Surface water reservoirs

Name	Year of dam completion	Catchment Area (km^2)	Live Storage (m^3 x10^6)	Irrigation Area[1] (ha)	Installed Capacity
Nam Ngum	1971	8460	4783	-	110[2]
Nam Pong	1966	11980	1920	53000	25
Lam Pao	1968	5960	1260	54000	-
Lam Dom Noi	1971	2097	900	24000	24
Lam Nam Oon	1973	1100	475	32500	-
Lam Takhong	1970	1430	290	38000	-
Lam Phra Plerng	1967	807	145	10500	-

Notes:

[1] When the project is fully implemented

[2] An additional fifth unit of 40 MW is being installed.

Location of major reservoirs

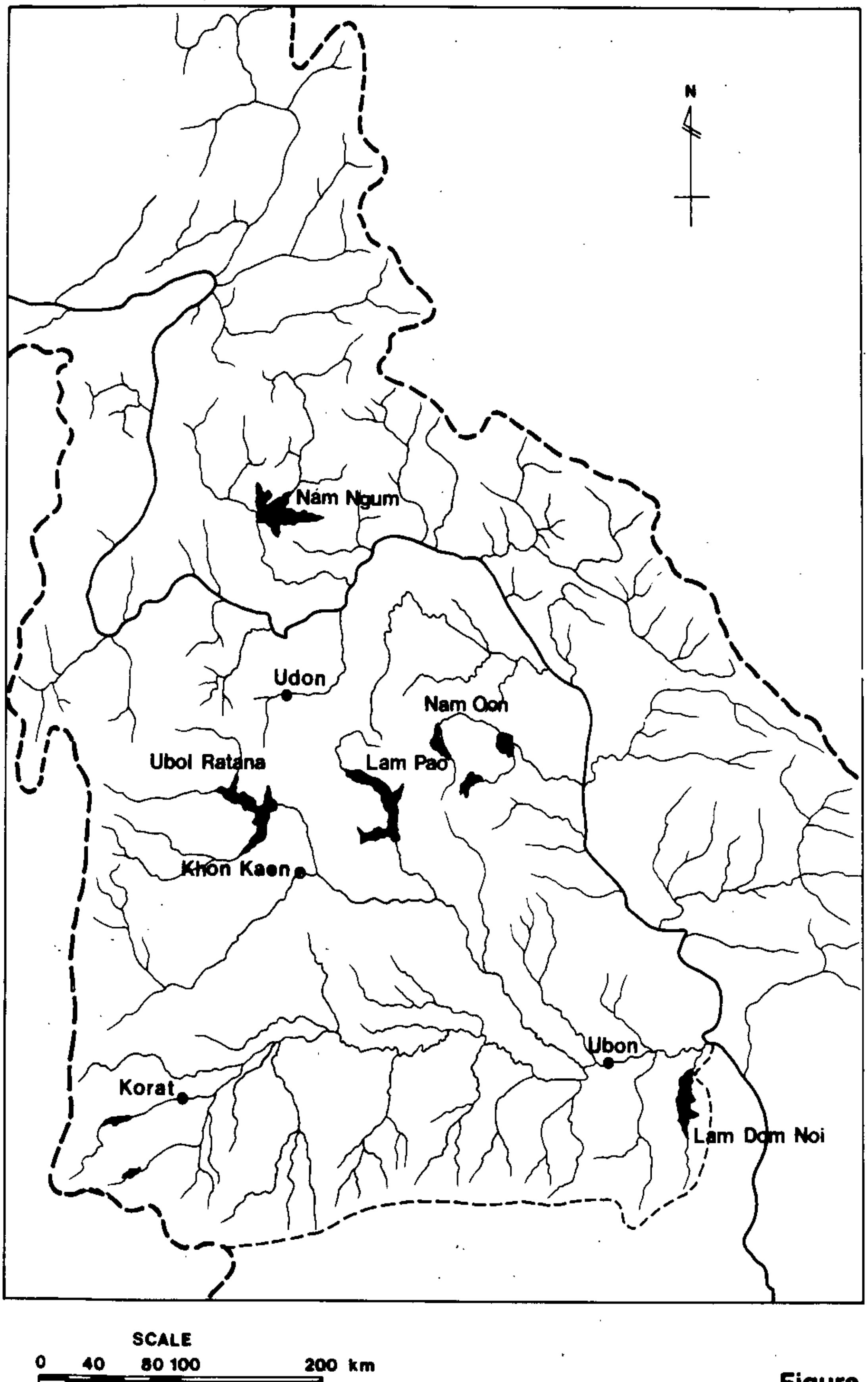


Figure 8

Table 5 shows the range of monthly reservoir data currently available at the Mekong Secretariat.

Irrigation schemes

The development and testing of the irrigation submodel has been based almost entirely on information relating to irrigated agriculture in northeast Thailand. The main reason for this is that very little information relating to schemes in the Lao PDR has been made available to date. By contrast the schemes in northeast Thailand appear to be better documented.

In our Phase 1 Report some of the problems relating to land use and cropped areas were raised, and we concluded that the data available from a number of agencies were inadequate for estimating rates of land use change. As far as gravity irrigated agriculture is concerned, the prime source of data is the Royal Irrigation Department, which collates the cropping statistics.

Tables 6 and 7 present summaries of cropped area data for three of the major schemes operating in northeast Thailand namely Nong Wai, Lam Pao, and Nam Oon; the locations of the schemes are shown in Figure 9. These data were all obtained through various channels from the RID. For Nong Wai scheme the data appear to be fairly consistent, with the exception of the wet season figures for 1975 to 1977, and the dry season figures in 1978. For Lam Pao the figures from all sources agree with the exception of the total dry season area in 1981, where a difference of about 20 per cent is apparent. At the Nam Oon scheme rather more anomalies are evident.

Records of diversions at a scheme headworks proved far more difficult to obtain, and also rather less reliable. A striking example of this can be demonstrated by two sets of figures giving the flows past the weir at Nong Wai (Table 8). These figures are derived from two separate sources, namely a monthly summary, which also give the headwork diversions, provided by the RID Operations and Maintenance Department, and the flow records for RID gauging station E22A which is located immediately downstream of the weir.

TABLE 5. Availability of reservoir data at the Mekong Secretariat

	Nam Ngum	Nam Pong	Lam Pao	Lam Dom Noi	Lam Nam Oon
Releases	1972-1980	1970-1983	1974-1979	1971-1983	1974-1983
Spill	"	"	"	"	-
Water Levels	"	"	"	"	-
Power Output	-	"	n.a.	"	n.a.
Estimated Inflows	-	"	1974-1979	"	1974-1983

Note: n.a. not applicable

- unavailable.

TABLE 6. Cropped areas of Nong Wai scheme (Rai)

1983	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	
Wet Season												*
			89115	89115	89115	118156	119244	121691	138515			
	78119	78119	78119	113799	113799	116856	119364	123861	138515			**
Dry Season												
Rice	98	1524	456	51	489	6294	16746	20705	28970	14762		*
	98	1526	456	51	489	6294	16746	20726	28260			**
			456	51	489	3600	16746	20725	28975	14762	64691	***
Upland Crops	601	531	723	653	3543	1767	2065	1207	2207			**
			723	653	3541	6102	2064	1115	2191	96	662	***
Vegetable	654	1795	514	718	894	963	1550	1122	2173			**
			515	718	895	1278	1550	1054		282	1559	***
Sugar cane					2	550						**
Total	1354	3853	1694	1422	4297	9025	20362	23055	32641			**
			1695	1422	4297	11530	20361	22894	31166	15165	66912	***
								23344	31161	15265		****

Sources of data:-

* RID telephone message to Secretariat Agriculture Division July 1983
note dry season areas are for rice only, and do not represent the total cropped areas

** From Nukool Thongtawee - then Regional Director Region number 5 - in February 1982

*** RID via Secretariat Agriculture Division July 1983

**** RID via Secretariat Agriculture Division June 1983.

TABLE 7. Cropped areas in northeast Thailand (Rai)

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
LAM PAO											
Wet season			115286	116737	116737	116640	116600	116600	117000		*
						116600	116600	116600	117000		****
Dry Season											
Rice	465	568	200	262	640	313	2495	2920	8646		*
			568	3098	262	640	330	1132	2902	8646	3963**
Upland Crops			1512	2372	3410	8582	6645	3945	9676	16767	17367**
Vegetable			263	234	820	1534	728	847		1516	2781**
Total			2343	5704	4492	10756	7706	5924	12578	26933	24111**
								5924	12578	26933	****
						10209	7655	5925	15060		
NAM OON											
Wet Season				35300	52000	138950	133110	59763	203201		*
						100000	137110	138200	203021		****
Dry Season											
Rice			10	200	1800	6948	22320	3034	3978	1642	*
			296	600	496	6909	22320	3051	3978	1642	349**
Upland Crops			375	203	1773	4365		1598	14266	11518	5867**
Vegetable			55	24	70			394	4737	1470	414**
Total			708	827	2339	11313	22320	5043	22981	14630	6630**
								5043	22981	14630	***
						24410	5093	20057	20505		****

Sources of data:-

- * RID telephone message to Secretariat Agriculture Division July 1983 note dry season areas are for rice only and do not represent the total cropped area
- ** RID via Secretariat Agriculture Division July 1983
- *** RID via Secretariat Agriculture Division June 1983
- **** From Nukool Thongtawee - then Regional Director Region number 5 - in February 1982.

Locations of irrigation schemes
for submodel verification

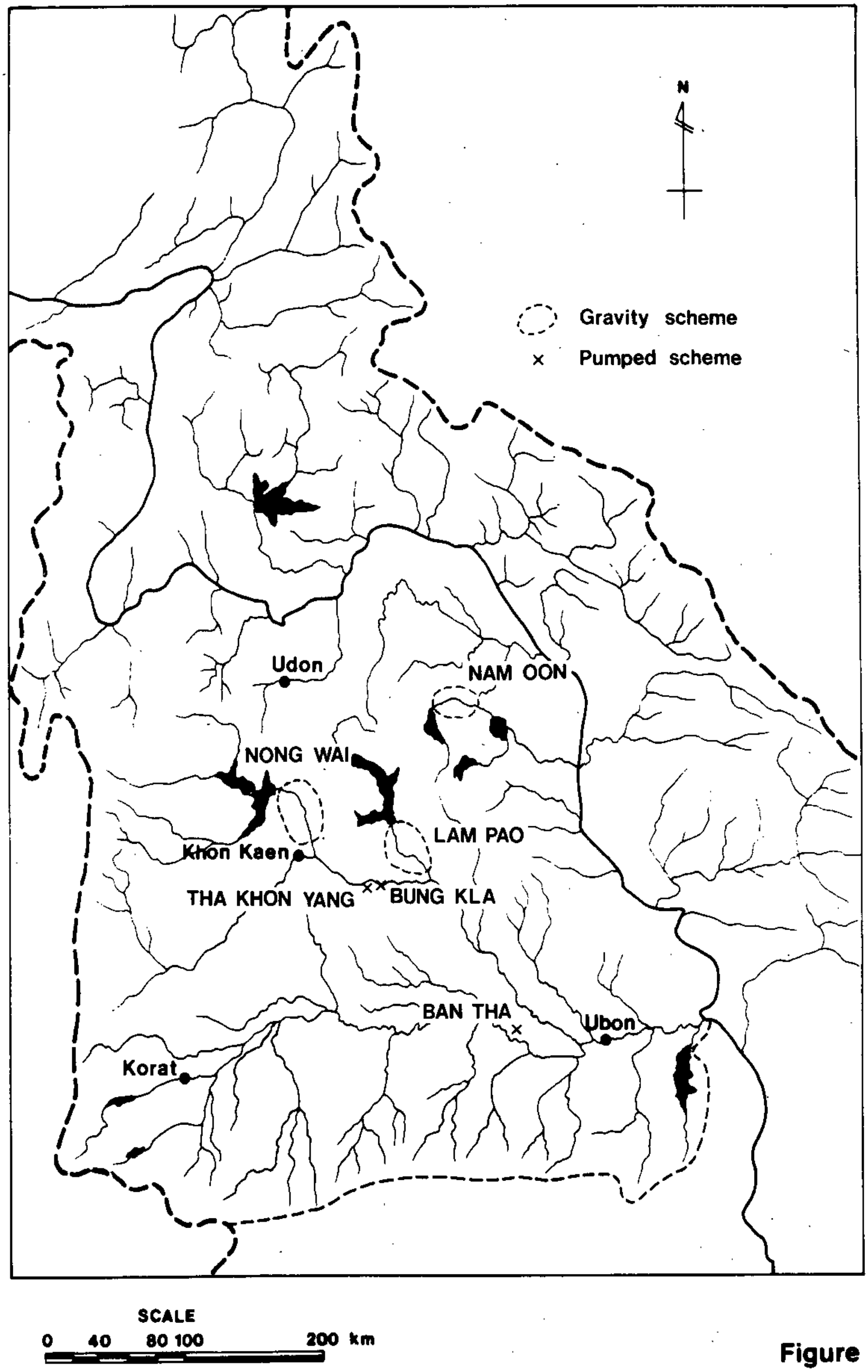


Figure 9

TABLE 8. Discharges past Nong Wai weir (million (m^3)

	A	M	J	J	A	S	O	N	D	J	F	M
1973												
Weir	19	12	42	71	46	85	117	30	26	32	92	138
Gauge	44	38	52	58	55	77	104	53	50	54	89	131
Difference	-22	-26	-10	13	-9	8	13	-23	-24	-22	3	7
1974												
Weir	125	238	254	129	49	56	28	26	34	28	37	54
Gauge	119	228	215	79	43	42	27	23	29	31	30	44
Difference	6	10	39	50	6	14	1	3	5	-3	7	10
1975												
Weir	96	73	103	103	37	232	463	185	115	104	105	136
Gauge	90	76	104	98	38	282	524	169	76	71	72	91
Difference	6	-3	-1	5	-1	-50	-61	16	39	33	33	45
1976												
Weir	307	224	154	112	54	52	215	501	142	122	101	151
Gauge	*	235	148	109	38	46	239	563	160	135	104	163
Difference	*	-9	6	3	16	6	-24	-62	-18	-13	-3	-12
1977												
Weir	236	343	150	124	155	271	128	128	99	119	86	75
Gauge			no data available									
1978												
Weir	158	181	206	178	523	790	*	200	128	114	123	147
Gauge	118	172	179	418	945	869	1256	305	184	139	130	146
Difference	40	9	27	-240	-422	-79	*	-105	56	-25	-7	-1
1979												
Weir	150	188	376	526	523	262	40	12	62	10	12	32
Gauge	146	175	385	531	508	279	28	17	61	14	15	27
Difference	4	13	-9	-5	15	-17	12	-5	1	-4	-3	5
1980												
Weir	29	54	302	648	574	901	1180	156	148	126	148	283
Gauge			no data available									
1982												
Weir	464	210	170	100	34	43	17	33	50	44	27	28
Gauge			no data available									
1982												
Weir	21	39	27	14	3	108	73	35	32	43	98	96
Gauge			no data available									

Notes: * data missing

Weir - monthly data from RID Operations and Maintenance department

Gauge - RID gauge E22A

The figures have been rounded to the nearest whole number.

There are some very large differences in these monthly figures, but there is no pattern of one set of figures being consistently higher or lower than the other set. The most likely explanation for the discrepancies seems to be that the flows over the weir are calculated from upstream water level and an appropriate weir equation. The crest of the weir is 125 m long, so a small error in the measurement of upstream water level will mean a large error in the calculated discharge. In contrast the other set of records are derived from observed river levels in the channel immediately downstream of the weir and an appropriate rating curve.

No direct measurements of drainage from irrigation schemes are made. Estimates of field drainage, and flows passing directly through the canal system without further diversion have to be inferred from the differences between observed flows at various points on the river system and diversions at the scheme headworks. Thus any errors in the individual records will tend to be compounded by differencing, so perhaps it is not surprising that this approach has not been very successful.

The majority of pumped irrigation schemes in northeast Thailand come under the auspices of the National Energy Adminstration (NEA). An inventory and location map of these schemes has been prepared by NEA, but it is somewhat incomplete. The schemes are classified by province, and each scheme can be identified by its name and project number.

The inventory has now been mounted on a data base in the Secretariat computer. A simple program in which the user identifies the scheme or schemes that he is interested in, allows data on project and cropped areas, as well as pumping capacities, to be retrieved.

Table 9 shows the characteristics of groups of schemes classified by province and also by source of water. The table illustrates the large number of schemes that technically exist as projects, but for which little or no data exist. It is extremely important that regular efforts are made to fill in gaps in the

TABLE 9. Summary of pump scheme characteristics by province

Province	Source	Number of schemes in group	Project area (ha)	Irrigated area (ha)	Dry season areas (ha) 1980	1981	1982	Total pump capacity (m^3/s)
Nong Khai	Mekong	55	25824	9024 (15)	1370 (41)	1767(33)	1930 (21)	15.5(4)
	Nam Mong	3	1440	800	236	140	179	.9
Nakhon Phanom	Mekong	29	13360 (1)	4511 (10)	507 (15)	660 (16)	725 (12)	1.8(23)
	Nam Oon	2	960	432	6 (1)	21 (1)	16 (1)	.3 (1)
	Nam Kam	1	480	320	72	61	58	n.a.
Mukdahan	Mekong	15	6688 (1)	2948 (2)	216 (6)	262 (4)	254 (3)	.3(14)
	Huai Bung	1	480	192	n.a.	n.a.	n.a.	.3
Ubon	Nam Chi	12	5760	1536 (4)	n.a.	n.a.	107 (8)	2.4(4)
	Nam Mun	8	3712	1392 (1)	7 (7)	16 (7)	36 (6)	2.1(1)
	Lam Se Bai	4	1920	672 (1)	26 (1)	39 (2)	53 (1)	1.2
	Lam Dom Yai	1	480	192	n.a.	n.a.	25	.3
	Mekong	1	480	192	n.a.	n.a.	n.a.	n.a.
Sisaket	Nam Mun	15	7200	2928 (1)	149 (11)	116 (11)	287 (5)	n.a.
Khon Kaen	Nam Chi	5	2400	1008 (1)	107 (2)	173 (1)	161 (1)	1.2(1)
	Nam Pong	3	1440	384	n.a.	n.a.	145 (1)	.6(1)
Surin	Nam Mun	1	480	192	n.a.	n.a.	n.a.	n.a.
Buriram	Nam Mun	4	1920	752	n.a.	n.a.	n.a.	n.a.
Loei	Nam Heung	3	1136	544	n.a.	n.a.	21 (1)	n.a.
	Nam Loei	3	1408	240	12 (2)	6 (2)	11 (2)	n.a.
	Mekong	1	480	192	n.a.	n.a.	7	n.a.
Korat	Nam Mun	1	480	192	n.a.	n.a.	n.a.	n.a.
	Nam Chi	2	960	n.a.	n.a.	n.a.	n.a.	n.a.
	Lam Ta Kong	1	480	n.a.	n.a.	n.a.	n.a.	n.a.
Roi Et	Nam Mun	2	960	384	n.a.	n.a.	n.a.	n.a.
	Nam Chi	33	15840	6016	270 (28)	425 (25)	1008 (16)	.6(31)
Yasothon	Nam Chi	20	9312	2881 (5)	390 (15)	280 (15)	477 (12)	4.6(5)
Maha Sarakham	Nam Chi	21	9376 (1)	4080 (3)	99 (18)	321 (15)	1132 (3)	1.8(15)

Notes: (1) n.a. not available
(2) numbers in brackets give the number of schemes for which no data were available to compute the group totals. The irrigated areas and total pump capacity are calculated only from the data available in each case.

existing inventory, and to include new schemes as and when they are constructed.

A more serious gap in our knowledge is perhaps the lack of detailed information on pump schemes operated by agencies other than NEA; it appears that the combined total of these other schemes may be significant.

As mentioned at the beginning of this section of the report we have concentrated on irrigated agriculture in northeast Thailand for two reasons. On the one hand these data are more easily available for that region, and on the other little agricultural development in the Lao PDR and Viet Nam has yet occurred that directly affects tributary and mainstream flows.

However for future planning it is important that existing schemes in these two countries are documented more fully. In Viet Nam some discussion relating to the collation of such information has already taken place; for the Lao PDR the current state of knowledge is still far from clear.

4. MODEL VALIDATION

Introduction

Any hydrological model is an attempt to represent the interaction of a number of physical processes whose behaviour can be expressed numerically or by analogue. The precise form and complexity of the numerical functions depends not only on man's understanding of the physics of the processes involved, but also on the purpose for which the model is being used. The individual components of a model, and hence the model itself, are only approximations to reality and can therefore never be wholly accurate.

It was never intended that the submodels should be capable of simulating in detail all the processes that dictate how a reservoir or irrigation scheme might be operated in practice from day to day. To model all the relevant social, economic and political as well as the hydrological factors would not be feasible. Therefore in common with procedures used at the design stage, the irrigation and reservoir submodels use predetermined operating strategies; these contain targets for irrigated area, downstream releases or electricity generation, and can be used to investigate whether the scheme can be operated in accordance with the chosen strategy, and how much water is abstracted from, or returned to the river network. Consequently any differences between scheme output calculated using a submodel and observed data will reflect not only the ability of the submodel to represent the scheme, but also whether the scheme operators have kept strictly to the target operating policy.

Reservoir submodel

The reservoir subprogram is a simple water balance of the inflows, outflows and losses from a reservoir. The calculation of the balance is implicit, in that for each timestep the difference between all the inputs to and outputs from the reservoir equal the change in reservoir storage. Although the program contains some approximations the equations themselves are entirely physically based, reservoir elevation-storage-area curves depend solely on the geometry of the reservoir basin, and turbine characteristic curves are based on the manufacturer's specification.

If reservoir inflows were known independently then it would be possible to verify the reservoir water balance directly. However inflows to the reservoirs in the region are all calculated as the balance of changes in reservoir storage, releases, spills and estimates of evaporation and other losses. So any test of the reservoir balance using inflows calculated in this way, would not be independent. There was no other way in which the resevoir balance could be verified independently.

The original program was a straightforward month by month simulation of the performance of a reservoir given a sequence of inflows and rainfall over the reservoir area; an additional option now allows a shorter timestep to be used. For a given set of operating rules and constraints, the program computes releases to meet demands and flood control targets; it calculates spills, energy and power generated and keeps a running balance of the status of the reservoir. The simulation is based on average conditions during each timestep.

This procedure implies a uniform inflow and a uniform change in reservoir contents throughout the timestep, conditions which are not entirely realistic. If excess inflows are concentrated towards the end of the timestep, then any spill will tend to be underestimated by the simple reservoir balance. Also the form of the reservoir area curve might mean that a simple average area derived from beginning and end of month values will always be an overestimate and that evaporation will be overestimated correspondingly. Similar effects could be noted for energy calculations from the way in which average head must be assessed.

Nevertheless for this work, where the subprogram is used to determine the releases from a reservoir into a river system, these approximations are considered to be acceptable.

Irrigation submodel

The data available for validation of the irrigation model comprise crop areas and observed diversions or abstractions at the scheme headworks; we have discussed the shortcomings and inconsistencies in these data in Chapter 3. Data from three gravity-fed and three pump schemes in northeast Thailand (Table 10 and Figure 9) were used to test the irrigation submodel; these schemes were chosen because the relevant data for them were readily available. Where necessary assumptions based on previous studies in the region, or on field visits, were made to complete any gaps. For information on pump schemes, the assistance from staff of the northeast Thailand pump irrigation project was particularly valuable.

On the gravity schemes diversions are highest during the wet season from May to November, but encouragement is being given to increasing the cropped area in the dry season, that is from December to April. To date the highest cropping intensities on the large gravity schemes has been around 50 per cent and 15 per cent in the wet and dry seasons respectively.

In contrast on the pumped schemes abstractions are highest during the dry season when farmers pay a fixed charge for water, based on the area that is actually cropped. Only occasional supplementary irrigation is practised during the wet season, when the farmers have to pay for the hours pumped. Thus they seem to delay the onset of pumping until it is absolutely necessary to irrigate to prevent serious damage to the crop.

The values of the irrigation duty and surface drainage estimated by the submodel are directly proportional to the cropped areas, so any errors in the values of cropped areas are directly reflected in these model outputs. Great difficulty was experienced in abstracting reliable data on cropped areas, particularly for the gravity-fed schemes. It is assumed that the data quoted for cropped areas in Tables 6 and 7, are the areas actually irrigated.

On such schemes no record appears to be kept of the cropped areas on individual blocks of a scheme located on different sides of a river, although discharges on the left and right bank main canals are recorded separately. This necessitated the blocks from both sides of the river being lumped together for modelling purposes, and observed monthly values of combined discharges were accepted as the irrigation duty for the gravity schemes.

