INTERIM COMMITTEE FOR COORDINATION OF INVESTIGATIONS OF THE LOWER MEKONG BASIN

WATER BALANCE STUDY PHASE 3 REPORT

INVESTIGATION OF DRY SEASON FLOWS

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LOWER MEKONG BASIN

WATER BALANCE STUDY

PHASE III

Investigation of dry season flows

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SUMMARY

This report is concerned with several aspects of the water resources of the Lower Mekong Basin. The river gaugings and rating equations are reviewed at ten mainstream gauging stations. An assessment of the quality of daily flow data at these ten sites is provided. One station, Pakse, in Laos has flow data of excellent quality. Suitable techniques for quantifying the dry season flow regime of the Mekong and its tributaries have been identified. Benchmark flow statistics describing the current dry season flow regime of the Mekong and its tributaries have been calculated. A preliminary method for estimating dry season flow characteristics at sites with no gauging stations, based on catchment area, annual average rainfall and soil type is provided. Changes in the dry season flow regime have been identified on all tributaries with large upstream reservoirs; dry season flows have been increased at the expense of wet season flows. Similar, but smaller, changes in the dry season flows of the Mekong below the Nam Ngum confluence have been noticed. In terms of annual rainfall, there has been no significant climate fluctuation in the basin. There is insufficient evidence at present to identify changes due to land use change. However reductions in average flows have been identified on some catchments which have irrigation development upstream. A simple technique to monitor the dry season flows in the future and assist with the detection of change has been provided and tested on known changes in the past. A time series model has been used to extend the flow record at Kratie using observed daily flow data for Pakse. A simple regression model has been developed to explain the flows in Tonle Sap in terms of the discharge at Kratie and the storage in the Great Lake. Synthetic flows generated using the model have been used to give indicative estimates of the flows into the delta. Computer software has been provided to update this study when more data becomes available in the future, and to include additional stations in the analysis. A computer program has been developed to estimate areal monthly and annual rainfall from 1950 for any catchment within the Lower Mekong Basin on a 40km x 40km grid.

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Glossary

a	Constant in regression equation
AAR.RMP	Average Annual rainfall map
ADF	Average Daily Flow
$AM(D)_T$	Annual minimum; duration D days, return period T years
AREA	Area
AR1950.RMP	Annual rainfall map 1950
b	Constant in regression equation
fse	Factorial standard error
HYDATA	Hydrological database and analysis system
MAM(D)	Mean Annual Minimum; duration D days
MAR	Mean Annual Runoff
MAR12.RMP	Mean monthly rainfall map, December (month = 12)
MR19501.RMP	Monthly rainfall map, January 1950 (month = 1)
MINITAB	Statistical analysis package
P(i)	Exceedance probabilities
Q(75)	75 percentile flow
Q(75%)	Q(75) expressed as a percentage of the ADF
Q(i)	Annual minimum flow series
Qk	Daily flow at Kratie
Qts	Daily flow in the Tonle Sap
R^2	Square of the correlation coefficient
RAINS	Rainfall information system
Sgl	Storage in the Great Lake
se	Standard error of estimate
SOIL	Soil index
UTM	Universal Transverse Mercator map projection
W(i)	Plotting position (Weibull)

Preface

The Lower Mekong Basin Water Balance Study was initiated as part of a continuing study aimed at monitoring the effects on the overall flow regime of man-made developments within the basin. The present study follows on from previous phases of the Water Balance Study funded by the Overseas Development Administration (ODA) of the United Kingdom Government. The previous phases of the study were carried out by the Institute of Hydrology, Wallingford, UK and are fully reported elsewhere (Institute of Hydrology, 1982 and Institute of Hydrology, 1984).

At its 20th session, held in Bangkok from 30th July to 4th August 1984, the Mekong Committee approved the project proposal in the document entitled "Water balance study: report on Phase II and proposal for Phase III" (MKG/R. 473/Rev.1). The objectives of Phase III were defined as:

(1) To determine a framework for continuous monitoring of the flow regime in the Lower Mekong basin under which the combined effect of existing and ongoing developments may be quantified.

(2) To review and gather essential data for the effective modelling of the planned development projects to enable assessment, during project planning and/or appraisal, of the likely effect on the downstream flow.

This report covers part of the work programme agreed for Phase III. In particular the following, more detailed, objectives were defined ("Water Balance Study, Phase III (Basinwide) - Hydrologic Studies", MKG/R. 87039 - June 1987) as the basis of the activities leading to the current report:

Immediate objectives

(1) To provide reliable rating curves for mainstream gauging stations.

(2) To identify and evaluate from the historic records the hydrologic characteristics that best describe the river's flow regime

Long term objectives

(1) To provide consistent and reliable measures of hydrologic characteristics throughout the basin.

(2) To establish regular procedures for evaluating most recently acquired data in the light of historic records.

(3) To establish a system of monitoring flow characteristics such that any future changes in the flow regime can be detected at an early stage.

This study was undertaken by three hydrologists from the Institute of Hydrology in co-operation with staff of the Mekong Secretariat, Bangkok, Thailand. The project started in January 1988 and was completed in August 1988. One IH staff member, Dr C S Green was based in Bangkok for the duration of the study and was assisted during advisory visits by Mr B S Piper (project supervisor) and Dr A Gustard (consultant in low flows).

This final report has been kept as short as possible to enable the reader to obtain a good understanding of the work undertaken. Appendices supplement this main report and amplify the more technical aspects for the reader concerned in detail with specific parts of the study.

In addition to producing this report, the project has provided the Mekong Secretariat with computer software to enable the flow regime of the mainstream and tributaries to be monitored in the future. This software is personal computer (PC) based and centres on the hydrological database and analysis package HYDATA (Institute of Hydrology, 1987). In addition to HYDATA, a program has been written to estimate areal rainfall anywhere in the Lower Mekong Basin from 1950 onwards. Although written with this study in mind, it should have benefits to other projects requiring estimates of monthly rainfall over any particular area.

The present study builds both on the analytical work of Phases I and II of the Water Balance investigations and the results of the recent programme of mainstream river gauging.

1. INTRODUCTION

The activities of the project required to meet the objectives defined in the Preface were:

(1) Review the river gaugings on the mainstream Mekong made since 1987 and determine any changes in rating equations.

(2) Identify techniques of hydrological analysis suitable for assessing the dry season flow regime of the lower Mekong and its tributaries.

(3) Apply these techniques to the data from the rivers of the region and produce "benchmark" flow statistics which describe the current dry season flow regime of each river.

(4) Identify any changes in dry season flow regime of the rivers studied.

(5) Provide techniques for use in the future to identify changes in the dry season flow regime.

(6) Provide an estimate of dry season flow indices for the mainstream Mekong at the inflow to the delta.

Additional activities added during the course of the project were:

(7) Undertake a comprehensive review of the river gaugings at all mainstream sites together with an assessment of the quality of flow data at these sites.

(8) Carry out a regional study of dry season flow characteristics to understand their variation between river basins.

(9) Produce dry season flow estimation procedures for sites with no flow records.

(10) Determine if the year to year variability of dry season flows was correlated with preceding wet season rainfall.

(11) Investigate climatic variability in the basin in terms of annual rainfall total.

Effective monitoring of the water resources of a river basin requires that accurate measurements of rainfall and streamflow are made on a regular basis at key points within the river system. Flow records based on uncertain rating curves cannot provide the basis for sound planning or development decisions. However the accuracy of some of the recent flow data for the mainstream Mekong has been uncertain since the interruption of the routine river gauging programme in 1975. In 1987 new current meters were provided by ODA, and the river gauging programme was restarted. These latest discharge measurements prompted the thorough review of gauging measurements and updating of rating curves that was a major part of this study.

The analysis of recent river gaugings and comparison with past river gaugings and rating equations has not only resulted in re-definition of the rating equations for many important mainstream sites, but also provided an insight into the quality of flow data at these locations. This has important implications for all users of flow data on the Mekong. (Section 3 of the main report and Appendix C.)

The techniques for measuring dry season flows were selected to provide a range of indices which would adequately describe the current flow regime of the Mekong and its tributaries. These statistics have been calculated for 44 mainstream and tributary gauging stations in the Lower Mekong Basin and provide the benchmark against which future changes can be measured. Stations were selected on the basis of the accuracy of low flow measurement and the length of record. In fact two stations on the main Mekong river were rejected following the rating review. Elsewhere, selection was based on the results of discussions with Mekong Secretariat staff. Changes in the dry season flow regime have been identified in rivers with major regulating reservoirs. To a lesser extent changes have also occurred in the downstream reaches of the mainstream Mekong, again as a result of reservoir regulation on the tributaries. At the time of this study there were no dams on the mainstream either in the Lower or Upper Basins of the Mekong. (Section 4 of the main report.)

This approach provides information at gauged locations. However by relating flow statistics from these 44 stations to the characteristics of their upstream catchment areas it was possible to provide a regional summary of the variability of dry season flows and to develop a design method for estimating dry season flows on ungauged, unregulated rivers. For ungauged, unregulated catchments dry season flows may now be estimated from catchment area, catchment annual average rainfall and soil type. These estimation methods do not give such an accurate estimate of low flow indices as do values calculated from recorded flow data. However they are very useful as a guideline for the many situations where flow data are not available. (Section 4.4 of the main report and Appendix B.)

From the analysis of the flow data it became clear that there had been historical changes to the sub catchments' flow regime at a number of stations. These changes were most apparent on tributaries downstream of major regulating reservoirs. A comparison of flows before and after impoundment enabled the scale of these changes to be quantified. Although smaller in comparison to average flow, changes have also been identified on the Mekong below the Nam Ngum confluence.

In all cases of regulation, both on the mainstream and tributaries, the effect has been to **increase** dry season flows. Average flows have been **reduced** slightly on regulated rivers, presumably due to irrigation and evaporation losses. High flows have been reduced after regulation. These effects are much as would have been expected from regulation; the main surprise is the increase in dry season flows on lower reaches of the Mekong itself.

An attempt was made to determine if annual minimum flows on certain catchments could be correlated with preceding wet season rainfall. If such a correlation were to exist, the relationship could be used to predict annual minima from past rainfall. First this would be useful in a real time basis for drought forecasting. Second, after the dry season had finished, observed dry season flow could then be compared with the predicted dry season flow. After a number of years of consistent over or under prediction, this would point to a change in dry season flow regime of the river. Although it appeared that average flow over the year could be reasonably well estimated from annual or seasonal rainfall, the correlations between rainfall and following dry season flows were too low to be of any predictive use. (Section 4.5.4 of the main report.)

Climatic variability is now being recognised as a phenomenon which should be considered with the design of water resource schemes. From the point of view of water resources the most important aspect of climatic change is change in the rainfall regime. This study has looked at the annual total rainfall over the period 1950 to 1986 for the Lower Mekong Basin as a whole, northeast Thailand, north Thailand, Laos, the Mekong delta in Vietnam and Kampuchea. This part of the study has shown that there appears to have been no consistent increase or decrease in annual rainfall over any region. (Section 4.5.3 of the main report.)

In 1987 there were no dams on the main river; however it is understood that plans for the implementation of hydropower reservoirs in the Upper Mekong Basin (Lancang) are being considered by the Peoples Republic of China. The first dam at Manwan is currently under construction with an installed generating capacity of 1250 MW. After completion of a second dam at Xiaowan, the installed capacity at Manwan will be increased to 1500 MW (Kunming Hydro-electric Investigation and Design Institute, 1985).

The flow into the delta just downstream of Phnom Penh is made up of two components, namely the main Mekong and a contribution from the Great Lake through the Tonle Sap. The catchment area down to Kratie is about 85% of the combined catchment area at the confluence of the Mekong and the Tonle Sap. The flow records at Kratie are thus particularly important. Regular observations of water level and discharge at Kratie were interrupted in 1969, so a simple time-series model was used to reconstitute the daily flow record since then.

A preliminary desk study, based on existing information available at the Secretariat, was carried out to investigate the behaviour of the Great Lake and the flows in the Tonle Sap. A multiple regression model was used to explain the flow in the Tonle Sap in terms of the flow at Kratie and the storage in the Great Lake. A time-series of daily flows into the delta from 1924 to 1972 (when observations of lake levels ceased) was reconstituted using the derived regression equations to give indicative estimates of the flow regime. (Section 5 of the main report and Appendix A.4.)

2. HYDROLOGICAL DATA

2.1 HYDATA

The Mekong Secretariat maintains a large database of hydrological and meteorological data for the Lower Mekong Basin. Many of these data are published in annual yearbooks (Mekong Secretariat, 1962-1986)

This study required the analysis of a large volume of hydrological and meteorological data. Had time permitted, it would have been possible to write specific software for this task and install this on the Mekong Secretariat's main VAX computer. These programs could then have read data directly from the Hydrologic and Meteorological Database (HMDB) on the VAX (Mekong Secretariat, 1986).

However the development and testing of software is a time consuming task. In the interests of efficiency, it was decided to make use of a software package incorporating all the analysis programs required. The package chosen was HYDATA (Institute of Hydrology, 1987) which has been developed over many years and is in use in many countries throughout the world. An additional advantage of this approach was that the package could be enhanced in the future with minimum effort when additional facilities became available.

HYDATA is a PC based package and remains with the Mekong Secretariat where staff have been trained in its use. It may now be used to help with future hydrological studies, assist with day to day data processing and extend the techniques of analysis reported here to other sites. Being a PC based system, HYDATA has the advantage of portability. Any hydrometric organisation in the countries of the Interim Committee should therefore be able to undertake the techniques of analysis described in this report.

Much of the data for this study was transferred to HYDATA on the project PC from the HMDB system on the VAX computer. HYDATA provided a "front end" by offering easy to use graphical and hydrological analysis programs to a subset of stations. The linking of the project PC to the VAX computer, and the mechanism for data transfer proved to be both easy to set up and quick to execute.

The station numbering system used by the Mekong Secretariat with HMDB (Mekong Secretariat, 1986) has been adopted for use with HYDATA and for this report.

Appendix A describes the installation and training connected with HYDATA at the Mekong Secretariat.

2.2 River gaugings and rating equations

The programme of river gauging on the mainstream, interrupted in 1975, was re-established in 1987. In 1987 ODA provided new current meters for some sites to coincide with the new programme. Therefore one objective of this project was to review the rating equations on mainstream sites, making use of the new gaugings.

Since 1960, when the programme of river gauging was originally established on the mainstream Mekong, many thousands of river gaugings have been undertaken. This represents about 25 man years of work in the field. Although these gaugings had been used to develop rating equations at the various sites from that date, only a few gaugings had been published (in 1960 and 1961). In order to ascertain the importance of continued river gauging at each site and to obtain a better understanding of the quality of flow data at these sites, the scope of the rating review was extended with this additional objective.

The rating review considered data from ten important sites on the Mekong as listed in Table 2.1 and shown on Figure 2.1.

Rating review stations

Number	*Station*	*Number of Gaugings*	*Number of Ratings*
10501	Chiang Saen	697	10
11201	Luang Prabang	294	8
11901	Vientiane	242	11
11903	Chiang Khan	652	10
11904	Pa Mong dam site	367	7
12001	Nong Khai	674	10
13101	Nakhon Phanom	668	15
13402	Mukdahan	1031	17
13801	Kong Chiam	601	10
13901	Pakse	201	5
Total		5427	103

Table 2.1

All available river gaugings from various sources were entered onto HYDATA by hand for these ten sites. However gaugings made at Nong Khai between 1982 and 1985, and at Mukdahan in 1983 and 1984 were not available in time to be included in analysis.

HYDATA was then used to fit rating equations on an annual basis, which is the practice at the Mekong Secretariat. These gaugings and ratings were used together with the published water level and daily flow data to assess the accuracy of data at these sites for periods when the river was gauged and for periods when it was not.

The results of this part of the study, outlined in Section 3 of this report, are discussed more fully in Appendix C.

Location map of gauging stations

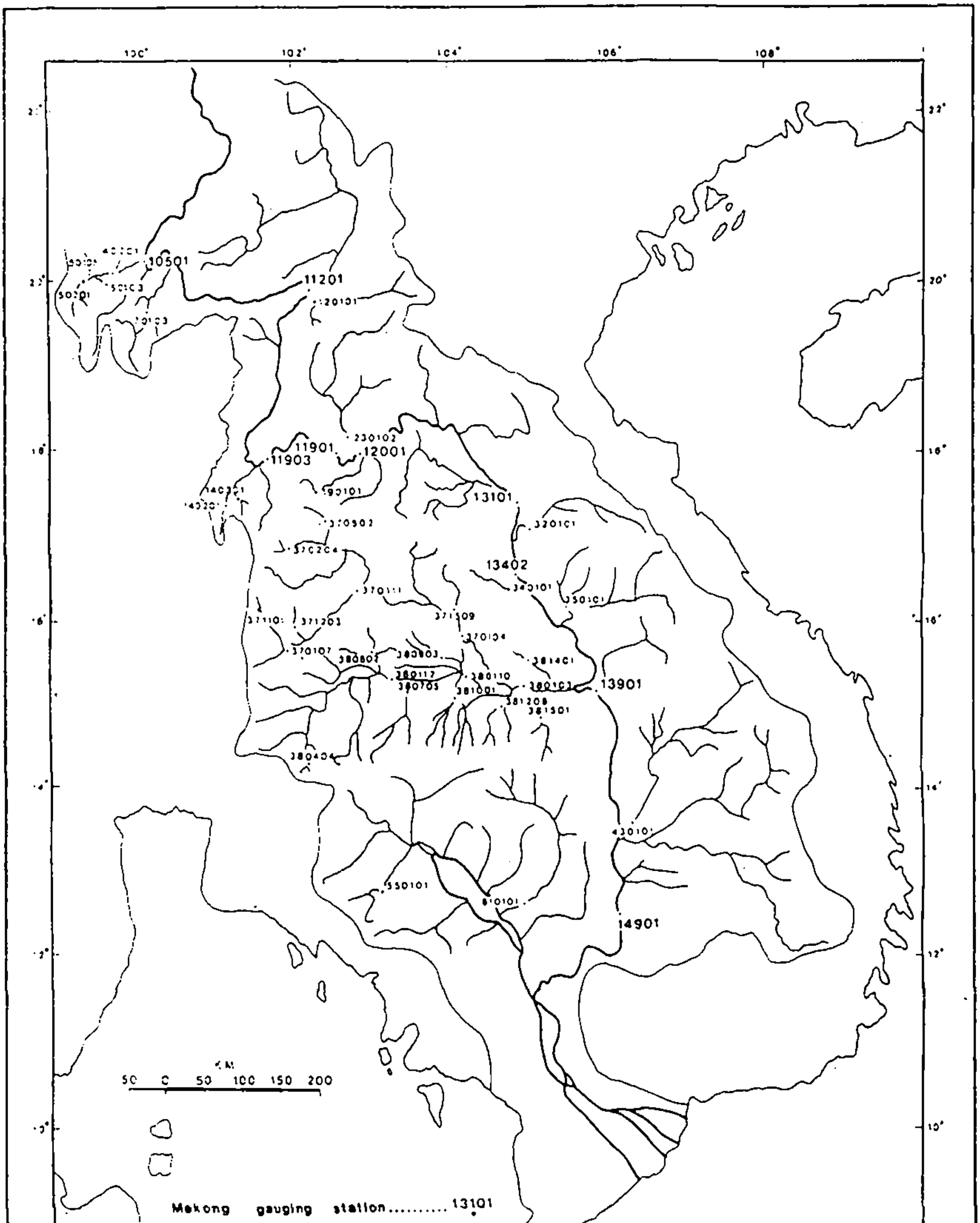

Figure 2:1

2.3 Flow data

The analysis of dry season flows required daily mean flow data from a number of stations throughout the Lower Mekong Basin. The stations were chosen to give as good geographical coverage as possible, to have at least seven years of daily mean flow data and to have data of at least reasonable quality, particularly at low flows. The selection of stations on the mainstream Mekong was based on the results of the rating review (Appendix C). The selection of stations on the tributaries was based on discussions with staff at the Mekong Secretariat.

Table 2.2 lists the 44 stations selected together with their length of record and catchment areas. Figure 2.1 shows the location of these stations together with their catchment boundaries.

Some of the data before 1960 on the mainstream has been generated by correlation techniques using records at adjacent stations (US Army Engineer Division, 1968). Although it is not clear which stations and periods have data based on correlation, these data have been accepted in this study as a worthwhile addition to the data set. Correlations between stations on the Mekong is good, so it is likely this early data is of reasonable quality.

Most of these data was provided by the Mekong Secretariat, but data for a few stations was made available by the Royal Irrigation Department in Bangkok.

Daily flow stations

Station Number	*Station name*	*Basin Area km²*	*Start Year*	*End Year*	*Yrs. Data*
10501	Mekong at Chiang Saen	189000	1960	1987	28
11201	Mekong at Luang Prabang	268000	1950	1987	38
11901	Mekong at Vientiane	299000	1913	1987	75
11903	Mekong at Chiang Khan	292000	1967	1987	21
12001	Mekong at Nong Khai	302000	1969	1987	19
13101	Mekong at Nakhon Phanom	373000	1924	1987	64
13402	Mekong at Mukdahan	391000	1923	1987	65
13901	Mekong at Pakse	545000	1923	1987	65
14901	Mekong at Kratie	646000	1924	1971	48
40201	Nam Mae Kham - Ban Huai Yano Mai	203	1975	1987	13
50103	Mae Kok at Dam Site	5870	1968	1987	20
50105	Mae Kok at Ban Tha Ton	2980	1970	1987	17
50201	Mae Fang at Ban Tha Mai Liam	1800	1970	1987	18
70103	Nam Mae Ing at Thoeng	5700	1969	1987	19
120101	Nam Khan at Ban Mixay (Ban Mout)	6100	1961	1987	27
140201	Nam Man at Dan Sai	401	1967	1987	21
140301	Nam San at dam site	703	1966	1987	22
190101	Huai Mong at Ban Na Ang(Ban Phu)	1307	1957	1987	31
230102	Nam Ngum at Tha Ngon	16500	1963	1985	23
320101	Se Bang Fai at Se Bang Fai	8560	1961	1985	25
340101	Huai Bang I at Ban Kham Soi	702	1964	1978	25
350101	Se Bang Hieng at Ban Keng Done	14900	1961	1977	17
370104	Nam Chi at Yasothon	43100	1953	1987	35
370107	Nam Chi at Ban Khai	6835	1968	1987	20
370111	Nam Chi at Ban Tha Phra	13171	1958	1987	30
370204	Nam Pong at Ban Pha Nok Khao E29	945	1970	1987	18
370502	Huai Phaniang at Ban Wang Mun	1260	1978	1987	10
371101	Huai Rai at Ban Non Kiang	1370	1975	1987	13
371203	Huai Pa Thao at Ban Tao Ton	326	1976	1987	12
371509	Nam Yang at Ban Na Thom	3240	1979	1987	9
380103	Nam Mun at Ubon	104000	1951	1987	37
380110	Nam Mun at Rasi Salai	44275	1965	1987	23
380112	Nam Mun at Satuk	28275	1964	1987	24
380404	Lam Chae at Ban Mak Krat	498	1977	1987	11
380602	Lam Phang Chu at Ban Hua Saphan	1094	1979	1985	7
380705	Lam Chi at Ban Lum Din	4630	1979	1987	9
380903	Lam Sieo Yai - Ban Ku Phra Ko Na	3230	1979	1987	9
381001	Huai Thap Than-Ban Huai Thap Tan	2030	1972	1982	11
381206	Huai Khayung at Ban Huai Khayung	2900	1979	1987	9
381401	Lam Se Bok at Ban Tha Bo Baeng	2132	1979	1985	7
381501	Lam Dom Yai at Det Udom	3340	1963	1981	19
430101	Se Kong at Ban Khmuon	29600	1961	1970	10
550101	Stung Sangker at Treng	2135	1963	1973	11
610101	Stung Sen at Kompong Thom	14000	1961	1970	10

Table 2.2

2.4 Rainfall data

Rainfall information was required in the study for the following purposes :

(1) Rainfall over the whole Lower Mekong Basin was needed for the regional study relating dry season flow indices to catchment characteristics.

(2) Average seasonal rainfall over the whole basin (defined in various ways) for the same purpose as (1).

(3) Rainfall over the catchment between Pakse and the delta was required for the hydrological model extending flow data to the delta.

(4) Annual and seasonal rainfall were required for the part of the study relating annual minimum flows to preceding wet season rainfall.

(5) The study of annual rainfall series were required for evaluating fluctuations in climate over the whole Lower Mekong Basin, northeast Thailand, north Thailand, Laos, the Mekong delta in Vietnam and Kampuchea.

These many uses of rainfall data demanded estimates of rainfall over a large area (600,000 km^2) and over a long time period. Consequently an areal rainfall estimation program was developed for the region, capable of predicting monthly or annual rainfall for any catchment within the Lower Mekong Basin. This program uses monthly rainfall data stored on HYDATA to produce estimates of rainfall on a 40km x 40km grid. The 40km grid size was chosen as a compromise between computer disk space required to store maps of monthly rainfall and adequate resolution for the purposes of this study. The computer program used for this part of the study was called RAINS (Rainfall Information System) and is described fully in Appendix A.

In addition to the ability to estimate areal rainfall, RAINS has simple Geographic Information System (GIS) capabilities, such as drawing, analysing and performing arithmetic operations on maps. In this capacity RAINS was also used in this study to handle basinwide information on soils. This is described in Section 2.5.

