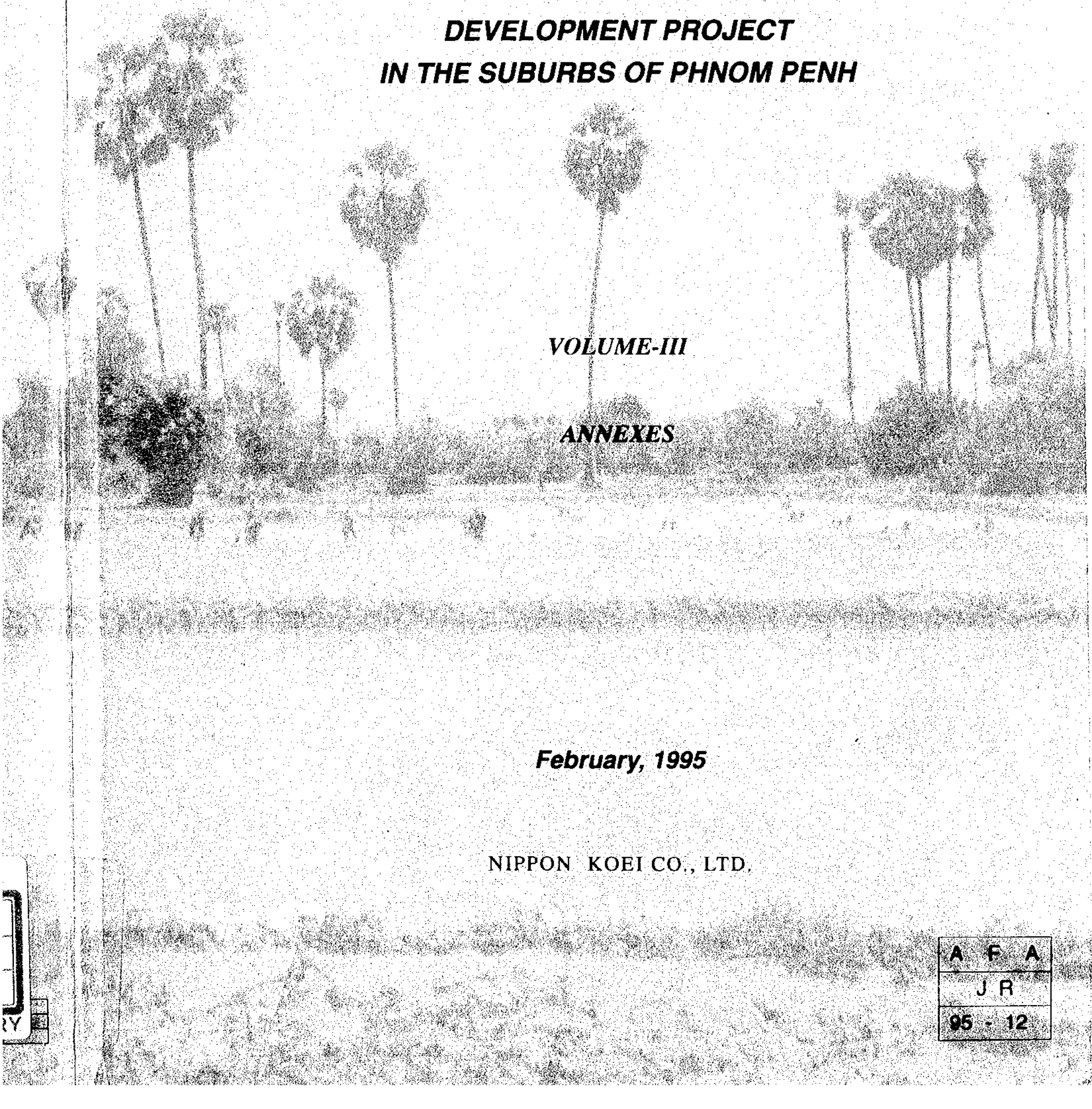
THE KINGDOM OF CAMBODIA
MINISTRY OF AGRICULTURE,
FORESTRY AND FISHERIES

JAPAN INTERNATIONAL
COOPERATION AGENCY
(JICA)

MASTER PLAN STUDY ON THE INTEGRATED AGRICULTURAL AND RURAL DEVELOPMENT PROJECT IN THE SUBURBS OF PHNOM PENH



VOLUME-III

ANNEXES

February, 1995

NIPPON KOEI CO., LTD.