TABLE 10. Irrigation schemes used to test submodel

	GRAVITY FED SCHEMES			PUMPED SCHEMES		
Name	Nong Wai	Lam Pao	Nam Oon	Bung Kla	Ban Tha	Tha Khon Yang
Region	Khon Kaen	Kalasin	Nakhon Phanom	Maha Sarakham	Sisaket	Maha Sarakham
Design area (ha)	40480	54080	32483	480	960	480
Capacity of intake channel	50.0	53.0	30.87	0.25	0.5	0.25
Rainfall stations	Khon Kaen	Kalasin Roi-et	Sakon Nakhon	Tha Khon Yang	Sisaket	Maha Sarakham Tha Khon Yang
Evaporation station	Khon Kaen	Roi-et	Nakhon Phanom	Roi-et	Ubon	Roi-et

On the pumped schemes records are kept of the number of hours pumped each month, and these were converted to a monthly average discharge using the capacities of the pumps, which are 0.25 m^3/sec for pontoon centrifugal type, and 0.3 m^3/sec for axial type. Most pumped schemes possess a single pump, but Ban Tha scheme had two. No record is normally kept of wet season cropped areas, and a nominal value of 10 per cent of the design area was used to run the model.

In the case of the Nong Wai scheme it was also possible to make an estimate of the observed surface drainage from the scheme. Although the scheme drains at a number of points to the Chi and Nam Pong rivers, it was possible to subtract from the downstream flows observed at Ban Kok on the Chi river, the upstream flows at Nong Wai (E22A) on the Nam Pong and at Ban Tha Phra (E16A) on the Chi, together with an allowance for the runoff from the catchment area intervening which does not form part of the Nong Wai scheme. Although these estimates are subject to considerable error in times of high flows, the mean monthly values over a period of years are considered to give a useful indication of the drainage from a typical gravity-fed scheme.

Using the irrigation model, monthly values of irrigation duty and surface drainage were simulated for several years of record from each of the six sample schemes. These values were compared with the corresponding observed values for the individual months. In certain years these monthly values corresponded quite closely, while in other years they differed substantially, for no apparent reason. Better agreement was obtained by averaging each month's values over the period of record, though occasionally a full year's data were omitted if certain individual observed month's data were missing.

Some typical results of the mean irrigation duty predicted by the model are shown in Figure 10. One striking feature of these results is that the computed dry season duties are considerably smaller than the observed values. One plausible explanation of these results is perhaps that, in order to encourage farmers on a scheme to increase their acreage of dry season crops, excess water is passed down the main canals to convince the farmers that an adequate supply will be available throughout the dry season.

Of the three different methods of calculating effective rainfall, the simulated monthly values averaged over the period of record differed little between using either the Joshua or Gibb function, but did differ markedly if the zero effective rainfall method was employed. In the latter method the gross rainfall has no effect on the value of the simulated irrigation duty, but only affects the surface drainage estimate. During the middle of the wet season the gravity-fed schemes' observed irrigation duty did not exhibit the reduction in values simulated by the model using the Gibb or Joshua methods (see Figure 10). It followed more closely the broad shape of the monthly values simulated by the zero method, although the latter tended to be proportionally larger. It appears, therefore, that in practice the general control of irrigation duty on these schemes is not sensitive to volume of gross rainfall falling on the fields, except when an exceptional period of heavy rainfall occurs.

Typical results from a pumped scheme, Tha Khon Yang, are shown in Figure 11. April is usually used as the initial month of a simulation run to coincide with the start of the hydrological year. However in this figure, November has been shown as the initial month to improve clarity.

On the pumped schemes, although the pumps are rated at 0.25 m^3/sec or 0.3 m^3/sec, the maximum pumping capacity of a single pump has been taken at half the rated value. This is because the pumps are not normally used for more than 12 hours per day. A warning flag in the program highlights periods when this maximum capacity is exceeded by the simulated duty; this occurred several times during the cropping season commencing in December 1978.

Observed and predicted irrigation duty

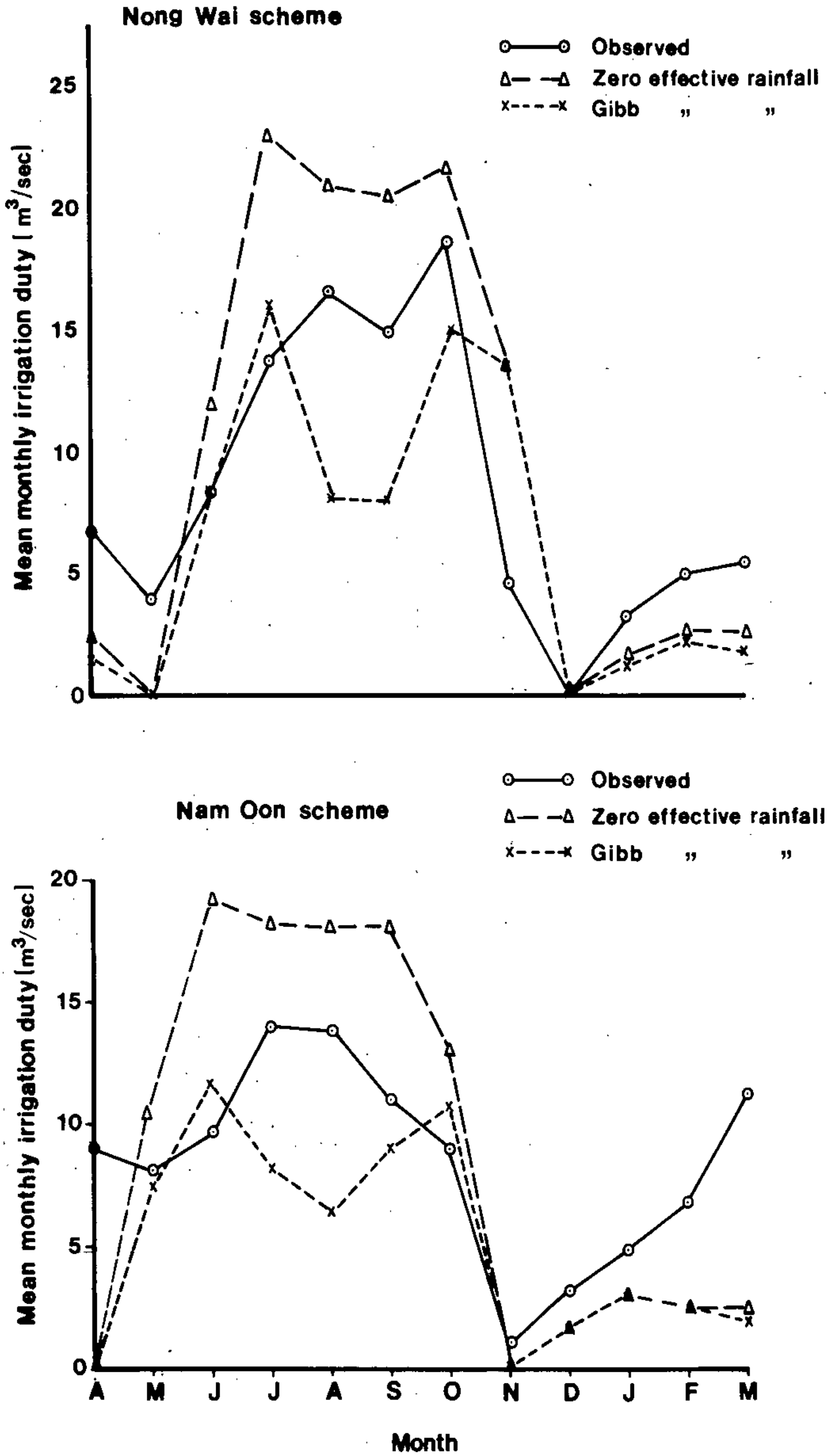


Figure 10

Observed and predicted irrigation duty

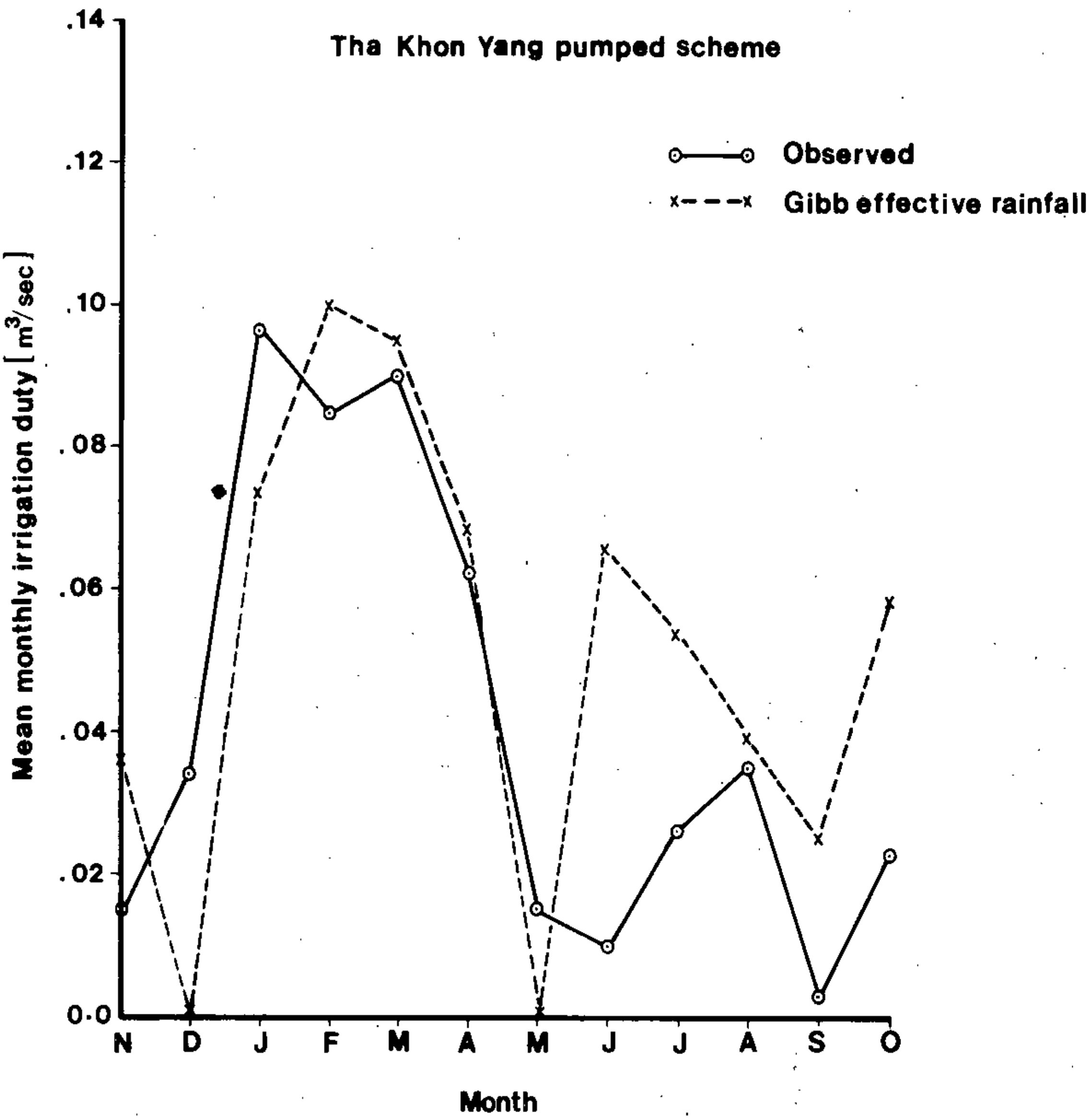


Figure 11

On the pumped schemes, although the model gives a reasonable representation of the irrigation duty in the dry season, it is less applicable during the wet season (Figure 11). The reason for this is that the schemes are used during this latter period, if at all, only for supplementary irrigation, and no record is kept of the monthly cropped area irrigated. There is some evidence on the Tha Khon Yang scheme, however, that in this case the irrigation duty control is more sensitive to gross rainfall falling on the fields. As mentioned above this is not unexpected, since the method of water charges means that individual farmers have to pay for sole use of the main pump for the hours in which it is supplying their crops.

In individual years there appears to be some variation in the timing of the observed irrigation duties on both gravity and pumped schemes throughout the region. For example, Nam Oon scheme duties give a closer fit if the model cropping calendar is put one month earlier than those for the other schemes, while Ban Tha requires a lag of between half and one month. For reasons of space the results for individual years are not reproduced here. Such variations may either result from genuine differences in the onset of the wet season rainfall or may suggest deficiencies in the model structure, such as the omission of a component to represent the water requirements of the nurseries.

Another method of validating the model's performance was to compare the surface drainage calculated in the model with the observed. Because of the locations of gauing stations relative to the diversions to, and drainage from, the main gravity schemes this comparison was only possible for the Nong Wai scheme. The "observed" surface drainage was calculated by the difference between the flows observed at selected points in the river network. This method of calculation may account for the negative drainages occurring during the dry season, or the latter may genuinely represent some loss to groundwater or evaporation occurring along the river reach.

There is no obvious explanation available to account for the large discrepancies between model and observed drainage during the period between September and November. However we have mentioned in Chapter 3 some problems associated with some of the streamflow data at the Nong Wai headworks. The highest flows occur during that period, and because the flows are estimated using rating curves whose accuracy at high flows must be doubtful, the apparent differences in Figure 12 need not be taken too seriously.

For the reasons given above it has not been possible to achieve an objective validation of the model. However given the quality of the input data available, the results show that this simple water balance model can adequately represent the type of irrigation practised in the region over the past decade. More detailed information, particularly on cropped areas in the different parts of the larger schemes and on surface drainage, would allow the submodel to be applied and tested in more detail.

For the purpose of providing estimates of net irrigation abstractions to be used in the network model, the irrigation submodel is considered to be satisfactory.

Network

The way in which a river network is defined in the network model is sufficiently flexible to accommodate the wide range of development schemes that could reasonably be expected to occur in the future.

Calibration of the channel routing parameters is a rather different problem, as it entails selective improvement of initial parameter estimates, by comparison of observed and simulated flows at the downstream end of the channel being considered. However the main Mekong, and many of its major tributaries, have already been the subject of modelling exercises using the SSARR model (US Army Engineer Division, 1968; AIT, 1982; NEDECO, 1982). These studies can therefore provide the basis for the selection of suitable routing parameters.

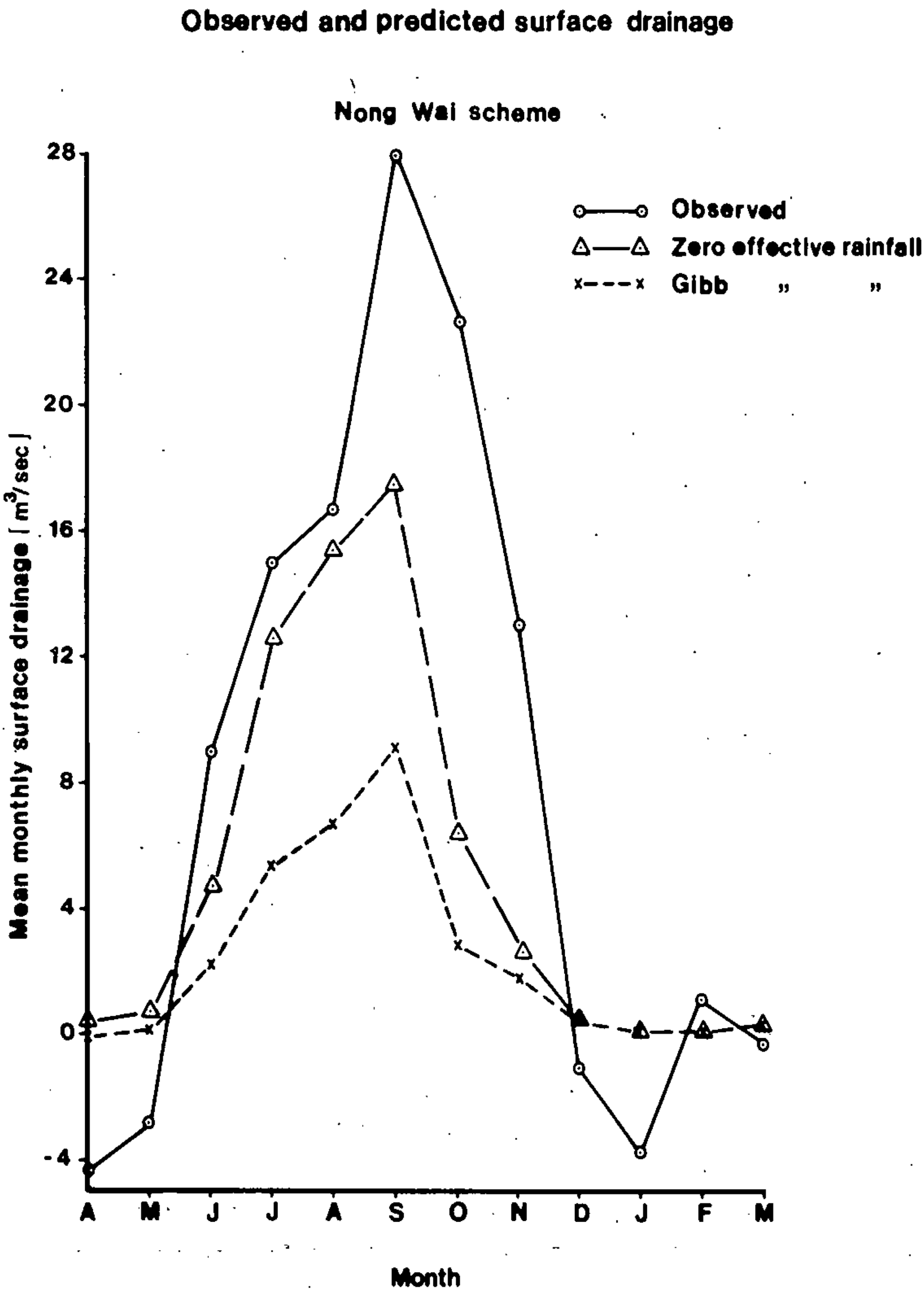

Observed and predicted surface drainage
Nong Wai scheme
Observed
Zero effective rainfall
Gibb " "
Mean monthly surface drainage [m3/sec]
28
24
20
16
12
8
4
0
-4
A M J J A S O N D J F M
Month

Figure 12

5. DEMONSTRATION RUNS

Introduction

The purpose of this section of the report is to illustrate how the Network model can be used to evaluate the relative benefits of operating a given network under different operating strategies. The examples given here are intended only to illustrate the use of the model. Their inclusion here does not necessarily imply that they are actively being considered by the operating authorities concerned.

Before the model can be run, a number of important decisions have to be made. The first is obviously to identify the configuration and components of the network. The network discussed below is part of the Mun-Chi basin in northeast Thailand (Figure 2); this right bank tributary drains into the Mekong between Mukdahan and Pakse. This particular network was chosen because it allows several aspects of the network model to be demonstrated, and reasonably good hydrological data were available. The network can either be considered separately in its own right, or as the upstream portion of a much larger network that could incorporate the Mekong itself.

Sets of hydrological input data have to be chosen to provide the necessary tributary inflows as well as rainfall and evaporation data needed for the irrigation submodel. This will clearly involve considerable care and judgement, and will depend to some extent on the precise purpose for which the model is being used.

The physical characteristics of any reservoirs or irrigation schemes will be known from published sources. However the user will have to choose the crops and cropping calendars to be tested for each scheme as well as specifying other parameters for the submodel. The operation of a reservoir depends not only on the demands put on it, but also on its contents at the start of the simulation and on its rule curves. The choice of rule curve is particularly important, and will be dependent on what is to be achieved downstream. A flood rule curve should be inviolate, because it must be adhered to, otherwise the physical safety of the dam might be jeopardised; but an operating rule curve allows considerable variations in releases to be achieved, whilst at the same time meeting all demands.

Network

The network used for this example is the Nam Chi, upstream of its confluence with the Nam Mum. The network therefore includes the Ubol Ratana reservoir, which is used for both hydropower and irrigation, and the Lam Pao reservoir which is used only for irrigation. The Nong Wai gravity irrigation scheme is located some 30 km downstream of Ubol Ratana, and the Lam Pao gravity scheme just downstream of its reservoir (Figure 3). There are also a number of pump irrigation schemes located on the banks of the Nam Chi, but because the data for these schemes are so incomplete (see Table 9) they have not been considered in this example.

Apart from these two reservoirs the main inflow points to this network are the Nam Chi at the Tha Phra gauging station, and the left bank tributary, the Nam Yang. Clearly it would be possible to make the network more complicated by representing some of the tributaries in more detail. The Nam Chi upstream of Tha Phra is a case in point, but to include this sub-basin would require streamflow data for more inflow points, some of which are not gauged at present.

The last comment begs the question of how ungauged inflows to a network might be determined. Current practice is to simulate runoff from rainfall using a deterministic model such as the SSARR model, but we feel that such an approach will not always be required for the network model. Indeed we have demonstrated in Part 2 of this report that there are some serious constraints to using the SSARR model in the region and particularly in catchments where there are few raingauges.

As mentioned earlier the network model is not intended to model the behaviour of a river system in absolute terms. Rather it is to be used to model the relative differences in output that arise from using the same set of tributary and mainstream inflows but with different operating strategies at the reservoir or irrigation schemes. So provided reasonable estimates of tributary inflows can be made, for example as a proportion of the flow measured in a nearby catchment, then detailed conceptual modelling may not always be required.

Baseline data

Two different approaches are available for specifying the downstream hydrograph against which the model output can be compared. The first would be to use the model with observed inflows and the actual releases, abstractions and returns for the component schemes of the network. Releases from a reservoir are almost always recorded but if no records of releases were available for an irrigation scheme then these could be simulated using the appropriate submodel and the records of actual cropped area and cropping patterns (Table 11). The second would be to use an observed hydrograph, if available, for the downstream output point. Appropriate downstream gauges for the network used here would have been the Nam Chi at Yasothon, or the Nam Chi at Maha Chana Chi.

This second approach would in theory allow an overall test of the model to be made. However as shown in Table 12 there are discrepancies between the observed annual data for these two gauges. So in practice it appears that the observed data are inadequate to allow one to distinguish between errors caused by the models or any of its components and errors that result from inaccurate data.

Consequently for the example that follows we have used the model to specify the downstream baseline conditions. The irrigation duties and return flows for both the Nong Wai and Lam Pao schemes were calculated using the actual irrigated areas shown in Table 11. The inputs to the network from the Ubol Ratana and Lam Pao reservoirs were taken as the observed releases; the two

TABLE 11. Cropped area of Nong Wai and Lam Pao schemes

(per cent)

	Nong Wai		Lam Pao	
Year	Wet Season	Dry season	Wet season	Dry season
1970	14.7	0.6		
1971	21.0	0.7		
1972	21.0	0.5		
1973	30.9	1.5		
1974	30.9	0.7		
1975	30.9	0.6	34.1	1.7
1976	45.0	1.9	34.5	1.3
1977	45.0	3.6	34.5	3.2
1978	46.2	8.0	34.5	2.3
1979	47.2	9.1	34.5	1.8
1980	49.0	12.9	34.5	3.7

Nong Wai total area 40480 ha

Lam Pao total area 54080 ha

TABLE 12. Network inputs and outputs: baseline conditions (million m^3)

	dry year	average year	wet year
Lam Pao			
abstraction	227	209	223
return	81	99	115
Nong Wai			
abstraction	150	124	264
return	56	66	110
Nam Yang			
inflow	915	1222	1294
Lam Pao reservoir			
release	1072	2679	2716
Ubol Ratana reservoir			
release	600	1519	4614
Nam Chi at Tha Phra			
inflow	754	1458	3827
Net input	3101	6710	12189
Observed flows			
Nam Chi	4000[1]	9530[1]	14200[1]
at Yasothon	3056[2]	7635[2]	12733[2]
Nam Chi at			
Maha Chana Chi	3935[2]	9804[2]	17579[2]

1 from Mekong Secretariat Yearbooks

2 from RID (1979 et seq.)

components of channel inflows of the Nam Chi at Ban Tha Phra and the Nam Yang were based on RID flow data (RID, 1979 et seq.). For the Nam Yang a multiplying factor, calculated from catchment area and rainfall, was used to estimate the inflows at the tributary junction. A summary of these inputs and outputs is given in Table 12, and shown graphically in Figure 13. These flows are then routed through the channel network to produce an outflow hydrograph at the outflow point (Figure 14). It is against these baseline conditions that the effects of alternative operating strategies can be assessed.

In these examples, where over 70 per cent of the network area is accounted for by the inputs and outputs given in Table 12, we have made no allowance for lateral inflows. The net inputs are broadly in line with the observed data, and so for this demonstration this approach is reasonable. In other examples, where the proportion of the contributing area not accounted for by major tributaries is larger, it might be necessary to make an allowance for lateral inflows and represent them as extra tributaries.

Components of the network

Once the configuration of the network has been fixed the user can then try out various operating strategies on each component individually. Any shortfalls can be identified and the operating strategy adjusted accordingly.

It may often be instructive to start by looking at the historic operation of the schemes and to identify whether there appear to be any improvements that might be made. Table 11 clearly shows that the percentage cropped areas are in general much lower than the target figures given in various consultants' reports. For the Nong Wai scheme, Salzgitter quote 100 per cent and 65 per cent for the wet and dry seasons respectively (Salzgitter, 1983); at Lam Pao the corresponding figures are 100 per cent and 60 per cent (Tahal, 1979).