In order to give as wide a geographical and time coverage of areal rainfall as possible, monthly rainfall from 116 raingauges were transferred to HYDATA. Tables 2.3(a-c) list the rainfall stations used in the study together with their location, elevation and period of record. The period of record lists, in decades, whether data are available, partially available or complete. Figure 2.2 shows the location of these raingauges within the basin.

It was hoped that there would be sufficient information for the areal rainfall procedure to derive basinwide monthly rainfall from 1910 to date, however there was insufficient data in the period 1910-1949 to make this possible. Consequently basinwide estimates of monthly and annual rainfall have been produced for this study over the period 1950-1986.

Long term annual average rainfall (1950-1980) on the 40km x 40km basinwide grid is shown in Figure 2.3.

Rainfall stations

Number & Country	Name	Lat. °N	Long. °E	Elvn. m	Record Period Decade 12345678
90502 v	Soc Trang (Khanh Hung)	9:36	105:58	3.2	-+--++-.
90503 v	Camau (An Xuyen)	9:10	105:10	2.0	....-+-.
90601 v	Tra Vinh (Vinh Binh)	9:56	106:20	4.0	---.---.
100307 k	Kompong Som	10:38	103:35	13.0	......--
100408 k	Takeo (Ville)	10:59	104:48	6.0	.....+.-
100503 v	Sa Dec	10:18	105:45	2.0	-+-.-+--
100504 v	Rach Gia	10: 0	105:53	3.0	--..-+-.
100505 v	Chau Doc	10:42	105: 7	6.0	.--..---
100603 v	Ho Chi Minh Ville(Aerodrome)	10:47	106:42	11.0	--.-++-.
100605 v	My Tho	10:21	106:22	2.0	.--.-+-.
110201 t	Khlong Yai	11:47	102:53	4.0	....-++-
110403 k	Phnom Penh	11:33	104:51	10.0	.....---
110503 k	Svay Rieng	11: 5	105:47	6.0	.....+--
120201 t	Trat	12:15	102:33	3.0	....-++-
120202 k	Pailin	12:52	102:37	170.0	.....+-.
120203 t	Chanthaburi	12:36	102: 7	5.0	....-++-
120204 t	Pong Nam Ron	12:51	102:17	180.0	....-++-
120213 k	Rattanak Mondal	12:49	102:37	170.0	.......-
120304 k	Dap Bat	12:30	103:50	19.0	.....-..
120401 k	Kompong Chhnang	12:15	104:40	6.0	.....---
120403 k	Krakor	12:31	104:11	5.0	.....+-.
120404 k	Kompong Thom	12:42	104:54	13.0	.....---
120504 k	Kompong Cham	12: 0	105:27	16.0	.....+--
120603 k	Kratie	12:29	106: 2	23.0	.....+.-
120606 k	Snuol	12: 4	106:25	180.0	.....+-.
120801 v	Buon Me Thuot	12:36	108: 5	461.0	.--.----
130202 k	Sisophon	13:36	102:58	16.0	.....--.
130204 t	Aranyaprathet	13:42	102:35	44.0	....-++-
130301 k	Banan	13:57	103: 9	19.0	.......-
130305 k	Battambang	13: 6	103:12	18.0	.....---
130405 k	Kompong Kdei	13: 7	104:18	13.0	.....--.
130501 k	Stung Streng	13:31	105:58	54.0	.....-..
130603 k	Lomphat	13:30	106:59	97.0	.....-..
140201 t	Nang Rong	14:35	102:48	183.0	.....-+-
140202 t	Chok Chai	14:44	102:15	192.0	......--
140205 t	Korat	14:58	102: 5	181.0	....+++-
140302 t	Surin	14:53	103:30	145.0	....+++-
140501 l	Muong Khong	14: 7	105:50	87.0	.....---
140503 l	Phiafay	14:48	105:56	100.0	..-..--.
140505 l	Pathoumphon	14:46	105:58	96.0	......--

Country code:

k = Kampuchea
l = Laos
t = Thailand
v = Vietnam

Record Period:
Decade 1 (1910-19)
Decade 2 (1920-29) etc
. = no data
- = partial record
+ = complete record

Table 2.3a

Rainfall stations

Number & Country		Name	Lat. °N	Long. °E	Elvn. m	Record Period Decade 12345678
140601	t	Det Udom	14:53	105: 4	125.0	.....-+-
140602	k	Voeun Sai	14: 0	106:46	220.0	.....-..
140703	v	Pleiku	14: 1	107:54	758.0	.-+.----
140704	v	Kontum (Lasan)	14:22	107:54	536.0	.-+-.---
150101	t	Chatturat	15:31	101:51	190.0	.....---
150102	t	Chaiyaphum	15:48	102: 2	190.0	....-++-
150202	t	Phon	15:47	102:37	175.0	.....++-
150301	t	Buriram	15: 0	103: 6	155.0	....-+--
150306	t	Phayakkaphumphisai	15:29	103:12	135.0	.....-+-
150308	t	Tha Tum	15:19	103:41	127.0	......--
150401	t	Ubon	15:15	104:52	127.0	....+++-
150404	t	Sisaket	15: 6	104:21	124.0	....-++-
150407	t	Rasi Salai	15:20	104:10	120.0	.....-+-
150503	t	Khong Chiam	15:22	105:28	90.0	......--
150504	l	Pakse	15: 7	105:47	93.0	.-+--++-
150507	t	Ban Nong Mek	15: 4	105:18	154.0	.....-+-
150601	l	Paksong	15:11	106:14	1270.	.---.---
150602	l	Saravane	15:43	106:26	170.0	.---.--.
160102	t	Phetchabun	16:25	101: 8	114.0	......+-
160104	t	Ban Song Khon	16:38	101:48	110.0	......--
160105	t	Ban Si Than	16:53	101:53	260.0	......--
160106	t	Phu Kradung	16:51	101:53	1289.	......--
160202	t	Khon Kaen	16:26	102:50	157.0	....+++-
160207	t	Chum Phae	16:29	102: 7	220.0	.....+--
160301	t	Roi Et	16: 3	103:41	140.0	....-++-
160302	t	Kalasin	16:26	103:31	142.0	....-+--
160303	t	Maha Sarakham	16:10	103:18	150.0	....-++-
160309	t	Kosum Phisai	16:15	103: 4	150.0	......--
160401	t	Mukdahan	16:32	104:43	138.0	....+++-
160403	t	That Phanom	16:58	104:43	130.0	.....-+-
160405	l	Savannakhet	16:33	104:45	155.0	.-----+-
160407	t	Kuchinarai	16:30	104: 3	166.0	.....-+-
160408	t	Ban Kham Pa Lai	16:43	104:38	147.0	......--
160502	l	Seno	16:40	105: 0	184.0	....-+--
160503	t	Khemarat	16: 2	105:13	139.0	.....-+-
160505	l	Keng Kok	16:26	105:12	126.0	..-..--.
170101	t	Loei	17:27	101:44	251.0	....-++-
170102	t	Wang Saphung	17:15	101:48	247.0	.....-+-
170104	t	Dan Sai	17:17	101: 9	330.0	.....-+-
170105	t	Chiang Khan	17:49	101:41	213.0	.....-+-

Country code:

k = Kampuchea
l = Laos
t = Thailand
v = Vietnam

Record Period:
Decade 1 (1910-19)
Decade 2 (1920-29) etc
. = no data
- = partial record
+ = complete record

Table 2.3b

Rainfall stations

Number & Country	Name	Lat. °:'N	Long. °:'E	Elvn. m	Record Period Decade 12345678
170107 t	Nam San Dam Site	17:28	101:15	815.0	.....-+-
170201 t	Tha Bo	17:54	102:35	173.0	.....-+-
170202 t	Udon Thani	17:23	102:48	178.0	....+++-
170203 l	Vientiane	17:57	102:31	170.0	......--
170206 t	Nong Khai	17:52	102:43	173.0	....-++-
170303 t	Wanon Niwat	17:39	103:46	160.0	.....---
170305 t	Sawang Daen Din	17:25	103:28	170.0	.....-+-
170401 t	Sakon Nakhon	17: 9	104: 8	160.0	....-++-
170403 t	Nakhon Phanom	17:25	104:47	140.0	....-++-
170406 t	Ban Phaeng	17:56	104:13	148.0	.....-+-
180001 t	Nan	18:47	100:47	201.0	.....-+-
180101 l	Paklay	18:12	101:24	220.0	.-+-.---
180201 l	Ban Keun	18:25	102:33	168.0	.....---
180202 l	Tha Ngon	18:10	102:40	170.0	.....-+-
180203 l	Ban Maknao	18: 1	102:58	161.0	.....---
180207 l	Vang Vieng	18:56	102:27	215.0	.---.---
180208 t	Ban Pha Tang	18: 2	102:23	174.0	......--
180210 l	Phong Hong	18:28	102:24	179.0	......--
180301 t	Phon Phisai	17:58	103: 5	160.0	.....-+-
180303 l	Paksane	18:24	103:38	159.0	.---.-+-
180305 t	Ban Tha Kok Daeng	18: 2	103:30	145.0	.....-+-
180401 l	Nam Thone	18: 4	104:15	150.0	.....--.
180402 l	Pak Ca Dinh	18:21	104: 1	300.0	.....--.
189901 t	Lampang	18:17	99:31	243.0	....-++-
189903 t	Chiang Mai	18:47	98:59	313.0	....-++-
190001 t	Thoeng	19:37	100:14	396.0	.....-+-
190008 t	Khao Ing Rod	19:26	100: 4	368.0	......--
190103 l	Sayaboury	19:12	101:44	300.0	.....---
190202 l	Luang Prabang	19:53	102: 8	304.0	.--.-++-
199901 t	Fang	19:53	99:14	470.0	....-+--
199904 t	Phayao	19: 8	99:54	395.0	....-+--
199907 t	Chiang Rai	19:55	99:50	416.0	....-++-
199910 t	Mae Kok Dam Site	19:57	99:54	391.0	.....-+-
200001 t	Chiang Khong	20:12	100:25	361.0	.....-+-
200002 t	Chiang Saen	20:16	100: 6	369.0	.....-+-
209902 t	Ban Mae Ai	20: 2	99:18	460.0	......--

Country code:	Record Period:
k = Kampuchea l = Laos t = Thailand v = Vietnam	Decade 1 (1910-19) Decade 2 (1920-29) etc . = no data - = partial record + = complete record

Table 2.3c

Location of raingauges

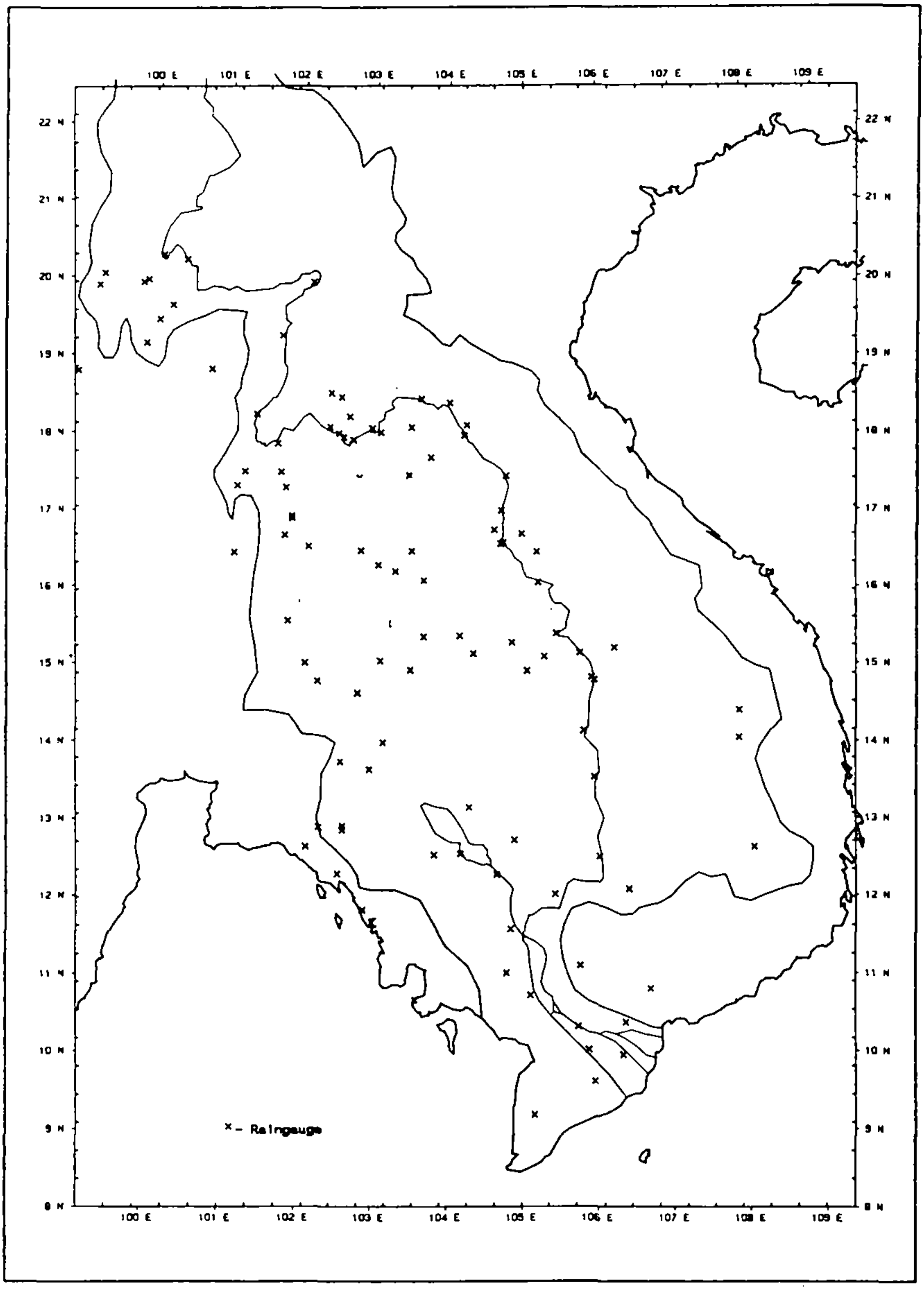

Figure 2.2

Annual average rainfall

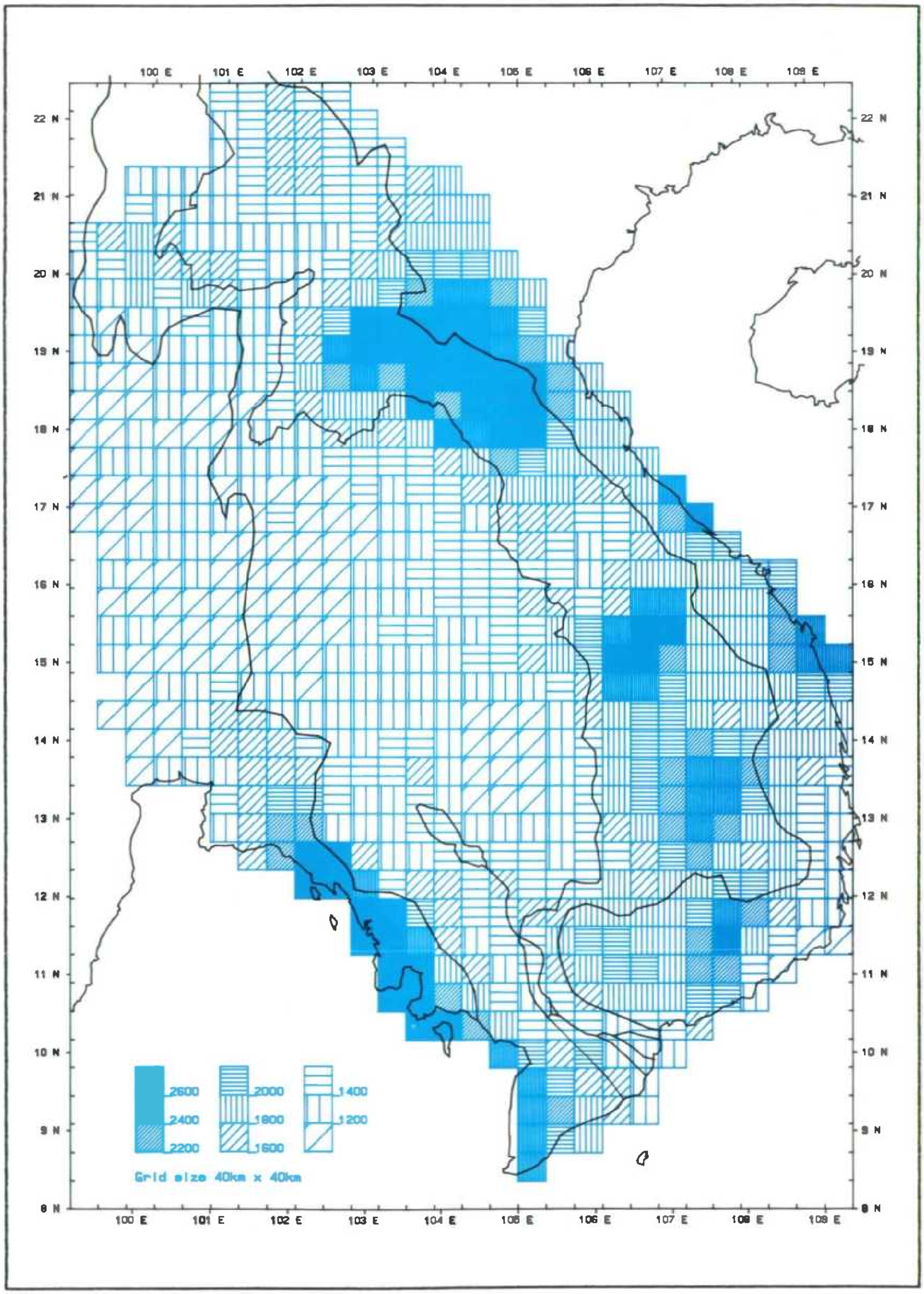

Figure 2.3

2.5 Soil map

A soil index was derived for the region to evaluate whether dry season flows are related to basin soil type. The index was derived using a method developed jointly by the UK Soil Survey and Land Research Centre, and the Institute of Hydrology based on the 1:1,000,000 Pedo-geomorphological map of the Lower Mekong Basin (Mekong Secretariat, 1977). This map uses the FAO-UNESCO nomenclature for soil classification. The 32 map units were allocated into one of nine groups (Table 2.4), so that each group had similar hydrological characteristics. The main criteria for allocating soils to a particular group were the hydromorphic properties of the soil profile, which indicated the extent of seasonal saturation, the soil depth, organic content and soil structure.

Values of the index were calculated for each catchment. A 40km x 40km grid was overlaid on the soil map and the percentage of each of the nine soil groups in each grid square was estimated. The 40km x 40km grid was chosen for compatibility with the areal rainfall grid described in Section 2.4. The computer program RAINS (Section 2.4) was then used to calculate the percentage of each soil type in each basin. As a result of the distribution of soil types within the study catchments a number of soil groups were not represented in the basins resulting in only groups 2, 3, 5, and 7 having a significant percentage. Regression analysis was used to relate dry season flow statistics to the percentage cover of these four soil groups and to combinations of the groups. The results indicated that groups 5 and 2 (very shallow soils and soils showing evidence of seasonal saturation) produce a lower, dry season flow response than the more permeable group 7 soils. The percentage of the catchment with soil group 7 was used as a soil index in developing flow estimation procedures. The index is based on a preliminary interpretation of the 1:1,000,000 soil map of the Lower Mekong Basin and the analysis uses a very coarse grid of 40km x 40km and thus the index should be regarded as provisional. Figure 2.4 shows the value of the soil index for each of the grid squares in the Lower Mekong Basin.

Hydrological soil groups

Hydrological Soil Group	Map Units (1)	Dominant Characteristics
1	29	Peat soils
2	10	Hard coherent rock within 10 cm
3	20	Moderately permeable with discontinuities, hard or concretionary 'lateritic' material and no hydromorphic properties within 100 cm of the surface
	13	Clay soil with strong shrink/ swell properties
	1 2 3 4 5 6 7 8 14 15 17 22 23 x xxx	Alluvial deposits and gleyed soils with seasonal saturation
6	9	Moderately permeable, gleyed soils with a peaty or organic rich topsoil, discontinuous hard or concretionary lateritic material and seasonal saturation
	16 18 19 21 24 25 26 27 28 xx	Medium textured, permeable, with no hydromorphic properties within 100 cm
8	11	Coarse textured - permeable with no hydromorphic properties within 100 cm
9	12	Shallow, calcareous over (fissured?) limestone

Note (1) Numeric classes and 'x' symbols are presented on the Pedo-geomorphological map of the Lower Mekong Basin (Mekong Secretariat, 1977)

Table 2.4

Soil Index

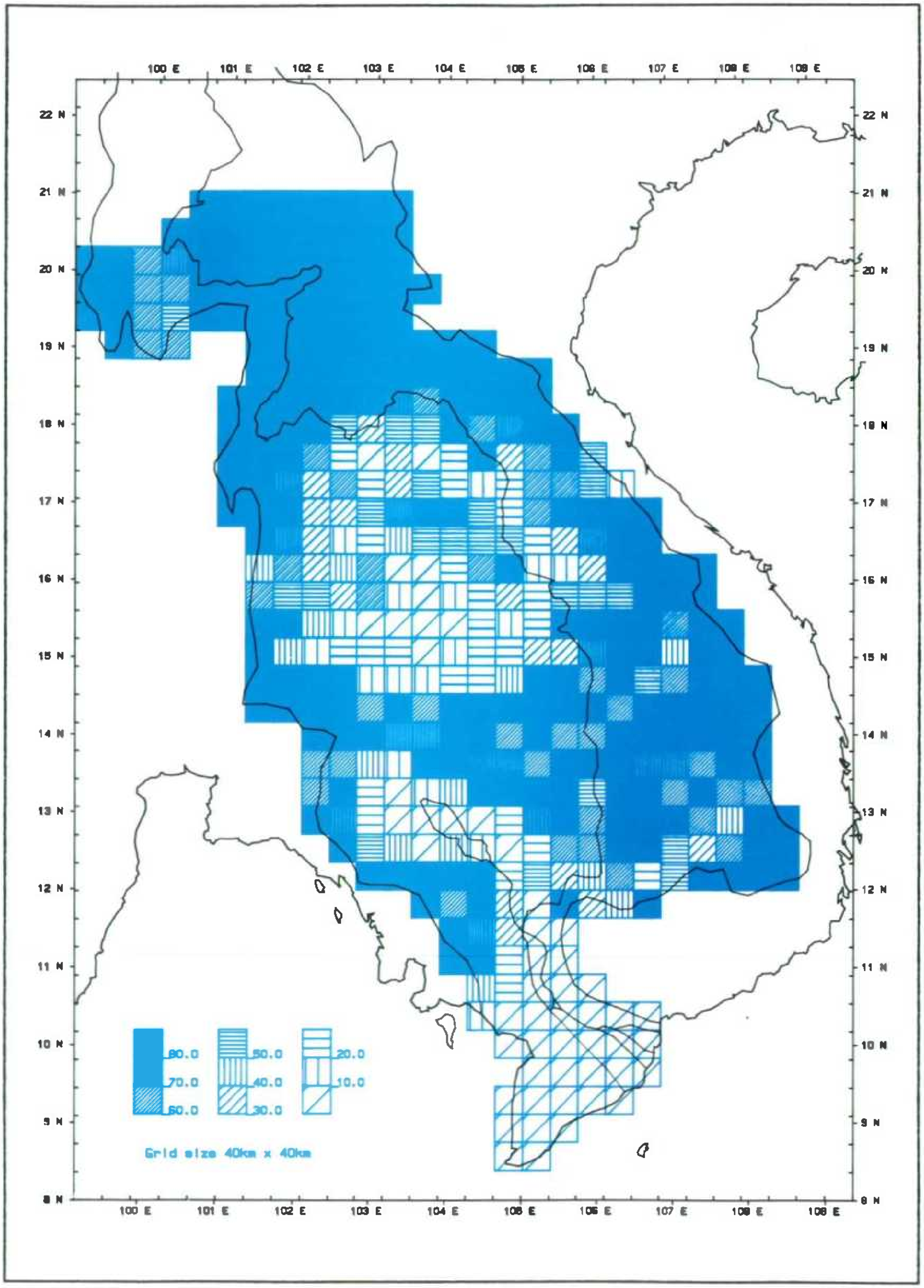

Figure 2.4

3. RATING REVIEW

3.1 Introduction

The original objective of the rating review was to assess the river gaugings carried out on the mainstream Mekong using the new current meter equipment purchased for the Mekong Secretariat by ODA in 1987. The programme of gauging the main river started in 1960 was halted in 1975 before being restarted in 1987. The revised ratings derived in this study are given in Appendix C.

During the course of this work it became clear that in the past many thousand river gaugings had been made on the Mekong since the programme of river gauging was first established in 1960. Although these gaugings had been used for fitting rating equations at the time, they had subsequently not been used. It was considered a useful addition to this study to collect details of all these gaugings from various sources and publish these in a data appendix to this report. Appendix C of this report therefore contains river gauging data for the ten important sites on the mainstream given in Table 2.1. Furthermore these gaugings are now available on HYDATA at the Mekong Secretariat for future use.

The rating review is presented in detail in Appendix C and the results are summarised below.