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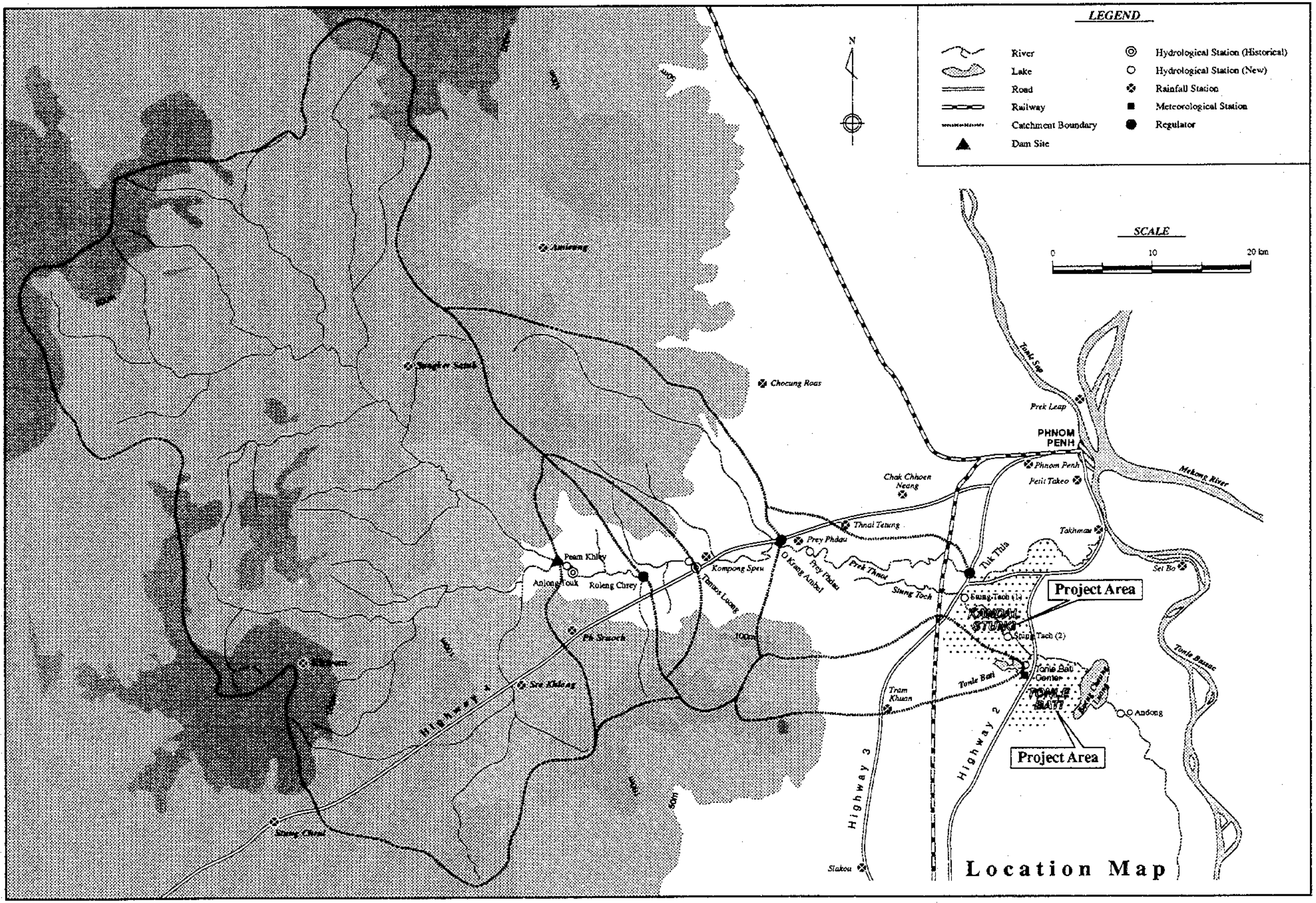
ANNEX I