Network inputs and outputs : Baseline conditions

[million m³]

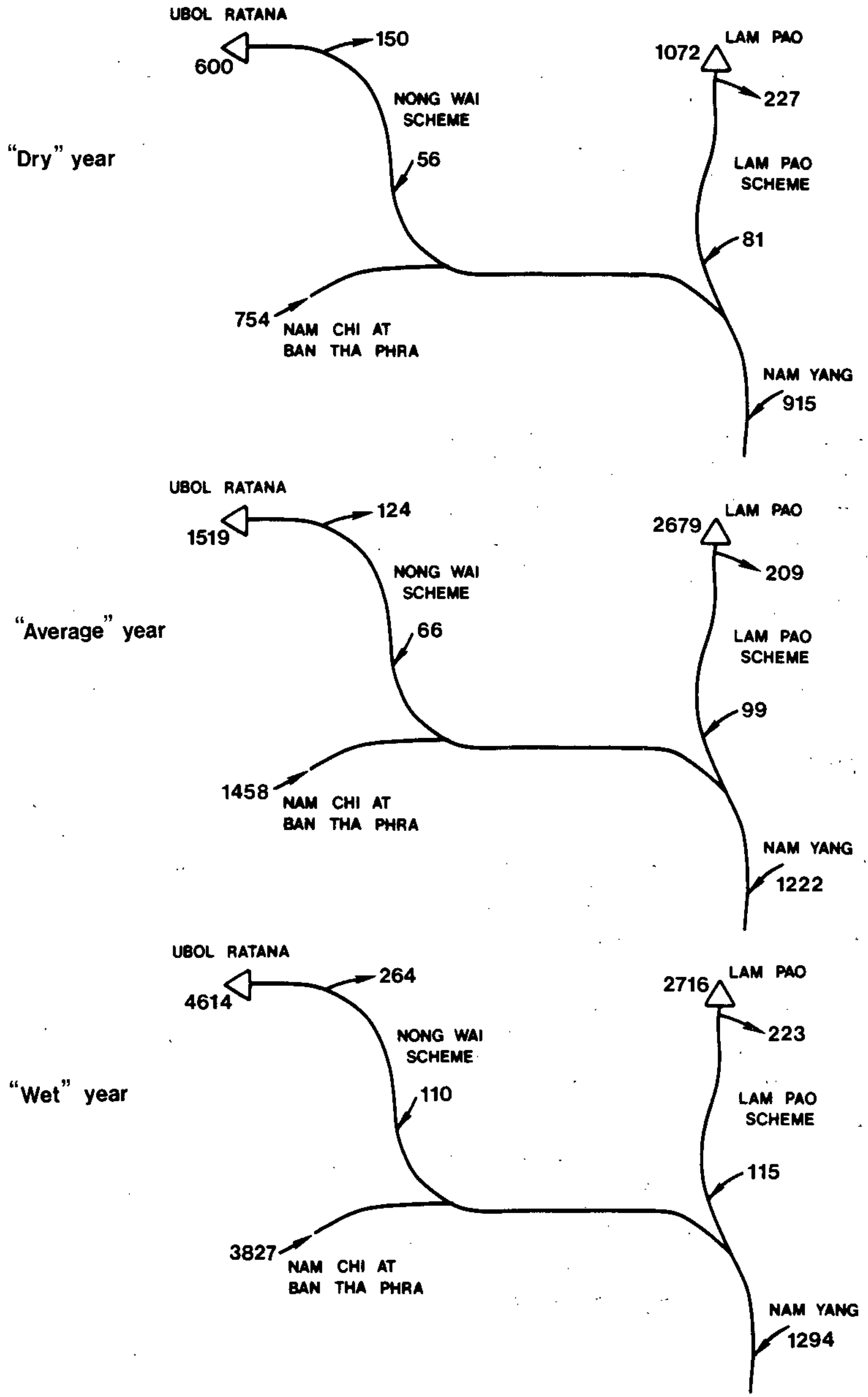


Figure 13

Downstream hydrograph - baseline conditions

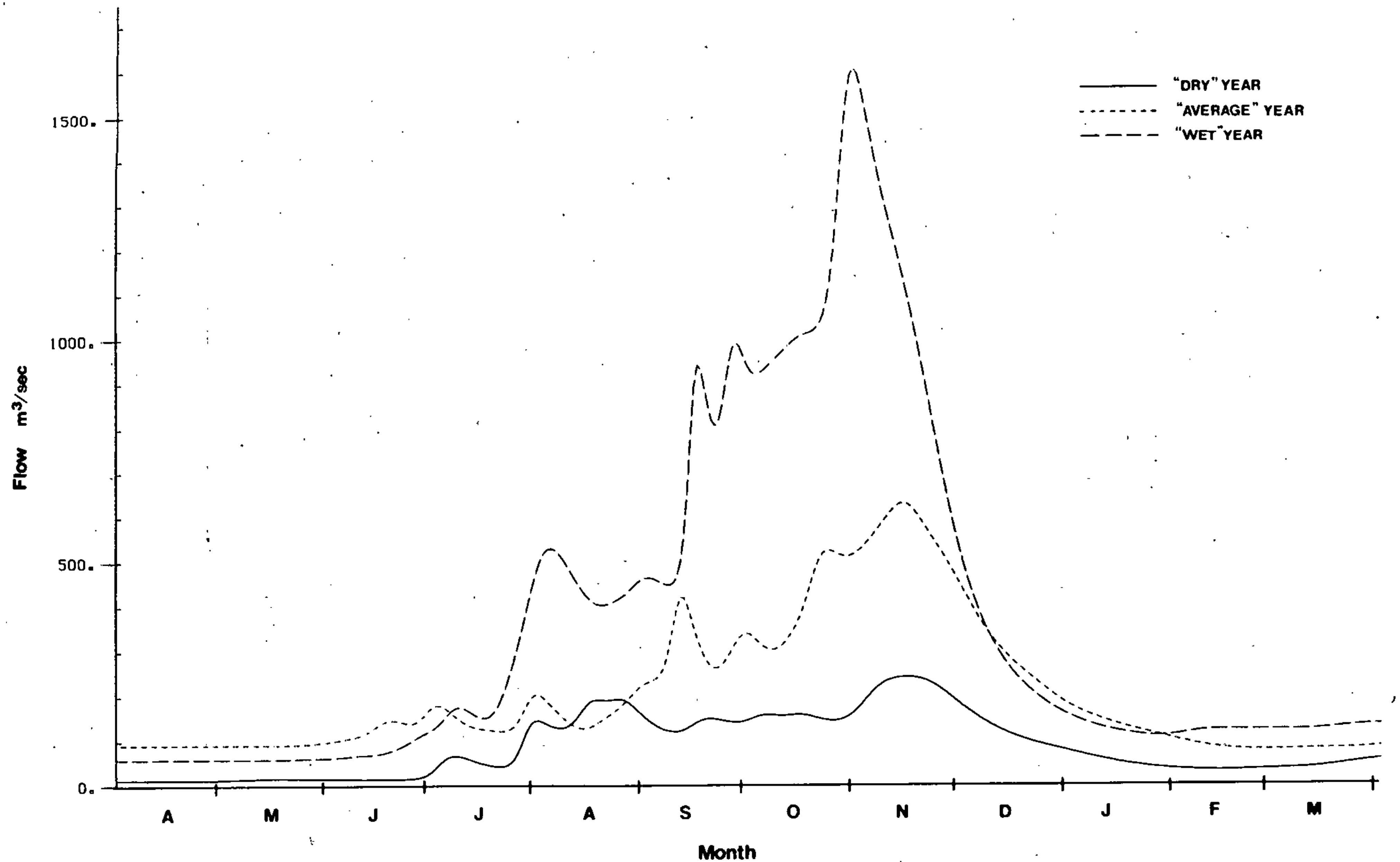


Figure 14

The question that then needs to be answered is whether there is enough storage available in the respective reservoirs to support those targets? The irrigation submodel is then used to estimate the irrigation duty at the relevant diversion points on the river network. Corresponding volumes of water, plus any allowance for compensation or residual flow requirements, must then be released from the reservoir upstream. These target releases and appropriate operating and flood rule curves can then be fed into the reservoir submodel and the performance of the reservoir simulated to investigate whether it could indeed meet the demands on it.

This procedure is appropriate only for an upstream reservoir that is operated for irrigation alone, or where irrigation at a multipurpose scheme is given the highest priority. If hydroelectric power generation is the priority use, then the reservoir submodel would be used to estimate the releases required to satisfy the power and/or energy requirements. The cropped area at irrigation schemes downstream could then be modified to be in line with these releases, although in practice there would be a less extreme separation between power and irrigation releases.

A set of operating policies for each of the component schemes is thus specified. The purpose of the network model is now to combine the operation of all the schemes in the network to estimate the residual flow in the main stem.

Examples of model runs

Once the network structure has been defined and each of the individual components tested to make sure that they can operate without failure to meet the demands put on them, the network model is then run with the baseline hydrological conditions to produce a hydrograph at the downstream point against which alternative development or operating strategies can be assessed. Three different operating policies are illustrated here as examples.

For Policy 1 we have assumed that the Lam Pao and Nong Wai schemes would be cropped at their design cropping intensity. On both schemes 100 per cent of the scheme area would be cropped in the wet season, with dry season intensities of 60 and 65 per cent for Lam Pao and Nong Wai respectively (Tahal, 1979). The irrigation submodel was used to calculate the abstractions required at the head works. These requirements, plus a nominal extra allowance to give some residual flow downstream of the abstraction points, are then used as the demands on the appropriate reservoir upstream. Reservoir rule curves for Ubol Ratana were taken from Mekong Secretariat, 1982. At Lam Pao the rule used (Tahal, 1979) follows the general pattern employed by RID that is effectively a design flood rule curve.

For Policy 2 all the components were left unchanged, except that Ubol Ratana was operated with electricity generated at 3.3 Gwh/month (EGAT, 1983) as the main priority. The purpose of this policy was to investigate whether the power releases would be sufficiently in excess of the irrigation requirements to give a noticeable effect downstream.

Policy 3 differs from Policy 2 in that the cropped areas of the irrigation schemes are set to the areas actually cropped during the years in question.

A summary of the network inputs and outputs under these three policies is given in Table 13, and illustrated in Figures 15 to 17.

Hydrographs of the routed flows at the downstream output point are shown in Figures 18 to 20; although the differences between the effects of the various operating policies are not particularly striking there are a number of points that are worth noting.

In all three years the beneficial effects during the dry season of hydropower releases in excess of downstream consumptive requirements are evident. In contrast when releases are matched to irrigation demands (as in Policy 1) there is very little residual flow even in the wet year.

TABLE 13. Network inputs and outputs: test runs (million m^3)

	Dry year			Average year			Wet year		
	Policy 1	Policy 2	Policy 3	Policy 1	Policy 2	Policy 3	Policy 1	Policy 2	Policy 3
Lam Pao									
abstraction	970	970	227	926	926	209	901	901	223
return	293	293	81	347	347	99	389	389	115
Nong Wai									
abstraction	769	769	150	694	694	124	709	709	264
return	220	220	56	265	265	66	253	253	110
Nam Yang									
inflow	915	915	915	1222	1222	1222	1294	1294	1294
Lam Pao reservoir									
release	1275	1275	1275	2529	2529	2529	2451	2451	2451
Ubol Ratana reservoir									
release	947	1178	1178	1528	1539	1539	4775	4783	4783
Nam Chi									
inflow	754	754	754	1458	1458	1458	3827	3827	3827

Network inputs and outputs : Dry year

[million m^3]

Policy 1

Policy 2

Policy 3

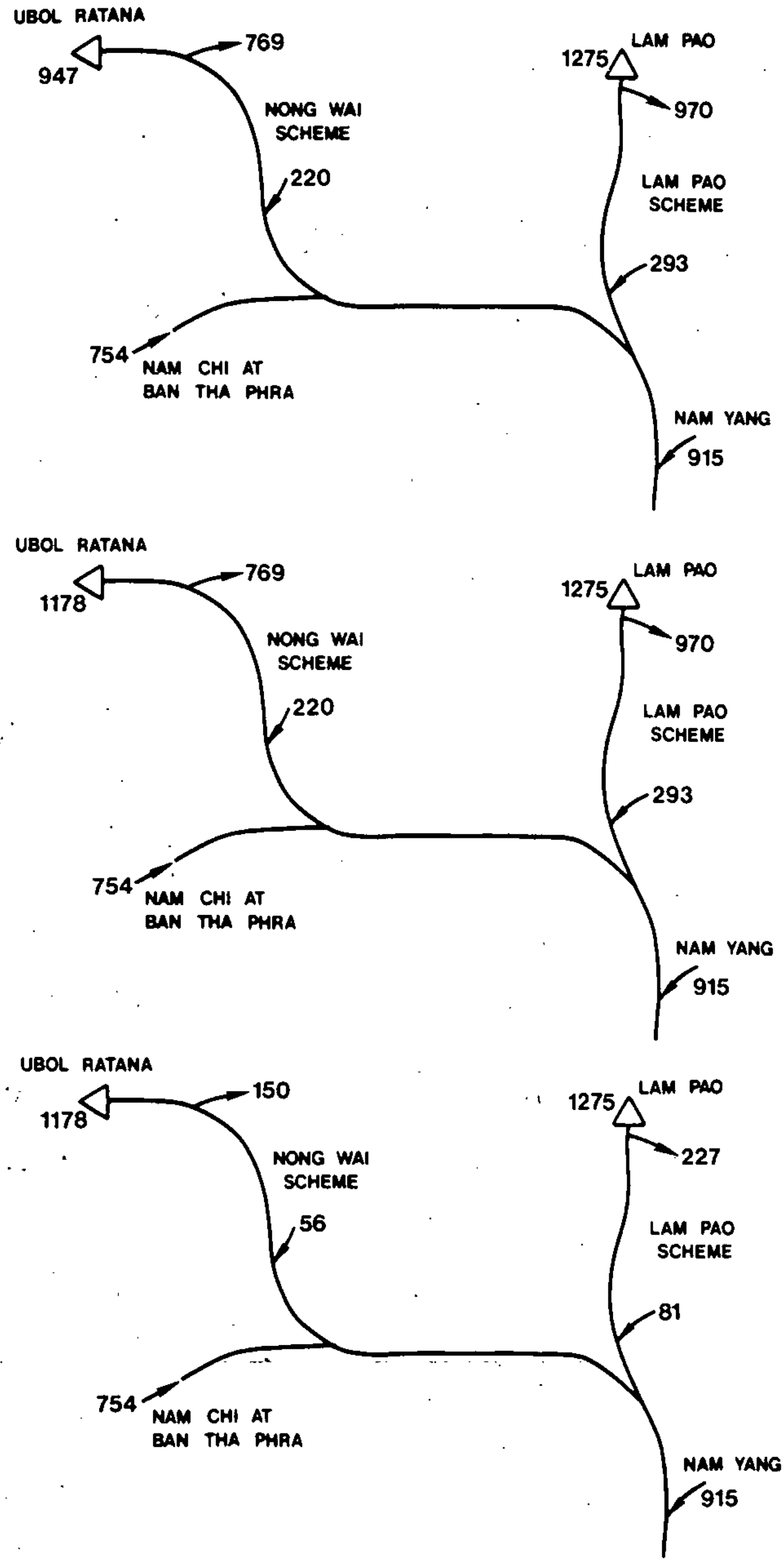
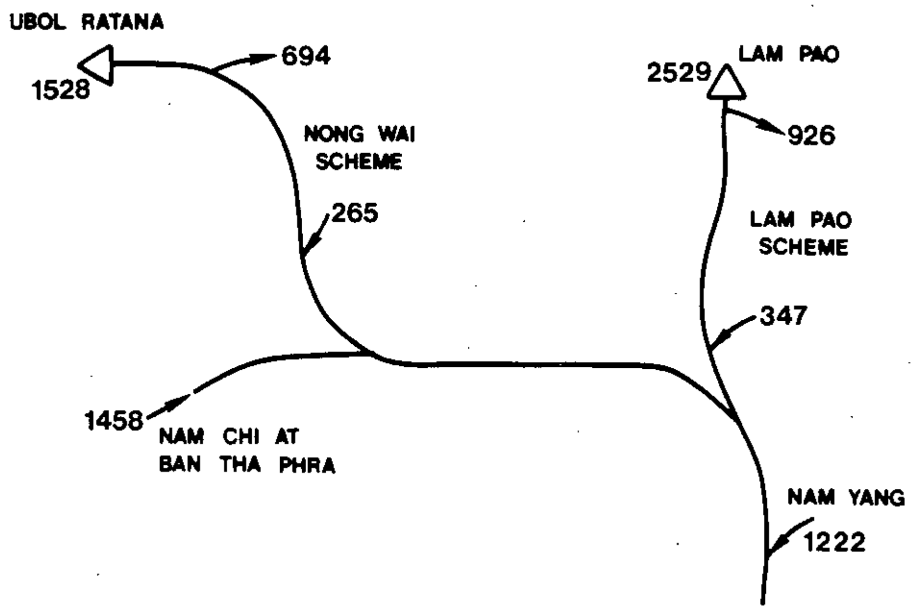


Figure 15

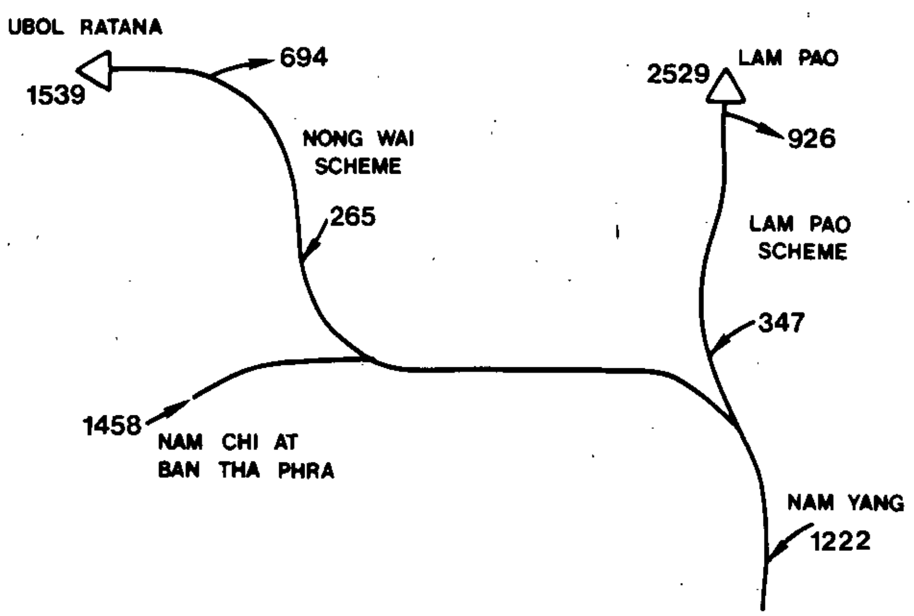
Network inputs and outputs : Average year

[million m³]

Policy 1



Policy 2



Policy 3

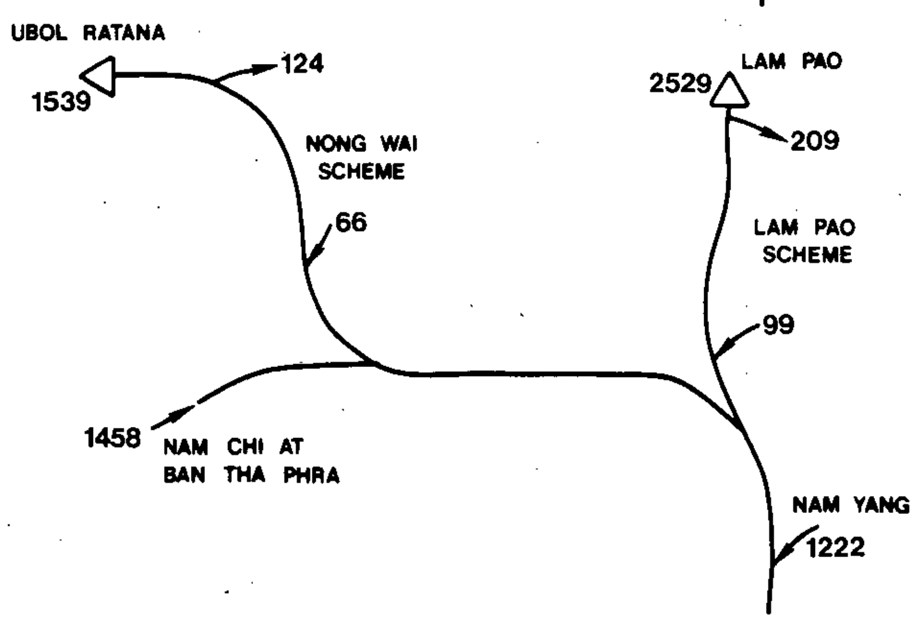


Figure 16

Network inputs and outputs : Wet year

[million m^3]