3.2 Summary of results

Having collected these gaugings and entered them onto HYDATA it was then possible to undertake an analysis to determine how stable the rating equations were at each site and hence the value of continuing the gauging programme. The results of this part of the study showed that, on average, the error in daily flow data increased by 66% for periods when stations are not gauged. This has illustrated the importance of a continuous programme of river gauging. The restart of the programme of river gauging on the mainstream after a 10 year break must therefore be welcomed as must the timely provision of new current meters by ODA.

Having obtained estimates of error in the daily flow data for periods when each site was gauged it was then possible to rank the stations in order of data quality. Table 3.1 shows these results for three types of application of flow data. The first application under "All" flow conditions is for general use of flow data, such as determining average discharge at a site. The second application is for users interested primarily in low flows, such as navigation and irrigation. The third application is for high flows which should be of interest to users of data for flood forecasting and flood estimation.

In general the results show the mainstream data to be of reasonable to high quality. One station, Pakse, has data of exceptionally high quality and as such should be considered as the most important gauging station on the Lower Mekong.

Table 3.1 shows that errors in daily data at low flows are greater than 20% for two stations, Nakhon Phanom and Kong Chiam. Consequently these two stations were excluded from the analysis of dry season flows described in this report. Table 3.1 may also be used to determine policy for future programmes of gauging on the mainstream. Stations with low errors may not need gauging so often and stations with high errors might be abandoned in favour of a more suitable site in the vicinity.

Rating curves are derived on an annual basis on the Mekong. For periods when the river is not gauged the most recently derived annual rating curve is used to calculate discharges. Since the ratings at each site vary in an apparent random manor with time, the use of an "average" rating for periods when gaugings are not possible is recommended. Long term rating equations for each site, based on all river gaugings, have been derived and are given in Appendix C. Since major shifts in rating occur during the flood season, it is recommended that rating equations be fitted from peak stage one year to peak stage the next, rather than on a calendar year basis.

This rating review led to some important recommendations concerning river gauging and fitting rating equations:

(1) Every effort should be made to continue the gauging programme on the Mekong.

(2) The data from Pakse are of the highest quality. It is therefore important to ensure the continuous return of stage data from this station.

(3) Long term rating equations should be used during periods when no gaugings are being made.

(4) The database of gaugings and ratings should be maintained at the ten mainstream sites and be updated when new gaugings are available.

(5) The analysis should be extended to other major sites of interest in the Lower Mekong to provide guidelines on data quality at more sites.

(6) The long term rating equations should be revised every five years using gaugings from the previous ten years in which gaugings have been made.

(7) Rating curves should run from the peak flow in one season to the peak flow in the next.

Stations ranked in order of data quality

Flow condition	Error	Number	Name
All	6%	13901	Pakse
	8%	11903	Chiang Khan
	10%	11201	Luang Prabang
	10%	12001	Nong Khai
	11%	10501	Chiang Saen
	11%	11901	Vientiane
	13%	11904	Pa Mong dam site
	15%	13402	Mukdahan
	17%	13101	Nakhon Phanom
	19%	13801	Khong Chiam
Low	7%	13901	Pakse
	11%	10501	Chiang Saen
	11%	12001	Nong Khai
	11%	11903	Chiang Khan
	11%	11201	Luang Prabang
	16%	11901	Vientiane
	18%	11904	Pa Mong dam site
	18%	13402	Mukdahan
	22%	13101	Nakhon Phanom
	25%	13801	Khong Chiam
High	3%	13901	Pakse
	6%	11903	Chiang Khan
	7%	11901	Vientiane
	8%	13402	Mukdahan
	10%	13801	Khong Chiam
	10%	13101	Nakhon Phanom
	11%	12001	Nong Khai
	11%	11904	Pa Mong dam site
	11%	11201	Luang Prabang
	11%	10501	Chiang Saen

Table 3.1

4. DRY SEASON FLOW ANALYSIS

4.1 Flow measures

4.1.1 Introduction

The main objective of the study was to provide a consistent analysis of river flows in the Lower Mekong Basin so that benchmark flow statistics can be established and used to evaluate any future changes to the hydrological regime. The term "flow measures" is used in this report for describing the way in which the flow regime of a river may be summarised. Three such measures have been calculated from the time series of mean daily flows: the mean discharge, the flow duration curve and the low flow frequency curve.

4.1.2 Mean flow

The mean flow is perhaps the most fundamental variable to describe historical flows, to assess changes in river flows and to compare the hydrology of different catchments. Expressed in cubic metres per second (m^3s^{-1}), the mean flow is controlled both by the area of the catchment, the nature of the catchment and the climate. Comparisons between stations and between rainfall and runoff are therefore simplified if the mean discharge is expressed as the average annual runoff over the catchment in millimetres (mm). Changes to the mean runoff will usually be the result of the variability of climate (particularly rainfall), changes in land use (which may influence the rate of losses from evaporation and transpiration) or artificial control of the river (nett imports or exports of water).

4.1.3 Flow duration curve

The cumulative frequency distribution of daily mean flows is a convenient measure for describing the complete range of flows from the dry to flood season. This is referred to as a flow duration curve. Figure 4.1 shows an example of the flow duration curve for the Mekong gauged at Pakse for the period before regulation on the tributaries (1923-1965). The curve is derived from daily data by assigning daily discharges to class intervals and counting the number of days within each class interval. The proportion of the total number of days above the lower limit of any class interval is then calculated and plotted against the lower limit of the interval. A normal probability scale is used for the frequency axis and a logarithmic scale for the discharge axis. These transformations assist in estimating discharges for given frequencies from the curve and if the logarithms of the daily discharges were distributed normally then the curves would plot as straight lines.

Flow duration curve for Pakse (1923-65)

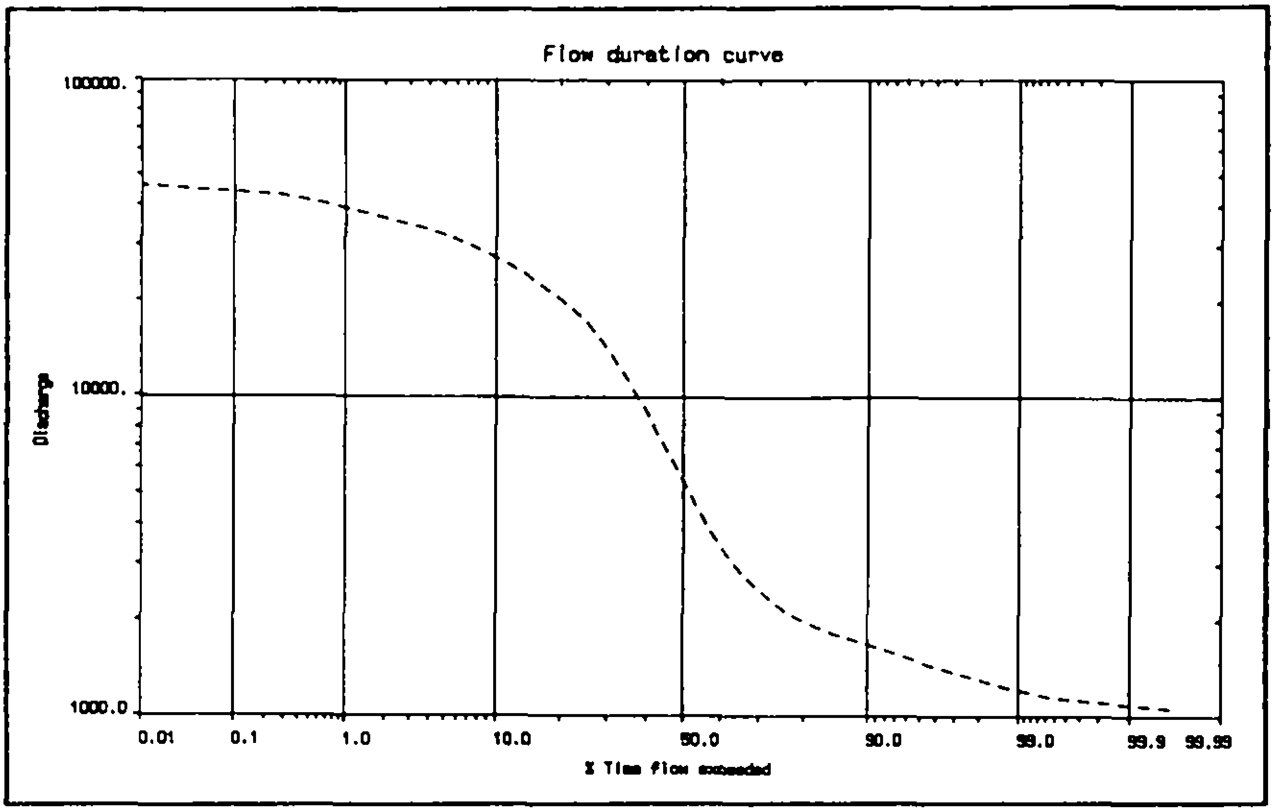

Figure 4.1

Low flow frequency curve for Pakse (1923-65)

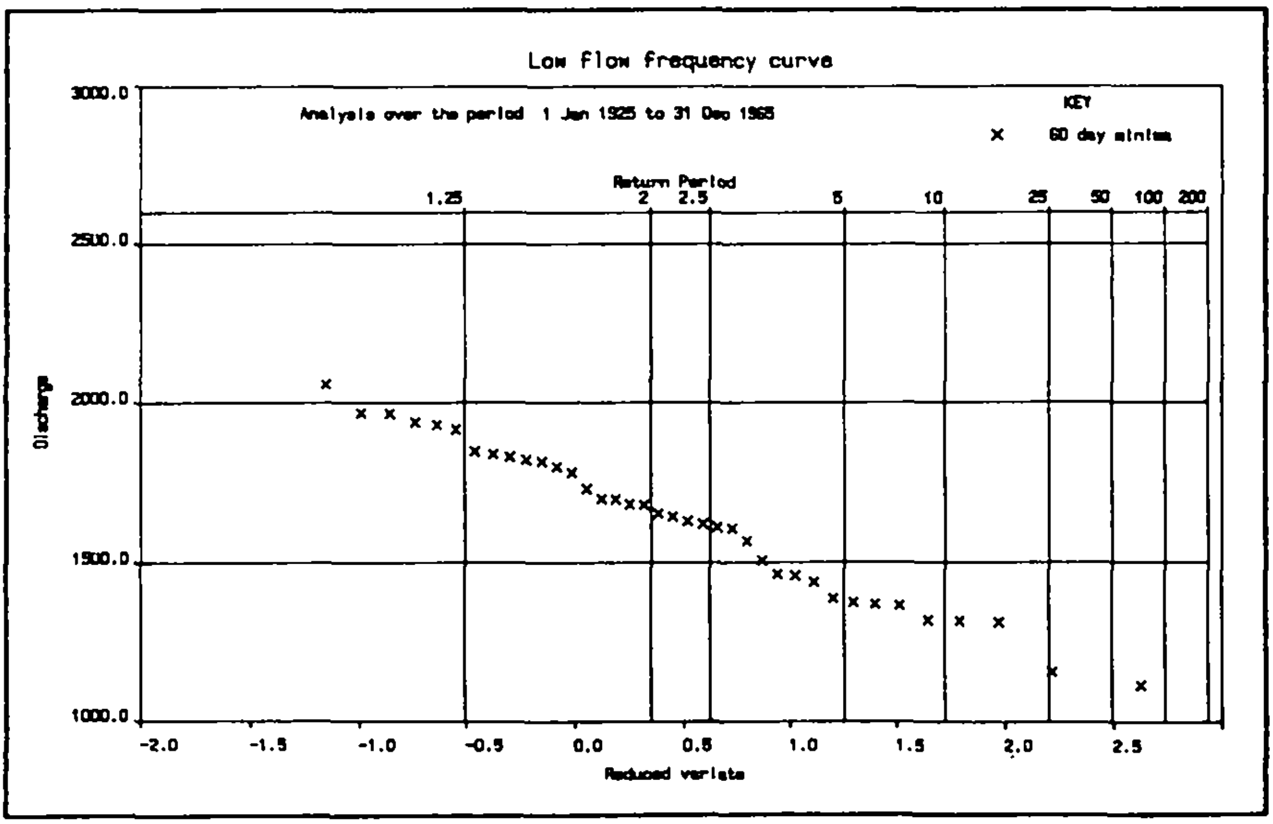

Figure 4.2

To assist in making comparisons between stations, and at the same station over different time periods, it is helpful to estimate "flow indices" from the flow duration curve. HYDATA was used to calculate seven different indices, defined as the discharge exceeded for 95, 90, 75, 50, 25, 10 and 5 percent of the time. These statistics provide a good description for water resource purposes of the entire flow range. They are used to estimate the proportion of time that a particular discharge will be exceeded. Conversely they also provide an estimate of the proportion of time that the flow will be less than a given discharge. For example the 75 percentile discharge is exceeded on average for 274 (365 x 0.75) days, or conversely on all but 91 (365 - 274) days in the year the discharge will be lower. The flow duration curve is thus the appropriate flow measure to use for a wide range of design problems requiring information on the average number of days in the year when a particular threshold discharge will not be met. Design problems may be expressed (and answered) in terms either of "what is the discharge with a given percentile exceedance", or "what is the percentile exceedance for a given discharge".

In the same way that there is no single design standard that is suitable for all flood design problems there is no single flow duration curve percentile that is appropriate for every dry season design problem. The appropriate percentile will depend on the "*frequency of failure to meet the design discharge*" which can be accepted. This frequency or "level of service" will be dependant on the particular scheme, for example, hydropower, irrigation, navigation, industrial abstraction, dilution of effluent, environmental improvement and the scale and national or local importance of the scheme. It may be considered appropriate to maintain the target abstraction rate for a high proportion of the time for urban supply or a major irrigation scheme; lower reliability might be appropriate for a smaller scheme of only local importance. It may also be appropriate to derive flow duration curves for particular seasons of the year according to the particular application. For example, if the group of months when irrigation is required for a particular crop can be identified, then the discharge for a given frequency during this period may be calculated using HYDATA. The frequency of failure is then specific to the growing season of the crop and is thus more appropriate than using the entire flow record.

4.1.4 Low flow frequency curve

While the flow duration curve is concerned with the proportion of time that a flow is exceeded, the flow frequency curve shows the proportion of years, or equivalently, the average interval between years (return period), in which the river flows are below a given discharge. Figure 4.2 illustrates the curve for the Mekong river gauged at Pakse for the period before regulation on the tributaries (1923-1965). The procedure for constructing the curve uses the Weibull distribution and is as follows:

(1) Find the lowest flow, Q(i), in each year of the N years of record for the duration of interest, D.

(2) Rank them from highest to lowest such that the highest rank, i=1, is given to the **largest** annual minimum, and i=N is given to the **smallest** annual minimum.

(3) Calculate the exceedance probability, P(i):

$$P(i) = (i - 0.44) / (N + 0.12)$$

(3) To each ranked flow, Q(i), assign a plotting position, W(i), to each ranking from:

$$W(i)= 4 [1 - \{ - \ln P(i)\}^{0.25}]$$

(4) Plot the annual minimum discharge, Q(i), against the plotting position, W(i).

The procedure is described in detail in the Low Flow Studies Report (Institute of Hydrology, 1980). For the study's 44 stations eye-fitted lines were drawn through the set of points produced by this method. For most stations a straight line provided a good fit to the data, indicating that the Weibull distribution is suitable for describing the annual minimum data in the Lower Mekong Basin.

The flow frequency curve has similar applications to the flow duration curve. However, because the frequency is expressed in terms of return period in years, it is more suitable for describing rare events with return periods of 10 or 25 years. It is important to note that the 90% exceedance probability on the flow duration curve is a much more common event than the 90 % exceedance probability (10 year return period) on the flow frequency curve.

Figure 4.2 shows the flow frequency plot for the 60 day annual minima. However the curve can be drawn for minima of any consecutive D day period. The appropriate duration to use will be determined by the specific design problem. Thus for navigation it may be appropriate to analyse the lowest 10 days in the year to provide estimates of the 10 day annual minima with a given return period but for irrigation requirements it may be more appropriate to consider longer duration minima of 30 or 60 consecutive days.

4.2 Selecting design dry season flows

For any particular water resource scheme there are a wide range of flow statistics which can be used for design purposes. In addition to deciding whether the flow duration (FDC) or flow frequency curve (FFC) is the most appropriate method of analysis, it is necessary to determine the frequency of interest. Furthermore, in the case of the flow frequency curve, the appropriate duration must also be selected; and in the case of the flow duration curve it may be useful to consider seasonal analysis. The selected flow statistic will thus depend on the specific scheme, for example hydropower, irrigation, navigation or effluent dilution, and upon the importance or scale of the scheme. It is therefore inappropriate to recommend a single design standard for all possible schemes; however the step by step procedure given in Table 4.1 will assist in determining the appropriate flow index to select.

Choosing a design method

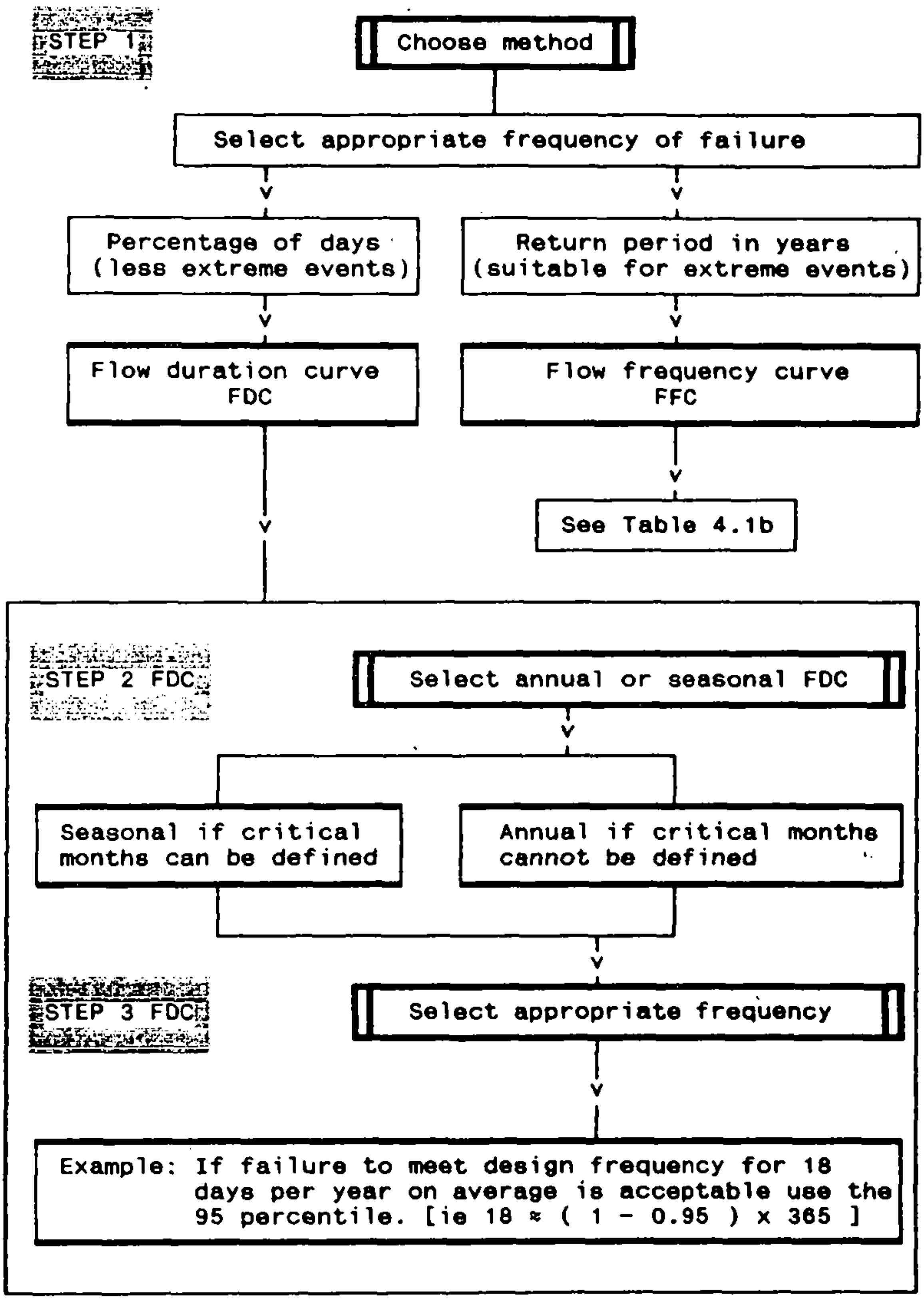

Table 4.1a

Choosing a design method

Continued from Table 4.1a

↓

STEP 2 FFC

Select appropriate duration

↓

Note - 1 day duration will be the lowest discharge recorded in the year. Longer durations will be calculated from the mean of D consecutive days

Select critical duration for your purpose

↓

STEP 3 FFC

Select return period

↓

Note : 25 year return low flow means this annual minimum, over the duration selected above, will not be exceeded once in 25 years

Table 4.1b

4.3 Benchmark flow statistics

Section 4.1 describes a number of flow statistics which may be calculated from a series of daily mean flow data. Although it is not appropriate to recommend key design standards for a wide range of applications it is possible to recommend flow indices which provide a useful summary of the flow regimes encountered in the Lower Mekong Basin. The selected indices are:-

(1) MAR, the mean annual runoff expressed as a depth in mm over the catchment area (shown in Figure 4.3).

(2) Q(P), seven percentiles from the flow duration curve expressed in m^3s^{-1} 95, 90, 75, 50, 25, 10, 5.

(3) MAM(D), the mean annual D day minima in m^3s^{-1}, for five different durations of 10, 30, 60, 120, 180 days.

(4) $AM(60)_T$, the 60 day annual minima of T year return period, for 4 different return periods of 2, 5, 10, 25 years, with discharge expressed as a ratio of the 60 day mean annual minima.

Table 4.2 lists each of these indices for the natural flow series (excluding the period when the river was regulated), together with the catchment area, start and end year of the analysis, the number of years of data, the number of years from which the mean annual minima was calculated (annual values were not calculated if there were more than 20 days missing in the year) and the average flow in m^3s^{-1}.

From Table 4.2 and Figure 4.3 it can be seen that the annual runoff ranges from 146 mm from the driest catchment (station 370111) to 1605 at the wettest (station 320101). There is a wide range in both MAM(D) and Q(P) reflecting the wide variation in both the size and climate of the catchments.

In order to make comparisons between catchments easier, it is helpful to express these flow statistics as a percentage of the average flow. These values are shown on Figures 4.4 for Q(75) and on Figure 4.5 for MAM(60) which display consistent trends of both indices, with generally lower values in northeast Thailand and Kampuchea and higher dry season flows in northern Thailand and Laos. There is also a consistent trend down the main Mekong river with the dry season flows expressed in m^3s^{-1} steadily increasing down the Mekong. However, when standardised by the average flow, the upstream stations on the Mekong are similar to the nearby tributary basins with MAM(60) equal to 30% of the mean flow and Q75 equal to 37% of the mean flow. In contrast at the downstream station of Kratie the MAM(60) and Q(75) are 14% and 19% of the mean flow respectively. This reduction is caused by the tributary inflows having lower dry season flows (expressed as a percentage of the mean flow) than the upper Mekong.