HYDROMETEOROLOGY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Lake
Road
Railway
Catchment Boundary
Dam Site
Hydrological Station (Historical)
Hydrological Station (New)
Rainfall Station
Meteorological Station
Regulator
SCALE
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10
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N
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ANNEX I

HYDROMETEOROLOGY

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1. INTRODUCTION

1.1 Regional climate and hydrology

The alternating monsoon system controls the climate in Cambodia. The wet season, the southwest monsoon, is from May to November when about 90% of the rainfall occurs. The remaining months, the northeast monsoon, are hot, dry and less humid with particularly high potential transpiration demands in March and April. The following table summarises the main features of the climate using data from Phnom Penh. This record is typical of the lowland region and represents the Project area. All the data quoted are from observations except the potential transpiration figures derived by Penman equation from the meteorological information.

Average meteorological data for Phnom Penh

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall	mm	6	9	28	71	139	143	150	160	236	256	130	37	1365
Minimum rainfall	mm	0	0	0	0	25	27	37	44	93	63	2	0	935
Maximum rainfall	mm	57	127	193	359	395	393	359	380	474	650	324	186	2310
Number of raindays		2	1	1	4	14	18	17	18	20	21	10	4	129
Maximum temperature	deg C	30.7	32.6	34.5	35.2	34.1	33.2	32.6	32.1	31.7	30.6	30.1	30.2	
Minimum temperature	deg C	21.2	22.7	24.2	25.4	25.3	25.0	24.7	24.7	24.4	24.2	23.6	21.7	
Sunshine	hours	8.6	9.0	9.0	8.0	7.3	6.3	6.3	5.6	5.8	6.8	7.6	8.5	
Humidity	%	67.4	65.3	62.5	67.0	75.4	77.0	78.7	79.3	82.4	81.9	76.6	71.2	
Wind speed	m/s	2.4	2.2	2.7	2.2	2.1	2.4	2.7	2.6	2.1	1.8	2.3	2.4	
Potential transpiration	mm	145	161	206	188	165	149	150	147	132	136	135	142	1857

The Chaine de l'Elephant mountains to the west of the project area modify the rainfall observed in the lowland area to the east that lies in their rain shadow. Annual rainfall of 3000 to 5000 mm is recorded to the west of the watershed, whereas 1300 mm is more typical of the lowlands to the east. All the upper basin of Prek Thnot lies in the eastern facing slopes. Average runoff from the upper basin is just over 300 mm. With actual transpiration losses about 1200 to 1500 mm per year, the average rainfall on the upper basin must be in the range 1500 to 1800 mm. Annual rainfall is near to the lowland average of about 1300 mm on most of the lower tributaries and on the smaller rivers including Stung Toch and Stung Tonle Bati.

Figure I-1 shows the seasonal distribution of the water balance components for the upper Prek Thnot basin. It shows that runoff from December to April forms a small part of the annual total. From May, through the remaining months of the wet season, runoff generally increases to a maximum in September or October. The hydrograph declines rapidly at the end of the wet season and the recession is similar in all years. Natural flows in Prek Thnot decline to 1 m^3/s or less towards the end of the dry season. Floods can occur at any time in response to intense rainfall, but the highest floods tend to occur towards the end of the wet season. Rarely, high floods have occurred unseasonably.

There was no control structure on the river when the hydrological records ceased in about 1970. In 1972, construction of the Roleng Chrey control gates was completed as part of the multi-purpose Prek Thnot dam project, although construction of the dam was suspended at an early stage due to war. Thus, flows in the lower part of the river are now controlled by the operation of the Roleng Chrey gates, and the flows seen at Kompong Tuol are not those that would have occurred under the natural river regime.