Policy 1

Policy 2

Policy 3

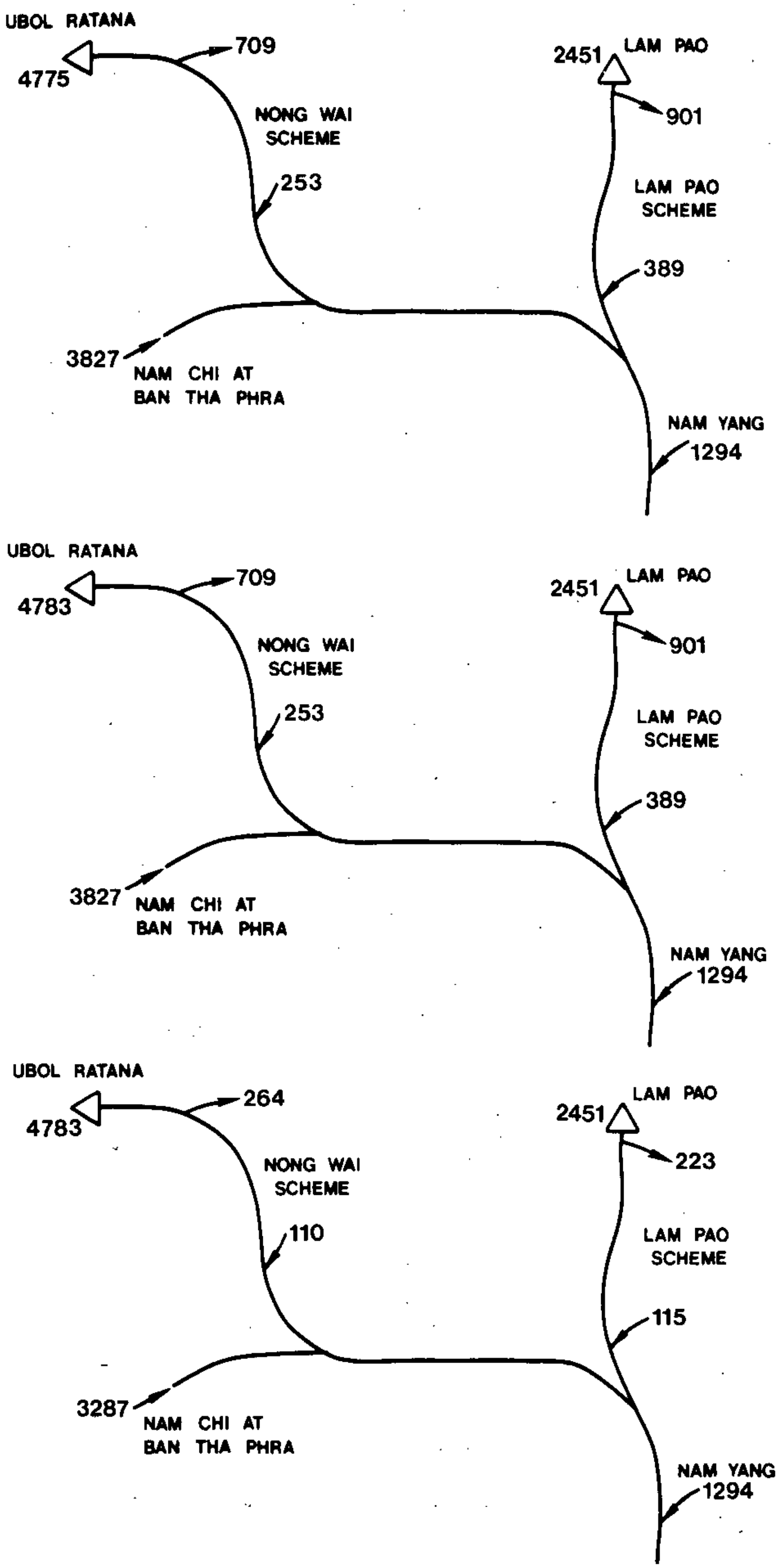


Figure 17

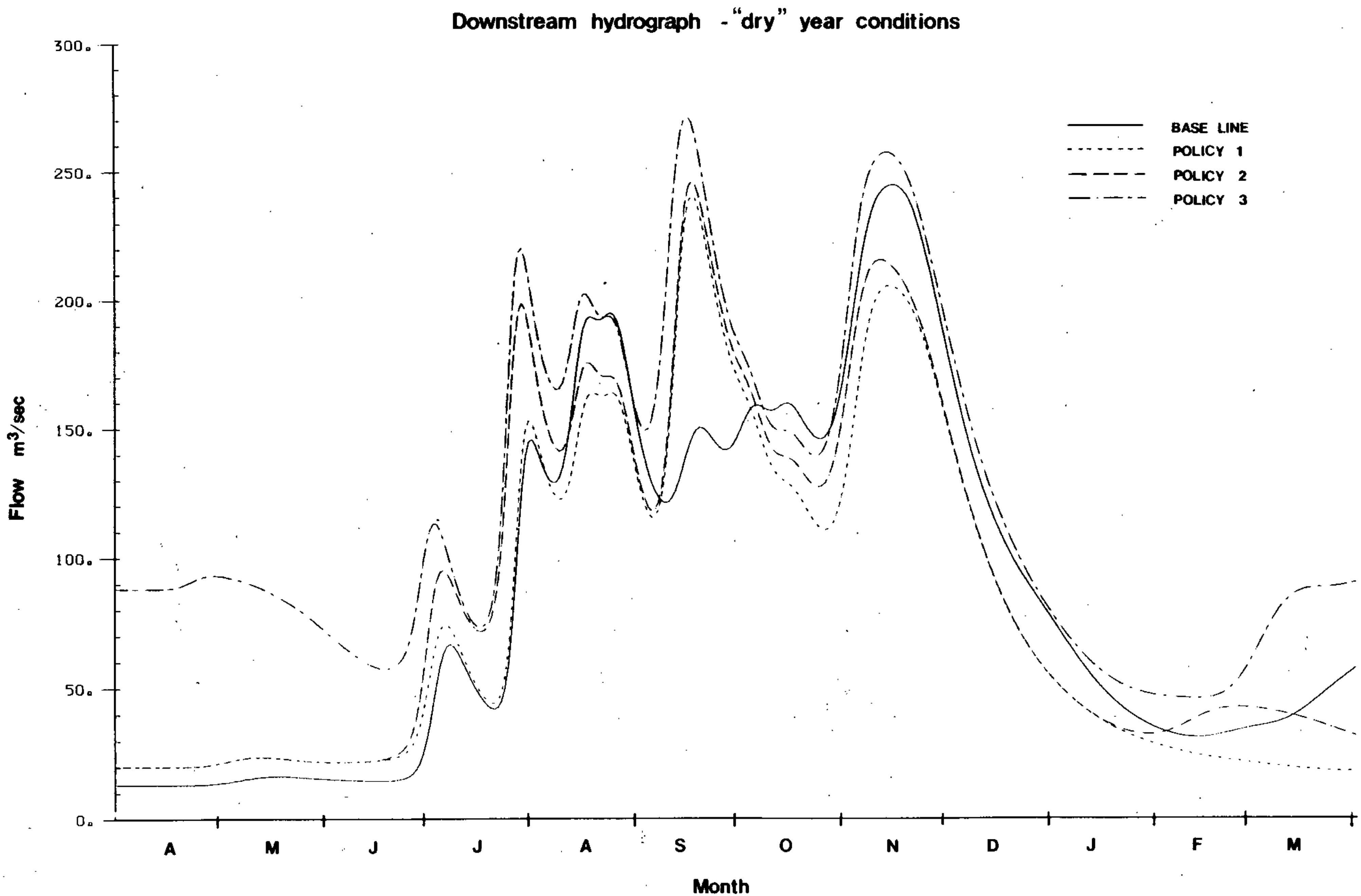

Downstream hydrograph -"dry" year conditions
BASE LINE
POLICY 1
POLICY 2
POLICY 3
300.
250.
200.
150.
100.
50.
0.
Flow m³/sec
A
M
J
J
A
S
O
N
D
J
F
M
Month

Figure 18

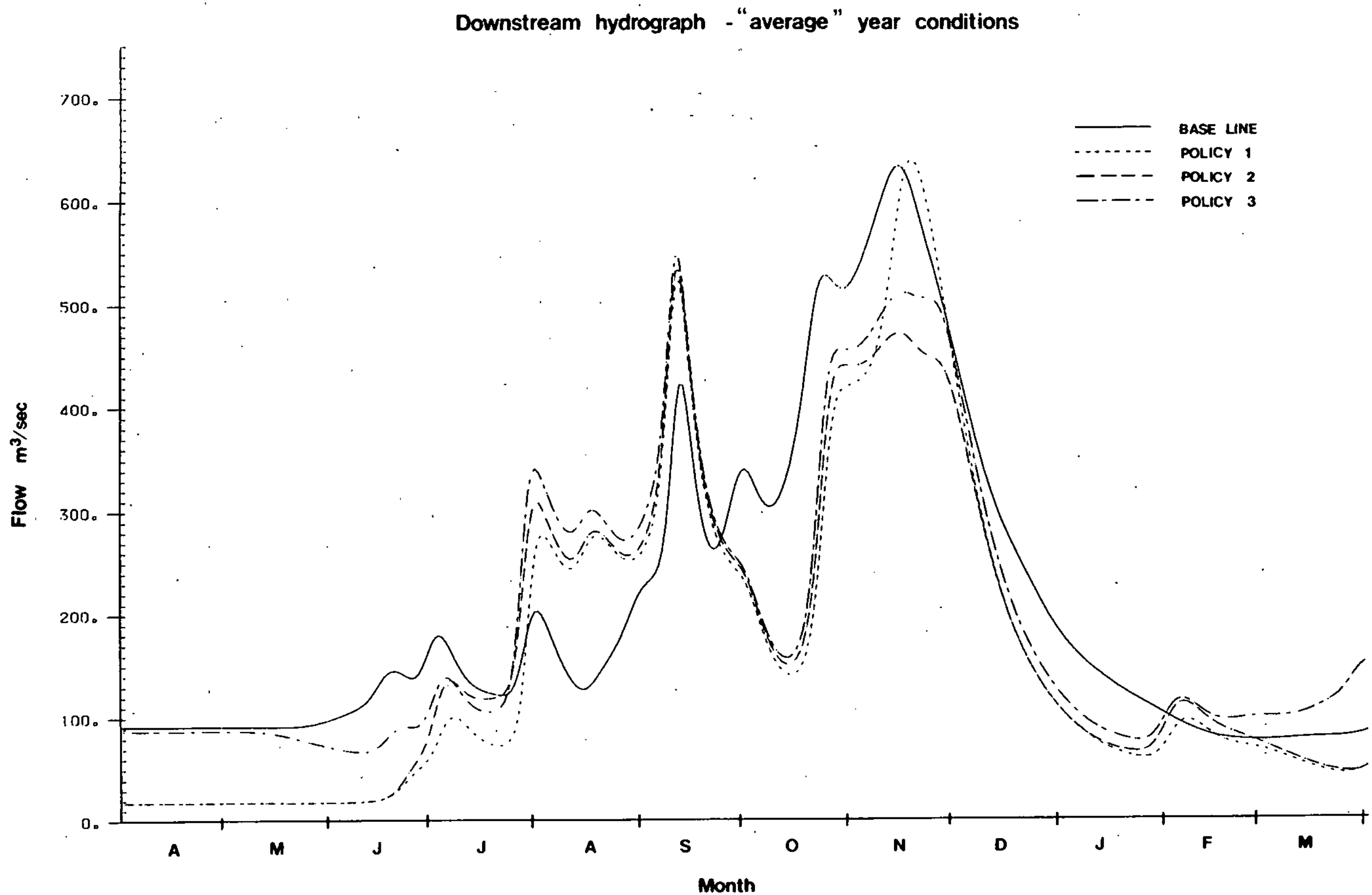

Downstream hydrograph - "average" year conditions
Flow m³/sec
700.
600.
500.
400.
300.
200.
100.
0.
A
M
J
J
A
S
O
N
D
J
F
M
Month
BASE LINE
POLICY 1
POLICY 2
POLICY 3

Figure 19

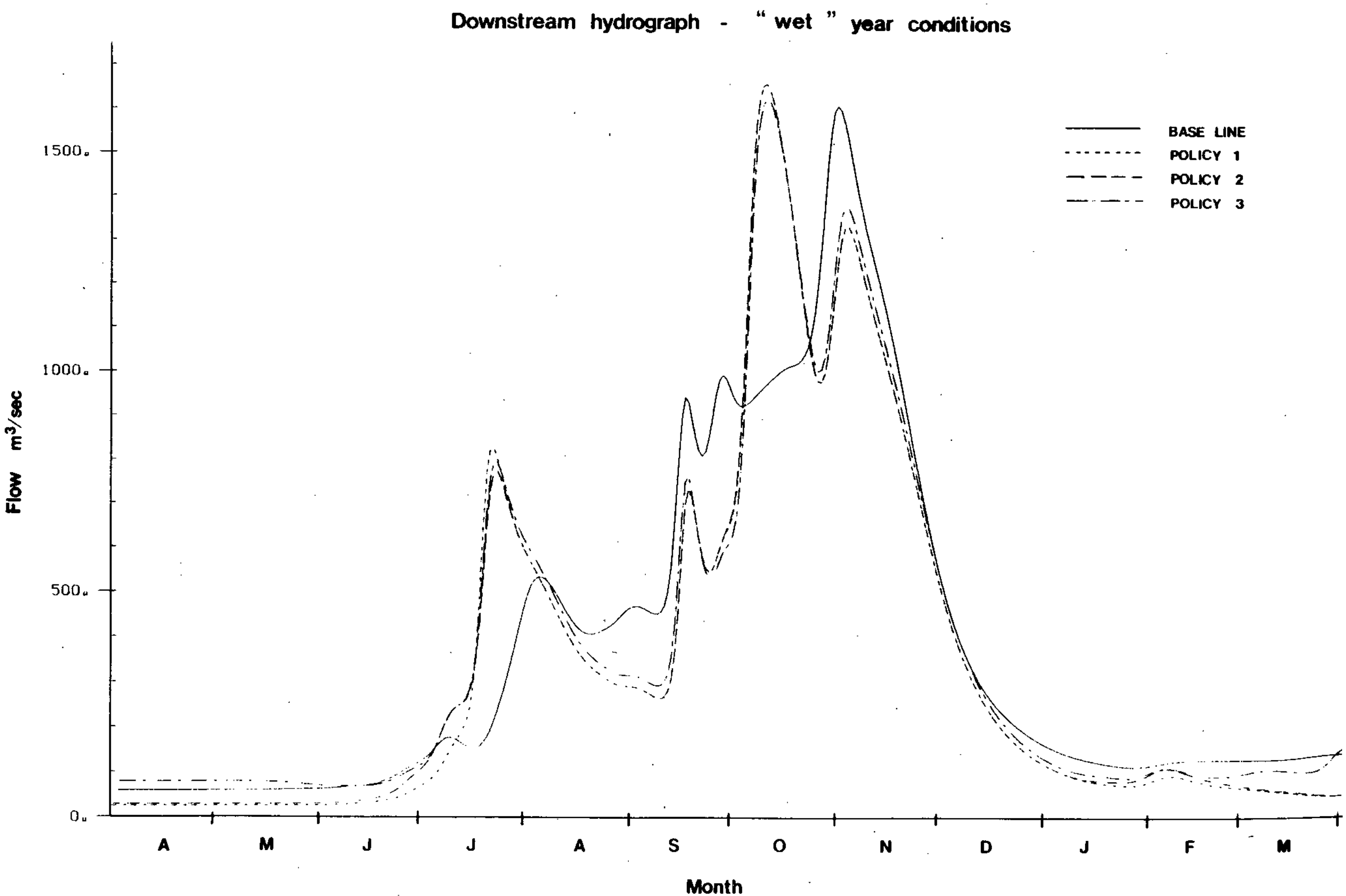

Downstream hydrograph - " wet " year conditions
Flow m³/sec
1500.
1000.
500.
0.
A
M
J
J
A
S
O
N
D
J
F
M
Month
BASE LINE
POLICY 1
POLICY 2
POLICY 3

Figure 20

The results of adhering strictly to reservoir operating rules are also well illustrated. In Figures 18 and 20, for example, all three policies result in a large peak in September which is not reflected in the baseline condition. This is caused by spill from the Lam Pao reservoir that is necessary to keep reservoir water levels below the flood rule curve. In Figure 18 the differences between Policies 1 and 2 in the periods June to August and September to November occur because the downstream irrigation demands are low, so that the water released from Ubol Ratana to meet the demand for energy passes through network to the downstream point. Under Policy 3 the relatively high discharges at each end of the graph are caused by releases from Lam Pao, that for this policy are not needed for irrigation downstream.

These effects also show up in Figures 19 and 20, although they appear to be less significant because the vertical axes on the graphs are different. The inference from these hydrographs is that even during average or wet years downstream dry season flows rely almost entirely on releases from upstream reservoirs. It appears that such releases are matched to downstream water requirements, with little regard for any residual flow once irrigation abstractions have been satisfied.

The example above illustrates how the network model could be used for one part of the Lower Mekong Basin. Comprehensive sets of data for reservoirs elsewhere in the region have been collected during this work. It now remains for these data, and the appropriate hydrological data from the Mekong Secretariat's data base to be used in any future work in which these reservoirs form part of the network under consideration.

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LOWER MEKONG BASIN:

WATER BALANCE STUDY

PHASE 2

Part 2 Rainfall Analyses

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Part 2 Rainfall Analyses

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LOWER MEKONG BASIN - WATER BALANCE STUDY, PHASE 2

PART 2 - RAINFALL

1. INTRODUCTION

For the planning and management of water resources, the estimation of rainfall over an area is a crucial part of the analysis. In assessing the water resources of a region the construction of a water balance is a fundamental first step requiring the estimation of basin rainfall, typically on an annual time scale, from the available measurements of point rainfall. For the design and operation of storage reservoirs, a monthly or pentad time interval is commonly used. In flood forecasting, estimates of basin rainfall on shorter time scales are required as inputs to a forecasting model. For irrigation water requirements, it is frequently necessary to interpolate rainfall to ungauged points.

While it is relatively straightforward to calculate the necessary estimates from the available measurements, the derivation of the accuracies of such estimates as a function of the density and configuration of the measurement network is a much more difficult problem. Statements of estimation accuracy of this kind are important since they provide a means of assessing whether the existing network of gauges can provide rainfall estimates of sufficient accuracy for the purpose at hand. Otherwise, they provide a basis for redesigning the networks.

In recent years, the necessary statistical methodology required to quantify the accuracies of point and areal rainfall estimates and use these in network design has been developed, and applied in real world case studies in the UK (O'Connell et al, 1978, 1979). However, this methodology has not been applied in the developing world where the need is undoubtedly greatest. The rainfall regimes of developing countries lying in tropical and semi-arid climatic zones are acknowledged to be extremely variable but this variability, and its impact on decision-making in water resources planning and management, has rarely, if ever, been satisfactorily quantified.

In Phase 1 (Institute of Hydrology, 1982) we attempted to devise 5 day (pentad) water balances for the wet season (April-November) using data from 4 basins in northeast Thailand. Preliminary water balance trials led to a simple conceptual model to describe the rainfall-runoff process, but satisfactory results could only be achieved by adjusting the estimates of areal rainfall by weighting factors. These factors had to be derived empirically for each basin and for each year of data using a subjectively chosen criterion such as reaching a soil storage of 150 mm at the end of the wet season.

Implicit in these results was the assumption that all the errors of observation were in the estimate of areal rainfall. While this is an oversimplification of the problem, the relative magnitude of rainfall and runoff in the region - typically 1100 mm for rainfall as opposed to 250 mm for runoff - and the conservative variation in evaporation from year to year mean that errors in the rainfall term will overwhelm any errors in the other variables. Consequently any rainfall-runoff modelling is likely to be severely constrained by the accuracy of estimation of areal rainfall.

The main objectives of these rainfall studies are therefore:

(i) to apply direct statistical methods to estimate the accuracy of areal rainfall estimates,

(ii) to define any strong regional patterns in the accuracy of areal rainfall estimates,

(iii) to assess the impact of these findings on the effectiveness of the SSARR model (and other simpler models),

and (iv) to provide data from which decisions about the density of gauges required to give adequate estimates of areal rainfall could be made.

No previous work in the region had been directly concerned with the assessment of errors in estimates of areal rainfall or their impact; our work lies firmly in the research domain. Therefore the results could not have been foreseen at the start of the study nor could we have anticipated how strong a data base would be necessary.

Sufficient data for this type of statistical analysis exist only for northeast Thailand; neither the Mekong Secretariat nor the other responsible organisations hold the amount of data required in terms of areal coverage or uninterrupted length of record for other parts of the Lower Mekong Basin. Consequently, these analyses were restricted to northeast Thailand. Moreover the isohyetal maps reproduced in the Mekong Secretariat's Yearbooks (Mekong Secretariat, 1962 et seq.) are not always extended far beyond the left bank of the Mekong or into the delta. Given that it is sometimes considered unwise to draw isohyets in these regions from the limited data that are available, it would be much more unreasonable to draw statistical inferences from such data on even a monthly timestep.

We were aware that the Mekong Secretariat had no extensive data base amenable for immediate analysis by computer, but following Phase 1 our expectations were of a suitable database existing elsewhere, possibly at AIT. In the event EGAT had the only accessible data base but this required considerably more work in translating magnetic tapes and quality control than could have been foreseen.

The correlation function described later were derived from monthly data and showed that much of the reduction of correlation with distance occurred within distances of a few tens of kilometres. For daily data the initial reduction of correlation with distance would have been much steeper. But few of the raingauge spacings are less 20 km so it would have been extremely difficult to establish correlation functions from daily data. Thus given the spacing of raingauges in the network eventually retained, the statistical analysis was restricted to monthly data.

2. AVAILABILITY OF DATA

Previous studies

The spatial distribution of raingauges in the Lower Mekong Basin, and the requirement of many years of continuous data means that any detailed analysis of areal rainfall has to be confined to northeast Thailand. Indeed there are a number of previous studies, concerned with the derivation of basic statistics or measures such as effective rainfall, that form a useful starting point.

The relationships between rainfall patterns and paddy yield in northeast Thailand were investigated in 1974 (Mekong Secretariat, 1974). Data from 96 stations were included, comprising 12 main and 84 secondary stations. The records for the secondary stations were short covering the period 1966-71; much longer periods, 20-22 years of daily rainfall and up to 60 years of monthly rainfall, were available for the main stations.

The initial analysis was concerned with serial correlation in the time series of annual falls at the main stations. Frequency distributions were fitted to the monthly data. The only areal analysis concerned the correlation of monthly records from the secondary stations and the main stations; for this purpose the gauges were divided into 12 groups with one main station in each group.

Another recent study was part of a drought analysis by AIT (AIT, 1978) which covered northeast Thailand plus Phetchabun province. A total of 58 gauges were used in the analysis, each gauge having a minimum of 20 years of daily data within the period 1952 to 1977 which was thought to contain the most reliable data.

Both these studies have been concerned with the derivation of basic statistics or measures of rainfall (such as implied crop yields or drought periods) at a point. The point estimates of the measures were mapped and areal inferences drawn. Thus while much valuable data have been assembled and useful basic statistical work done, the studies do not provide estimates of the accuracy of areal rainfall estimates directly.

Sources of data

Raingauges in Thailand are operated by a number of different agencies, the two most important being the Meteorological Department of Thailand (MDT) and the Royal Irrigation Department (RID). Data from many of these stations are published in the Mekong Secretariat Yearbooks as monthly summaries; for some gauges daily falls are also published, and in the 1980 Yearbook data from over 90 gauges were included.

These data represent an enormous quantity of information and it would have required an unacceptable amount of time and effort to assemble them in a computerised data base for subsequent analysis. Consequently the availability of computer compatible data from other sources was investigated.

At the Secretariat itself daily data for 17 gauges in Thailand, as well as for some in the Lao PDR and Viet Nam, were available for the period 1952 to 1978 (Mekong Secretariat, 1981). A more extensive data base has been used by the Asian Institute of Technology (AIT) for a number of studies (i.e. AIT, 1978; Apichart, 1980).

AIT were also involved in the project "Development of a Water Resources Information System for Thailand" (WRIST) (AIT, 1980). Since then the System has been passed over to EGAT for implementation; unfortunately it is not yet possible for users to access rainfall data directly using WRIST. However it transpired that EGAT store an archive of daily rainfall data on 7 magnetic tapes for the period since 1952. This archive contains data for some 500 stations listed by the RID (RID,1978), and covers the whole of Thailand. The data base at AIT had been created from direct copies of these tapes.

The origin of the tapes at EGAT was unclear, but eventually the following explanation was elicited. The RID and MDT, who between them operate the great majority of rainfall stations, swap duplicates of their field data sheets. In the late 1970's daily data from over 1000 gauges throughout Thailand were punched and apparently verified by the RID. The EGAT archive itself was then created from these cards; thus it appears that previous computer based studies of rainfall all used data from the same basic source, namely those collated and punched on cards at the RID. In none of these studies has routine checking or quality control of the data been carried out.

The most straightforward way of obtaining these data on magnetic tape was from the EGAT archive. First those gauges in northeast Thailand were identified in the RID directory (RID, 1978); subsequently our selection was based on the following, somewhat subjective, criteria:

(1) the record should be over 10 years in length;
(2) the gauge is operated by the MDT and located at an Amphoe Office;
(3) the raingauge is operated by the RID and located at one of their offices or major schemes;
(4) the raingauge is located at an agricultural or other experimental station.

The daily rainfall for the selected gauges were then accessed from the EGAT archive. Thus an edited version of the EGAT magnetic tape daily archive, which is stored in hydrological years, was then written onto two tapes for subsequent transfer to the Mekong Secretariat. These edited EGAT tapes include records from 187 raingauges in northeast Thailand, and cover the period from April 1952 to March 1980.

A summary of other sources of published data is given in Table 1.

On the EGAT tape, station numbers follow the RID system of 5 digit numbers. The first 4 digits indicate province and location in terms of district office etc. The last digit refers to operating agency and type of gauge; 0 and 1 are RID gauges, 2 and 3 MDT gauges, and 4 and 5 gauges operated by other government departments. Even numbers are standard gauges, odd numbers indicate recording gauges.

TABLE 1.

Sources of rainfall data

Source	Abbreviation	Medium
Electricity Generating Authority of Thailand. Archive created from RID punched cards.	EGAT	Magnetic tape
Mekong Secretariat Year Books; monthly data for most stations, daily for selected stations, published since 1964. Data obtained from MDT.	MYB	Published
Mekong Secretariat (1975); data summarised monthly for 15 main stations in northeast Thailand for the period 1952-1970.	MKG29	Published report
Corps of Engineers; data on listing at the Mekong Secretariat for 8 main stations in northeast Thailand, daily for the period up to about 1965.	CEL	Listing
Mekong Secretariat (1981); small data base of daily rainfall for 17 gauges in northeast Thailand, as well as some in the Lao PDR and Vietnam, for period 1952 to 1978.	MKG/338	disc and tape

A 3 digit system of numbering is used in the Mekong Secretariat; this does not include all the stations of interest and therefore has not been used in this work. The CEL data (see Table 1) follow a third system, but because so few stations are involved it has been ignored.

Gauge locations

Both the RID and the Mekong Secretariat define gauge locations by latitude and longitude. However the locations of gauges published by each agency sometimes disagree. For the statistical analysis, grid references to the nearest kilometre were more appropriate because the distances between gauges can then be calculated directly. Consequently some time was spent on establishing consistent locations for the gauges on maps from which the corresponding grid references could be derived directly.

An index list of all the stations was prepared in ascending order of RID gauge number; where available the corresponding Mekong Secretariat number was also included, together with latitude and longitude, and altitude. All the gauges were then marked on maps and their locations verified against published values of latitude and longitude.

Many of the gauges are located at Amphoe offices and could be located accurately on 1:500,000 maps. In those cases where several gauges are grouped in the same locality such as within a Changwat, or where gauges are at barrages, gauging stations or irrigation tanks, locations were marked on 1:50,000 maps by the MDT or RID. Grid references were then read off for these locations so that the distances between gauges were accurate to within ± 1 km.

The resulting list of raingauges, their identification numbers, and locations are given as Table 2. Note that those stations with more than seven years of data missing completely, or with more than 14 years with some missing records are listed separately at the end of the table.