Benchmark statistics for natural catchments

Number	Name	Area km²	Start year	End year	No. yrs.	MAM yrs.	ADF m³s⁻¹	MAR mm	MAM 10	MAM 30	MAM 60	MAM 120	MAM 180	Ratio 2	Ratio 5	Ratio 10	Ratio 25	95%	90%	75%	50%	25%	10%	5%
									Mean Annual Minimum (MAM) - m³s⁻¹ Duration - Days					Ratio to MAM(60) Return period - Years				Flow Duration - m³s⁻¹ Percentiles						
10501	Mekong at Chiang Saen	189000.	1960	1987	28	26	2744.	458.	741.8	773.0	818.3	915.1	1079.	1.011	0.910	0.855	0.808	748.	825.	1014.	1755.	3073.	6009.	7303.
11201	Mekong at Luang Prabang	268000.	1950	1987	38	36	3860.	455.	936.2	976.5	1037.	1174.	1418.	1.011	0.882	0.821	0.753	913.	1029.	1292.	2325.	5473.	9131.	11104.
11901	Mekong at Vientiane	299000.	1913	1987	75	73	4503.	484.	1070.	1119.	1174.	1312.	1571.	1.011	0.882	0.814	0.740	1041.	1164.	1447.	2646.	6565.	11260.	13627.
11903	Mekong at Chiang Khan	292000.	1967	1987	21	19	4254.	460.	940.5	983.5	1045.	1203.	1500.	1.011	0.910	0.848	0.794	950.	1049.	1357.	2662.	6220.	9920.	12153.
12001	Mekong at Nong Khai	302000.	1969	1987	19	17	4674.	480.	1065.	1111.	1186.	1353.	1647.	1.005	0.930	0.889	0.855	1081.	1188.	1498.	2812.	6671.	11103.	13401.
13101r	Mekong at Nakhon Phanom	373000.	1924	1978	47	46	7732.	654.	1284.	1346.	1428.	1640.	2062.	1.005	0.862	0.794	0.719	1260.	1427.	1855.	4048.	12269.	20091.	23638.
13402r	Mekong at Mukdahan	391000.	1923	1978	48	46	8455.	681.	1359.	1422.	1505.	1728.	2184.	1.005	0.862	0.801	0.726	1341.	1514.	1970.	4439.	13568.	21955.	25862.
13901r	Mekong at Pakse	545000.	1923	1965	43	41	10550.	611.	1509.	1577.	1664.	1920.	2493.	1.005	0.849	0.801	0.726	1477.	1679.	2280.	5477.	17422.	27525.	32505.
14901	Mekong at Kratie	646000.	1924	1965	42	41	14150.	690.	1844.	1920.	2029.	2399.	3194.	1.005	0.882	0.821	0.753	1837.	2027.	2742.	7818.	23207.	37256.	44001.
40201	Nam Mae Khan - Ban Huai Yano Mai	283.0	1975	1987	13	11	5.035	783.	1.166	1.291	1.433	1.734	2.090	1.011	0.767	0.630	0.509	1.030	1.238	1.838	3.259	6.391	10.510	14.044
50103	Nam Kok at Dam Site	5870.0	1968	1987	20	18	116.6	627.	22.80	25.67	28.47	35.11	44.35	1.011	0.888	0.786	0.598	23.03	27.79	39.81	72.93	161.21	263.98	342.60
50105	Mae Kok at Ban Tha Ton	2980.0	1970	1987	17	16	71.34	756.	17.04	19.88	20.91	25.01	30.38	1.011	0.835	0.744	0.652	17.19	20.00	20.11	47.69	95.80	154.01	199.64
50201	Mae Fang at Ban Tha Mai Liam	1880.0	1970	1987	18	16	27.25	478.	2.765	3.382	4.112	5.697	8.246	0.937	0.658	0.509	0.353	2.481	3.412	6.061	14.97	41.27	69.10	85.32
70103	Nam Mae Ing at Thoeng	5700.0	1969	1987	19	17	65.22	341.	1.683	1.984	2.626	4.490	7.462	0.910	0.645	0.509	0.360	1.452	2.048	4.565	17.33	79.14	200.26	297.59
120101	Nam Khan at Ban Mixay (Ban Hout)	6100.0	1961	1987	27	23	99.08	517.	18.40	20.80	23.33	27.21	32.30	0.971	0.740	0.624	0.495	15.96	19.38	29.00	49.11	114.04	203.16	357.00
140201	Nam Nan at Ban Tai	481.6	1967	1987	21	19	5.595	640.	0.285	0.343	0.413	0.570	0.930	1.011	0.740	0.604	0.453	0.286	0.374	0.644	2.165	6.020	14.757	22.40
140301	Nam San at dam site	703.0	1966	1987	22	20	8.238	370.	0.367	0.499	0.634	0.809	1.380	1.011	0.781	0.650	0.529	0.412	0.558	0.971	2.650	9.830	22.021	34.82
190101	Huai Nong at Ban Na Ang(Ban Phu)	1307.0	1957	1987	31	25	9.287	222.	0.076	0.090	0.115	0.169	0.281	0.550	0.000	0.000	0.000	0.000	0.018	0.116	0.692	4.399	26.810	51.29
230102r	Nam Ngum at Tha Ngon	16500.	1963	1970	8	*	755.7	1445.	*	*	*	*	*	*	*	*	*	84.43	92.95	123.4	281.6	1049.	2296.	2799.
320101	Se Bang Fai at Se Bang Fai	8560.0	1961	1985	25	22	435.4	1605.	20.90	22.92	24.24	26.99	33.97	0.984	0.842	0.801	0.733	20.06	23.36	29.92	67.76	509.5	1476.	2175.
340101	Huai Bang I at Ban Khan Soi	702.0	1964	1978	25	13	9.100	409.	0.160	0.214	0.276	0.456	0.666	0.820	0.360	0.127	0.000	0.061	0.131	0.386	1.270	6.447	23.96	47.47
350101	Se Bang Hieng at Ban Keng Done	19400.	1961	1977	17	14	580.2	877.	23.80	27.33	31.56	41.91	63.20	0.991	0.767	0.645	0.523	24.17	32.02	49.07	131.7	506.6	1429.	2311.
370104r	Nam Chi at Yasothon	43100.	1953	1965	13	12	249.0	183.	4.789	5.324	6.366	8.731	10.59	0.916	0.624	0.460	0.312	4.642	6.476	11.06	57.10	392.7	813.9	989.0
370107	Nam Chi at Ban Khai	6835.0	1968	1987	20	18	37.66	174.	0.630	1.031	1.418	2.104	3.804	0.903	0.584	0.420	0.250	0.651	1.047	2.445	7.104	30.46	87.63	126.2
370111	Nam Chi at Ban Tha Phra	13171.	1958	1987	30	28	61.07	146.	0.845	1.139	1.817	3.024	6.482	0.814	0.488	0.258	0.061	0.550	1.083	2.711	10.09	42.65	182.9	381.2
370204	Nam Pong at Ban Pha Nok Khao E29	945.0	1970	1987	18	11	23.75	793.	7.118	7.684	8.402	9.979	11.97	0.149	0.040	0.000	0.000	0.299	0.613	1.311	6.118	33.47	64.80	95.35
370502	Huai Phaniang at Ban Nong Nan	1260.0	1978	1987	10	*	8.149	204.	*	*	*	*	*	*	*	*	*	0.009	0.000	0.012	1.006	6.985	20.90	48.08
371101	Huai Rai at Ban Non Liang	1370.0	1975	1987	13	10	14.30	329.	0.480	0.584	0.697	0.972	1.920	1.005	0.801	0.692	0.504	0.511	0.671	1.163	3.692	14.30	41.33	64.94
371203	Huai Pa Thao at Ban Tao Ton	326.0	1976	1987	12	10	4.062	393.	0.214	0.282	0.343	0.467	0.749	0.957	0.638	0.468	0.299	0.194	0.251	0.449	1.832	3.437	10.61	16.27
371509	Nam Yang at Ban Na Thon	3240.0	1979	1987	9	*	35.70	340.	*	*	*	*	*	*	*	*	*	0.302	0.779	1.050	5.075	20.67	113.8	201.1
380103r	Nam Mun at Ubon	104000.	1951	1965	15	10	677.9	206.	10.27	11.91	14.62	20.64	44.50	0.923	0.645	0.502	0.360	11.77	16.16	33.70	246.1	1060.	2063.	2592.
380110r	Nam Mun at Rasi Salai	44275.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380112r	Nam Mun at Satuk	28275.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380404	Lam Chae at Ban Nak Srat	498.0	1977	1987	11	*	5.841	370.	*	*	*	*	*	*	*	*	*	0.031	0.082	0.298	1.090	8.250	15.60	22.07
380602	Lam Phang Chu at Ban Nua Saphan	1094.0	1979	1985	7	*	7.456	221.	*	*	*	*	*	*	*	*	*	0.000	0.000	0.010	0.639	4.732	17.31	30.94
380705	Lam Chi at Ban Lam Pia	4630.0	1979	1987	9	*	29.47	201.	*	*	*	*	*	*	*	*	*	0.137	0.259	0.922	4.063	29.18	88.97	170.9
380903	Lam Siao Yai - Ban Sa Phra So Ma	3230.0	1979	1987	9	*	18.04	176.	*	*	*	*	*	*	*	*	*	0.130	0.277	1.195	3.701	11.97	56.10	116.7
381001	Huai Thap Than-Ban Huai Thap Tan	2030.0	1972	1982	11	*	20.35	316.	*	*	*	*	*	*	*	*	*	0.061	0.128	0.314	0.818	7.248	66.42	141.9
381206	Huai Khayung at Ban Huai Khayung	2900.0	1979	1987	9	*	37.18	405.	*	*	*	*	*	*	*	*	*	0.516	0.777	1.665	7.378	43.96	119.2	183.7
381401	Lam Se Bok at Ban Tha Bo Beang	2132.0	1979	1985	7	*	46.96	695.	*	*	*	*	*	*	*	*	*	0.033	0.157	0.490	4.427	51.08	150.8	220.1
381501	Lam Dom Yai at Det Udom	3340.0	1963	1981	19	16	44.35	419.	0.333	0.479	0.650	1.029	1.870	0.719	0.482	0.360	0.231	0.201	0.437	1.208	6.041	50.05	143.1	215.0
430101	Se Kong at Ban Khamon	29600.	1961	1970	10	*	1346.	1435.	*	*	*	*	*	*	*	*	*	103.6	215.0	293.7	527.3	1619.	3832.	5253.
550101	Stung Sangker at Treng	2135.0	1963	1973	11	*	69.63	1079.	*	*	*	*	*	*	*	*	*	2.854	3.317	6.319	20.22	81.39	182.4	260.3
610101	Stung Sen at Kompong Thom	14000.	1961	1978	10	*	105.2	417.	*	*	*	*	*	*	*	*	*	4.969	5.719	7.944	33.98	200.3	477.2	793.3

"r" after station number indicates that the catchment is now regulated - refer to Table 4.3 for current benchmark flow statistics

* indicates no information available

Table 4.2

Benchmark statistics for regulated catchments

Number	Name	Area km2	Start year	End year	No. yrs.	MAM yrs.	ADF m^3s^{-1}	MAR mm	Mean Annual Minimum (MAM) - m^3s^{-1} Duration - Days 10	30	60	120	180	- Ratio to MAM(60) Return period - Years 2	5	10	25	Flow Duration - m^3s^{-1} Percentiles 95%	90%	75%	50%	25%	10%	5%
10501	Mekong at Chiang Saen	189000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11201	Mekong at Luang Prabang	268000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11901	Mekong at Vientiane	299000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11903	Mekong at Chiang Khan	292000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
12001	Mekong at Nong Khai	302000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
13101	Mekong at Nakhon Phanom	373000.	1979	1987	9	7	6744.	571.	1414.	1470.	1577.	1821.	2242.	0.996	0.847	0.772	0.691	1393.	1559.	2022.	3823.	10285.	17299.	20015.
13402	Mekong at Mukdahan	391000.	1979	1987	9	7	7271.	587.	1417.	1483.	1576.	1794.	2226.	1.003	0.921	0.881	0.833	1469.	1603.	1985.	3869.	11414.	19135.	21062.
13901	Mekong at Pakse	545000.	1979	1987	9	7	9764.	565.	1784.	1844.	1963.	2217.	2781.	1.009	0.928	0.888	0.847	1810.	1968.	2425.	5816.	15166.	25247.	29140.
14901	Mekong at Kratie	646000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
40201	Nam Mae Khan - Ban Huai Yano Mai	203.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50103	Mae Kok at Dam Site	5870.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50105	Mae Kok at Ban Tha Ton	2980.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
50201	Mae Fang at Ban Tha Mai Liam	1800.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
70103	Nam Mae Ing at Thoeng	5700.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
120101	Nam Khan at Ban Hisay (Ban Mout)	6100.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
140201	Nam Man at Ban Sai	401.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
140301	Nam San at dam site	703.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
190101	Huai Mong at Ban Na Ang(Ban Pho)	1307.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
230102	Nam Ngum at Tha Ngon	16500.	1979	1985	7	4	738.4	1411.	232.5	258.7	276.9	297.4	314.5	0.999	0.894	0.833	0.779	251.0	279.7	333.2	470.0	892.4	1772.7	2215.
320101	Se Bang Fai at Se Bang Fai	8560.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
340101	Huai Bang 1 at Ban Khan Soi	702.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
350101	Se Bang Hieng at Ban Keng Done	19400.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
370104	Nam Chi at Yasothon	43100.	1969	1987	19	17	179.2	131.	28.27	33.05	38.51	48.05	58.97	0.991	0.523	0.278	0.034	11.09	21.40	46.26	80.39	209.5	499.9	780.6
370107	Nam Chi at Ban Khai	6835.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
370111	Nam Chi at Ban Tha Phra	13171.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
370204	Nam Pong at Ban Pha Nok Khao E29	945.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
370502	Huai Phaniang at Ban Nong Nam	1260.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
371101	Huai Rai at Ban Non Liang	1370.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
371203	Huai Pa Thao at Ban Tao Ton	326.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
371509	Nam Yang at Ban Na Thom	3240.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380103	Nam Mun at Ubon	104000.	1971	1987	17	15	660.3	280.	66.99	72.13	77.79	88.61	114.1	0.964	0.781	0.686	0.584	61.62	69.97	93.42	195.6	907.0	2026.	2539.
380110	Nam Mun at Rasi Salai	44275.	1971	1987	17	15	216.7	154.	2.475	3.160	3.949	6.046	12.17	0.881	0.597	0.409	0.380	2.151	2.894	6.941	26.57	214.9	707.6	1061.
380112	Nam Mun at Satuk	20275.	1971	1987	17	13	75.32	84.	1.052	1.210	1.473	2.225	4.708	0.849	0.246	0.000	0.000	0.626	1.140	3.107	9.925	59.52	224.1	389.1
380404	Lam Chae at Ban Nak Erat	490.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380602	Lam Phang Chu at Ban Non Saphan	1094.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380705	Lam Chi at Ban Lam Dia	4630.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
380903	Lam Siao Yai - Ban Ku Phra Ko Na	3230.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
381001	Huai Thap Than-Ban Huai Thap Tan	2030.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
381206	Huai Khayung at Ban Huai Khayung	2900.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
381401	Lam Se Bok at Ban Tha Bo Saeng	2132.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
381501	Lam Dom Yai at Det Udom	3340.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
430101	Se Kong at Ban Kheuon	29600.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
550101	Stung Sangker at Treng	2135.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
610101	Stung Sen at Kompong Thom	14000.	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

* indicates no information

Table 4.3

Annual runoff in millimetres

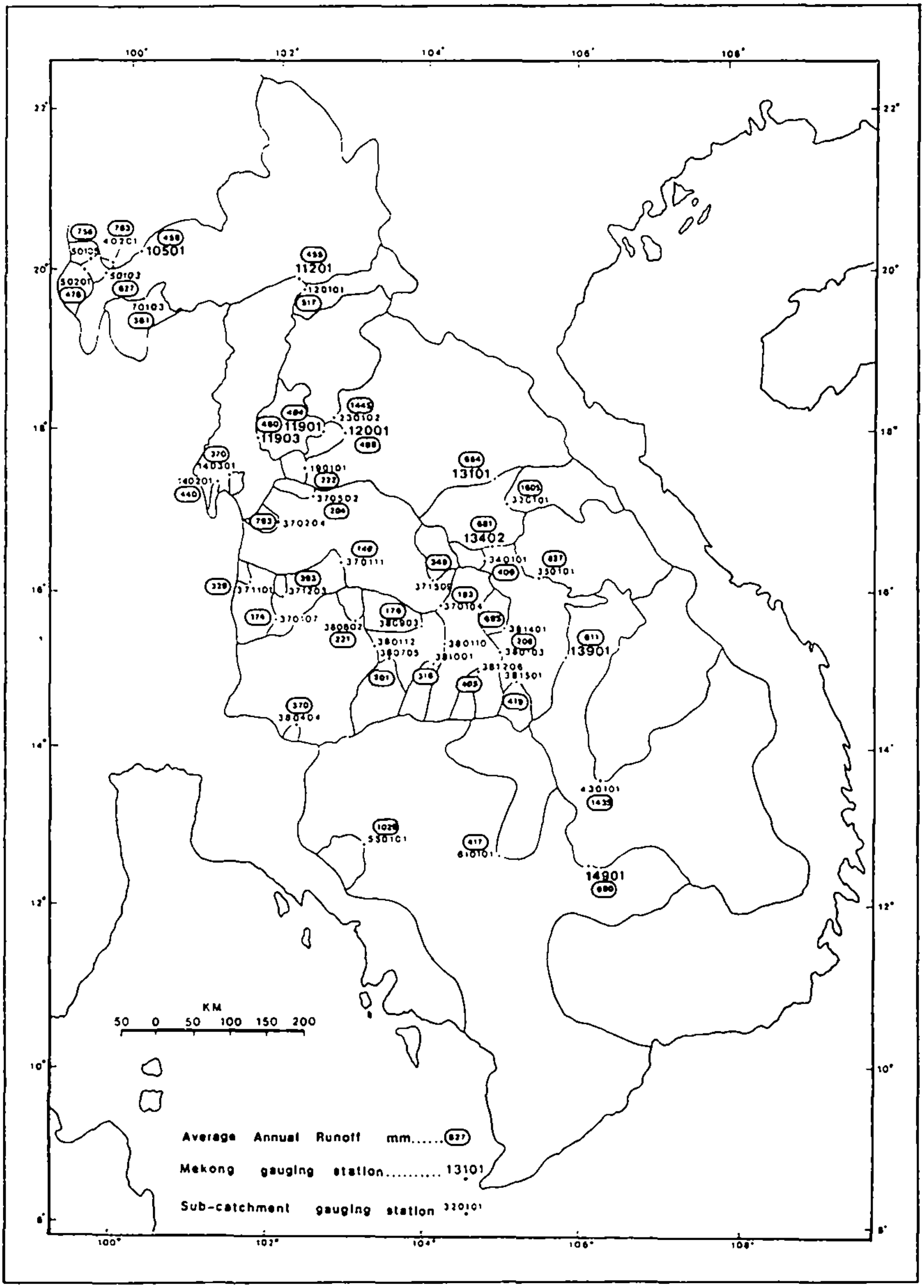

Figure 4.3

Distribution of Q75%

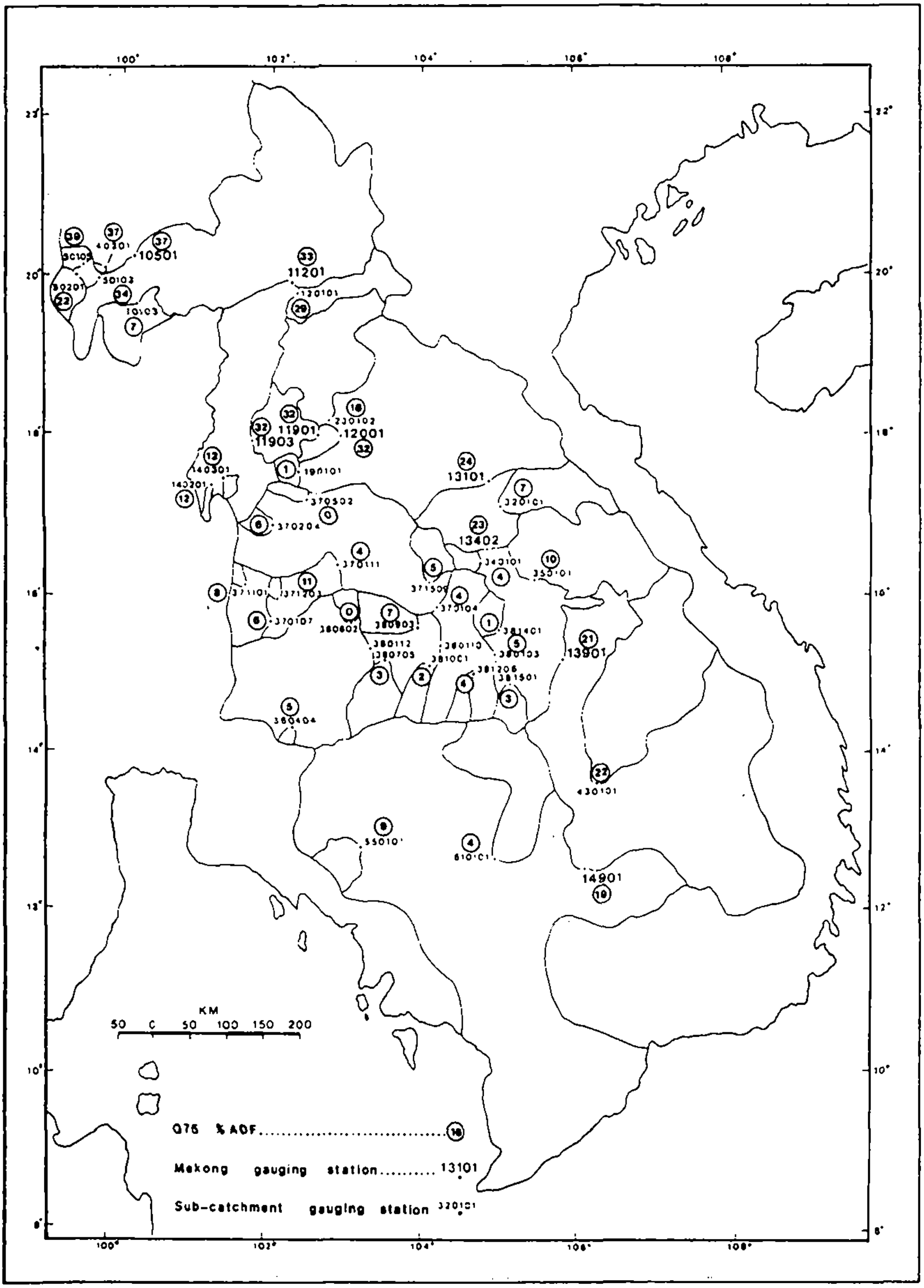

Figure 4.4

Distribution of MAM(60)%

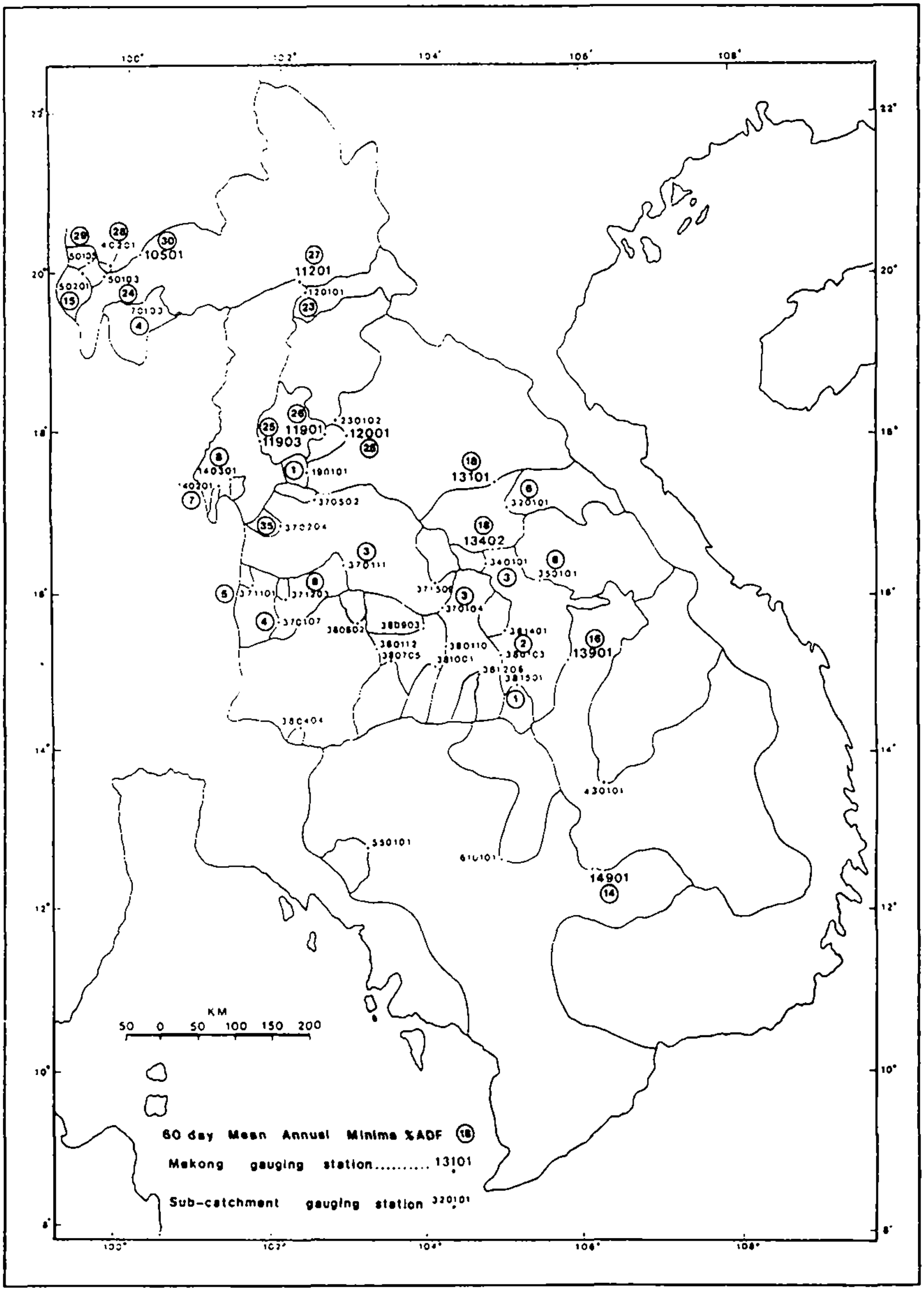

Figure 4.5

The ratio of the 60 day, T year return period, discharge to the mean annual 60 day minimum may be used to estimate the more extreme dry weather flow conditions. Table 4.2 shows consistent ratios on the main Mekong sites, but a greater variability elsewhere.

It is recommended that the flow indices shown on Table 4.2 are used as benchmark flow statistics for those stations indicated as being unregulated. Table 4.3 should be used for catchments which are now regulated. Thus significant departures, perhaps consistently above or below the mean MAM(D) and Q(P) values over a period of 5 years could be used as a threshold for carrying out a more detailed investigation of the nature and causes of the change. In general, if any changes are restricted to isolated catchments then the reason for change will be related to water resource development or land use change. However, if the change is more widespread then the change will be related to climatic fluctuation. It is important to note that as hydrological time series become longer, previous records will be broken and thus the occurrence of the most extreme event on record is not in itself an indication of a significant change in the regime. Procedures for evaluating the causes of a change in the dry season flow regime are described in Section 4.5.