Specific runoff from the lower tributaries of Prek Thnot, and in the smaller rivers, should be less than from the headwater basin. Rainfall is lower, losses are higher, and there is greater potential for retaining water in the bunded fields and other natural storages. Runoff is not perennial; flow ceases soon after the end of the wet season and the river valleys are cultivated.

The river morphology is very complicated especially in the lower reaches of Prek Thnot and there is ample evidence of different drainage patterns in the past. Backwater effects from Tonle Bassac influence flow direction as well as water level. During the wet season, Prek Thnot flows southwards towards Boeng Cheung Luong in a distributary that starts 3 km upstream from Takhmau. Boeng Cheung Luong also receives flow from Stung Tonle Bati and Stung Toch in addition to local drainage. While the lake normally drains towards Tonle Bassac, this flow is reversed in months when Tonle Bassac rises rapidly.

1.2 Availability of data

There are few long hydrometeorological records. The rainfall record for Phnom Penh is exceptional in that it is largely complete since 1901, with a gap of six years from 1974 to 1980. Rainfall was also measured at Kompong Speu intermittently from 1904.

New rainfall stations were established in the region in the 1950s and 1960s, and a reasonably good network of stations was started and was being extended to the mountain areas, including the headwaters of Prek Thnot. However, the civil war in the early 1970s progressively closed all hydrometeorological stations, and no records exist for most stations after 1974. A few rainfall and meteorological stations have been restarted in the past decade and a national meteorological network is being reconstructed. LWS supports a national programme for meteorological stations; other NGOs have established rainfall and climate stations, usually in support of their own programmes.

Although flow measurement on Prek Thnot was started in 1902, there are many long gaps in the record and measurements were made only near Kompong Speu and near the proposed dam site. In total there are less than 10 years record at any one site, and two of the records largely overlap. This hampers estimation of long term runoff at the dam site and estimation of flood frequency. No other flow records exist either in the lower part of Prek Thnot or for the other smaller rivers. No flow measuring stations have been restarted in the Prek Thnot basin.

The location of all rainfall and hydrological stations with historical data used in this study are shown in the location map at the beginning of this Annexe.

The historical data that have been preserved through the Pol Pot era are held by the Bureau of Hydro-Meteorology in their offices at Pochentong. In most cases the raw data are in manuscript on the original sheets. None is computerised and all are in danger of being lost by damage or decay. From 1960 until 1974, a selection of data for Cambodia was published in the Lower Mekong Hydrologic Yearbooks. Currently, national systems for the collection, processing and publication of hydrometeorological data are being reconstructed with the support of the Mekong Secretariat in Bangkok.

This project includes the setting up of several hydrological stations in Prek Thnot basin and a new meteorological station. The calibration of the new hydrological stations is only partly complete, and there are insufficient new data to affect the estimates of water resources derived from the historical records. However, some of the records now collected allow an assessment of the impact of the Roleng Chrey gates on the distribution of the water resource. This in turn allows some appreciation of the changes in operating policy that are needed to ensure that the expected resource is available to the priority project area.

The least well documented issues are the flood and sediment regime of the river and particularly the man-made influences on the major floods. Some further field investigations allow limited additional analysis of the flood and sediment regime of the river.

1.3 Previous studies of Prek Thnot

The most recent major study of irrigation potential in the Prek Thnot basin was made by SMEC[1] and Euroconsult[2] as part of a reappraisal of the Prek Thnot Multipurpose Project. In terms of the water balance, Euroconsult studied the hydrology, cropping plans and irrigation requirements: SMEC carried out a simulation of the proposed reservoir and defined the design floods. Their studies defined a staged development to meet urgent needs for improvement of irrigation. Thus, they considered the resources available in both the run-of-river and with-dam cases, including power priority and irrigation priority as separate options in the case of the dam.

Euroconsult faced the same difficulties of data scarcity, and uncertainty over the resources available for irrigation, as exist at present and are outlined above. Their response to the problem of water resources evaluation for irrigation planning in the run-of-river case was to define a typical drought year based on a critical period which they defined as December to April. The year 1964 was selected to represent an 80 % design reliability for irrigation. They also used a set of runoff equations to estimate runoff in the lower tributaries of Prek Thnot and the smaller rivers. These estimates did not play an important part in their run-of- river analysis because flows are negligible during the critical period and local storage was not considered in detail.