TABLE 2. Raingauge directory

RID Code	Mekong Code	Name	Grid Ref	Lat(°N)	Long(°E)	Altitude(m)
2012	530	BURI RAM	2971658	15 00	103 06	155
2022	529	PRAKHON CHAI	2941616	14 36	103 05	159
2033	528	NANG RONG	2631619	14 38	102 48	183
2052	455	SATUK	3161691	15 18	103 18	132
2062	527	LAM PLAI MAT	2671661	15 01	102 50	165
2072	457	PHUTTHAISONG	2861719	15 32	103 00	141
5012	465	CHAIYAPHUM	1831750	15 48	102 02	190
5023	466	CHATTURAT	1621722	15 34	101 51	190
5032	406	PHU KHIEO	1941811	16 22	102 08	210
5042	468	BAMNET NARONG	1421715	15 30	101 39	205
5052	404	KASET SOMBUN	1741802	16 17	101 58	235
5062	463	KHON SAWAN	2101762	15 56	102 17	174
5100	0	RID CHAIYAPHUM	1651718	15 32	101 52	0
11012	419	KALASIN	3411817	16 26	103 31	142
11022	418	YANG TALAT	3271814	16 24	103 22	141
11032	421	KAMALASAI	3491806	16 20	103 35	140
11042	420	SAHATSAKHAN	3491855	16 47	103 35	160
11053	424	KUCHINARAI	3991828	16 32	104 04	166
14013	411	KHON KAEN	2691819	16 26	102 51	157
14022	409	MANCHA KHIRI	2371784	16 08	102 33	160
14033	458	PHON	2431748	15 49	102 36	175
14042	410	BAN PHAI	2571779	16 04	102 44	170
14052	0	PHU WIANG	2211842	16 39	102 23	0
14062	0	NAM PONG	2721848	16 42	102 51	0
14073	405	CHUM PHAE	1911830	16 33	102 06	220
14082	415	KRANUAN	2951848	16 42	103 05	210
14160	0	RID KHON KAEN	2711817	16 25	102 51	0
18013	363	LOEI	1531936	17 29	101 44	251
18022	364	THA LI	1211948	17 37	101 25	260
18032	365	DAN SAI	901912	17 17	101 09	330
18042	361	WANG SAPHUNG	1561915	17 18	101 46	247
18052	362	CHIANG KHAN	1461980	17 54	101 40	213
18090	0	HUAI NAM MAN WEIR	1511936	17 29	101 43	0
18110	0	HUAI NAM WAK TANK	1181949	17 37	101 24	0
21012	417	MAHA SARAKHAM	3191790	16 11	103 18	150
21022	414	BORABU	2991774	16 02	103 07	210
21032	454	WAPI PHATUM	3271753	15 51	103 23	141
21043	413	KOSUM PHISAI	2941797	16 15	103 04	150
21052	416	KANTHARAWICHAI	3181805	16 19	103 18	150
21063	456	PHAYAKKAPHUMPHISAI	3071717	15 31	103 12	135
21080	0	RID MAHA SARAKHAM	3211790	16 11	103 19	0
21090	0	HUAI KHA KHANG REG	3351789	16 10	103 27	0
21120	0	EKASATSUNTHON TANK	2971770	16 00	103 06	0
21170	0	RONG HUA CHANG TNK	3041771	16 01	103 10	0
24012	343	NAKHON PHANOM	4771923	17 24	104 47	140
24022	429	THAT PHANOM	4711873	16 57	104 44	130

TABLE 2 continued

24032	427	NA KAE	4471873	16 57	104 30	145
24042	428	MUKDAHAN	4721828	16 32	104 44	138
24052	344	THA UTHEN	4571944	17 35	104 36	168
24062	345	SISONGKHRAM	4171952	17 38	104 13	145
24072	0	DONG BANG-I FOR ST	4571813	16 23	104 36	0
24082	346	BAN PHAENG	4171988	17 58	104 13	148
24092	425	KHAM CHAI	4381833	16 34	104 25	182
25013	525	KORAT	1861657	14 58	102 05	181
25022	464	NON THAI	1861682	15 12	102 04	170
25042	460	BUA YAI	2251724	15 35	102 26	170
25052	459	PHIMAI	2321680	15 11	102 30	160
25062	523	SUNG NOEN	1581648	14 54	101 49	213
25072	522	SIKHIU	1481648	14 54	101 43	233
25082	467	DAN KHUN THOT	1531682	15 12	101 46	213
25093	572	CHOK CHAI	1951630	14 44	102 10	192
25102	524	PAK THONG CHAI	1801629	14 43	102 01	305
25112	526	KHON BURI	2041607	14 31	102 15	210
25122	0	CHAKKARAT	2221662	15 01	102 25	0
25132	0	PAK CHONG SERUM ST	1141628	14 43	101 25	0
25142	0	BAN MAI SAM RONG A	1401645	14 52	101 39	0
25162	461	KHONG	2141709	15 26	102 20	175
25212	0	NON SUNG AG EX STN	2061680	15 11	102 16	0
25291	0	RID KORAT	1851656	14 57	102 04	0
25300	0	PHIMAI BARRAGE	2321681	15 13	102 30	0
25511	0	LAM PRA PLERNG	1601617	14 36	101 51	0
30012	357	NONG KHAI	2611977	17 52	102 45	173
30022	354	PHON PHISAI	2971993	18 01	103 05	160
30032	358	THA BO	2441975	17 51	102 35	173
30042	342	BUNG KAN	3582032	18 21	103 39	164
49013	450	ROI ET	3571775	16 03	103 41	140
49022	452	KASET WISAI	3481731	15 39	103 34	130
49032	448	SUWANNAPHUM	3711726	15 36	103 48	137
49042	582	THAWATCHABURI	3761781	16 07	103 51	135
49052	447	AT SAMAT	3801752	15 51	103 53	0
49062	423	PHON THONG	3911802	16 18	103 59	140
49072	451	CHATURAPHAKHIMAN	3461752	15 51	103 34	142
49082	445	PHNOM PHRAI	4051734	15 41	104 07	130
49092	446	SELAPHUM	3861773	16 02	103 56	150
49102	0	ROI ET AG EXP STN	3511777	16 04	103 36	0
49110	0	THA SABANG WEIR	3831773	16 02	103 55	0
50013	347	SAKON NAKHON	4101899	17 10	104 09	160
50023	351	SAWANG DAEN DIN	3371933	17 28	103 28	170
50032	348	PHANNA NIKHOM	3781920	17 21	103 51	170
50042	350	WARITCHAPHUM	3551914	17 18	103 38	194
50052	0	SANG KHO H'WAY OFF	3781868	16 53	103 51	0
50062	349	WANON NIWAT	3681950	17 38	103 45	160
57013	441	SISAKET	4281672	15 07	104 20	124

TABLE 2 continued

57022	536	KHUKHAN	4141627	14 43	104 12	142
57032	0	KANTHARAROM	4551670	15 06	104 34	0
57042	444	UTHUMPHON PHISAI	4081671	15 07	104 09	135
57052	443	RASI SALAI	4081697	15 20	104 09	120
57063	0	KANTHARALEK	4621619	14 39	104 39	0
62013	533	SURIN	3381646	14 53	103 29	145
62022	534	SANGKHA	3761619	14 38	103 51	160
62032	449	RATTANABURI	3771694	15 19	103 51	130
62052	535	SIKHORAPHUM	3691653	14 57	103 48	138
62062	532	PRASAT	3291620	14 38	103 24	167
67013	435	UBON	4861686	15 15	104 53	127
67022	433	PHIBUN MANGSAHAN	5251686	15 15	105 15	110
67032	438	AMNAT CHAROEN	4601754	15 51	104 38	155
67052	580	KHEMARAT	5241773	16 02	105 14	139
67062	439	KHUANG NAI	4521702	15 23	104 33	122
67072	436	WARIN CHAMRAP	4861681	15 12	104 52	124
67082	434	TRAKAN PHUTPHON	5031726	15 37	105 02	131
67112	431	SI MUANG MAI	5541694	15 19	105 30	90
67122	437	MUANG SAMSIP	4711716	15 31	104 44	140
67132	537	DET UDOM	5081648	14 54	105 04	125
67142	538	BUNTHARIK	5441632	14 45	105 25	145
67152	430	CHANUMAN	5011792	16 13	105 01	130
67182	0	UBON SERIC STN	4771693	15 19	104 47	0
67220	0	RID UBON	4851682	15 12	104 52	0
68013	356	UDON THANI	2651923	17 23	102 46	178
68022	355	PHEN	2791958	17 42	102 55	168
68032	352	NONG HAN	2991921	17 22	103 07	170
68042	360	NONG BUA LAM PHU	2291903	17 12	102 27	215
68052	353	KUMPHAWAPI	2891893	17 07	103 01	170
68062	359	BAN PHU	2321957	17 41	102 29	190
68072	0	NON SANG	2411866	16 52	102 34	0
68100	0	RID UDON THANI	2661926	17 55	102 48	0
68110	0	HUAI LUANG BARRAGE	2451927	17 25	102 36	0
68201	0	HUAI MONG	2171945	17 35	102 20	0
72012	442	YASOTHON	4081746	15 48	104 09	128
72022	440	KHAM KHUAN KAEO	4271731	15 39	104 19	122
72032	0	MAHACHANACHAI	4181717	15 32	104 15	0
72042	426	LONG NOK THA	4481791	16 12	104 31	145
2082	0	NIKHOM BAN KRUAT	2951597	14 26	103 06	0
2092	0	LAHAN SAI	2681595	14 25	102 51	0
2102	0	KRASANG	3171650	14 55	103 18	0
2130	0	RID OFFICE BURIRAM	2981658	14 59	103 07	0
5072	0	CHAIYAPHUM SD STN	1801752	15 50	102 01	0
5082	0	BAN KHWAO	1671747	15 47	101 54	0
5092	0	BAN THAEN	2171815	16 24	102 21	0
5284	0	CHULAPHON DAM	1451829	16 32	101 40	0
11062	0	NIKHOM KUCHINARAI	3841840	16 39	103 54	0

Table 2 continued

11072	0	KALASIN SEED STN	3271813	16 24	103 23	0
11082	0	K SOMDET	3671846	16 42	103 45	0
14092	0	THA PHRA AGR ST	2691807	16 20	102 50	0
14112	0	KHON KAEN SEED STN	2691823	16 29	102 50	0
14122	0	KHON KAEN AG EX ST	2651818	16 26	102 48	0
14132	0	NIK. KHUAN UBONRAT	2581848	16 42	102 44	0
14143	0	CHONNABOT	2461780	16 05	102 37	0
14152	0	NONG SONG HONG	2641740	15 44	102 48	0
18062	0	LOEI AGROMET STN	1501927	17 24	101 42	0
18073	0	PHU KRADUNG	1661872	16 55	101 52	0
18082	0	PHU KRADUNG NT PRK	1571871	16 54	101 47	0
21072	0	CHIANG YUN	2971814	16 24	103 06	0
24102	0	NIKHOM MUKADAN	4521809	16 22	104 33	0
24112	0	NAKHON PHANON SEED	4771925	17 25	104 47	0
24122	0	MUKDAHAN SERI STN	4641828	16 32	104 40	0
24130	0	RID NAKHOM PHANOM	4771922	17 23	104 47	0
25152	0	BAN SAN CHAO SCH	1641592	14 23	101 53	0
25172	0	KLANG DANG FOREST	1021620	14 38	101 18	0
25192	0	NIKHOM PHIMAI	1931674	15 08	102 08	0
25222	0	PHIMAI RICE EX STN	2301685	15 14	102 29	0
25252	0	HUAI THALAENG	2831659	15 00	102 59	0
25262	0	CHUM PHUANG	2581698	15 21	102 45	0
25272	0	PAK CHONG AGROMET	1141629	14 43	101 25	0
30052	0	NONG KHAI SERI STN	2581977	17 52	102 43	0
30062	0	NIKHOM PHON PHISAI	3132019	18 15	103 14	0
30072	0	SEKA	3891983	17 55	103 57	0
30082	0	SI CHIANG MAI	2441987	17 57	102 35	0
36013	0	MUANG	891818	16 25	101 09	0
36023	0	LOM SAK	1011857	16 47	101 15	0
36032	0	LOM KAO	991870	16 53	101 14	0
50072	0	SAKHON NAKHON AGST	4041900	17 11	104 06	0
50092	0	AKAT AMNUUAI	3921945	17 35	103 59	0
50102	0	PHU PHAN NT PARK	3831872	16 56	103 54	0
50304	0	NAM PHUNG DAM	3921877	16 58	103 59	0
57072	0	SI SA KET SEED	4231662	15 02	104 17	0
57082	0	NIKHOM PRU YAI	4151616	14 37	104 14	0
57092	0	NIKHOM HUAI KHLA	4201661	15 01	104 15	0
57102	0	KHUN HAN	4381616	14 37	104 26	0
62043	0	THA TUM	3591696	15 20	103 41	0
62072	0	NIKHOM PRASAT	3231619	14 37	103 21	0
62082	0	SEED MULT ST	3351646	14 53	103 28	0
62092	0	CHAMPON BURI	3281698	15 21	103 24	0
62102	0	SURIN AG EX ST	3331646	14 53	103 27	0
62112	0	SAMRONG THAP	3861661	15 01	103 56	0
67192	0	KHONG CHIAM	5291715	15 30	105 16	0
67202	0	PHANA	4841733	15 41	104 51	0
68082	0	NIKHOM CHIANG PIN	2531919	17 21	102 40	0

Preliminary tests of data quality

Reading and translation of the EGAT tape was difficult and time consuming. The data were not in a wholly consistent format, some records were unreadable, not all records started in 1952 and other complete years were missing at some stations. Consequently we decided to spend some time on the identification and checking of suspect data.

Initially two approaches were tested using the results of analysis of the EGAT tape on the NERC computer. Firstly daily rainfalls greater than 140 mm (560 values) were abstracted. Secondly for each calendar month, the values at one station were compared by regression analysis to the mean of all other stations. Those values departing from the regression line by more than 4 times the regression standard error were flagged as were values differing by more than 200 mm from the expected value. This second approach identified about 1100 suspect monthly values or outliers from approximately 3400 station years of data.

For a preliminary investigation in Bangkok of some of these suspect values eight stations were chosen for which daily and monthly data were also available from the three sources CEL, MKG29 and MYB (see Table 1 for definition of abbreviations). The occurrences of daily falls greater than 140 mm and the outliers as identified above were compared to check whether these values were confirmed by each of the alternative sources of data.

Overall it seemed that this procedure did illustrate that some rogue values were confirmed by the various data sources; however there were other inconsistencies between the sources that were identified in passing. Since no one source could of itself be assumed to be more correct than any other, this process did not help to identify which data might be discarded. Nor could it indicate which stations might be less reliable than the others. It might at best identify random transcription, punching or publishing errors. Consequently this process was not followed up at other stations.

Another approach to quality control, better suited for running on computer, was then tested by hand. This method is similar to one used routinely by the UK Meteorological Office (Shearman, 1975), where observations are checked before being stored on the rainfall archive. Their method compares the falls at a given gauge with the corresponding data at neighbouring gauges. Any inconsistencies are flagged, and the suspect values checked in detail; confirmed errors are rectified where possible by reference to the field sheets, and a correct set of data prepared.

For this test four gauges were chosen as subject stations; the area around each was divided into quadrants and the nearest gauge in each quadrant identified. If there was no neighbour within 50 km in any quadrant, then the nearest unused station in any orientation was used instead. This ensured that a total of 4 gauges was used in the subsequent comparisons.

The results obtained supported the value of using local data to check outliers and unusually large daily falls identified in the original data set. However they also suggested that definite judgements that data are right or wrong would be difficult to draw. In particular there was no evidence that fewer unconfirmed outliers could be identified at the main, or supposedly "good", gauges than at the secondary, possibly unreliable, stations.

Another type of comparison was also carried out by hand in Bangkok, and involved comparison of calendar year rainfalls. This was an attempt to compare the data from the various sources on a more general basis than that described above. Five raingauges spread around northeast Thailand were chosen for this analysis.

For each gauge the annual data were abstracted from the EGAT and Mekong Secretariat sources of data. Agreements to within 1 per cent were flagged, as were discrepancies exceeding 10 per cent. These latter were examined in greater detail to identify whether differences in the data for a given month or months could account for the annual discrepancy, or whether the data for the whole year were inconsistent. The corresponding data from nearby gauges were also examined in an attempt to identify which source showed the greater likelihood of being correct given these other local data.

The most striking feature of the results is that 9 out of the 13 occurrences of major disagreement refer to the first 6 years of the period reviewed - that is the calendar years 1953 to 1959. Also the evidence from nearby stations tended to support the EGAT or Mekong Secretariat sources on a roughly equal basis. It was interesting to note that in many cases the disagreements did not coincide with occurrences of outliers or extreme values identified using the methods described above.

One particular error in data from the EGAT tape was identified: this was the omission of the January, February and March data in one year. The hydrological year starts in April; the cards were punched at RID in hydrological years from field sheets which are written in calendar years. Thus this error might have arisen from confusion between calendar year and hydrological year data. Further checks showed that the frequency of zero rainfall in the months January to March on the EGAT tape is about twice the frequency indicated by published data (Mekong Secretariat, 1975).

Another important feature of these comparisons concerns the Nam Songkhram basin in the north east corner of northeast Thailand. This is a region of higher rainfall and rainfall gradient than the rest of the northeast, and there are few raingauges. Consequently checking data by monthly and annual comparisons was particularly difficult.

Quality control options

Many of the issues raised by these preliminary attempts at quality control are interesting and could be pursued at much greater length. However it was not in the brief of this project to carry out such detailed investigations of the quality of the available data. Consequently, because the resources allocated for this part of the study had already been used up it was decided that we should aim to constrain any further quality control of the complete data base to the objective of limiting the impact of possibly erroneous data on our analysis as quickly and effectively as possible. Four possible ways of achieving this were identified.

Firstly we could omit all data up to March 1959 as indicated by the annual comparisons above. This would reduce the period for analysis from 28 years to 21 though for many stations the early years of the nominal period of record are missing anyway. The benefits of omitting the most suspect years of data must be balanced against the poorer correlation measures which would result from using a shorter sample period.

Secondly we could omit the dry season data particularly January to March. This would be equivalent to using seasonal rather than annual rainfall.

Thirdly we could limit the coverage of our analysis to the Mun-Chi basin which comprises about 75 per cent of the area of northeast Thailand. The areas excluded, particularly Loei and Sakhon Nakhon provinces, are least like the rest of the northeast in terms of relief, average rainfall and rainfall gradient. Alternatively we could consider these areas and particularly Sakhon Nakhon province (the Nam Songkhram basin) as suitable for separate comparative analysis.

Fourthly we could adopt some variant of the UK Meteorological Office quality control procedure in which the principal criterion is consistency between neighbouring stations. Such a procedure could reduce considerably the number of suspect values identified earlier.

Selected quality control procedure

The method of data validation finally adopted was based on a test of consistency between corresponding records at neighbouring gauges. The first step was to identify a set of neighbours for a given gauge. In each quadrant about the gauge, gauges lying within a distance of 75 km were identified; if there were more than three such gauges, then the three closest were retained. Then, at most one gauge from each quadrant was eliminated in reverse order of distance from the central gauge until eight or fewer neighbours remained in all. This procedure ensures that there are no more than 8 neighbours identified, and that no more than 3 of these are located in any one quadrant.

Once the set of neighbouring gauges has been identified their monthly data are then tested against the corresponding data at the central gauge. Monthly thresholds, T_i, were defined by

$$T_i = 48 + 0.2 * \mu_i$$

where μ_i is the mean rainfall for month i at the central gauge. Each value of monthly rainfall, M, was then checked in turn; if any of the neighbouring gauges had a recorded value within ± T of M then the M was accepted: otherwise further tests were applied.

If the month in question was in the period April to October and M was zero, a special test was used: the decision to accept or reject was based, as follows, on the number of neighbours with non-zero values:

(i)	if number of neighbours is 0	reject
(ii)	if number of neighbours is 1	reject, unless neighbour < 20 mm when accept
(iii)	if number of neighbours is 2	reject, unless two neighbours have values < 20 mm when accept.

Non-zero values of M in April to October were tested in the same way as the November to March values, with the proviso that any zero values at neighbouring gauges were treated as if they were missing. For the period November to March, M was accepted outright if some of the neighbouring values were higher and some lower. However if all the neighbouring values were higher, then the following criteria were used:

(i) reject if M < 0.33 * smallest neighbouring value,

(ii) reject if the difference between M and its smallest neighbour is > 1.5* T AND also > the range of the neighbouring values or 48 mm (whichever is the larger).

If neither of these tests resulted in rejection the value M would be accepted as being probably valid.

On the other hand if all the neighbours had lower values, then M was rejected if two or more of the following statements held:

(i) M > 1.5 * largest neighbouring value

(ii) the difference between M and its largest neighbour was > 1.5 * T,

(iii) the difference between M and its largest neighbour was > range of neighbouring values or 48 mm (whichever is the larger).

These procedures were programmed on the NERC computer, and one pass through the complete data set of 52200 station-months from 187 stations was made. The checking procedure identified and rejected 171 values of zero rainfall in the period April to October and 499 other values; thus less than 1.3 per cent of the data were rejected overall. The "cleaned" data set used in subsequent analysis then comprise 51530 station months of data.

While the tests described above seem arbitrary, the various criteria were chosen to provide a reasonably uniform test of the data in all months of the wet season. The criteria were established by a process of trial and error; the final choice of rejection criteria being those that most closely matched the judgements that an experienced hydrologist would make.

3. STATISTICAL ANALYSIS

Introduction

In order to investigate variations in the statistical properties of rainfall across northeast Thailand, the region was divided up into the eight different areas which are shown in Figure 1. Separate regions were chosen partly to take account of the different river basins and partly to separate the mountainous regions of the northeast and northwest where annual rainfall tends to be higher than in the rest of the region (NEDECO, 1982). Some statistics of the monthly rainfalls and of the year to year variations in each of the eight groups are given in Table 3. Note that four of the 187 gauges referred to in Chapter 2 lie outside the region and have been excluded from the rest of this analysis. Each calendar month is treated separately, but no attempt to analyse data for the dry months of December and January has been attempted.

The main purpose of the statistical analysis presented here was to provide a basis for assessing how well the average rainfall over a given area can be estimated just by taking the average of the falls recorded at a limited number of raingauges. The results can also be used to indicate the density of gauges that would be required to produce results of given accuracy. Because much more time than could have been foreseen was required to carry out the essential quality control described in Chapter 2, and for ease of computation we have concentrated in this part of the analysis on monthly rainfall and specifically the months February to November for which rainfall shows reasonable spatial coherence.

O'Connell et al. (1978) set out a method for calculating the accuracy of estimates of areal rainfall. A simplified version of that method is used here, and a number of assumptions have been made during the analysis. However these should not have a large effect on the conclusions drawn from the analysis.