4.4 Dry season flow estimation procedure

The benchmark flow statistics are useful both for detecting change and for providing dry season flow statistics to assist with the design of water resource schemes. For the latter application these values can only be used for design studies at or close to the sites of the gauging station.

A preliminary investigation was carried out to determine the feasibility of estimating dry season flows at sites without flow data from the characteristics of the upstream catchment area. These estimation equations, produced as a result of this study, are for use on the tributaries and not the main Mekong river. This is because the Mekong itself is well gauged. The data used in this part of the study thus exclude the main Mekong stations and the regulated flow records of tributary stations.

Section 4.1 describes how, for each flow measure such as the flow duration curve, a single "dry season flow index" was calculated. For example, how the 75 percentile was derived from the flow duration curve Q(75). Multiple regression analysis was used to relate these indices (Table 4.2) to the catchment characteristics described in Appendix C. The statistical package MINITAB, which has facilities for transformation, correlation, regression, analysis of residuals and standard plotting routines, was used for this analysis. The most useful predictive variables were catchment area, annual average rainfall and soil type. Details of the estimation procedure are described in Appendix B. The equations presented are of a preliminary nature and could be improved by using a finer resolution grid for the derivation of catchment characteristics, more flow records and further development of the design procedure. Also the error of estimation associated with some of the equations is quite high. Nevertheless the equations are a very useful as guideline for the many situations where flow data are not available.

4.5 Historical changes in dry season flows

4.5.1 Introduction

The dry season flow measures were used to identify changes in the flow regimes over time. This was done by examining mean annual runoff, annual values of the 60 day annual minima and by comparing flow duration curves over different periods. An initial inspection of the data indicated that the main changes .were due to regulation of the river flow following the development of irrigation and hydropower reservoirs. An analysis of the natural flow records was also carried out to identify, firstly, whether there had been any change in the natural dry season flows and secondly, to relate dry season flows to seasonal rainfall.

4.5.2 Regulation

Table 4.4 gives details of the major reservoirs in the Lower Mekong Basin:

Details of major reservoirs

Name	Completion Year	Catchment Area km²
Nam Ngum (Stage 1 30 MW total)	1971	8460
Nam Ngum (Stage 2 110 MW total)	1978	8460
Nam Ngum (Stage 3 150 MW total)	1985	8460
Nam Pong/Ubol Ratana (25 MW)	1966	11980
Lam Pao	1968	5960
Lam Dom Noi (24 MW)	1971	2097
Lam Nam Oon	1973	1100
Lam Takhong	1970	1430
Lam Phra Plerng	1967	807
Chulabhorn Dam (40 MW)	1972	545
Nam Pung Dam	1965	296

Table 4.4

Although Nam Ngum has been installed in three stages, Stage 2 was the most important development at this site when the installed generating capacity was increased from 30 MW to 110 MW and a reservoir of substantial storage was constructed. Although Stage 1 undoubtedly had some effect on the flows in the Nam Ngum itself, the reservoir storage capacity was not great so would have had a small, if not insignificant, influence on the flows in Mekong. Stage 3 involved an increase in installed generating capacity, with no further increase in storage. From the point of view of flows in the Mekong below the confluence of the Nam Ngum, Stage 2 completion in 1978 was therefore the most significant event. Since 1978 no major dams have been completed in the basin. The assessment of the effect of regulation on the Mekong below the Nam Ngum confluence therefore considers the natural record to include all data before 1966, and the status quo of current regulation to have been established in 1979. The mainstream stations affected are those downstream of Nong Khai.

Six flow records were identified as being downstream of one or more of these reservoirs with a sufficient length of record before and after impoundment to enable a comparison of the two regimes to be made. Table 4.5, based on information already presented in Tables 4.2 and 4.3, gives the percentage change in the flow indices due to regulation at these six sites.

Change in flow indices after regulation

Flow index	Station 13101	13402	13901	230102	370104	380103
MAR	-13%	-14%	-8%	-2%	-28%	-3%
MAM(10)	+10%	+4%	+18%	*	+490%	+552%
MAM(30)	+10%	+4%	+17%	*	+520%	+505%
MAM(60)	+10%	+5%	+18%	*	+505%	+432%
MAM(120)	+11%	+4%	+15%	*	+450%	+329%
MAM(180)	+9%	+2%	+12%	*	+217%	+145%
$AM(60)_2$	+9%	+5%	+18%	*	+554%	+455%
$AM(60)_5$	+9%	+12%	+26%	*	+407%	+544%
$AM(60)_{10}$	+7%	+15%	+31%	*	+259%	+627%
$AM(60)_{25}$	+6%	+20%	+38%	*	-34%	+763%
Q95	+10%	+10%	+23%	+197%	+156%	+423%
Q90	+9%	+6%	+17%	+201%	+230%	+332%
Q75	+9%	+1%	+10%	+170%	+318%	+177%
Q50	-6%	-13%	-8%	+49%	+46%	-21%
Q25	-16%	-16%	-13%	-15%	-47%	-15%
Q10	-14%	-13%	-8%	-23%	-39%	-2%
Q5	-15%	-15%	-10%	-21%	-28%	-2%

* indicates insufficient data for annual minima calculation for station 230102

Station Number	Station name
13101	Mekong at Nakhon Phanom
13402	Mekong at Mukdahan
13901	Mekong at Pakse
230102	Nam Ngum at Tha Ngon
370104	Nam Chi at Yasothon
380103	Nam Mun at Ubon

Table 4.5

The results of Table 4.5 show:

(1) A decrease in the mean flow (MAR, the mean annual runoff) at all sites. The total annual flow at all sites has therefore been reduced. This is to be expected since there will always be some losses as a result of reservoir operation, whether they are just evaporation from the reservoir surface in the case of hydropower or combined with the much higher losses due to the consumptive use of water in irrigation schemes.

(2) At all sites the mean annual minimum (MAM) discharges have been increased for all durations. This again is an effect which can be explained by the conventional operation of dams, storing water in the wet season for controlled release throughout the year. Where major irrigation schemes abstract or divert the regulated flow from a reservoir, the effect may not be so clear. The gauge at Yasothon on the Nam Chi (370104) is located downstream of the large scale irrigation schemes at Nam Pong/Nong Wai and Lam Pao. There is also extensive pumped irrigation upstream of the gauge. Whilst the MAM for 370104 have increased after regulation, MAR shows a high percentage reduction. This is probably due to increased consumptive use of water on the irrigation schemes. If irrigation efficiencies are improved in the future, there would be less water draining back into the river channels, and there would be a tendency for the MAM to fall.

(3) The annual minima at different return periods have, in general, shown an increase for the same reason. The reduction in $AM(60)_{25}$ for Nam Chi at Yasothon is probably the result of estimation error at the high return period.

(4) Similarly discharges for given flow percentiles from the flow duration curve have increased at low flows (at or below Q75), and decreased in the higher flow range (at or above Q25).

(5) High flows have been reduced at all sites as indicated by the reduction of discharges at or above Q25. Again, this is an expected result of any dam operation.

These results confirm the expected effect of regulation on downstream river flows for all tributaries with enough data to make the comparison. However the most surprising result is the effect of reservoir operation on the Mekong itself. Pakse, which has excellent flow data (Section 3.2), shows an 18% increase in the 60 day mean annual minimum, MAM(60), and a 10% increase in Q75 with an overall loss in annual runoff volume of 8%.

4.5.3 Climate

Other than regulation, discussed above, it is possible for the flow regime in a catchment to change due to a climatic variability. Unlike regulation, where there is a definite commissioning date, climatic changes are gradual, and happen slowly over many years. For this reason, and the fact that changes due to climate are small compared to the natural variability from year to year, they are more difficult to identify than changes due to regulation.

Climatic change is a complex subject and can manifest itself in many different ways. In this study we are concerned with water resources and concentrated on the dominant variable in that field, rainfall. Although there are many different ways in which the rainfall or year to year variability of rainfall can change (Parker and Folland, 1988), we have considered the simplest, annual total rainfall.

In order to see if there has been a change in the Lower Mekong Basin in recent years, annual total rainfall over the following areas was estimated using the computer program RAINS described in Section 2.4:

(1) The northern part of Thailand inside the Mekong basin.

(2) The northeast of Thailand inside the Mekong basin.

(3) Laos inside the Lower Mekong Basin.

(4) Kampuchea inside the Lower Mekong Basin.

(5) The Mekong delta in Vietnam.

(6) The whole of the Lower Mekong Basin.

Figure 4.6(a-f) shows these annual rainfall totals plotted as a time series from 1950 to 1986 for each region with the mean annual rainfall identified. From this figure it is clear that there has been no substantial change in annual rainfall over this period of time in any region. Long term climatic trends, measured in terms of annual total rainfall, are not apparent over the basin and therefore will not affect river flows.

4.5.4 Land use and irrigation

The remaining possibilities for change in flow regime are change in land use and increases in irrigation demand. Like climate discussed above, these factors are normally small compared to the effect of a major dam, they happen gradually over a period of time and are masked by the natural year to year variability of dry season flows.

In 1982, the first phase of the UK supported water balance studies (Institute of Hydrology, 1982), the effect of land use change on water resources was studied; it was concluded that there was insufficient evidence to identify changes in flow regime. Now, in 1988, more information on the change in land use over time is becoming available in a convenient computer compatible form at the Mekong Secretariat. Land use information is being transferred onto the Geographic Information System called ARC-INFO. This programme of work is expected to take another one or two years. When complete, this should form an excellent database from which land use change can be quantified. Also by that time there will be another 7 - 8 years of flow data at each site to assist with the study. It would then be possible to establish more rigorously any links between changes in land use and flow regime.

The actual consumptive use of water on an irrigation scheme should, in theory, be easy to estimate. Increases in area lead to increased use, and hence a decrease in dry season flows when crop demands are highest. In practice however, it is difficult to calculate actual consumptive use.

Annual rainfall time series (1950-86)

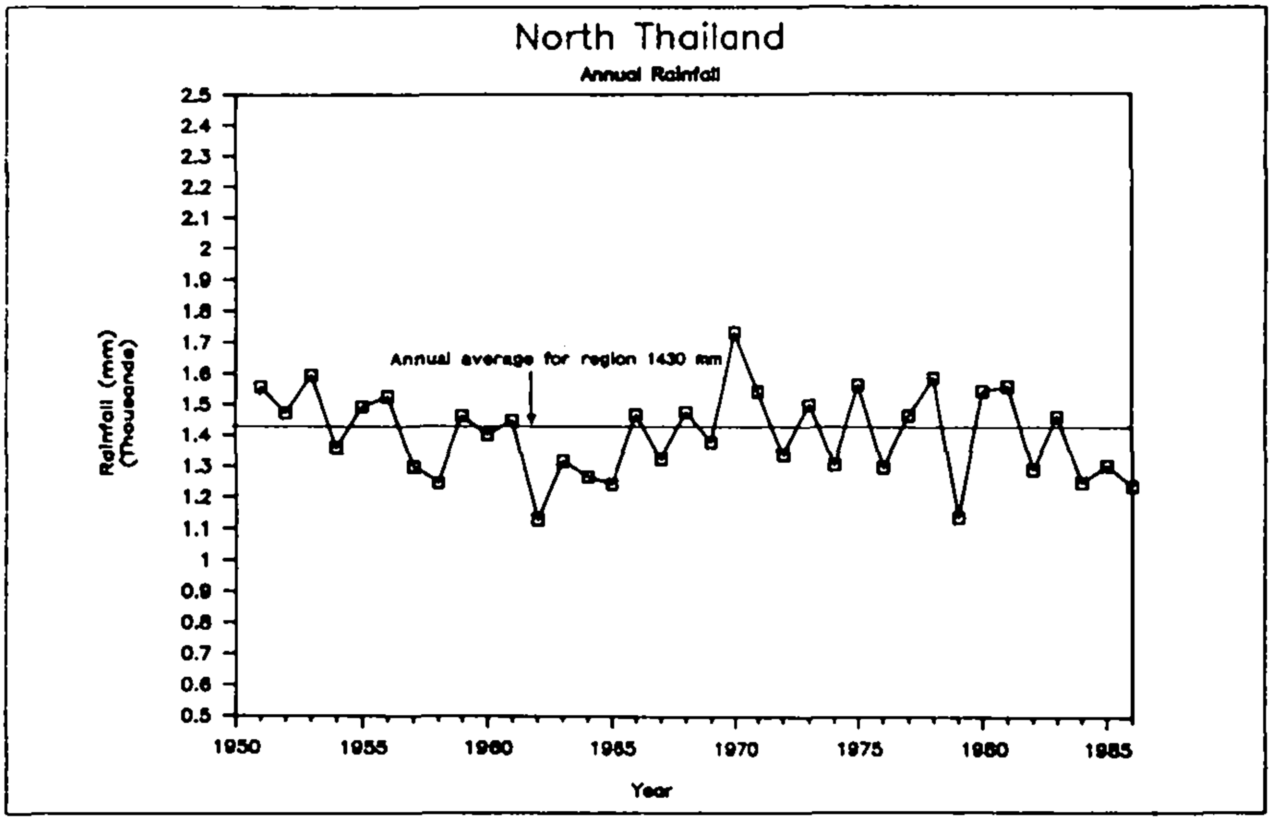

Figure 4.6a

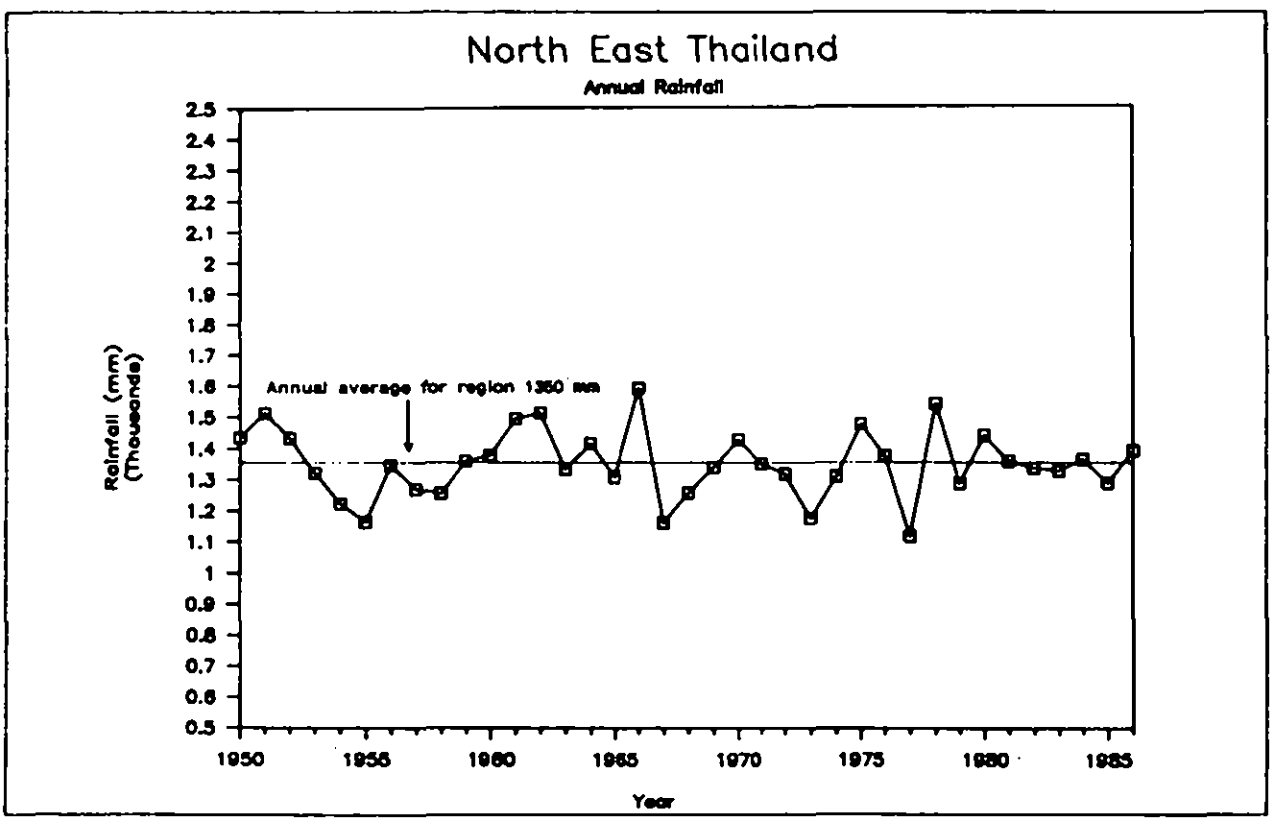

Figure 4.6b

Annual rainfall time series (1950-86)

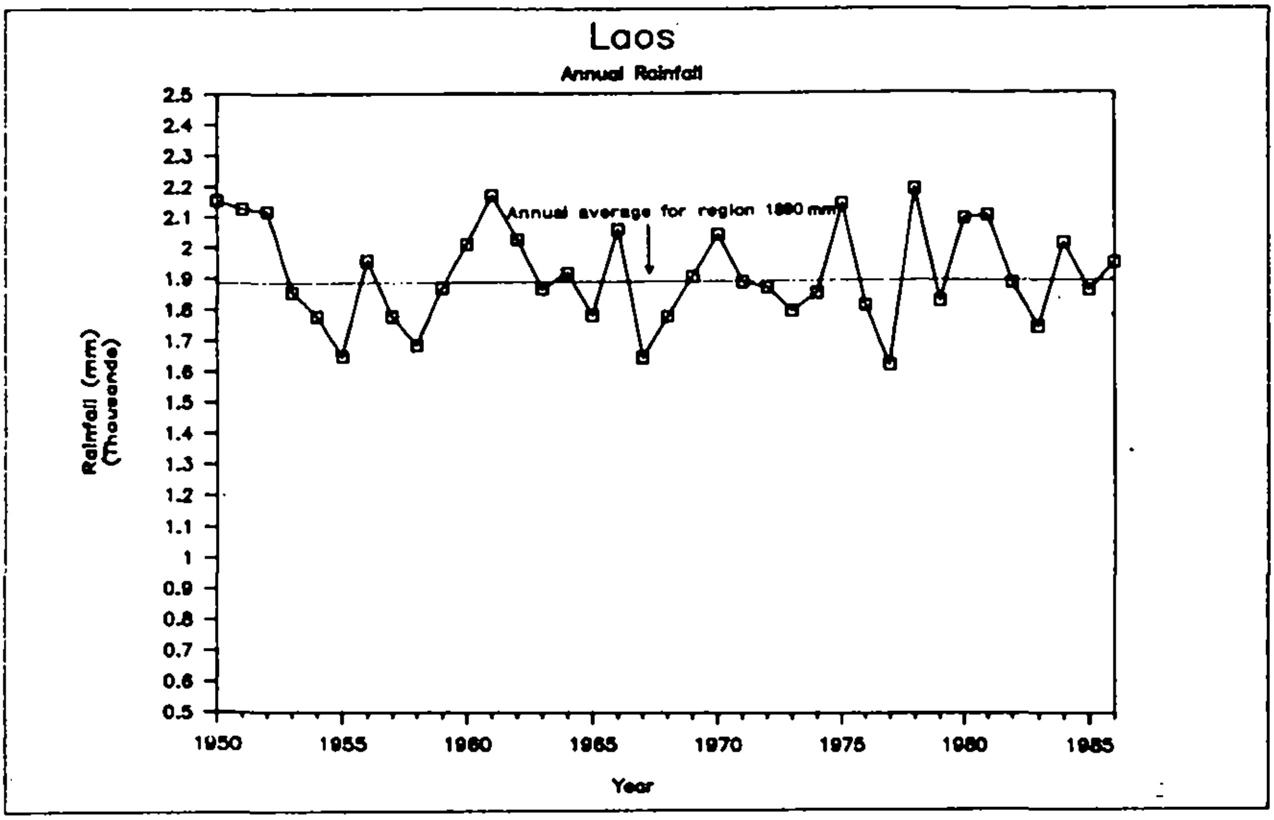

Figure 4.6c

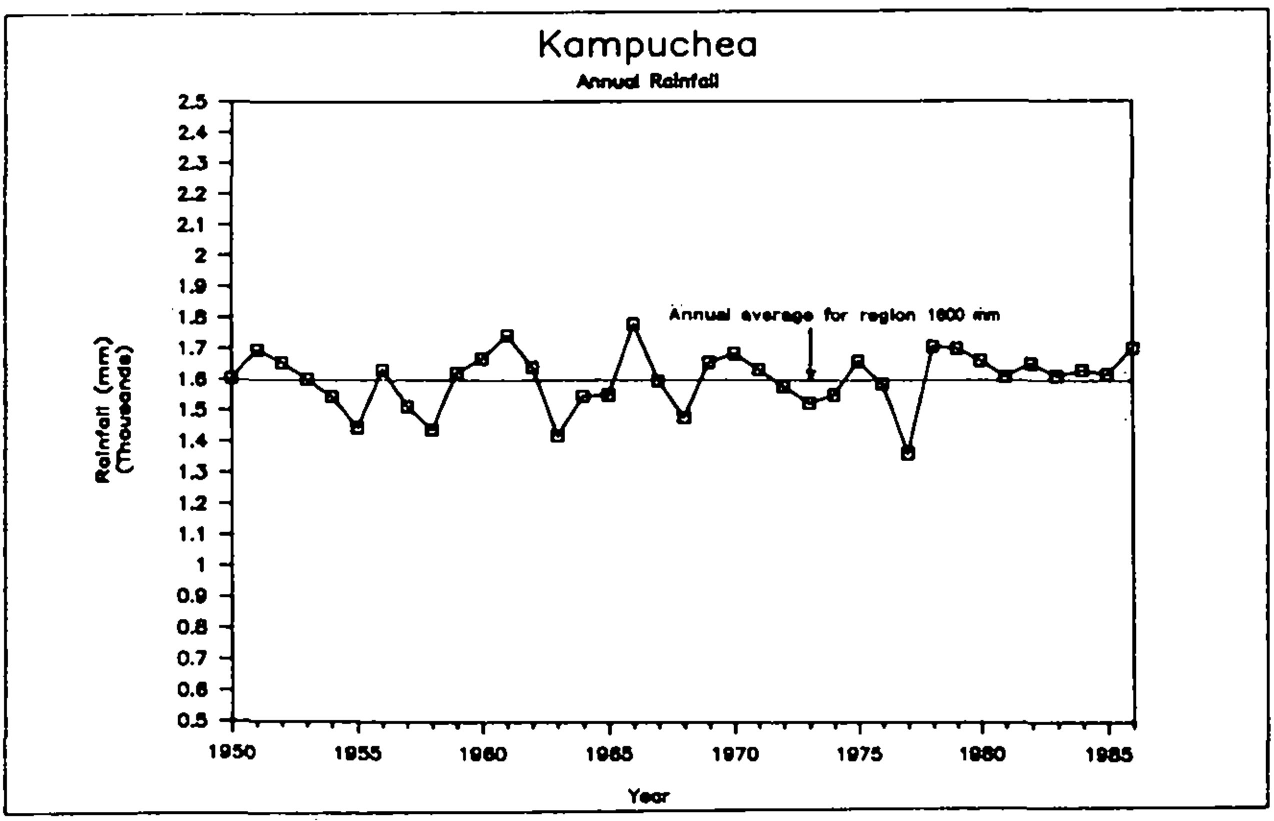

Figure 4.6d

Annual rainfall time series (1950-86)