Euroconsult also extended the short record of runoff at the dam site by reference to the long rainfall series at Phnom Penh. The shorter record for Kompong Speu was also used. The resulting 72-year series of monthly flows was used by SMEC in their simulation of reservoir performance. Using the alternative cropping plans proposed by Euroconsult, SMEC studied the options for the generating hydropower while irrigating a large area downstream of the dam.

Earlier studies by Tahal[3] are also relevant. They covered much the same ground as the later studies, but with markedly different results particularly with regard to cropping plans and irrigation water requirements, and in some aspects of the reservoir operation. Tahal did not study the run-of-river development.

1.4 Scope of this Annexe

The hydrology of Prek Thnot is covered in Chapters 2 and 3, which are based on a new interpretation of the historical rainfall and runoff data. Crop water demands and a model for effective rainfall under paddy cultivation are described in Chapter 4.

The water resource available to the Project Area is examined in Chapter 5, where it is assumed that water sharing will occur in future between upstream and downstream irrigation projects. The potential for overall irrigation development with the proposed dam is also reviewed in this Chapter.

Chapters 6 and 7 describe the hydrological observations initiated as part of this project, and the use of the limited amount of data collected to describe the impact of the current operation of Roleng Chrey on flows in the lower river. This analysis is extended one stage further to identify a form of operation that would ensure the equitable sharing of water under drought flow conditions in future.

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1 Snowy Mountains Engineering Corporation, Prek Thnot Multipurpose Project, Reappraisal Report, Volume 1-Summary, Jan 1992.

2 Euroconsult, Prek Thnot Multipurpose Project, Reappraisal Report Vol 5 - Irrigation, Jan 1992.

3 Tahal, Prek Thnot Pioneer Agricultural Project, Project Preparation, Main Report, Jan 1975

Chapter 8 covers the estimation of floods and sediment flows using both the historical data, regional and other empirical methods, and observations of flood damage in recent years including the flood of August 1994.

2. RAINFALL

2.1 Review of the available data

Records from only two stations, Phnom Penh and Kompong Speu, can be regarded as long term records, although the latter has gaps of many years duration. Computer files of daily data have been compiled for these stations and for Slakou, amounting to a total of 42 station years. Otherwise, all data are monthly and annual totals.

The remaining stations in the region have operated for much shorter periods, usually limited to the 1950s and 1960s. Stations are generally located in towns and villages along the main highways. Station details are given in Table I-1. The records are held by the Bureau of Hydro-Meteorology (BoHM) at Pochentong. Over the last decade a few new stations have been opened, mostly on projects supported by the NGOs. There is no Departmental programme for the rehabilitation of the rainfall station network, although the BoHM has outline plans to install one rainfall station in each district.

The data are compiled from a variety of sources including the Lower Mekong Hydrologic Yearbooks, Euroconsult (1992), the UNDP project and the BoHM. Sometimes inconsistencies are found between data from different sources and between daily and monthly data. Where possible, these are checked and mistakes of interpretation or arithmetic are corrected. Generally, stations with less than four years of data are neglected in this analysis.

Many gaps in the records hinder statistical analysis and records for the dry season are open to doubt. The distinction between no data and no rainfall is not always clear and can lead to misleading conclusions about dry season rainfall. Records from the last ten years are more likely to contain periods of missing data than the earlier records. Where possible, the data are checked using standard techniques, but most tests are of little value when record lengths are very short.

2.2 Regional variation in rainfall

It is well known that the lowland area to the east of the Chaine de l'Elephant mountains lies in a rain shadow area. Rainfall is high on the western and southwestern slopes of the mountains where annual totals of 3000 to 5000 mm are recorded. All the upper basin of Prek Thnot lies in the eastern facing slopes. Average runoff from the upper basin is just over 300 mm. With actual transpiration losses about 1200 to 1500 mm per year, the average rainfall on the upper basin must be in the range 1500 to 1800 mm. Annual rainfall is near to the lowland average of about 1300 mm on most of the lower tributaries and on the smaller rivers including Stung Toch and Stung Tonle Bati.