Raingauge regions

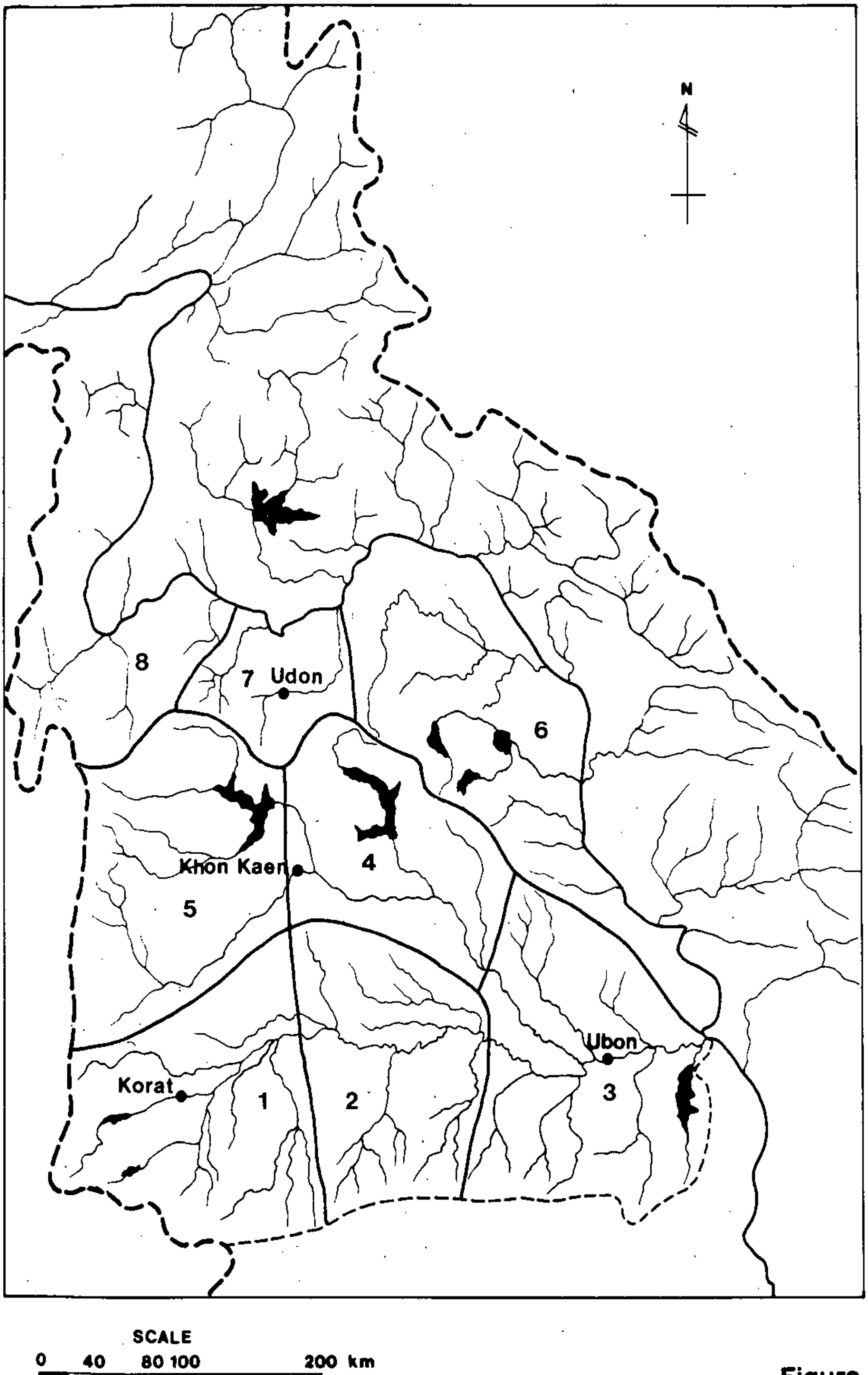


Figure 1

TABLE 3. Regional statistics of monthly rainfalls

Region	1	2	3	4	5	6	7	8
number of gauges	23	34	26	32	19	29	12	8
mean rainfall (mm)								
April	78	78	74	68	82	90	79	86
May	155	169	187	177	164	233	210	190
June	114	169	223	181	136	322	237	154
July	127	171	244	196	134	306	223	138
August	137	196	300	226	150	416	283	181
September	266	292	287	268	277	279	277	250
October	135	107	97	69	109	55	74	104
November	26	19	15	7.9	14	5.1	8.3	13
December	2.7	1.7	1.3	2.4	6.1	2.0	2.2	4.0
January	4.3	2.7	2.1	4.5	4.9	4.7	5.2	6.6
February	17	11	7.1	12	14	14	13	18
March	45	29	27	29	40	35	32	42
standard deviation (mm)								
April	44	54	56	47	48	53	45	50
May	80	93	103	97	81	97	91	90
June	65	81	108	94	74	143	99	85
July	65	77	98	91	75	107	87	79
August	74	90	117	96	69	171	120	85
September	105	106	118	109	116	119	124	100
October	81	79	74	55	88	54	59	80
November	36	27	22	16	21	11	15	21
December	7.6	5.1	3.7	6.8	15	6.8	6.9	11
January	11	7.9	7.0	13	13	12	14	13
February	22	19	15	19	20	20	19	23
March	39	29	33	32	34	33	29	36

Correlation of point rainfalls

The first step in our analysis is to describe the correlation of point rainfalls at different sites. To give the correlation, ρ, between falls at sites d km apart a function $\rho(d)$ was defined as

$$\rho(d) = a + (1-a-\varepsilon)\exp\{-bd\} \qquad (d > 0)$$
$$= 1 \qquad (d = 0)$$

where a, b and ε are parameters of the function whose values are determined from the available data. The method assumes that the year-to-year standard deviation is constant over the area for which the accuracy is being calculated, and that the correlation function does not vary either. To provide a convenient form of using the results of this analysis, we have sought to arrive at a simple description of the correlation function for the whole of the northeast. We have derived values for the parameters of this correlation function which give a reasonable fit to the sample correlations calculated from the observed data. This has involved some judgement of what parameters could be combined over regions without distorting the fit too much.

The parameter ε represents the proportion of the variation of rainfall which is attributable to purely local meteorological effects, or possibly to measurement errors: an analysis of the eight regions separately suggested that a value of $\varepsilon = 0.1$ would suit all the regions and each different month. With this value of ε fixed, the analysis was repeated and it was found that the number of separate parameters could be further reduced. We concluded that, for each calendar month, a single value of b could be applied for all eight areas, with different values of parameter a for each area. However the differences in the values of a between these areas are not great and it would be reasonable to average the values of a for different areas if the catchment under study was, for example, completely contained within two adjacent areas. The final parameter values are given in Table 4, together with values appropriate to the eight areas combined.

TABLE 4. Parameters of intersite correlations

$$\rho(d) = a + (1-a-\varepsilon)\exp\{-bd\} \qquad (d \text{ in km})$$

$$\varepsilon = 0.1$$

Month	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov
parameter b	.045	.065	.096	.065	.056	.070	.057	.048	.024	.056
parameter a										
region 1	.274	.274	.239	.535	.427	.358	.445	.407	.469	.655
2	.328	.262	.318	.542	.402	.329	.416	.382	.557	.512
3	.337	.438	.403	.578	.489	.389	.341	.408	.469	.470
4	.390	.415	.369	.539	.495	.449	.358	.448	.466	.538
5	.275	.384	.305	.479	.498	.603	.428	.501	.591	.554
6	.362	.426	.320	.381	.545	.506	.615	.497	.630	.422
7	.377	.333	.335	.458	.471	.393	.404	.450	.658	.547
8	.484	.400	.359	.409	.500	.598	.471	.338	.338	.635
combined a	.354	.360	.339	.519	.469	.426	.413	.426	.524	.536

Derivation of statistics of areal rainfall

The second step involves specifying the particular area under consideration together with the spatial arrangement of the raingauges within (or just outside) that area. Given the shape of the area under consideration and the relative positions of the raingauges, the accuracy of the estimate of areal rainfall can be defined as follows in terms of:-

(i) the size of the area,

(ii) the year-to-year standard deviation of point rainfalls,

(iii) the parameters of the correlation function.

Let the recorded rainfall at P gauges for a given month be $X_1, \ldots, X_P$: or in vector form $\underset{\sim}{X}$. The estimate of areal average rainfall is then

$$E = \underset{\sim}{b}^T \underset{\sim}{X}$$

where

$$\underset{\sim}{b} = P^{-1} (1 \quad 1 \quad 1 \ldots 1)^T$$

ie E is just the simple average of the gauged rainfalls. If the distance between gauges i and j is d_{ij}, then given the assumptions already made, the year-to-year variance of the estimated rainfall is

$$V_E = \underset{\sim}{b}^T \underset{\sim}{\Sigma}_{XX} \underset{\sim}{b}$$

where $\underset{\sim}{\Sigma}_{XX}$ is the P x P matrix with entries $s^2\rho(d_{ij})$, and s^2 is the year-to-year variance of monthly point rainfall for the particular month. The year-to-year variance of the true areal average rainfall, T, is given by

$$V_T = \frac{s^2}{A_o^2} \int_A \int_A \rho\{d(\underset{\sim}{v},\underset{\sim}{w})\} d\underset{\sim}{v}\, d\underset{\sim}{w}$$

where each integral is a two dimensional integral over points $\underset{\sim}{v}$ or $\underset{\sim}{w}$ within the region A, and A_o is the area of A in km^2. Here A is the region over which the areal average is taken, and the function $d(\underset{\sim}{v},\underset{\sim}{w})$ is the distance (km) between points $\underset{\sim}{v}$ and $\underset{\sim}{w}$, i.e.

$$d(\underset{\sim}{v},\underset{\sim}{w}) = |\underset{\sim}{v}-\underset{\sim}{w}|$$

The covariance between the true areal average rainfall and its estimate is given by

$$C_{TE} = \underset{\sim}{b}^T \underset{\sim}{\sigma}_{XT}$$

where $\underset{\sim}{\sigma}_{XT}$ is a P x 1 vector with elements

$$\{\underset{\sim}{\sigma}_{XT}\}_i = \frac{s^2}{A_o} \int_A \rho\{d(\underset{\sim}{v}_i, \underset{\sim}{w})\}\, d\underset{\sim}{w}$$

where $\underset{\sim}{v}_i$ is the position of the i'th gauge.

The variance of the estimation error is then given by

$$\text{var}\ (T - E) = V_T - 2\, C_{TE} + V_E$$

and since, under the assumptions, the estimate is unbiassed, the root mean square error (rmse) of estimation is readily obtained in the form

$$\text{rmse} = su$$

where u is then the fraction of the original year-to-year standard deviation of point rainfall remaining as estimation error.

The accompanying tables can be used to obtain values for the year-to-year standard deviation of the true areal average rainfall and for the estimation error factor, u.

General results

For a square region with sides of x km, the year-to-year standard deviation of the areal average rainfall itself can be obtained from Table 5 as follows:

(i) from Table 4 take parameter values of a and b appropriate to the month of the year and the region in question,

(ii) enter Table 5 at value of a and bx and read off the corresponding value,

(iii) multiply this value by the standard deviation of the point rainfalls given in Table 3.

The resulting estimate of standard deviation of the true average areal rainfall is always less than the standard deviation of the point rainfalls. This is solely due to the effects of spatial averaging and does not depend on the presence or absence of any raingauges.

Tables 6 and 7 give the standard deviation of the estimation error when the record from a single gauge is used as the estimate of areal average rainfall; Table 6 for a gauge located at the centre of the square, and Table 7 for a gauge located at one corner.

These two tables are used in the same way as Table 5. Note that for those entries marked *, the estimation error is larger than the variation of the areal average (in Table 5) and in these cases estimating the areal value by the long term mean is a better estimate than just using the single gauge value. In fact it would be possible to form an even better estimate by forming a weighted average of the long term mean and the site value(s); this approach has not been pursued any further here. Note also, that in Table 7, the estimation error starts to decrease with increasing area for large areas: this is related to the decrease in variability of the areal average rainfall.

TABLE 5. Standard deviation of true average rainfall

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.947	.947	.947	.948	.948	.948	.948
0.02	.946	.946	.946	.946	.947	.947	.947
0.04	.943	.943	.944	.944	.945	.945	.946
0.07	.938	.939	.940	.941	.942	.943	.944
0.1	.934	.935	.937	.938	.939	.941	.942
0.2	.920	.922	.925	.928	.930	.933	.936
0.4	.894	.899	.904	.909	.914	.919	.924
0.7	.859	.867	.876	.884	.892	.901	.909
1.0	.829	.840	.852	.863	.874	.885	.896
2.0	.754	.774	.793	.812	.830	.848	.866
4.0	.676	.705	.733	.760	.786	.811	.836
7.0	.631	.666	.699	.731	.762	.791	.819
10.0	.614	.651	.687	.721	.753	.784	.814
20.0	.598	.638	.675	.711	.745	.777	.808
40.0	.593	.634	.672	.708	.742	.775	.807

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.

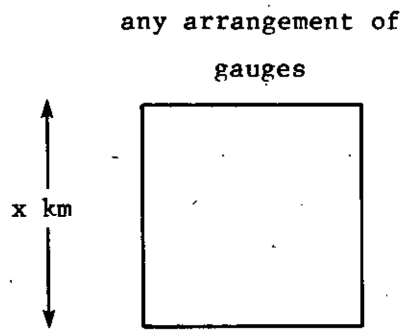


TABLE 6. Estimation error of areal average rainfall (1 gauge at centre)

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.318	.318	.318	.318	.318	.317	.317
0.02	.320	.320	.320	.319	.319	.319	.318
0.04	.325	.324	.323	.322	.322	.321	.320
0.07	.331	.329	.328	.327	.326	.324	.323
0.1	.337	.335	.333	.331	.329	.328	.326
0.2	.356	.353	.349	.346	.342	.339	.335
0.4	.391	.385	.379	.372	.366	.359	.352
0.7	.438	.428	.418	.408	.398	.387	.376
1.0	.478	.466	.453	.440	.426	.412	.398
2.0	.578	.560	.540	.520	.499	.477	.455
4.0	.689*	.664	.637	.610	.582	.552	.520
7.0	.756*	.727*	.697	.665	.632	.597	.560
10.0	.780*	.750*	.719*	.686	.651	.615	.576
20.0	.800*	.769*	.736*	.702	.666	.628	.588
40.0	.805*	.773*	.740*	.706*	.670	.631	.591

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.

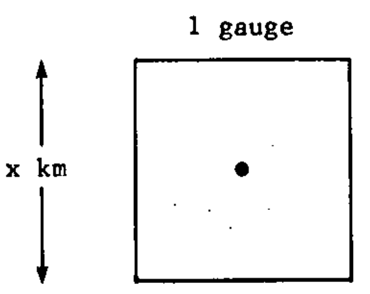
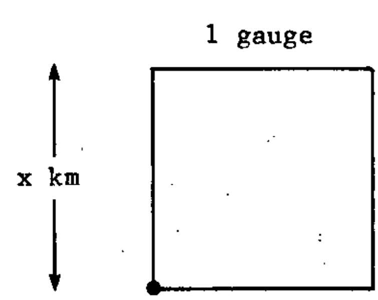


TABLE 7. Estimation error of areal average rainfall (1 gauge at corner)

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.325	.324	.323	.323	.322	.321	.320
0.02	.333	.332	.330	.329	.327	.326	.324
0.04	.349	.346	.343	.340	.337	.334	.332
0.07	.371	.366	.362	.357	.352	.347	.342
0.1	.391	.385	.378	.372	.366	.359	.352
0.2	.448	.438	.427	.416	.405	.394	.382
0.4	.532	.516	.500	.483	.465	.447	.428
0.7	.617	.596	.574	.551	.528	.503	.477
1.0	.673	.649	.624	.597	.570	.541	.510
2.0	.766*	.736	.706	.674	.640	.604	.567
4.0	.810*	.778*	.745*	.710	.673	.635	.594
7.0	.814*	.782*	.748*	.714	.677	.638	.596
10.0	.812*	.780*	.747*	.712	.675	.636	.595
20.0	.808*	.777*	.743*	.709	.672	.634	.593
40.0	.807*	.775*	.742*	.708*	.671	.633	.592

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.



Alternative arrangements of 2, 13, and 25 gauges were also considered: Tables 8 to 10 give results equivalent to Tables 6 and 7 but for the alternative arrangements of gauges.

It would have been possible to pursue other forms of analysis and consider other arrangements of gauges within regions of different generic shapes. Alternatively the estimation error of rainfall for a particular catchment could have been calculated directly. However it was our intention to present some results that could be applied to northeast Thailand in general, rather than any specific catchment or irrigation area in particular.

Interpretation of results

These results can also be used directly to determine the density of gauges in a given area that would be required to give a specified error in the rainfall estimate. An example is given below.

Suppose that for a particular analysis the root mean square error of areal average rainfall should be less than, say, 10 mm. Then by extracting information from Tables 3 and 4 and Tables 9 and 10 it is possible to find the largest area for which 13 and 25 gauges respectively would be just sufficient to achieve this requirement. Table 11 is based on the statistics for regions 1 and 2, that is the catchment of the Nam Mun down to Rasi Salai. From the standard deviation of monthly rainfall, s, and the required error of 10 mm, the corresponding target for the proportion of the standard deviation is given by 10/s. The maximum value of bx that just achieves this can then be read off from either Table 9 (for 13 gauges) or Table 10 (25 gauges).

The results in Table 11 imply that the required error criterion is hardest to meet in September; this is largely because of the high year to year variability of that month's rainfall. Taking the whole year except for September, then the results suggest that 13 gauges would provide sufficient accuracy for an area of about 50 km by 50 km; that is a spacing of 13.9 km (= $50/\sqrt{13}$). An area of about 270 km by 270 km could be covered by 25 gauges with a spacing of 54 km. For areas of these sizes and numbers of gauges then the root mean square error in September would in each case be about 12 mm which would probably be acceptable.

TABLE 8. Estimation error of areal average rainfall (2 gauges)

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.227	.227	.226	.226	.226	.225	.225
0.02	.230	.230	.229	.228	.228	.227	.227
0.04	.236	.235	.234	.233	.232	.231	.230
0.07	.245	.243	.242	.240	.238	.236	.234
0.1	.254	.251	.248	.246	.243	.240	.238
0.2	.278	.274	.269	.265	.260	.255	.250
0.4	.317	.310	.302	.294	.287	.279	.270
0.7	.359	.349	.338	.328	.316	.305	.293
1.0	.389	.377	.365	.352	.338	.324	.310
2.0	.450	.434	.418	.401	.383	.365	.345
4.0	.506	.487	.468	.447	.426	.403	.379
7.0	.542	.521	.499	.477	.453	.428	.401
10.0	.556	.535	.512	.489	.464	.438	.410
20.0	.567	.545	.522	.498	.472	.445	.417
40.0	.569	.547	.524	.500	.474	.447	.418

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.

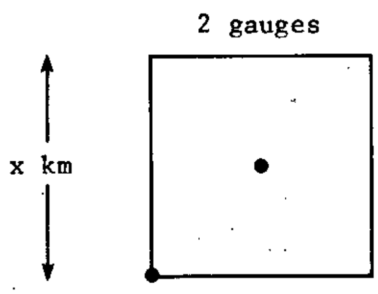


TABLE 9. Estimation error of areal average rainfall (13 gauges)

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.088	.088	.088	.088	.088	.088	.088
0.02	.088	.088	.088	.088	.088	.088	.088
0.04	.088	.088	.088	.088	.088	.088	.088
0.07	.089	.089	.089	.089	.088	.088	.088
0.1	.089	.089	.089	.089	.089	.089	.088
0.2	.091	.091	.091	.090	.090	.090	.089
0.4	.094	.094	.093	.093	.092	.091	.091
0.7	.099	.098	.097	.096	.095	.094	.093
1.0	.103	.102	.100	.099	.098	.096	.095
2.0	.116	.114	.111	.109	.107	.104	.102
4.0	.137	.134	.130	.126	.122	.117	.113
7.0	.161	.156	.151	.145	.139	.133	.127
10.0	.178	.172	.165	.159	.152	.144	.136
20.0	.206	.198	.190	.181	.172	.163	.153
40.0	.219	.210	.201	.192	.182	.172	.168

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.

13 gauges

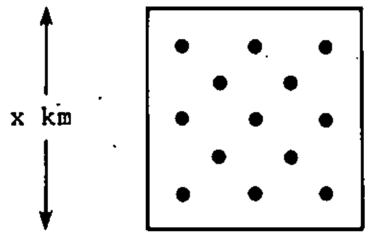


TABLE 10. Estimation error of areal average rainfall (25 gauges)

bx \ a	0.35	0.4	0.45	0.5	0.55	0.6	0.65
0.01	.063	.063	.063	.063	.063	.063	.063
0.02	.063	.063	.063	.063	.063	.063	.063
0.04	.064	.064	.064	.064	.063	.063	.063
0.07	.064	.064	.064	.064	.064	.064	.064
0.1	.064	.064	.064	.064	.064	.064	.064
0.2	.065	.065	.065	.065	.064	.064	.064
0.4	.067	.066	.066	.066	.065	.065	.065
0.7	.069	.068	.068	.067	.067	.066	.066
1.0	.071	.070	.070	.069	.068	.068	.067
2.0	.078	.076	.075	.074	.073	.071	.070
4.0	.089	.087	.085	.083	.081	.079	.076
7.0	.104	.101	.098	.095	.091	.088	.084
10.0	.115	.112	.108	.104	.100	.095	.091
20.0	.139	.134	.128	.123	.117	.111	.104
40.0	.154	.148	.142	.136	.129	.122	.114

Result is entry multiplied by standard deviation from Table 3. Entry at a and bx, with a and b from Table 4.

25 gauges

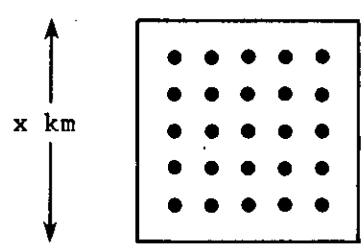


TABLE 11. Accuracy of areal rainfall in Regions 1 and 2

Month	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov
Parameter b*	.045	.065	.096	.065	.056	.070	.057	.048	.024	.056
" a*	.301	.268	.278	.538	.414	.343	.430	.395	.513	.584
Std dev , S+	20	34	49	87	73	71	82	105	80	31
10/S	.5	.294	.204	.115	.137	.141	.122	.095	.125	.323
largest bx_{13}	-	-	15	3	4	4	3	0.5	4	-
largest x_{13}	-	-	156	46	71	57	53	10	167	-
largest bx_{25}	-	-	-	20	20	20	15	6	20	-
largest x_{25}	-			308	357	285	263	125	833	-

Notes: for detailed explanation see text

* from Table 4

\+ from Table 3

x_{13}, x_{25} are the sizes of the largest regions such that 13 and 25 evenly spaced gauges are sufficient to estimate areal average rainfall with a rmse of 10 mm.

Estimates of synthetic sequences of areal rainfall

For use in Chapter 4, we require to be able to take a given sequence of rainfall values and, regarding this sequence as the true areal average rainfall, to add pseudo-random noise in such a way that the resulting sequence has the same properties (and relation to the "true" rainfall) as would an estimate of areal rainfall derived as the arithmetic average of a given number of point measurements.

It is not strictly correct to generate such "estimated" rainfalls by the formula

$$E_i \;=\; T_i + \varepsilon_i$$

with ε_i independent of T_i and the standard deviation of ε_i given by su as calculated above. This is because in practice the estimation errors ε_i are not uncorrelated with the true rainfalls T_i. A valid procedure would be to generate the required "estimated" rainfalls using the expression

$$E_i \;=\; \mu + \beta\,(T_i - \mu) + \eta_i, \qquad \mathrm{cov}(\eta_i, T_i) = 0$$

where μ is the long-run mean and β and $\mathrm{var}(\eta_i)$ are determined by

$$\beta \;=\; C_{TE}/V_T$$

$$\mathrm{var}(\eta_i) \;=\; V_E - \beta^2 V_T$$

These parameters again depend on the number and configuration of the gauges supposed to be used in forming the estimated rainfall, as well as on the month of the year. Examination of the numerical values of these parameters in a range of situations revealed the following:

(i) the coefficient β approached close to 1 for increasing numbers of gauges.

(ii) values of β both less than or greater than 1 occur.

(iii) the most extreme values occur for the case of a single gauge.

(iv) the dependence on position is exemplified by the change in β from 0.930 to 1.086 for certain correlation parameters, in the case of a single gauge moving from one corner to the centre of a square.

(v) the values 0.930, 1.086 were the most extreme values found over the range tabulated.

Note however that no situations involving gauges outside the given area were considered.

In view of these findings it seemed reasonable, and most convenient, to take $\beta = 1$ for the simulations to be performed. This was both because of the small range found and because there seems always to be an arrangement of any given number of gauges giving exactly this value for β. For the later analysis we have no particular configuration of gauges in mind, but areal averages would typically be found from at least four gauges and the approximation $\beta = 1$ is then very good.

If the arrangment of gauges were such that $\beta = 1$, then this would imply that $C_{TE} = V_T$ and thus give a value for $\mathrm{var}(\eta_i)$ identical to the estimation error variance derived earlier. Thus the conclusion is that we can use the formula

$$E_i = T_i + \varepsilon_i$$

for generating the required simulations of "estimated" rainfalls, even though this is not exactly correct in all cases. At many stages in the overall analysis a number of approximations are made and the error introduced here is unlikely to be the worst.

One can contrast the above problem with the apparently similar one of having a sequence of observed areal rainfalls, estimated by a simple arithmetic average, and wishing to generate stochastically sequences to represent the possible range of true areal average rainfalls. This can be done by generating values of T_i from E_i by the formula

$$T_i = \mu + \gamma\ (E_i - \mu) + \zeta_i\ ,\ \mathrm{cov}(\zeta_i, E_i) = 0$$

with

$$\gamma = C_{TE}/V_E$$

$$\mathrm{var}(\zeta_i) = V_T - \gamma^2 V_E.$$

In this case values of the coefficient γ differ greatly from unity when the estimate is the simple average. While one might actually wish to do this kind of simulation in practice, for example to examine the range of flow realisations implied by a given estimated rainfall sequence, it is also true that using the same value of γ to construct a new estimate of areal average rainfall as

$$E_i^* = \mu + \gamma(E_i - \mu)$$

would result in a better estimate of the true rainfalls: ie one with smaller estimation error.

4. THE IMPACT OF RAINFALL ERRORS ON RUNOFF ESTIMATES

Introduction

Many hydrological problems require estimates of runoff to be derived from estimates of areal rainfall either observed or forecast. Runoff record extension and gap filling are examples of this and in these cases the stability of the medium to long term runoff statistics is important. Another class of problems involves forecasting sometimes from rainfall forecasts and here it is the short to medium term runoff statistics which have greatest impact on the usefulness of the forecast.

the rIn all these examples runoff is estimated from rainfall by a modelling procedure of which there are many kinds. It is difficult always to separate the different causes of error in the runoff estimates; significant errors might arise from the use of an imperfect model. Furthermore, the historic runoff data on which the model is calibrated are subject to errors of observation and rating which affect the estimation of model parameters and lead to errors in the runoff generated using the model. This and other problems of error definition are discussed more fully in O'Connell et al, 1977, 1978.

In this study our purpose is to illustrate the general effect of errors in areal rainfall estimates on runoff generation rather than to provide detailed results for various time intervals and various river basins. We can say as a generality that errors should become less significant as the time interval of interest lengthens and as the catchment area is increased. We have chosen to look at two time intervals, a pentad or five day interval and a year, although in practice all the annual runoff occurs between April and January as a result of effective rainfall in the months April to November. The choice of catchment area is more difficult; a moderately large area is needed if it is to contain sufficient reliable raingauges.