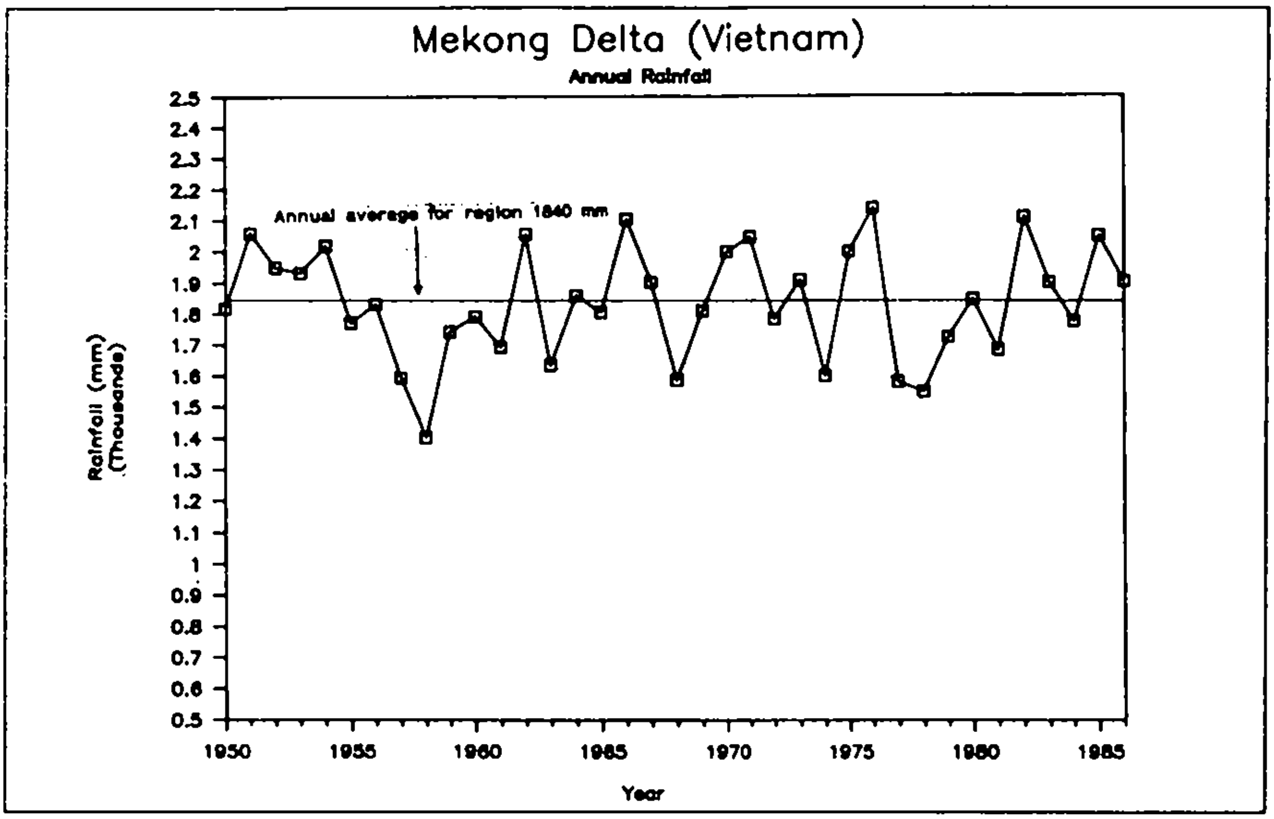

Figure 4.6e

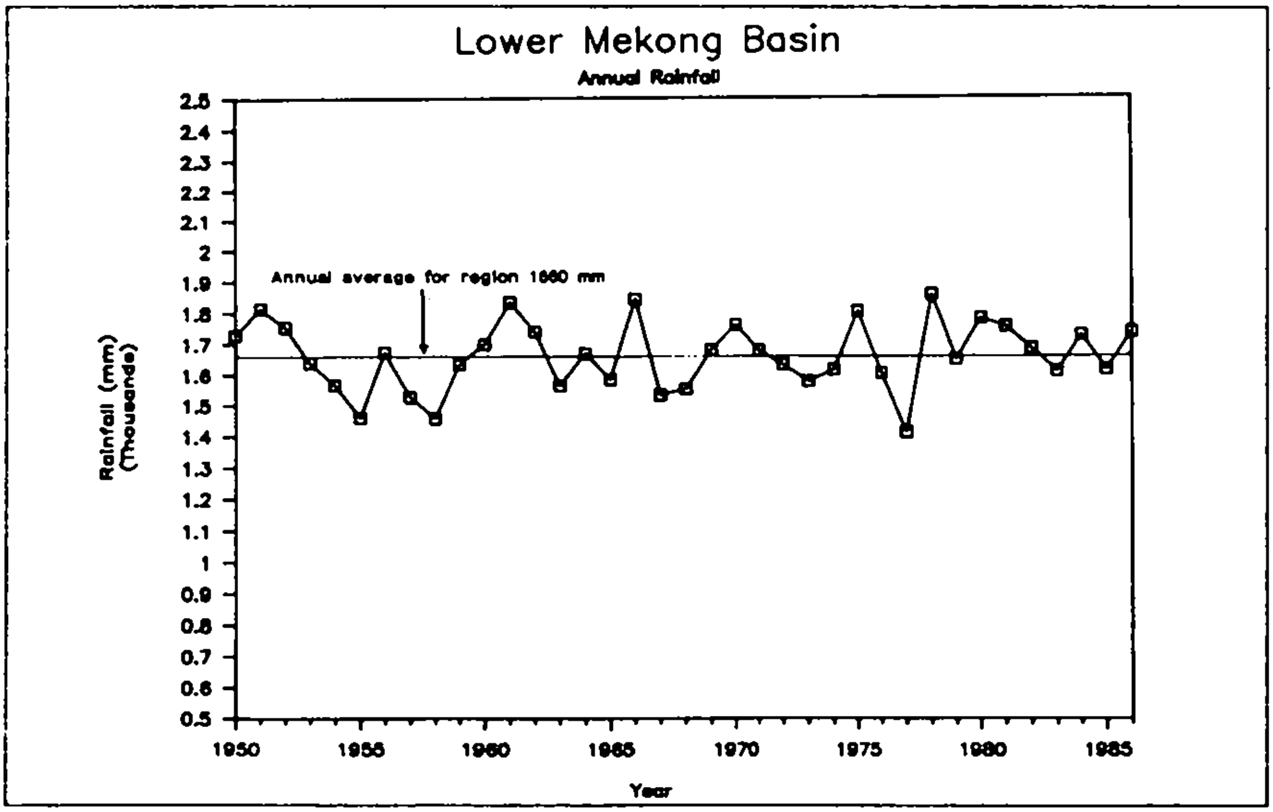

Figure 4.6f

The locations and irrigable area of the main types of irrigation scheme are well documented. The actual consumptive demands of these schemes are more difficult to quantify, as in practice few measurements of scheme performance are made. Scheme demands can be estimated using appropriate basin simulation models, but this requires knowledge of scheme operation, cropping patterns, application efficiencies and so on.

Without easy access to such quantative information of land use and irrigation demands, one simple but subjective way to look for change in behaviour of dry season flows is to examine the time series of annual minima. If there is a tendency for annual minima to increase with time, then this should be apparent from an inspection of this time series. In order that trends over different types of catchment could be studied, the catchments were divided into four groups given in Table 4.6 below:

Catchment grouping

Group number	Description	Stations
1	Tributary - regulated	230102 370104 380103 380110 380112
2	Mekong - regulated	13101 13402 13901 14901
3	Mekong - natural	10501 11201 11901 11903 12001
4	Tributary - natural	All remaining stations

Table 4.6

For each station the 60 day duration annual minimum series was standardised by its mean giving a non-dimensional time series of ratios of annual minimum in each year to the mean. Series from each station could then be compared directly without being influenced by the size of catchment. Furthermore, the non-dimensionality enabled average annual minima time series to be derived for each of the four groups; these are shown in Figures 4.7(a-d).

Figure 4.7a, for stations in Group 1, clearly shows the increase in annual minima resulting from regulation. The start of major reservoir construction in the early 1960's is also evident.

Figure 4.7b, for stations in Group 2, shows a steady increase in annual minima since the late 1960's for Mekong stations affected by regulation. However, when compared with the long historic sequence available at these sites, the recent increase in annual minima due to regulation is of the same order as has occurred naturally in the past.

Grouped annual minima

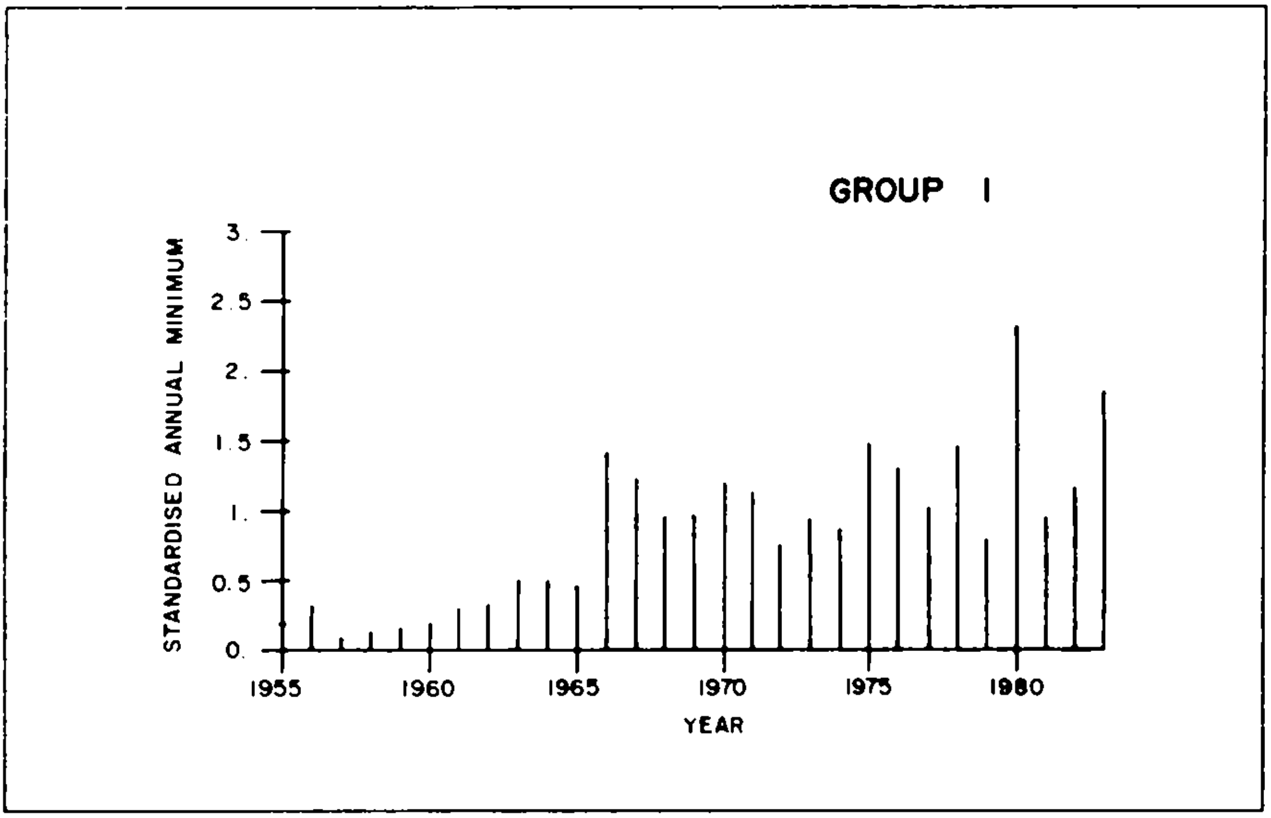

Figure 4.7a

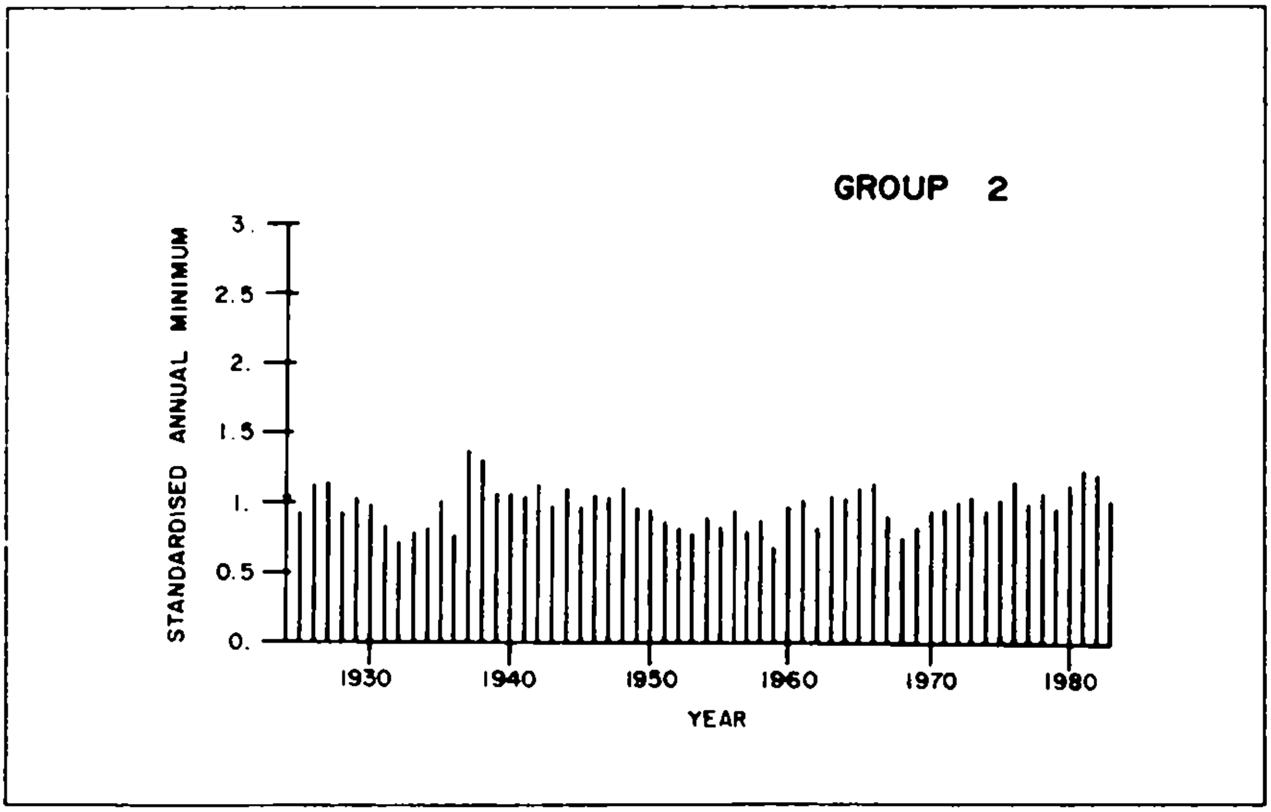

Figure 4.7b

Figure 4.7c, for stations in Group 3, and Figure 4.7d (Group 4), show no sustained change in annual minima on natural tributary and natural mainstream catchments.

Similar time series of standardised annual minima were produced for individual stations rather than groups of stations to investigate change on individual catchments. In general these plots indicated that stations within a group behaved very much as the group itself. The variation of annual minima with time for individual stations was, as might be expected, greater than for the group as a whole.

The main problem with detecting change due to land use and pumped irrigation is that the natural variation of annual minima from year to year is greater than the more subtle change in flow regime introduced by a gradual change in land use or pumped irrigation. However if some of the natural variation in annual minima from year to year could be explained by climatic factors then this would help in identifying changes due to land use or pumped irrigation.

Rainfall on the catchment during the preceding wet season was considered to be one possible factor which might affect the following dry season annual minimum. This hypothesis was tested on three different catchments:

(1) Station 320101, the Se Bang Fai at Se Bang Fai. This station is located in a relatively wet area in Laos (mean annual rainfall 1820 mm).

(2) Station 370111, the Nam Chi at Ban Tha Phra. This station is located in the relatively dry area of northeast Thailand (mean annual rainfall 1140 mm).

(3) The Mekong between station 11901, Vientiane, and station 13901, Pakse (mean annual rainfall 1680 mm). Here the annual minima was calculated as the Pakse annual minimum minus the Vientiane annual minimum.

The computer program RAINS, described in Section 2.4, was used to estimate monthly rainfall over these three catchments for the period of record of annual minima (starting in 1950 for the Vientiane-Pakse basin). In each case, although there was a reasonable correlation between seasonal rainfall and seasonal runoff, there were insignificant correlations between rainfall and annual minima. Various combinations of rainfall were tried; preceding year annual total, seasonal rainfall based on different months in the preceding wet season and rainfall during the current dry season. Unfortunately no significant and consistent correlation could be found between annual minima and any of the rainfall measures described. The conclusion drawn from this part of the study was that annual minima cannot be satisfactorily predicted from these rainfall measures.

Consequently it appears that changes in dry season flows due to land use and pumped irrigation schemes can only be detected from a long time series of annual minima and looking for a significant departure above the mean annual minimum. Although, as discussed above, the study of annual minima was able to identify the major changes due to regulation. There was insufficient evidence to detect changes due to land use or pumped irrigation, either on the four groups considered, or on stations individually. Nevertheless Section 4.6 below describes a simple procedure which may be used on any catchment to assist with the detection of change in dry season flow regime in the future.

Grouped annual minima

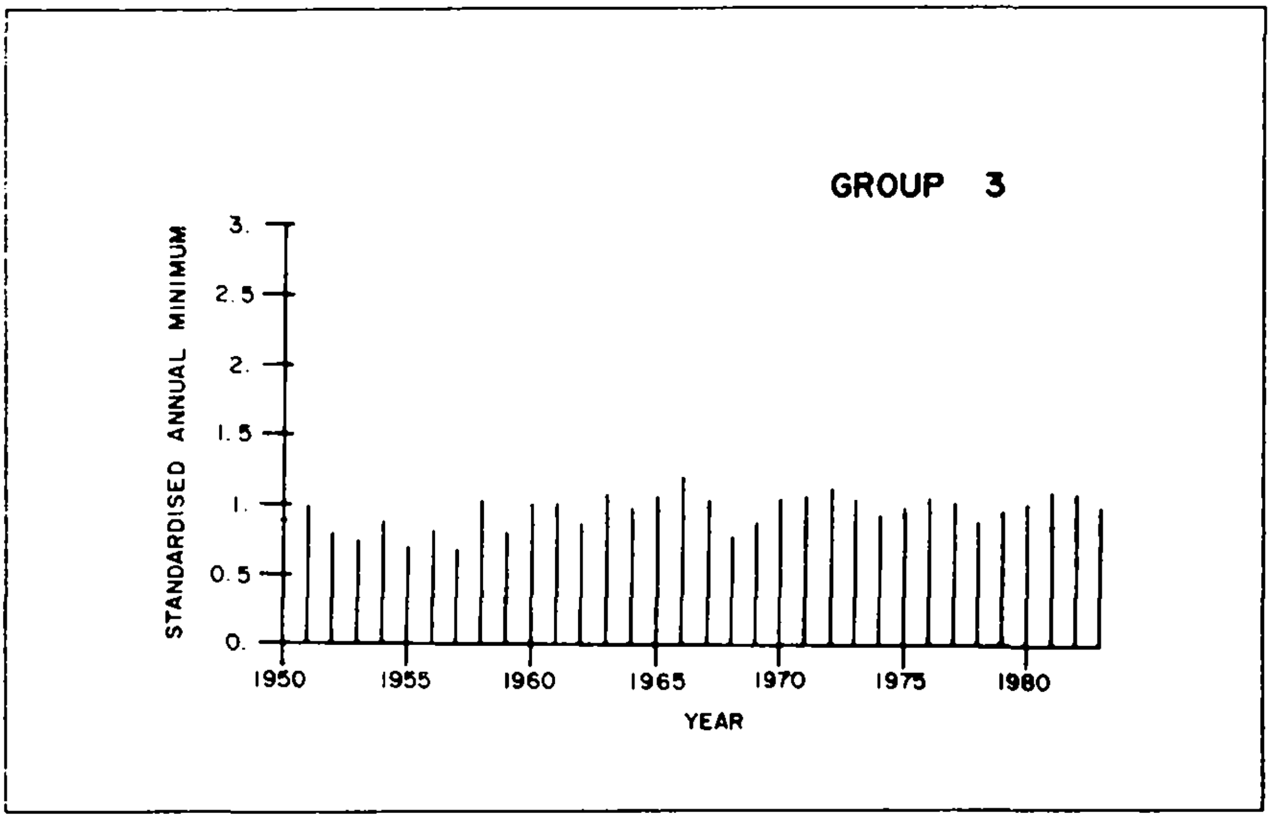

Figure 4.7c

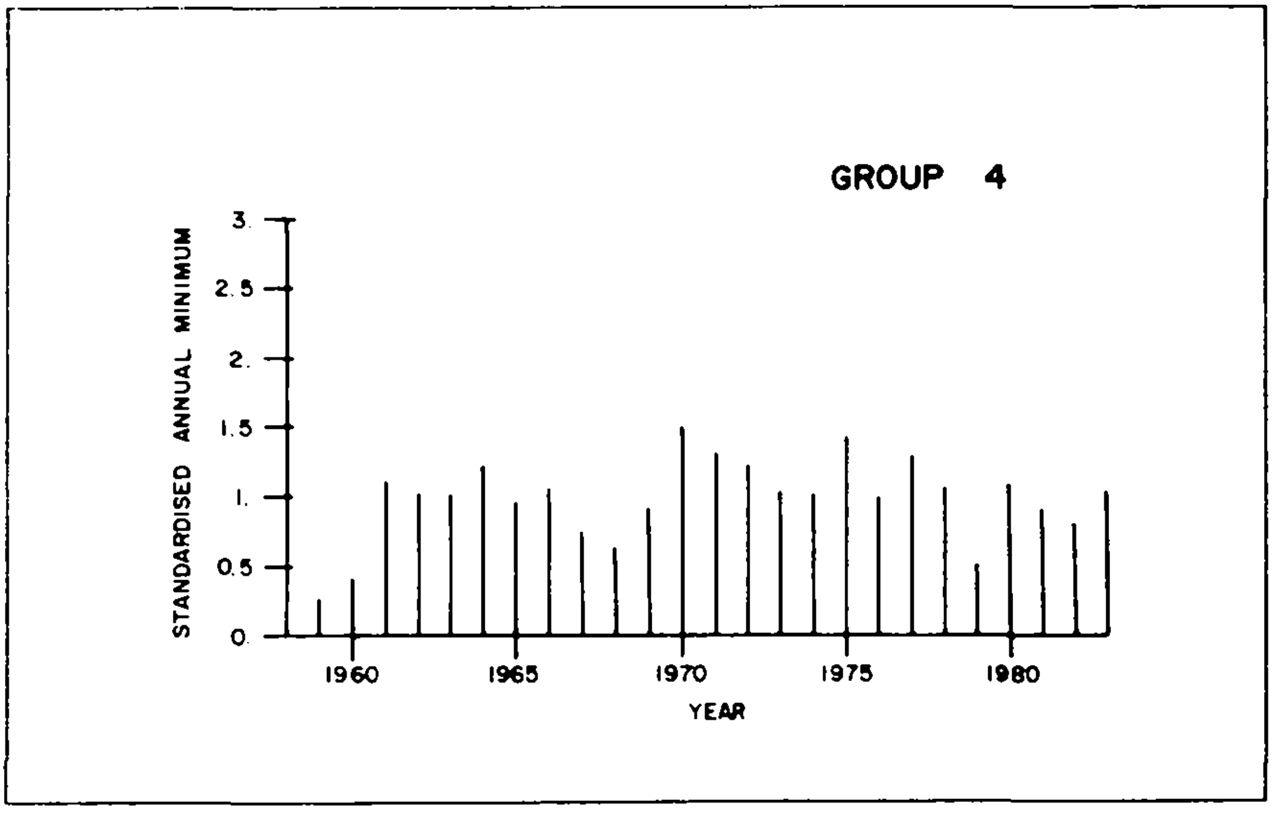

Figure 4.7d

4.6 Detecting future change.

Section 4.5 concluded that there has been a change in dry season flow regime on those catchments affected by major reservoirs upstream. To date there has been no apparent change due to climate in terms of annual rainfall and there is insufficient evidence at present to determine the effect of land use change and pumped irrigation on river flows.

This section describes a procedure which may be used in the future to assist with the recognition of change. This simple method is based upon the procedure described in Section 4.5.4, where the 60 day duration annual minimum time series is standardised by the mean. This standardised time series is then plotted and subjective judgement used to identify change. In this way catchments may be considered individually, grouped as in Table 4.6 or grouped in other ways such as those catchments which have experienced the same land use change.

Benchmark dry season flow statistics have been established for all stations considered in this study (Section 4.3). It is proposed that future change be measured against these. Table 4.7 gives the benchmark MAM(60) statistic for all catchments with sufficient data, using the new regulated value of MAM(60) where appropriate. Table 4.7 also gives the start year of the current flow regime and indicates whether it is still a natural catchment or whether it is regulated. For natural catchments the start year is the beginning of the hydrological record; in the case of catchments which are now regulated it is the year after the most recent major dam construction.

The procedure for investigation of change on any catchment is based on the 60 day duration annual minimum series and is as follows:

(1) Derive the 60 day annual minimum series in m^3s^{-1} from the start year given in Table 4.7 to the current year. The annual minima should be found in the water year starting on 1st September and running through to 31st August of the following year.

(2) Standardise this annual minimum series by dividing each minimum with the benchmark mean annual minimum given in Table 4.7.

(3) Plot this series of standardised annual minima and look for a trend.

(4) A trend may be more easily identified by plotting the cumulative departure from the mean annual minimum as a time series.

(5) Since standardised annual minima have been used, catchments may be grouped to look for a change over particular types of catchment, for example those experiencing similar changes in land use.

A computer program, CHANGE, has been written to carry out this analysis and plotting. CHANGE is described in Appendix A.