We have chosen to look at the Mun basin above Rasi Salai. The catchment area contains over 30 raingauges having reliable data over the 23 year period for which runoff records are available for the station at Rasi Salai. The catchment area is 45108 km^2

In this chapter we use the results of the statistical analysis to generate sequences of areal pentad rainfall corresponding to different densities of raingauges. The simple conceptual model (from Phase 1 of this study) and a simplified version of the SSARR model are fitted to the observed data so that the optimum values of the parameters of the models can be defined. Generation of alternative flow sequences using the models and the generated sequences of areal pentad rainfalls then provides measures of the effect of rainfall errors on the pentad and annual flows.

For convenience we have used the term 'annual' to cover the 10 month period April to January. This period covers the whole of the runoff season and most of the rainfall. March is the only month excluded which has significant rainfall and this rainfall is very unlikely to produce significant runoff.

Rainfall on the Mun basin above Rasi Salai

From the rainfall database described previously there are 56 gauges in the catchment area of interest shown in Figure 2. We have examined the degree of completeness of these records and their quality using the comparative tests described in Chapter 2, for the years 1957 to 1979; those being the years for which we have runoff records from Rasi Salai. We find that 35 gauges meet the arbitrary criteria of less than 3 years with incomplete records and less than 8 errors indicated by quality control. Of these 35, we have eliminated 3 gauges which have very near neighbours so as to give a more uniform spread of gauges over the whole basin. An index of these stations is given in Table 12.

The areal rainfall on a pentad time scale was derived by simple average from 32 gauges covering the 45108 km^2 basin, a gauge density of 1 gauge per 1400 km^2. Elimination of data from gauges with less complete records should ensure that the areal rainfall data derived in this manner represents the true areal rainfall distribution in a consistent way.

Raingauges in the Mun basin above Rasi Salai

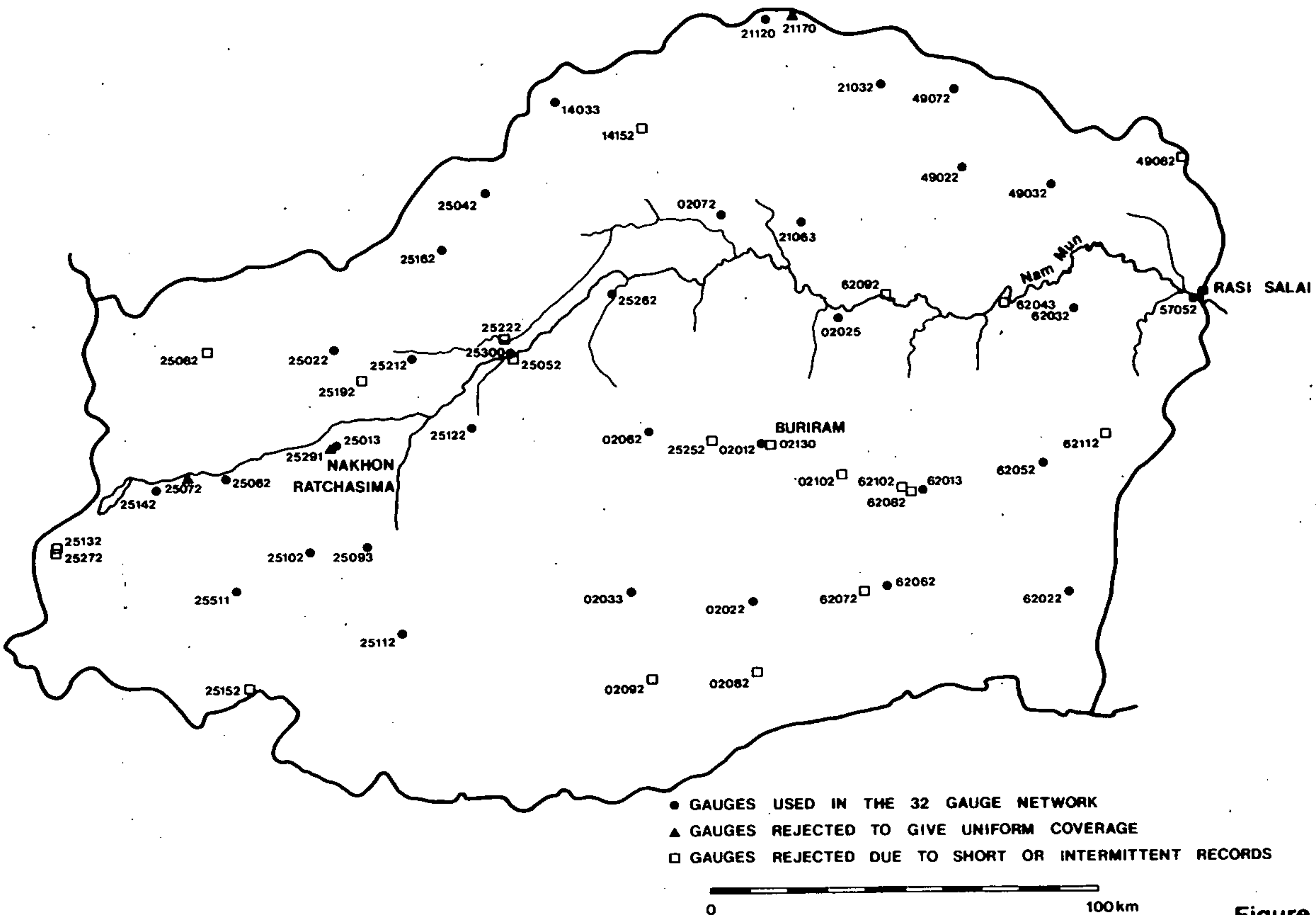


Figure 2

TABLE 12. Raingauges used in the analysis of the Mun basin above Rasi Salai

RID Code	Mekong Code	Name	Grid Ref	Lat(°N)	Long(°E)	Altitude(m)
2012	530	BURI RAM	2971658	15 00	103 06	155
2022	529	PRAKHON CHAI	2941616	14 36	103 05	159
2033	528	NANG RONG	2631619	14 38	102 48	183
2052	455	SATUK	3161691	15 18	103 18	132
2062	527	LAM PLAI MAT	2671661	15 01	102 50	165
2072	457	PHUTTHAISONG	2861719	15 32	103 00	141
14033	458	PHON	2431748	15 49	102 36	175
21032	454	WAPI PHATUM	3271753	15 51	103 23	141
21063	456	PHAYAKKAPHUMPHISAI	3071717	15 31	103 12	135
21120	0	EKASATSUNTHON TANK	2971770	16 00	103 06	0
25013	525	KORAT	1861657	14 58	102 05	181
25022	464	NON THAI	1861682	15 12	102 04	170
25042	460	BUA YAI	2251724	15 35	102 26	170
25062	523	SUNG NOEN	1581648	14 54	101 49	213
25093	572	CHOK CHAI	1951630	14 44	102 10	192
25102	524	PAK THONG CHAI	1801629	14 43	102 01	305
25112	526	KHON BURI	2041607	14 31	102 15	210
25122	0	CHAKKARAT	2221662	15 01	102 25	0
25142	0	BAN MAI SAM RONG A	1401645	14 52	101 39	0
25162	461	KHONG	2141709	15 26	102 20	175
25212	0	NON SUNG AG EX STN	2061680	15 11	102 16	0
25300	0	PHIMAI BARRAGE	2321681	15 13	102 30	0
25511	0	LAM PRA PLERNG	1601617	14 36	101 51	0
49022	452	KASET WISAI	3481731	15 39	103 34	130
49032	448	SUWANNAPHUM	3711726	15 36	103 48	137
49072	451	CHATURAPHAKHIMAN	3461752	15 51	103 34	142
57052	443	RASI SALAI	4081697	15 20	104 09	120
62013	533	SURIN	3381646	14 53	103 29	145
62022	534	SANGKHA	3761619	14 38	103 51	160
62032	449	RATTANABURI	3771694	15 19	103 51	130
62052	535	SIKHORAPHUM	3691653	14 57	103 48	138
62062	532	PRASAT	3291620	14 38	103 24	167

The Mun basin above Rasi Salai comprises regions 1 and 2 as defined in the statistical analysis in Chapter 3. Using the data given in Table 4, we can define the parameters a and b for each calendar month from April to November. This covers the main wet season and estimates for other months can be ignored. Entering Tables 5 to 10 with the parameter estimates yields values of the estimation error factor for monthly areal average rainfall which, when multiplied by the standard deviation of monthly rainfall at a point, gives the estimated standard deviation of errors associated with mean values from the relevant number of gauges. Table 13 shows the results of this procedure for 1, 2, 13 and 25 gauges. For each month we have derived a typical standard deviation of monthly point rainfall by taking the median of values computed separately for all 32 stations.

Figure 3 shows how the estimation error factors of monthly areal rainfall vary according to the number of raingauges and by months. The curves are extrapolated slightly to yield values for a 32 gauge network. These values and the estimates of the standard deviation of errors in monthly areal rainfall are shown in Table 14.

As the curves in Figure 3 are of very similar slope we can derive a general factor relating the standard deviation of errors for a small network to that for the 32 gauge network. These factors, listed in Table 15, show how the errors may be expected to grow as progressively smaller networks are used.

TABLE 13. Estimate of parameters defining error levels for monthly rainfall

Mun basin above Rasi Salai

Month	a	b	bx	Estimation error factor of monthly areal rainfall for the number of gauges shown 1	2	13	25
A	0.278	0.096	20.4	0.844	0.600	0.218	0.146
M	0.538	0.065	13.8	0.665	0.473	0.162	0.108
J	0.414	0.056	11.9	0.745	0.530	0.174	0.115
J	0.344	0.070	14.9	0.793	0.564	0.192	0.127
A	0.428	0.057	12.1	0.736	0.524	0.173	0.114
S	0.394	0.048	10.2	0.754	0.538	0.173	0.113
O	0.513	0.024	5.1	0.622	0.452	0.132	0.087
N	0.584	0.056	11.9	0.629	0.448	0.150	0.100

Note: x is taken to be the square root of the catchment area, that is 212.4 km.

Variation of estimation error factor with number of gauges for each calendar month (April – November)

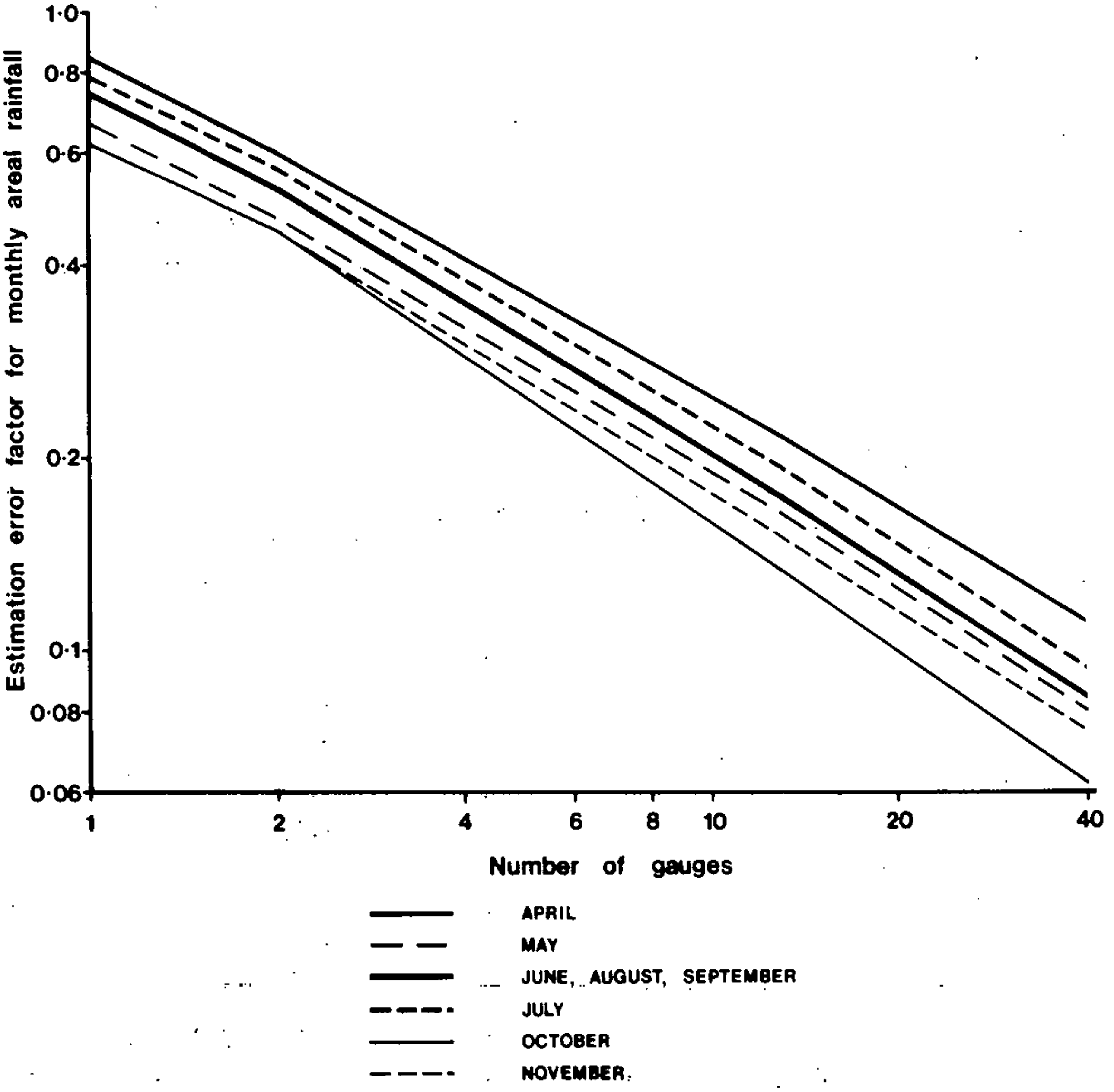


Figure 3

TABLE 14. Standard deviation of errors in monthly rainfall

Mun basin above Rasi Salai

Month	Estimation error factor for 32 gauge network	Standard deviation of year to year point rainfall (mm)	Standard deviation of errors in monthly areal rainfall (mm)
A	0.126	49.7	6.3
M	0.091	89.0	8.1
J	0.096	76.6	7.4
J	0.107	66.7	7.1
A	0.096	85.5	8.2
S	0.096	109.8	10.5
O	0.072	81.5	5.9
N	0.085	33.4	2.8

TABLE 15. Scaling factors for smaller raingauge networks

Number of raingauges	Factor
1	7.6
2	5.4
4	3.5
7	2.6
10	2.1
15	1.6
20	1.4
25	1.2
32	1.0

Note: the standard deviation of errors in monthly areal rainfall for n gauges is obtained by multiplying the standard deviation for the 32 gauge network by the appropriate factor.

Rainfall-runoff models

It is not the purpose of this work to identify the most appropriate form of model for northeast Thailand nor is it intended to carry out exhaustive studies of parameter estimation. Rather we have used two models, a simplified version of the SSARR model and the conceptual model used in Phase 1, to help define the effect of errors in rainfall on the predictions of runoff resulting from use of models of the conceptual type.

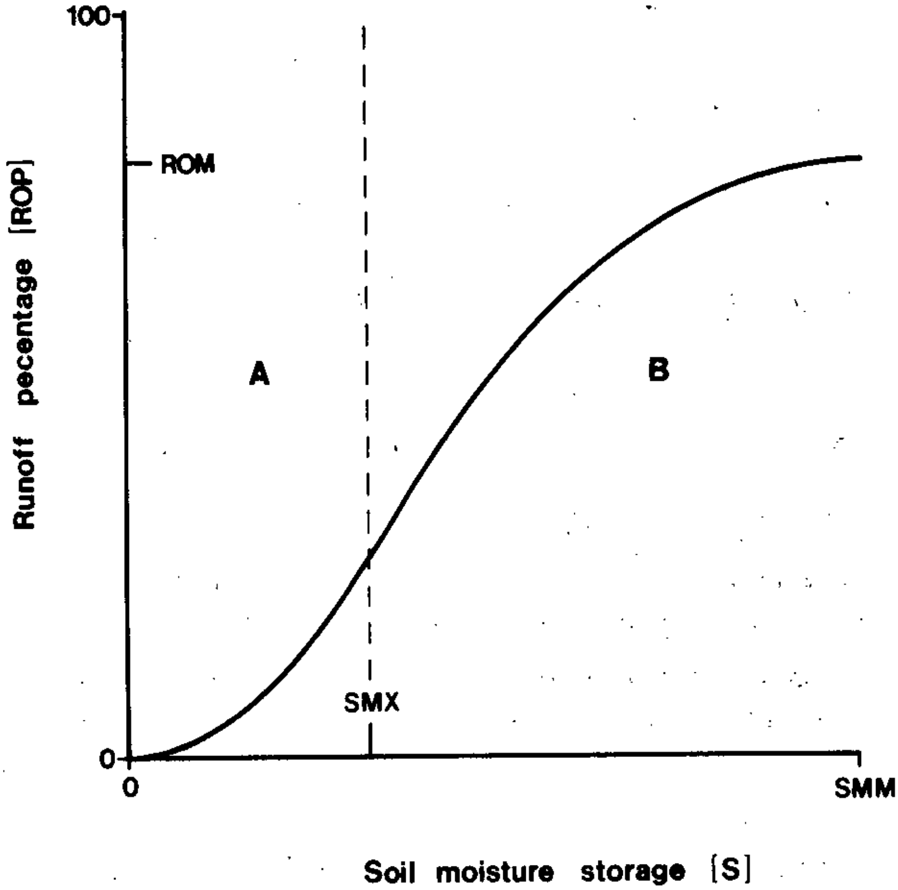
We have used a pentad time interval to avoid the large computing load which would have followed from use of a shorter time scale; a monthly time interval would have been too coarse and would not have provided an adequate test of the models.

The models were fitted using the full 23 year joint record of rainfall and runoff. Annual and pentad sums of squares of differences between observed and predicted runoff were used jointly as measures of the goodness of fit of the models.

In its complete form SSARR is a very complicated form of conceptual model particularly because a number of relationships between variables are specified by look up tables which implies a very large number of model parameters. The simplified version of the model used in this analysis identifies two important aspects of the model, surface runoff generation and runoff routing. We have used a formal 3 parameter relationship between runoff percentage and soil moisture storage. Routing is achieved using the Muskingum procedure using 2 parameters; a further parameter is used to incorporate a linear time delay in the routing process.

Figure 4 shows the 'S curve' relationship between runoff as a percentage of gross rainfall and soil moisture storage. The equations quoted show how the runoff percentage is related to the 3

Form of the runoff percentage – soil moisture curve used in the SSARR model



In region A $$ROP = ROM * \frac{S^2}{SMM * SMX}$$

In region B $$ROP = ROM * \left[1 - \frac{(SMM - S)^2}{SMM\ (SMM - SMX)} \right]$$

Figure 4

parameters defining the S curve. In the Muskingum routing procedure the routing storage SR is defined in terms of inflow to and outflow from the storage as:

$$SR = PK (PX.inflow + (1 - PX).outflow)$$

The delay parameter NDEL is an integer number of pentads.

A simple conceptual model was defined in Phase 1 of this study and is used here for comparison with the SSARR model. In practice the only difference between the two models as formulated here is in the runoff generation part of the model; both use 3 parameters.

Fitted model parameters

Both models were fitted initially assuming that there was no year by year bias in the estimation of areal rainfall from the 32 gauge network. When optimum parameter values had been identified annual rainfall weighting factors were introduced so as to reduce the annual error in runoff prediction to zero. As expected this produced a modest improvement in fit at the pentad level although at the cost of introducing an extra 23 parameters!

The optimum parameter values and the fitting statistics are given in Table 16; a summary of the annual data and simulated runoff is given in Table 17.

Taking account of all these measures we can conclude that the version of the SSARR model is reasonably effective in simulating runoff although it explains only 70 per cent of the variance of annual runoff. Overall it gives an unbiassed estimate of mean annual runoff and reproduces the observed variability of runoff about the mean. This is achieved with only 4 of the 6 parameters active.

TABLE 16. Summary of model fitting

		Simple Model		SSARR Model	
Optimum parameter values:		SUM	95	ROM	0.51
		SLM	145	SSM	160
		FR	5.5	SSX	0
		PK	7.0	PK	3.9
		PX	0	PX	0
		NDEL	1	ETF	0
				NDEL	2
Initial variance of runoff:	annual		96928		96928
	pentad		24657		24657
Unexplained variance: RWF = 1	annual		76919		29073
	pentad		8022		3645
variable RWF	annual		0		0
	pentad		5012		2306
Explained variance % RWF = 1	annual		20.6		70.0
	pentad		67.5		85.2
variable RWF	pentad		79.6		90.6
Observed annual runoff:	mean		151		151
	sd		66		66
Simulated Annual runoff: RWF = 1	mean		146		148
	sd		100		64
Rainfall weighting factors:	mean		1.015		1.004
	sd		0.084		0.073

TABLE 17. Summary of annual model fitting

YEAR	Rainfall	Observed runoff	Simulated runoff	Difference	Simulated evaporation
Simple Conceptual model					
1957	1028.	106.	139.	- 33.	889.
1958	1206	172.	271.	- 98.	936.
1959	1250.	189.	295.	- 106.	955.
1960	1273.	188.	233.	- 45.	1040.
1961	1076.	133.	60.	73.	1016.
1962	1378.	248.	342.	- 94.	1036.
1963	1183.	131.	145.	- 14.	1038.
1964	1244.	176.	138.	39.	1106.
1965	1061.	72.	69.	3.	992.
1966	1435	261.	355.	- 94.	1081.
1967	1027.	102.	56.	46.	971.
1968	1075.	93.	60.	33.	1015.
1969	1166.	136.	119.	17.	1047.
1970	1114.	100.	36.	64.	1078.
1971	1078.	148.	85.	63.	993.
1972	1183.	209.	209.	0.	974.
1973	942.	40.	51.	- 10.	892.
1974	1029.	61.	43.	18.	986.
1975	1098.	125.	78.	47.	1021.
1976	1259.	249.	225.	25.	1034.
1977	988.	122.	119.	3.	869.
1978	1256.	285.	190.	96.	1067.
1979	1004.	118.	53.	65.	950.
SSARR model					
1957	1028.	106.	117.	- 11.	911.
1958	1206.	172.	195.	- 23.	1011.
1959	1250.	189.	231.	- 42.	1020.
1960	1273.	188.	216.	- 28.	1057
1961	1076	133.	101.	32.	975.
1962	1378	248.	255.	- 7.	1123.
1963	1183.	131.	170.	- 39.	1013.
1964	1244.	176.	160.	17.	1084.
1965	1061.	72.	79.	- 7.	982.
1966	1435.	261.	310.	- 49.	1126.
1967	1027.	102.	86.	17.	942.
1968	1075.	93.	80.	13.	995.
1969	1166.	136.	159.	- 23.	1007.
1970	1114.	100.	115.	- 14.	1000.
1971	1078.	148.	113.	34.	964.
1972	1183.	209.	159.	50.	1024.
1973	942.	40.	68.	- 27.	875.
1974	1029.	61.	85.	- 24.	944.
1975	1098.	125.	131.	- 6.	967.
1976	1259.	249.	199.	51.	1060.
1977	988.	122.	103.	19.	885.
1978	1256.	285.	184.	102.	1073.
1979	1004.	118.	85.	33.	918.

Note: all rainfall weighting factors = 1.000

The simple conceptual model performs much less well despite having one further active parameter. This performance does not justify its use in the rest of the analysis.

The introduction of annually derived rainfall weighting factors ensures a perfect fit on an annual basis and provides a modest improvement in the explained variance on a pentad time interval. Table 18 shows the factors derived for both models. As in our Phase 1 study, the factors show no clear trend with time and the means and standard deviations are comparable to those derived for the Huai Samran and Lam Se Bai catchments. We can see no rational basis for using rainfall weighting factors as formal parameters of a model. We understand that the Mekong Secretariat use these factors as weights to be attached to each gauge of the network being used partly as a means of providing an unbiassed estimate of areal rainfall. But as the factors are readjusted for each year of data, it does not seem to be possible to separate the two functions that the factors fulfil.

The effect of smaller raingauge networks

We have assumed that the areal pentad rainfalls derived from the historic data of the 32 gauge network can be considered to represent the true rainfall. We have shown that it is reasonable to derive alternative estimates of rainfall from the 32 gauge network can be obtained by adding a random error which has a standard deviation, different for each month, given in Table 14. Similarly rainfall sequences representing estimates based on fewer raingauges can be obtained simply by increasing the standard deviation of errors by the factors given in Table 15.