Benchmark MAM(60)'s and start year

Station Number	*Station name*	*Benchmark MAM(60)* $m^3 s^{-1}$	*Benchmark Year*	
10501	Mekong at Chiang Saen	818.	1960	N
11201	Mekong at Luang Prabang	1037.	1950	N
11901	Mekong at Vientiane	1174.	1913	N
11903	Mekong at Chiang Khan	1045.	1967	N
12001	Mekong at Nong Khai	1186.	1969	N
13101	Mekong at Nakhon Phanom	1577.	1979	R
13402	Mekong at Mukdahan	1576.	1979	R
13901	Mekong at Pakse	1963.	1979	R
14901	Mekong at Kratie	# 2470.	1979	R
40201	Nam Mae Kham - Ban Huai Yano Mai	1.43	1975	N
50103	Mae Kok at Dam Site	28.5	1968	N
50105	Mae Kok at Ban Tha Ton	20.9	1970	N
50201	Mae Fang at Ban Tha Mai Liam	4.11	1970	N
70103	Nam Mae Ing at Thoeng	2.63	1969	N
120101	Nam Khan at Ban Mixay (Ban Mout)	23.3	1961	N
140201	Nam Man at Dan Sai	0.41	1967	N
140301	Nam San at dam site	0.634	1966	N
190101	Huai Mong at Ban Na Ang(Ban Phu)	0.115	1957	N
230102	Nam Ngum at Tha Ngon	*	1979	R
320101	Se Bang Fai at Se Bang Fai	24.2	1961	N
340101	Huai Bang I at Ban Kham Soi	0.276	1964	N
350101	Se Bang Hieng at Ban Keng Done	31.6	1961	N
370104	Nam Chi at Yasothon	38.5	1969	R
370107	Nam Chi at Ban Khai	1.42	1968	N
370111	Nam Chi at Ban Tha Phra	1.82	1958	N
370204	Nam Pong at Ban Pha Nok Khao E29	8.40	1970	N
370502	Huai Phaniang at Ban Wang Mun	*	1978	N
371101	Huai Rai at Ban Non Kiang	0.697	1975	N
371203	Huai Pa Thao at Ban Tao Ton	0.343	1976	N
371509	Nam Yang at Ban Na Thom	*	1979	N
380103	Nam Mun at Ubon	77.8	1971	R
380110	Nam Mun at Rasi Salai	3.95	1971	R
380112	Nam Mun at Satuk	1.47	1971	R
380404	Lam Chae at Ban Mak Krat	*	1977	N
380602	Lam Phang Chu at Ban Hua Saphan	*	1979	N
380705	Lam Chi at Ban Lum Din	*	1979	N
380903	Lam Sieo Yai - Ban Ku Phra Ko Na	*	1979	N
381001	Huai Thap Than-Ban Huai Thap Tan	*	1972	N
381206	Huai Khayung at Ban Huai Khayung	*	1979	N
381401	Lam Se Bok at Ban Tha Bo Baeng	*	1979	N
381501	Lam Dom Yai at Det Udom	0.650	1963	N
430101	Se Kong at Ban Khmuon	*	1961	N
550101	Stung Sangker at Treng	*	1963	N
610101	Stung Sen at Kompong Thom	*	1961	N

R = Currently regulated   N = Currently natural
# = estimated using model (Section 5)
* = insufficient record to define MAM(60) at present

Table 4.7

Table 4.8 shows this annual minima analysis for Chiang Saen and Figure 4.8 shows the results plotted as recommended. Since the annual minima are standardised, the annual minima will plot with a mean value of 1 up to the most recent year available to this study. Similarly the cumulative departure from the mean will return to zero at this date (in Table 4.8 the cumulative departure from the mean does not return exactly to zero because the standardising MAM(60) has been rounded to three figures - 818 m^3s^{-1}). In the future, when each new year of data becomes available, this plot and similar plots for other stations, should be updated. The plot of cumulative departure from the mean may be interpreted as follows:

(1) Horizontal or near horizontal sections of the graph indicated no change.

(2) Sections of the plot with a descending slope indicate a trend showing a reduction in annual minima with time.

(3) Sections of the plot with an ascending slope indicate a trend showing an increase in annual minima with time.

(4) Future trends should only be inferred after studying the historic section of the plot to determine the natural variability of the river.

Plots similar to Figure 4.8 were produced for all stations with sufficient data listed in Table 4.7. For many stations there appears to be no positive increase or decrease in dry season flows with time. For the remaining stations there could be a trend, but the length of record is insufficient to indicate whether the trend is real or just part of the natural variability of river flow. These plots have been left with the Mekong Secretariat and it is recommended that they be updated and reviewed for change on an annual basis.

If Table 4.8 and Figure 4.8 are updated as recommended, this should provide the first indication of a change in dry season flow regime on the Mekong as a result of the Manwan hydropower project in the People's Republic of China (Section 1.).

An interesting test of this method was to apply it retrospectively to stations which have been identified as undergoing a change in dry season flow regime. Section 4.5.2 identified changes in rivers affected by major irrigation schemes upstream and changes in the Mekong downstream of the Nam Ngum confluence.

Figure 4.9 shows the method applied to data from the Nam Chi at Yasothon which was regulated in 1965. Annual minima have been standardised by the natural MAM(60) derived in the period before regulation. Note the large jump in 60 day annual minimum flows after 1965 and the sudden rise in cumulative departure from the mean. The abrupt change in dry season flow regime is clearly illustrated.

Similarly Figure 4.10 shows the method applied to the Mekong at Pakse with the annual minima standardised by the natural MAM(60) derived from the period before regulation on the tributaries in 1965. Here the increase in 60 day annual minima after 1965 is not so obvious as for the Chi at Yasothon, but the plot of cumulative departure from the mean demonstrates this trend quite clearly. The regulation at Nam Ngum is mainly responsible for this change. Note however that there was a substantial increase in departure from the mean in the 1940's; it is only with the 20 years of data now available from 1965 that the recent increase in dry season flows has been identified as a real change at Pakse and not just part of the natural variability of the river.

Annual minimum analysis - Chiang Saen

Station number : 10501
Station name : Mekong at Chiang Saen
Mean annual minimum : 818 $m^3 s^{-1}$

Year	Annual minimum (cumecs)	Annual minimum (standardised)	Cumulative departure from the mean
1960	774.000	0.946	-0.054
1961	748.017	0.914	-0.139
1962	644.017	0.787	-0.352
1963	817.817	1.000	-0.352
1964	723.200	0.884	-0.468
1965	825.450	1.009	-0.459
1966	936.700	1.145	-0.314
1967	936.333	1.145	-0.169
1968	640.983	0.784	-0.386
1969	740.000	0.905	-0.481
1970	919.167	1.124	-0.357
1971	901.367	1.102	-0.255
1972	962.633	1.177	-0.079
1973	855.317	1.046	-0.033
1974	815.917	0.997	-0.036
1975	816.783	0.999	-0.037
1976	854.000	1.044	0.007
1977	804.467	0.983	-0.010
1978	706.433	0.864	-0.146
1979	845.833	1.034	-0.112
1980	832.217	1.017	-0.095
1981	852.517	1.042	-0.052
1982	816.933	0.999	-0.054
1983	867.067	1.060	0.006
1984	772.217	0.944	-0.050
1985	867.250	1.060	0.011
1986			
1987			
1988			
1989			
1990			

Table 4.8

Standardised annual minima - Mekong at Chiang Saen

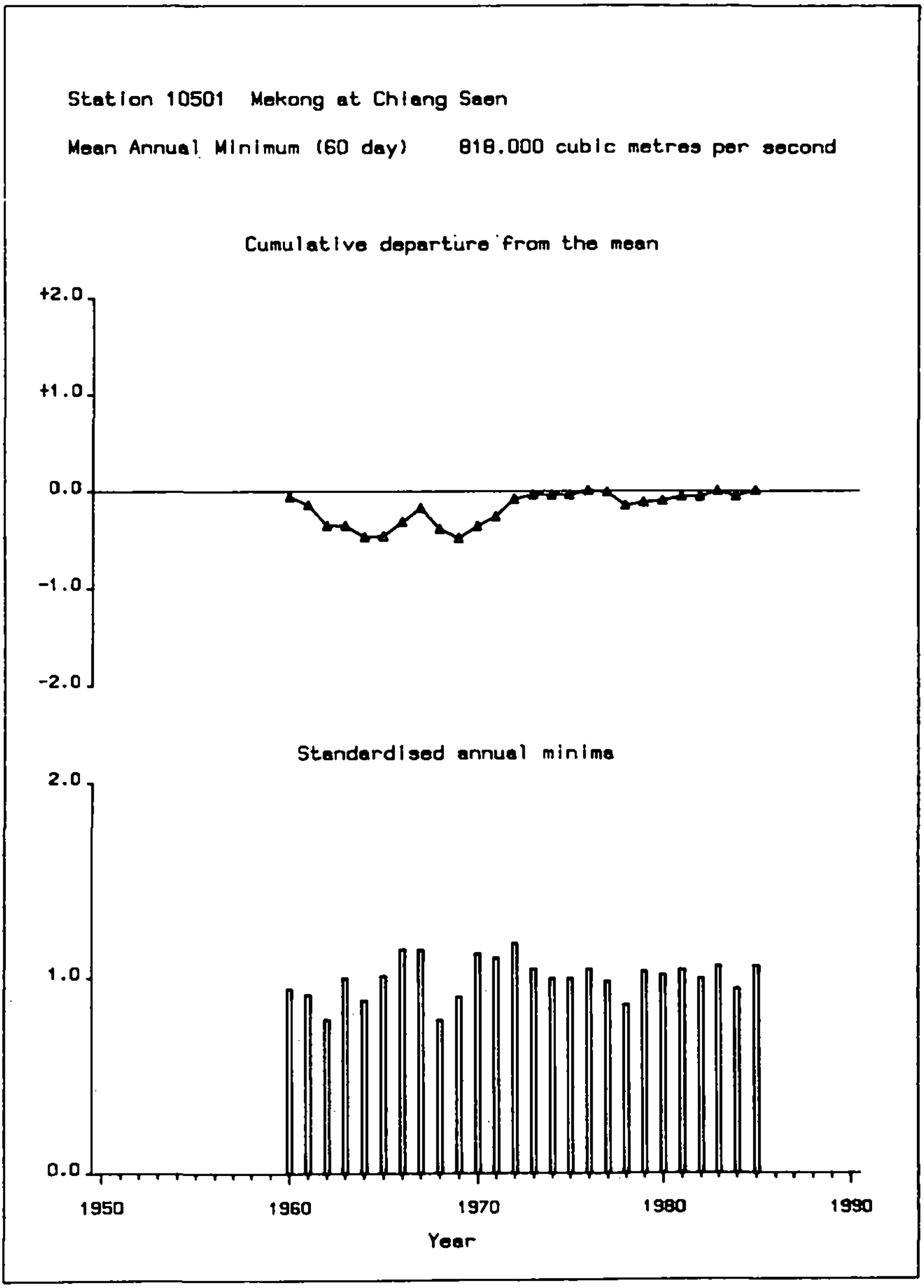

Figure 4.8

Standardised annual minima - Nam Chi at Yasothon

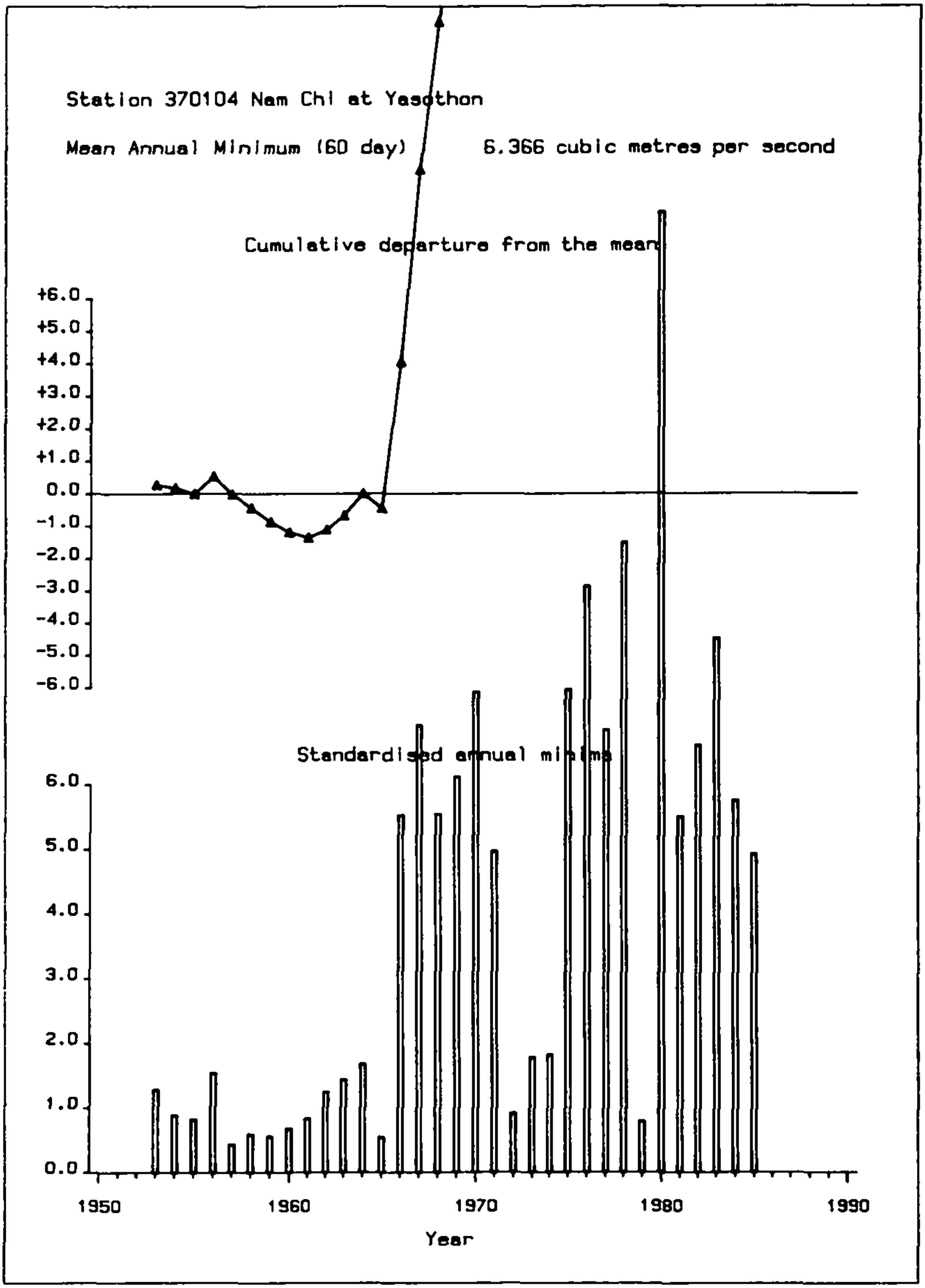

Figure 4.9

Standardised annual minima - Mekong at Pakse

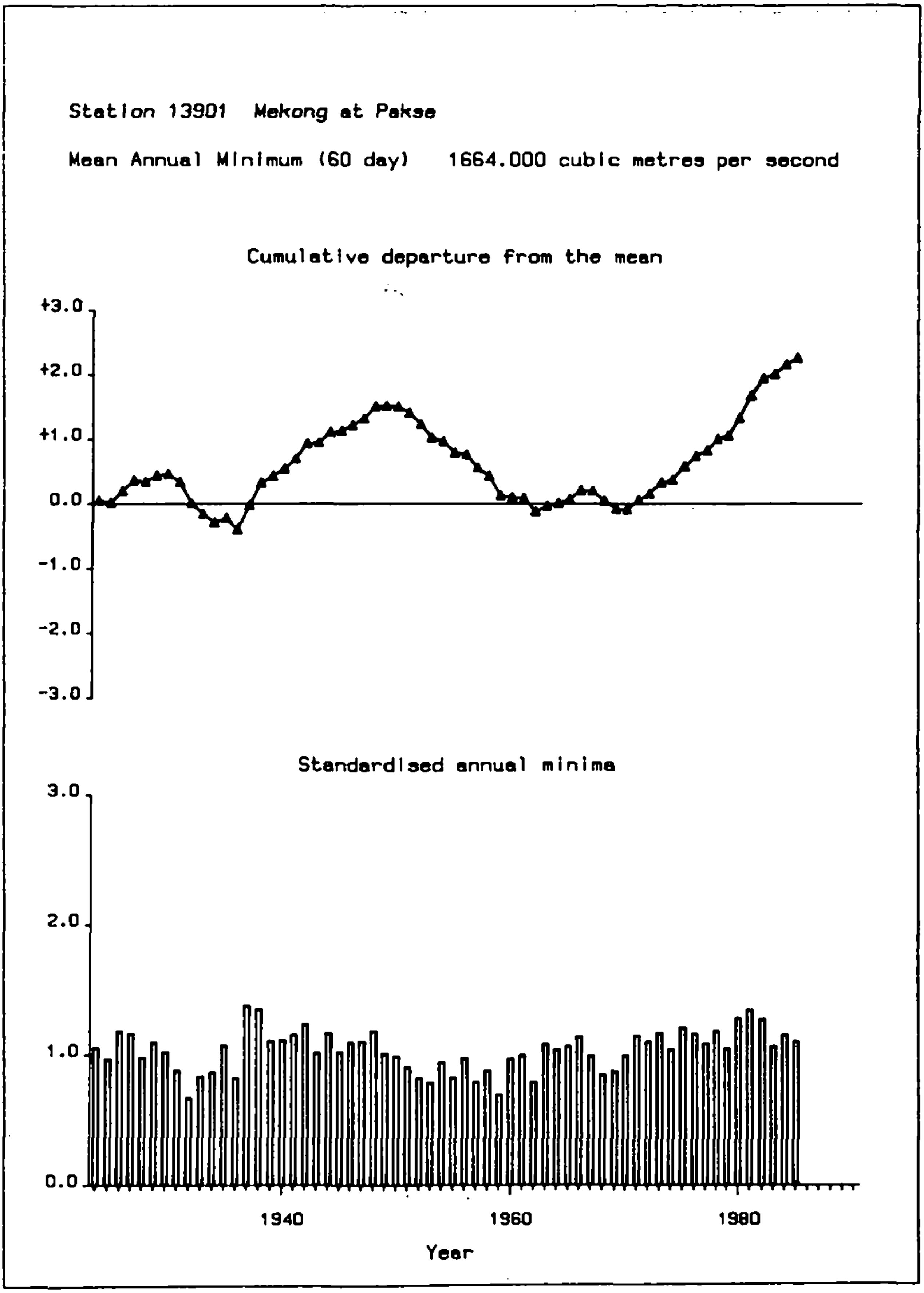

Figure 4.10

Pakse to delta model - location of stations

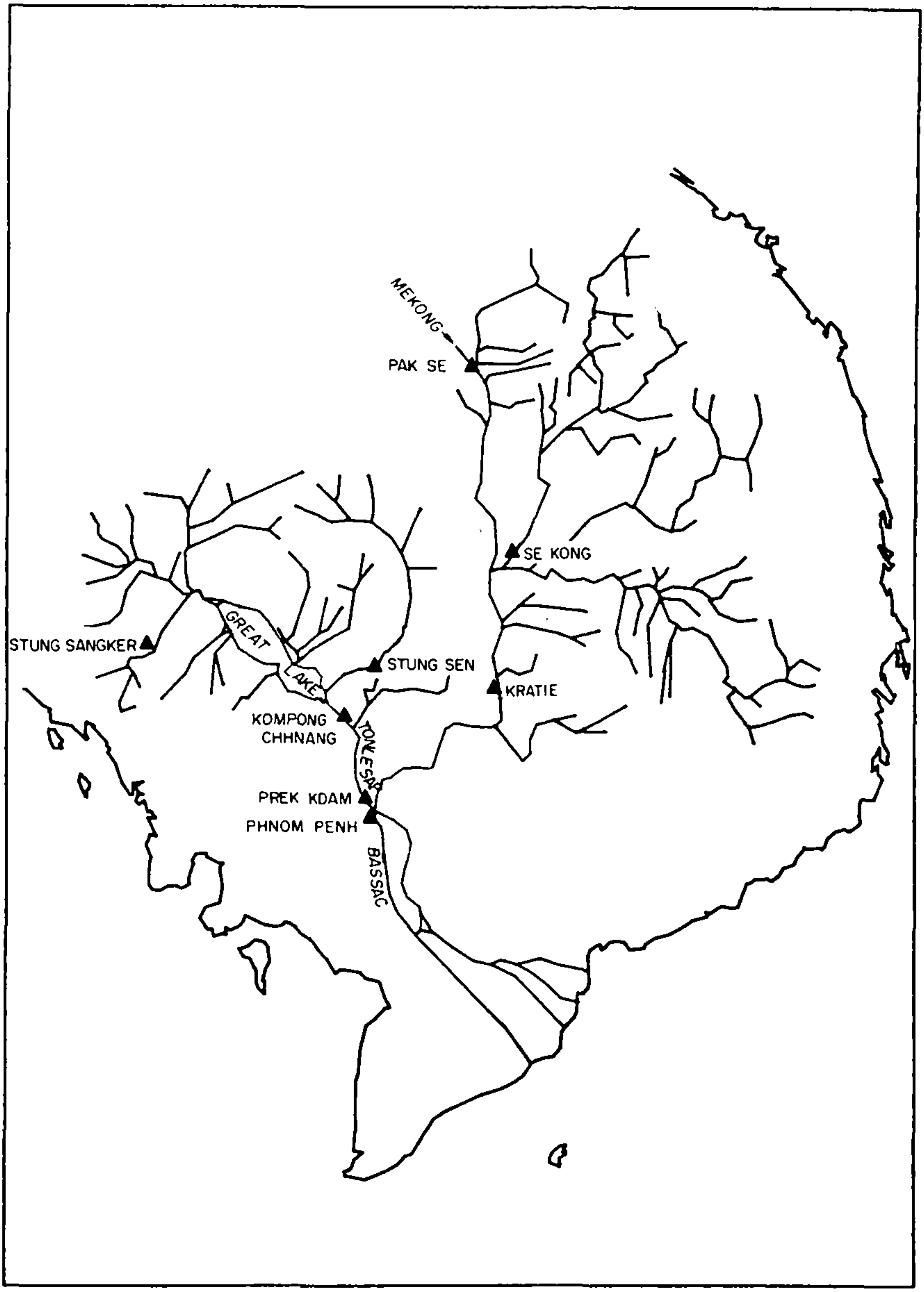

Figure 5.1

5. INFLOWS TO THE DELTA

5.1 Background

The inflows to the Mekong delta are made up of two components; flows from the Mekong upstream of Phnom Penh and flows from the catchment of the Great Lake via the Tonle Sap (Figure 5.1). Just downstream of Phnom Penh the river splits into the Mekong and the Bassac. The hydraulics of the confluence of these watercourses at Quatre Bras are extremely complicated as a result of tidal influences, the low elevation and slopes of the rivers and sedimentation in the river channels.

The Great Lake demonstrates unique behaviour; when the Mekong rises, the flow in the Tonle Sap changes direction and Mekong water flows into the lake. Towards the end of the wet season as the recession in the Mekong proceedes, the flow in the Tonle Sap again changes direction and water from the lake contributes to the flow into the delta.

A full understanding of these complex phenomena is hindered by lack of data, particularly in recent years. However given the importance of quantifying the flows into the delta a preliminary desk study into the behaviour of the Great Lake was carried out using existing information. The objective of this work was to identify simple models that could be used to generate a sequence of inflows to the delta. This synthetic record would then be subject to the dry season flow analysis described in Section 4. Full details of the models are given in Appendix A; a short description of the data available, the models derived and the results of the simulations are given here.

5.2 Available data

5.2.1 Rainfall

The availability of monthly rainfall data is given in Section 2.4. Time series of monthly data for the period 1950-1986 can be derived for any catchment or sub-catchment in the basin.

5.2.2 Streamflow

A summary of the availability of daily streamflow records on HMDB and HYDATA for the Mekong downstream of Pakse is given in Table 5.1. The intermediate catchment between the gauges at Pakse and Kratie is 101,00 km^2, and although part of this catchment is gauged on the Se Kong at Ban Khmuon, no records are available for the period since 1970.

Daily flow stations for Pakse - delta model

Station Number	Station name	Basin Area km^2	Start Year	End Year	Yrs. Data
13901	Mekong at Pakse	545000	1923	1987	65
14901	Mekong at Kratie	646000	1924	1971	48
20102	Tonle Sap at Prek Kdam	84400	1960	1973	14
430101	Se Kong at Ban Khmuon	29600	1961	1970	10
550101	Stung Sangker at Treng	2135	1963	1973	11
610101	Stung Sen at Kompong Thom	14000	1961	1970	10

Table 5.1

Daily records for only two of the tributary catchments feeding the Great Lake are available; these cover about 20% of the contributing catchment area and include the period from the early 1960's up to 1973. Records for the flow in the Tonle Sap are also available for most of this period.

Flows in the Tonle Sap are based on stage readings taken at Prek Kdam; these had been converted to discharge using a set of rating equations that depend on the difference in water level between the Tonle Sap and the Mekong at Phnom Penh. Continuous flow records are available for most of the 1960's.

5.2.3 Lake storage

Records of daily lake water level are available on HMDB for the period 1924 up to 1969; data for some short periods in the early 1980's have recently become available. The relationship between lake water level and storage and surface area has been studied in detail (SOGREAH, 1966). The published curves refer to lake level measured at Kompong Luong du Lac, however the daily water level records available on HMDB and HYDATA are for a gauge at Kompong Chhnang. Unfortunately no long-term water level records for Kompong Luong du Lac could be located.

In order to derive a long series of lake storage, a simple relationship between the water level at the two sites was derived using data from Carbonnel and Guiscafre (1964). Identified shifts in gauge datum were taken into account, and a continuous record of daily lake storage was derived for the period 1924 up to 1969. The recent water level data from the 1980's are not continuous, and the level of the gauge datum is in doubt; for this reason these most recent data were not used in the analysis.

5.3 Kratie flow model

The catchment of the Mekong at Kratie makes up about 85% of the combined catchment area of the Mekong and Tonle Sap just downstream of Phnom Penh. Flows records at Kratie are thus particularly important for the analysis of dry season inflows to the delta.

Reliable flows records for Kratie stopped at the end of 1969, so it was necessary to reconstitute the flows since then. A simple time series model was derived to explain Kratie flows in terms of the flow upstream at Pakse. A different relationship for the dry and the wet seasons was derived, given by the following equations:

Wet season -

$$Qk_t = 1.375 \times Qp_{t-1} \qquad m^3s^{-1}$$

Dry season -

$$Qk_t = 1.256 \times Qp_{t-1} \qquad m^3s^{-1}$$

where,

Qk_t is the flow at Kratie on day t,
Qp_{t-1} is the flow at Pakse on day t-1,

This very simple model was fitted for the period 1961 to 1964, and then tested on data for 1965 to 1968. Plots of observed against predicted flows are given in Figure 5.2 and 5.3. The model was then used to extend the daily flow record at Kratie for the period since 1969.

5.4 Great Lake model

The purpose of this model was to estimate a long-term time series of daily flows in the Tonle Sap; these could then be added to the corresponding flows at Kratie to give an indication of the inflows to the delta. It was decided to derive a simple model using multiple regression analysis as continuous records of lake storage and Kratie flows were available from 1924. Insufficient rainfall and tributary flow data were available to make a water balance approach possible.

It was found that the flow in the Tonle Sap (measured in either direction, with positive values flowing away from the lake) could be explained simply in terms of the flow at Kratie and the storage in the lake. A slightly better fit was achieved by dividing the year up into two parts; the start of one part was chosen when the recession at Kratie was well under way, and the other when the flow in the Tonle Sap changes direction in the early part of the year.

The model has the form

$$Qts = a + (b \times Qk) + (c \times Sgl) \qquad \text{million } m^3$$

where,

Qts is the flow in the Tonle Sap (+ve towards the delta)
Qk is the flow at Kratie
Sgl is the storage in the Great Lake
a, b and c are parameters found by regression with different values for the two parts of the year.

Model calibration

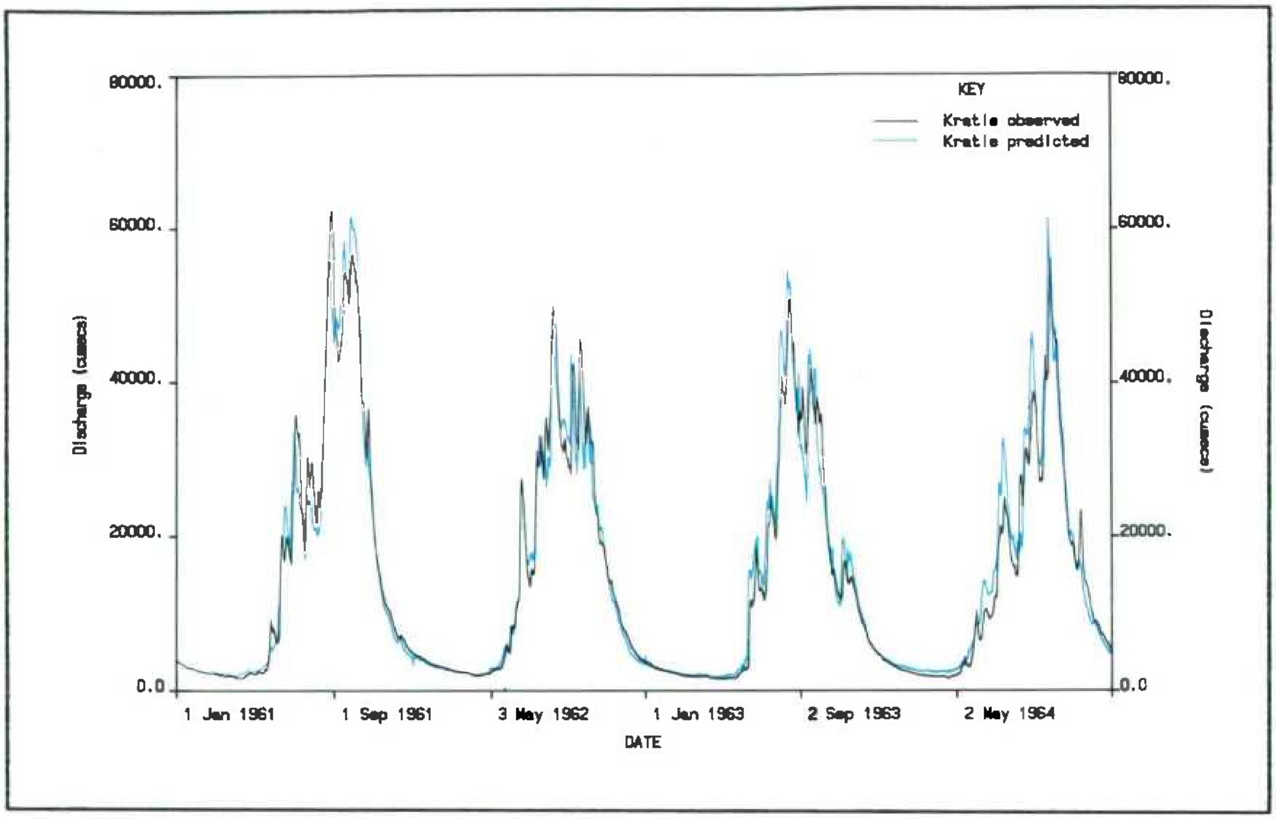

Figure 5.2

Model testing

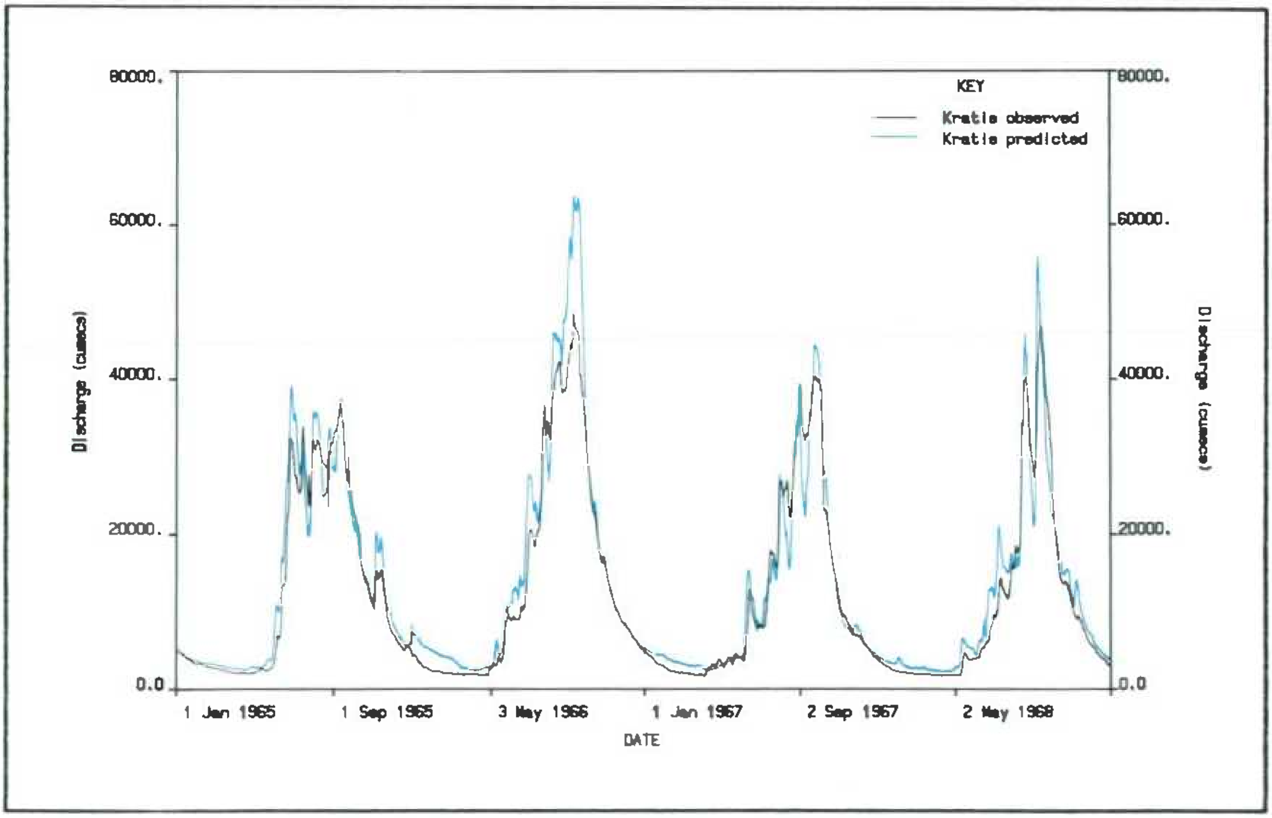

Figure 5.3

The regression analysis gave R^2 values of 78% and 86% respectively for each part of the data set.

A plot of the observed and predicted flows is given in Figure 5.4. The plot shows that the general pattern and magnitude of flows in the Tonle Sap can be reproduced by this relatively simple model.

Flows into the delta at an imaginary gauging station (number 999000 on HYDATA) were then estimated by adding the Kratie flow and the Tonle Sap flow together. This new time series, estimated for the period from 1924 to 1960 and observed for the period 1961 up to 1969, were then transferred to HYDATA for analysis.

Tonle Sap model calibration

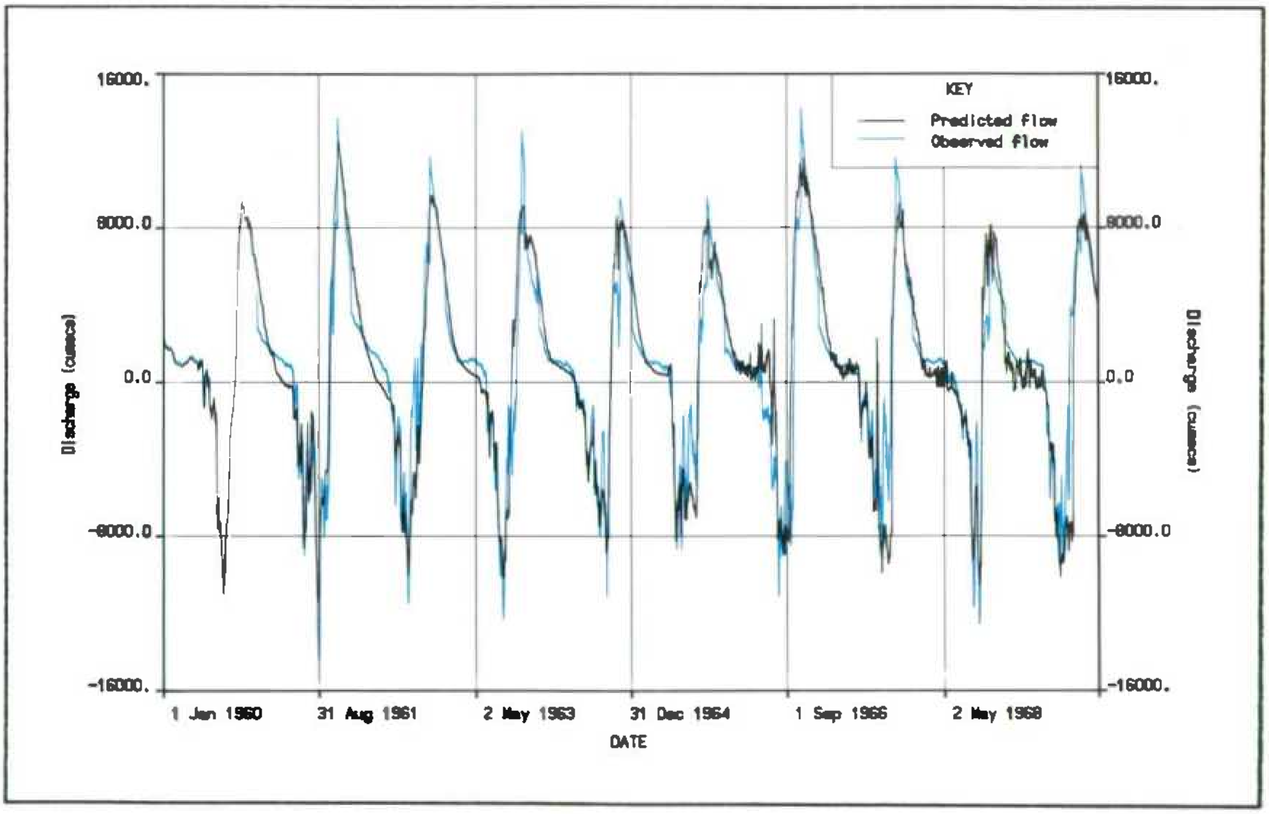

Figure 5.4

5.5 Dry season flow characteristics

The reconstituted flow records at Kratie and station 999000 estimated by the models described above were then analysed according to the procedures given in Section 4. By extending the Kratie record up to 1986 it was possible to derive dry season flow characteristics for the period of regulation. Because the lake storage records do not extend into the period of regulation, only natural flow characteristics for the delta flows have been derived. The results of the analysis are given in Table 5.2; the results for the Mekong at Pakse are included for comparison. As to be expected, the percentage changes in flow indices for Kratie between the natural and regulated periods are very similar to those observed at Pakse.

Comparison of flow indices

	Station				
	14901			13901	999000
Flow index	Natural	Regulated	Change	Change	Natural
MAR	690 mm	666 mm	-4%	-8%	648 mm
MAM(10)	1846	2240	+21%	+18%	2702
MAM(30)	1920	2316	+21%	+17%	2783
MAM(60)	2029	2470	+22%	+18%	2902
MAM(120)	2399	2820	+18%	+15%	3402
MAM(180)	3194	3590	+12%	+12%	4871
$AM(60)_2$	2039	2508	+23%	+18%	2951
$AM(60)_5$	1790	2317	+29%	+26%	2679
$AM(60)_{10}$	1666	2210	+33%	+31%	2545
$AM(60)_{25}$	1528	2110	+38%	+38%	2409
Q95	1837	2286	+25%	+23%	2717
Q90	2027	2509	+24%	+17%	2949
Q75	2742	3225	+18%	+10%	3821
Q50	7018	7387	+5%	-8%	10656
Q25	23207	21356	-8%	-13%	24445
Q10	37256	34965	-6%	-8%	33738
Q5	44001	40211	-8%	-10%	38684

Units $m^3 s^{-1}$ except where stated differently

Station Number	Station name
13901	Mekong at Pakse
14901	Mekong at Kratie (in regulated period flows generated by model)
999000	Delta inflows in natural period (from model)

Table 5.2

The annual minima flow indices for station 999000 show an increase over those at Kratie due to the runoff from the intermediate catchment area of over 85,000 km^2, and the overall regulating effect of the Great Lake. The consequence of part of the wet season flows of the Mekong being stored in the lake is illustrated by the reduction of the low percentile flows (Q25, Q10 and Q5) taken from the flow duration curve.

A plot of the annual minima for Kratie standardised by the natural MAM(60) for the period before regulation is given as Figure 5.5. Like Figure 4.10 (Mekong at Pakse) this plot also shows the persistent effects of upstream regulation for the period since 1965

The correlation between MAM(60) at Kratie and MAM(60) for the delta inflows is 0.67. The dry season flows into the delta are therefore only partly dependent on the dry season flows at Kratie. The Great Lake storage is therefore also an important factor in affecting the dry season flows. Although it has been demonstrated that since 1965 the Kratie MAM(60) have risen due to upstream regulation on the tributaries, reliable information on the Great Lake level, and hence storage, are not available since 1969. It therefore not possible to say for certain whether the inflows to the delta have increased since 1965 in line with the Mekong since there is no information on the other component, lake storage.

It should be remembered that the increase in dry season flows in the Mekong has been at the expense of a reduction in average flow and flood flows. Since the flood flows are an important component of the Great Lake recharge, it is possible that the Great Lake is no longer filling to the same level. If this were the case, the contribution from the Great Lake to dry season flows to the delta would be reduced. As soon as information becomes available from Kampuchea, it is important that this analysis is updated.

5.6 Discussion

The analysis described above has illustrated that it is possible to model the behaviour of the Great Lake and the flow in the Tonle Sap using simple statistical models, without having to model the physical processes in detail. However because of the limitations of the observed data used in this part of the analysis and the extensive use of generated data, the results presented should only be taken as indicative. Hydrological measurements to validate the assumptions made for this analysis should be restarted as soon as is realistically feasible.

Standardised annual minima - Mekong at Kratie

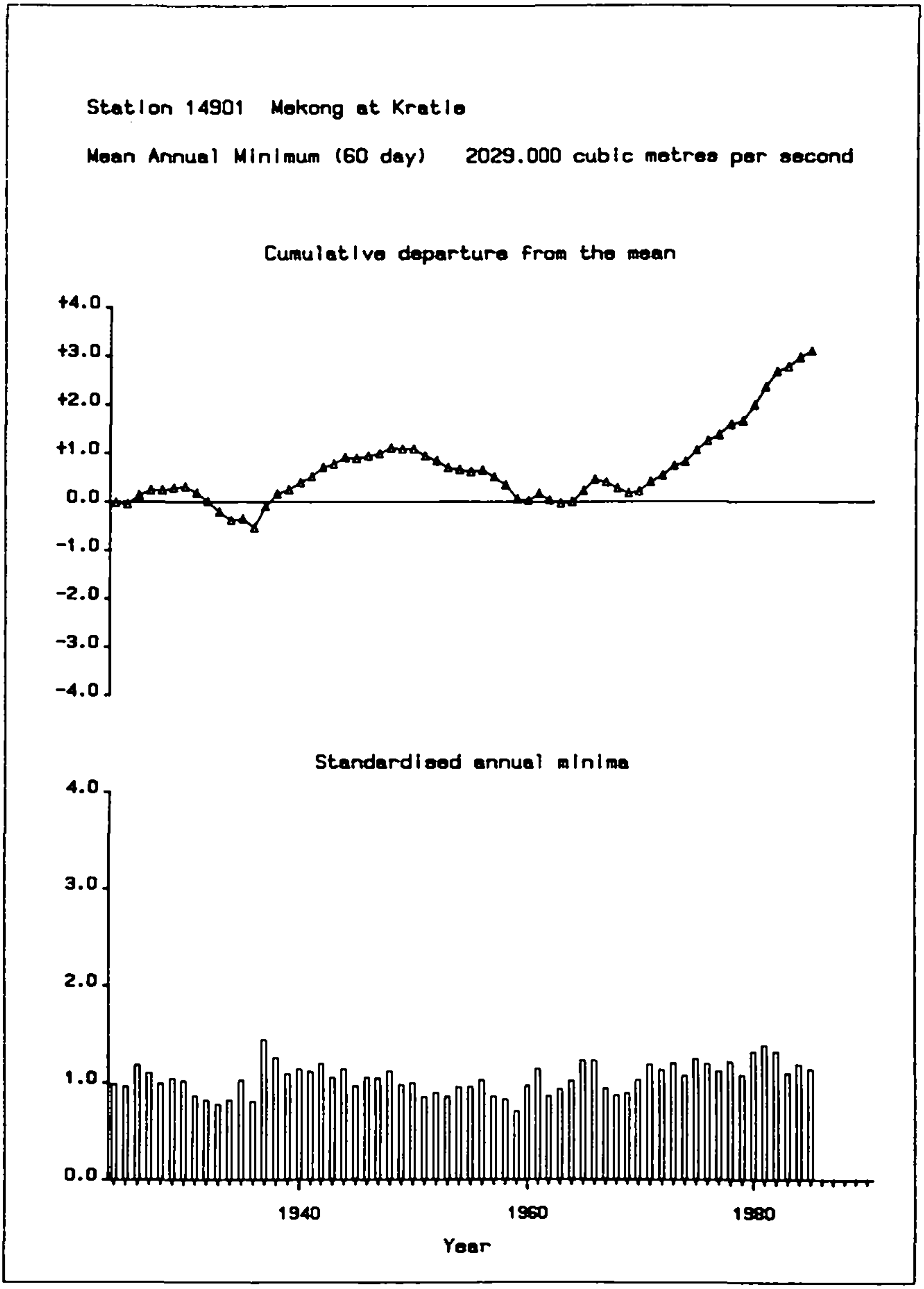

Figure 5.5

6. CONCLUSIONS AND RECOMMENDATIONS

Suitable dry season flow indices have been identified for use on the Lower Mekong Basin and derived for 44 mainstream and tributary catchments where sufficient data exist. These indices may be used as a benchmark against which any future changes in flow regime can be measured.

This study has successfully related these indices to the catchment area, catchment annual average rainfall and soil type. These preliminary relationships may be used on sites with no river gauging station to obtain an initial estimate of the flow indices.

A simple step by step approach has been provided as a guide for selection of the most appropriate dry season flow index for a given application.

Historic changes in the flow regime of the tributaries has been identified downstream of major reservoirs. Changes in the dry season flow regime of the mainstream has been identified at all stations downstream of the Nam Ngum confluence. However in proportion to total flow, the changes are more significant on the tributaries. In both cases there has been an increase in dry season flows. The increase in the mainstream flows can be attributed to the regulation on the tributaries and in particular to the turbine releases from the Nam Ngum reservoir during the dry season.

The preliminary investigation into climatic change since 1950, in terms of total annual rainfall, showed that there has been no significant change.

It has not been possible to attribute changes in the dry season flow regime to changes in land use and increases in irrigation demand. Before changes due to these factors can be identified several years more data at all sites will be required.

Flows in the delta have been estimated using simple time-series and regression models based on the flow at Kratie and storage in the Great Lake. The dry season flow indices calculated from this reconstituted flow sequence are consistent with those measured on the Mekong at Pakse and Kratie during the period before regulation on the tributaries. The flows observed at these mainstream gauging stations when combined with Great Lake storage can thus give an indication of the flow conditions into the delta. Analysis of the series of mean annual minima for Kratie and the delta inflows has indicated the important role of the Great Lake in maintaining dry season flows into the delta.

A simple method for detecting changes in the dry season flow regime in the future has been developed and tested on known changes on the tributaries and the mainstream. One of the first changes likely to be discovered in the future by this method will be the effect of hydro-electric schemes on the Upper Mekong (Lancang) in the People's Republic of China.

In addition to this report, the Mekong Secretariat has been provided with a software package (HYDATA) capable of performing not only many of the techniques of analysis described in this report, but more besides. Staff of the Mekong Secretariat have been given training in the use of HYDATA. Any of the member countries should be able to use the facilities of HYDATA to study additional stations since the package is an IBM PC/XT or PC/AT compatible.

In addition to HYDATA a computer program to handle monthly and annual rainfall data over the whole Lower Mekong Basin has been developed (RAINS). The applications of this program go beyond the many uses of rainfall data used in this study and should find uses on other projects in the Secretariat in the future. RAINS also holds information about hydrological properties of soils throughout the basin on a 40km x 40km grid.

A comprehensive review of the river gaugings and rating equations at ten important sites on the Lower Mekong has shown that a continued programme of river gauging is necessary to maintain data quality. The accuracy of the flow data at these sites has been found in general to be of good quality. The data from Pakse in Laos have been shown to be excellent.

In addition to revised rating equations in 1987, long term average rating equations have been produced for each of the ten mainstream sites. These equations, intended for use when no gaugings are being undertaken, should provide a less biased estimate of flow than using the most recently derived rating equation.

The main recommendations of this report are that:

(1) The procedure for detecting change in dry season flows should be used every year. In particular the procedure should quickly identify any changes resulting from the completion of the Manwan dam in the People's Republic of China.

(2) The facilities provided in the software packages HYDATA and RAINS be exploited to the full to enable a greater understanding of the hydrological data which have been collected over the years.

(3) The detailed recommendations concerning river gaugings and rating equations given in Section 3 and Appendix C are adopted. In particular the river gauging programme should be reviewed, so that priorities for future gaugings can be set. The available resources could then be directed to those stations where improvements to the rating curves are needed. Those stations with accurate and stable ratings would require less intensive gauging.

(4) Every opportunity should be taken to ensure that routine hydrological measurements at Kratie, the Tonle Sap and the Great Lake can be restarted in the near future.

(5) The remaining work programme for the overall Phase III project (of which the current study is only part) is completed. In particular simulation techniques based on either existing or new river basin models (as appropriate) should be used to study the effect of planned developments on the downstream flow regime.

(6) The Water Balance Study should continue along the lines of the future work programme set out below.

The current study has also identified certain areas of work for subsequent investigations under the Water Balance Study which will be of important practical benefit to the Mekong Secretariat. These are:

(1) Development of a flood design manual for the Lower Mekong Basin. This study would again make use of the flow data from many sites throughout the basin. The design manual produced would provide engineers and hydrologists with a consistent tool for flood estimation for flood protection

works, dam construction, urban and agricultural development, bridge and culvert design and spillway design.

(2) To improve on the preliminary dry season flow estimation procedure at ungauged sites presented in Appendix B, by reducing the grid size, including more stations and catchment characteristics. This would draw on the results of the present study and also make use of the catchment characteristic data necessary for the flood study ((1) above). Both studies would make use of the land use database the Mekong Secretariat is compiling on the ARC-INFO computer system.

(3) To develop computer aided procedures for fitting rating equations affected by backwater and small scale tidal influences. Such procedures would be of great benefit to the Secretariat and member countries where many gauging stations have ratings which are a function of both the water level at the measuring site and another site further downstream.

(4) Further work should be carried out on the development of the Pakse to delta model. In particular any more recent data from Kampuchea on flows in the Mekong at Kratie and the level of the Great Lake should be studied to obtain an updated inflow sequence to the delta. This updated inflow sequence should then be analysed using the methods described in this report so that any changes in flow regime into the delta may be identified.

(5) The work on estimation of areal rainfall from point rainfall undertaken in this report should be expanded using data from more raingauges and a finer grid resolution. This would have many applications including the proposed flood and low flow studies and hydrological models. In addition a frequency analysis of rainfall of various durations should be carried out for basin planning purposes. The relationships obtained here would be of direct benefit in flood estimation procedures.

(6) To investigate the feasibility of using remote sensing for the estimation of water level. This technique, using data from radar altimeters on board a satellite, could prove useful in obtaining water level elevation of the Great Lake and possibly the Mekong itself.

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