One inconsistency has to be overcome: the errors were estimated on a monthly basis, whereas we wish to carry out this part of the analysis by pentads. We have therefore computed the monthly areal rainfall for each month and, for each sequence generated, determined the random error associated with that month. This error was then distributed between the 6 pentads in proportion to the pentad rainfall pattern. Only occasionally, when the month's error exceeded the month's areal rainfall were the 6 pentad rainfalls set to zero. In practice this caused very little bias in the estimated average annual rainfall. In some ways this procedure was a reasonable way out of a difficulty commonly encountered in sequence generation. As many of the areal pentad rainfalls are zero it would have been difficult to impose random errors directly on the pentad sequence as many negatives would have resulted. Setting these to zero would then have imposed significant bias on the mean rainfall.

In all, 100 sequences were generated for networks comprising 1, 2, 4, 10 and 32 gauges.

Derivation of runoff sequences

It would be possible to recalibrate the parameters of the model to compensate in part for errors in the rainfall data. To some extent the optimum parameters we have defined have taken some account of the likely but unknown errors in the recorded rainfall sequence used in fitting the model. However a procedure involving recalibration for each perturbed rainfall sequence would mask the true effect of errors in the rainfall. We have therefore held the model parameters at the values derived by fitting the model to the 23 year recorded rainfall and runoff.

It is possible to estimate the accuracy of prediction of runoff using the perturbed rainfall sequences in two ways. Either we can consider the model as imperfect and compare each new runoff sequence with the single measured historic sequence; or we can develop a single synthetic sequence from the historic rainfall and the model, which is now assumed to be perfect, and compare all new runoff sequences with this synthetic sequence.

We have followed both approaches since they offer an approximate way of separating errors due to the model and errors due to the rainfall. The separation cannot be exact because the values of the model parameters are not necessarily "true" values because of their interdependence with errors in the historic rainfall sequence and indeed errors in the observed runoff.

TABLE 18. Derived annual rainfall weighting factors

Year	from simple conceptual model	from SSAR model
1957	0.928	0.970
1958	0.867	0.950
1959	0.859	0.922
1960	0.947	0.960
1961	1.113	1.087
1962	0.902	0.987
1963	0.977	0.912
1964	1.054	1.024
1965	1.008	0.975
1966	0.918	0.932
1967	1.103	1.044
1968	1.107	1.027
1969	1.023	0.960
1970	1.078	0.970
1971	1.121	1.076
1972	1.000	1.090
1973	0.972	0.889
1974	1.033	0.922
1975	1.054	0.989
1976	1.028	1.110
1977	1.005	1.068
1978	1.103	1.168
1979	1.146	1.060
Mean	1.015	1.004
SD	0.084	0.073

Table 19 shows the statistics of annual rainfall and runoff derived from 100 sequences for each number of raingauges; Table 20 shows the percentage explained variance calculated with reference to the historic and the synthetic runoff sequences; and Table 21 shows the average standard deviation of annual runoff taking one year at a time. This last statistic is estimated by taking each of the 23 years in turn, for which there are 100 perturbed rainfall estimates and thus 100 predicted runoff sequences, and taking the average of the 100 estimates of the standard deviation of annual runoff. In practice there was little variation across the years; the standard deviation was not particularly sensitive to high or low rainfall years.

Interpretation of the Results

Before discussing the effect of errors in the rainfall on estimates of runoff, it is worth reviewing the kinds of errors associated with areal rainfall estimates and the approach that we have followed in this study. Errors arise primarily because of our imperfect knowledge of the rainfall distribution across the area in the time interval of interest. From meteorological and topographical considerations we can expect there to be some average distribution about which there will be fluctuations. Thus from a given raingauge network there will tend to be a bias in the estimate of areal rainfall plus a random error which represents the departure from the average areal distribution of rainfall. Both the bias and the random error will be enhanced by measurement errors.

For simplicity in this analysis we have assumed that the 32 gauge network gives an estimate of the long term average rainfall that is without bias. The errors imposed on the monthly (and pentad) areal rainfalls derived from this network are random errors related primarily to the natural fluctuations in rainfall distribution. By scaling up these errors to simulate the effect of a smaller raingauge network we have implied that the networks comprising fewer gauges also give unbiassed estimates of long term areal rainfall.

TABLE 19. Statistics of the generated annual rainfall and runoff sequences

(mm)

Number of raingauges		1	2	4	10	32
Factor		7.6	5.4	3.5	2.1	1.0
23 year mean annual rainfall:	mean	1151	1147	1146	1146	1146
(100 sequences)	sd	33.3	24.0	15.5	9.3	4.4
Average standard deviation of annual rainfall over 23 years		195	166	145	134	129
23 year mean annual runoff:	mean	168	158	152	149	148
(100 sequences)	sd	12.9	9.5	6.4	3.9	1.9
Average standard deviation of annual runoff over 23 years		84	76	70	67	65

TABLE 20. The effect of rainfall errors on overall model performance
SSARR model

		1	2	4	10	32
Number of raingauges		1	2	4	10	32
Factor		7.6	5.4	3.5	2.1	1.0
Average explained variance (%) 100 trials - compared with historic runoff sequence	annual	neg	25.2	51.6	63.6	68.9
	pentad	60.3	72.3	79.7	83.2	84.8
Average explained variance (%) 100 trials - compared with optimum generated runoff	annual	neg	43.3	75.5	90.9	97.8
	pentad	69.6	84.0	93.0	97.4	99.4

TABLE 21. The effect of rainfall errors on single year runoff
SSARR model

	1	2	4	10	32
Number of raingauges	1	2	4	10	32
Factor	7.6	5.4	3.5	2.1	1.0
Average standard deviation of annual runoff for 100 values of runoff in each of 23 years (mm)	61.3	45.1	30.2	18.6	9.1

In practice the use of a small network of gauges will tend to give a biassed estimate of the areal rainfall, but when the model is fitted to a period of rainfall and runoff record the parameters will, to a large extent, take values which compensate for any bias.

The rainfall statistics in Table 19 show that the procedure used to impose errors on the 32 gauge areal estimates did not cause any significant drift in the 23 year mean annual rainfall. However the imposition of progressively larger errors caused a marked upward drift in the 23 year mean annual runoff generated by the model. Further trials not reported here showed that the drift was not caused by sampling error in the 100 sequences used. Rather the cause lies in the structure of the SSARR model where runoff is generated from net rainfall in a non-linear way after evaporation has been subtracted from gross rainfall. Thus a combination of positive errors in rainfall could have a proportionately greater effect on runoff generation than would a combination of negative errors of the same magnitude.

Any tendency to overestimate runoff could be countered by parameter adjustment during model fitting and to a large extent synthesis of runoff records from rainfall estimated from the same network would be unaffected by drift. However a tendency to overestimate runoff could result from extension of a runoff record from an historic rainfall record derived from a network having fewer gauges than the network used in the fitting period. Also the application of the model to an ungauged catchment having a sparse network of raingauges could lead to an overestimate of runoff.

Figure 5 shows how the standard deviation of the 23 year mean annual rainfall and runoff could be expected to increase as the number of raingauges in the network is progressively reduced. For any number of raingauges the graph suggests that the coefficient of variation of mean annual runoff is about 3 times that of mean annual rainfall.

Table 20 and Figure 6 show how the variation in runoff over the 23 year period might be affected by errors in the rainfall

Standard deviation of the 23 year means of generated rainfall and runoff

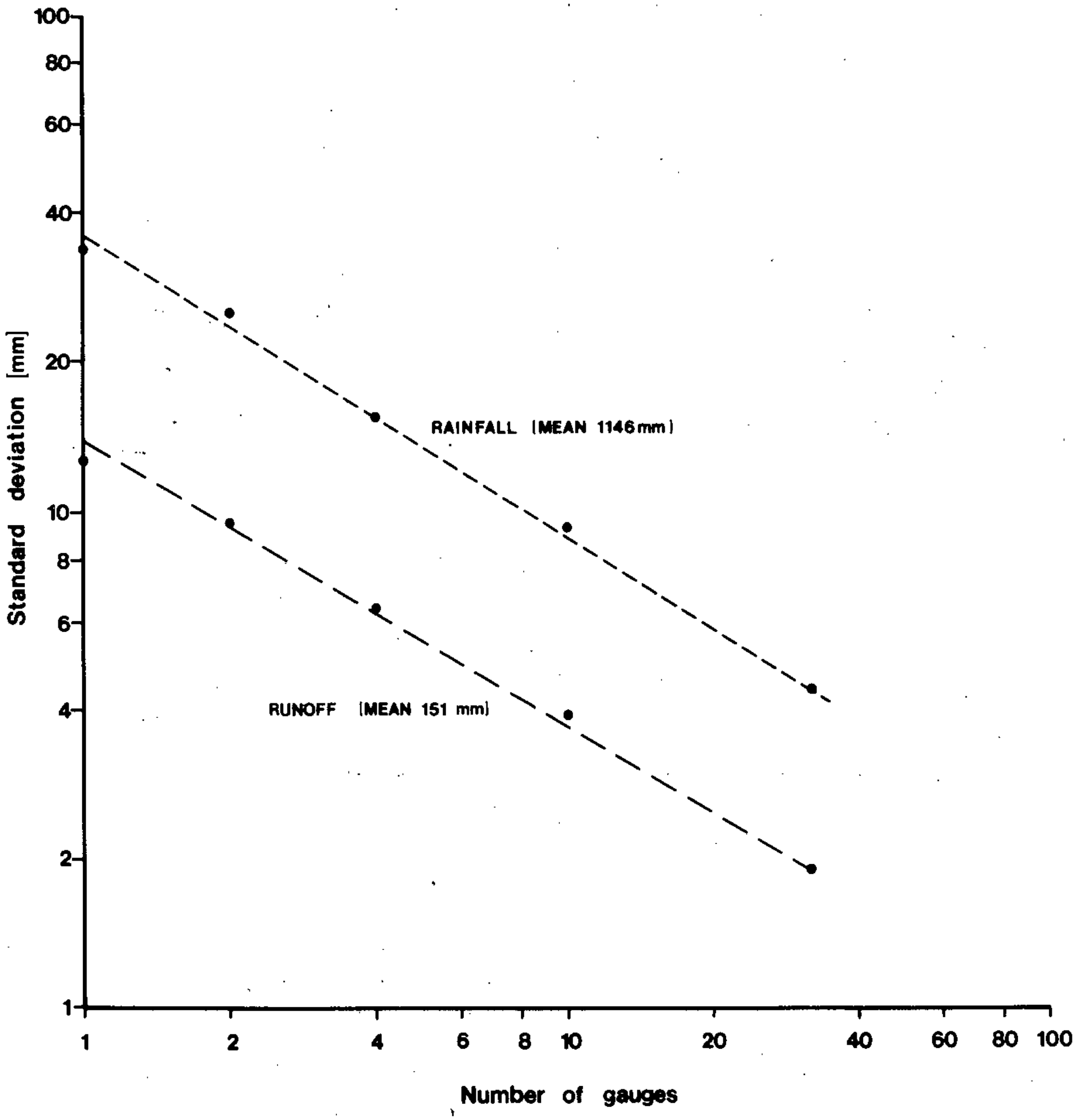


Figure 5

Average explained variance, % - SSARR model

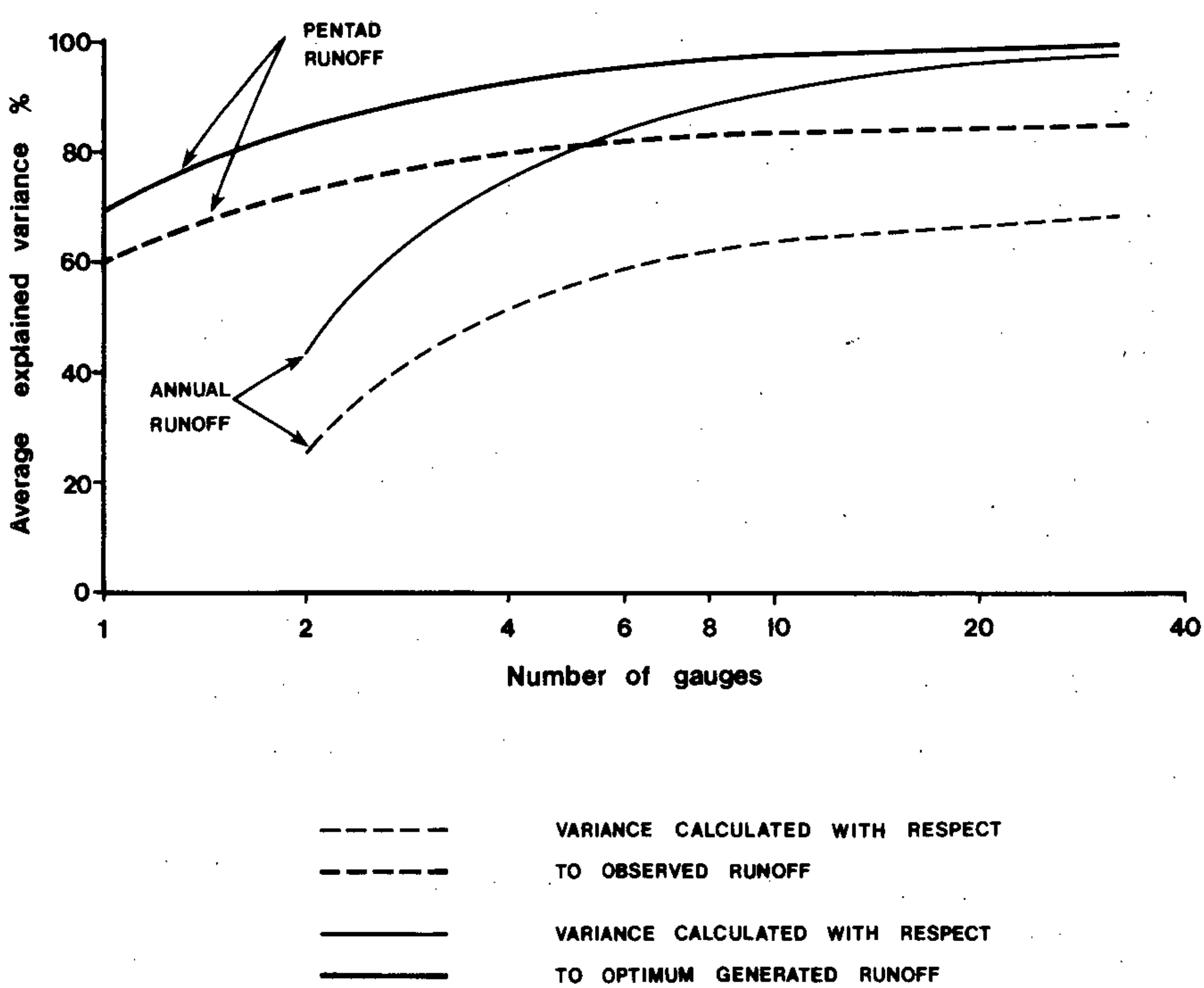


Figure 6

estimates. If we make the broad assumption that the unexplained variance measured from the observed runoff series is caused by errors in rainfall and errors due to the model, and that the unexplained variance relative to the optimum generated runoff series is primarily due to errors in rainfall, we can draw some general conclusions about the desirable number of raingauges in the network. For example if the unexplained variance attributable mainly to errors in rainfall is to be less than 25 per cent of the total, a network of at least 7 gauges is needed for variances calculated by pentads, and at least 10 gauges for variances calculated on an annual basis.

When the SSARR model is used in a forecasting sense we need a measure of the effect of errors in rainfall on runoff generated for a short period. Figure 7 shows how the average standard deviation of runoff in a single year is affected by the number of raingauges in the network. The mean annual runoff is about 150 mm so that for 95 per cent confidence that the runoff will be in error by less than 20 per cent a network of at least 14 gauges will be required.

Standard deviation of single year generated runoff

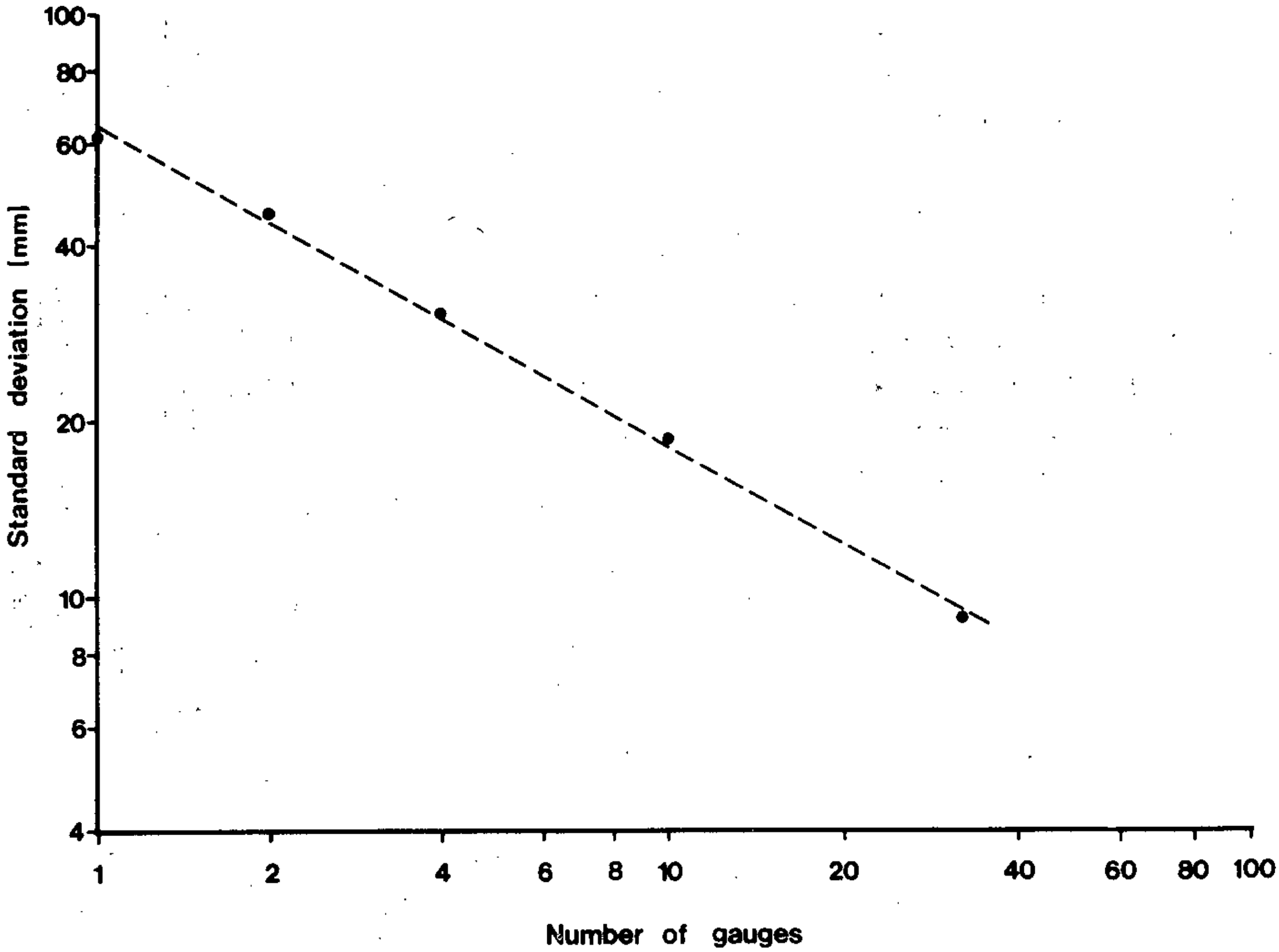


Figure 7

5. SUMMARY

The purpose of this chapter is to summarise the various steps in our analysis of rainfall in northeast Thailand, and to make some general comments about the implications of these results on hydrological studies of the Lower Mekong Basin as a whole. Throughout our work we have concentrated on following a sequential approach to the problem, making simplifying assumptions where appropriate. Thus the philosophy behind our analysis evolved as the work progressed and as the magnitude of some of the problems encountered became apparent.

One of the major constraints on the work was the requirement to establish a suitable rainfall data base that covered as long a period and as large a region as possible. Consequently we were obliged to spend a disproportionate amount of time investigating the various sources of available data. In the end our analysis was restricted to monthly data for northeast Thailand; this arose not only because that area had the best coverage of raingauges with long records, but also because the data were available on magnetic tape.

It was hoped that these data would be in a form amenable to immediate statistical analysis by computer. This was not the case because translation of the tape proved to be difficult and time consuming. It was also necessary to develop a robust quality control procedure. In the event we are satisfied that the data finally retained were sufficiently reliable to justify the type of statistical analysis that was adopted subsequently.

It would have been very much more difficult to undertake such statistical analysis using data from other parts of the Lower Mekong Basin where records are generally much shorter and the density of raingauges is much lower than in northeast Thailand. While the accuracy of rainfall estimates is not necessarily causally related to the gradient of the isohyets, there is no evidence to suggest that the areal coherence of rainfall is any greater with higher rainfall. Thus, at best, raingauge densities of the order indicated by our results should be needed in the Lao PDR. As such densities are many times greater than existing coverage, it is clear that we would be merely echoing many previous workers who have pointed out the deficiency. To bring the density up to that of northeast Thailand, a formidable task, would at least allow analysis of the kind carried out for northeast Thailand. Only after several years of uninterrupted measurements could realistic comparison of rainfall coherence then be made.

In an attempt to give the reader an idea of the scale of work involved, the preliminary tests of quality control and the method of data validation finally adopted are described in detail. As mentioned earlier the basis for the statistical analysis comes from previous work where the method is described in detail; consequently only a brief description has been included in Chapter 3.

However we have presented the results of the analysis in some detail. They are in a form that should be relatively easy for interested readers to interpret for their own use in tackling a wide range of problems including ones similar to the example given in Chapter 4. For instance the Tables in Chapter 3 provide the basis for estimating the accuracy of areal rainfall estimates for all regions in northeast Thailand and for a wide range of catchment areas. Within the financial resources of our study and given the problems of setting up an acceptable rainfall data base, we limited the statistical analysis to a time-base of one month, which is the usual time interval for general water resources investigation. This did not prevent us applying the results on a pentad (5 day) basis.

As an example of how these results might be interpreted in the context of rainfall-runoff modelling, we have described some modelling work on the Nam Mun river above Rasi Salai that used the SSARR model. It is perhaps difficult to draw any direct conclusions from this exercise that can be applied to the Lower Mekong Basin as a whole. Nevertheless there are some general comments and implications from the work that are worth expressing here.

On the basin used in our example, the SSARR model performed better than the simple conceptual model, but the errors in fitting the model were large nevertheless. Our results imply that on the Mun basin at least 10 raingauges would be required to keep the portion of the unexplained variance attributable to errors in rainfall to less than 25 per cent. Furthermore if the model is to be used in forecasting, there appears to be a significant risk that the generated runoff would be progressively overestimated as the number of raingauges in the network decreased. Clearly the hydrologist should attempt to ensure that a sufficient network of raingauges is available for a given catchment to give acceptable errors in predicted runoff before embarking on an extensive programme of conceptual modelling.

If we are to make a broad recommendation on the basis of the analysis presented here it is that at least as much effort should go into the improvement of areal rainfall estimation as goes into the development and fitting of models. Past computing constraints which limited the input to the SSARR model to data from 7 stations have probably provided the major cause of inaccuracy in runoff estimation. Arguably the areal rainfall estimates should be prepared separately from the model anyway; but new computing facilities should now remove these historic constraints.

We have also shown how the results of the statistical analysis could be used to estimate the density of raingauges required to obtain a specified accuracy in the estimates of areal average rainfall. Different levels of accuracy of rainfall estimates are acceptable for different purposes, and it is important that the needs of all interested users of rainfall data should be considered. Invitations to different users to state their requirements may be politic, but experience has shown that it is the short-period rainfall estimates which are most difficult to keep within acceptable limits. These are required for runoff forecasting from rainfall for the purposes of flood warning or reservoir operation on smaller catchments. Given the accuracy required a rational decision could then be made on the basis of this report for periods as low as 5 days regarding the density of raingauges required to give a generally acceptable accuracy of areal rainfall estimates. Strictly the results only apply to northeast Thailand, but if one makes the assumption that the rainfall regimes in other parts of the Lower Mekong Basin are similar, then they may also be applied with caution to other regions.

It must be re-emphasised that the analysis described above has only been possible because a sufficiently extensive body of rainfall data already existed, and could be considered reliable. We attempted some retrospective quality control, but this was far from satisfactory. We hope that one outcome of this report might be that quality control of raw data is pursued more actively than at present, and that more of the existing data are incorporated into future analyses or modelling studies.

The generalised correlation functions derived from monthly data showed that the initial reduction of correlation with distance occurred within distances of a few tens of kilometres. For daily data the rate of reduction would have been much greater. Few raingauges are closer than 20 km, so it is not certain that there would have been enough data points to define adequately daily correlation functions. While this should not preclude a continuation of the statistical studies, it is not clear that even the existing network of raingauges in northeast Thailand is sufficiently dense for such detailed analysis to be feasible at few short time intervals. Nevertheless we hope that sometime in the future this type of analysis might be repeated not only for shorter time intervals, but also for other parts of the Lower Mekong Basin.

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