This represents a sharp reduction in rainfall across the watershed and it is important to try to establish whether there are differences between the rainfall characteristics in the upper Prek Thnot basin and those observed in the lowland areas. A rainfall-runoff model will be easier to transfer between catchment areas if, for example, rainfall intensities are of the same order. Monthly data are compared for stations to the west of the watershed, those in the eastern lowland area, and from Kirirom, the only station in the upper Prek Thnot basin with a useful length of record. For convenience of terminology, the descriptions 'Western stations' and 'Eastern stations' is used.

Several interesting features emerge. Figure I-2 shows that the seasonal distribution of rainfall is broadly the same on both sides of the watershed, only the amount is different. Figure I-3 shows that the number of raindays is markedly higher for the Western stations. This implies that many storms do not penetrate far enough inland to cause rainfall in the Eastern stations. The important distinction between the two groups is shown by Figure I-4 that illustrates the average rainfall per rainday. For the Eastern stations, and for Kirirom, the average intensity of rainfall is seen to be fairly constant throughout the year. In other words some months are wetter than others only because it rains more often not because it rains more intensely. In contrast, the Western stations show a substantial increase in average rainfall intensity in the wet season, particularly in July and August. Thus the wetter months at these stations are wetter because it rains more often and more intensely.

The rainfall record for Kirirom appears to have more in common with the records from the lowland, Eastern stations than it does with the Western stations. Thus, there is likely to be some similarity in the response of Prek Thnot basin and the lowland catchments. The lowlands should differ in their response to rainfall only in terms of the monthly amounts and not the short term intensities. Thus we might expect a model to be more transferable between catchments than would have been the case if rainfall characteristics differed more widely.

2.3 Spatial variability of annual and seasonal rainfall

Because of the many short gaps in the record, the best estimate of mean annual rainfall at a station is obtained from the total of the calendar month averages. In this way all the available information contributes to the estimate of the annual mean. An average of the annual totals from only complete years of record neglects over half the information for some stations. Throughout this report the annual average is derived in this way. An alternative way of avoiding the many gaps in the record, most of which occur in the dry season, is to use the wet season total instead. About 90 % of the annual rainfall occurs in the period May to November.

Mean monthly and annual rainfall for all stations, and the average number of raindays are summarised in Table I-2. It is not possible to draw a reliable isohyetal map from this information. The network is too sparse and often the annual mean is based on only a few years of record. Much of the variability in short term rainfall records is caused by random variations in storm occurrence that can mask real differences between stations.

Some useful indication of the spatial variation of mean annual rainfall is obtained by plotting rainfall against position. Figure I-5 shows mean annual rainfall plotted against longitude represented by the easting of the UTM coordinates. The Western stations have also been included in this analysis. There is a small increase in average rainfall from east to west and a large increase to the rainfalls observed on the western side of the mountains. More stations in the mountains would be needed to define the locus of highest rainfall, but most, if not all, the upper Prek Thnot basin lies in the rain shadow.

Spatial correlation of rainfall is examined using the longer records available for Phnom Penh and Kompong Speu. Figure I-6 shows that the correlation is visually poor even on an annual basis. When the outlier value for 1917 is neglected[1], the correlation coefficient between the two series of annual totals is only 0.56 ($r^2 = 0.32$). A marginally worse result is obtained for the wet season (May-November) totals; the correlation coefficient is only 0.43 ($r^2 = 0.18$) if the outlier is neglected. These results represent long term conditions. They are based on joint records of 37 years for annual values and 48 years for the wet season totals.

Over shorter periods the correlation is even lower. This accords with the observation that rain storms are of limited areal extent and that there is little pattern in their occurrence. While there will be a tendency for rainfall to occur in some periods rather than others, due to regional meteorological conditions, the rainfall is not necessarily widespread.

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1 An outlier can cause an apparent correlation even between data sets that are otherwise totally uncorrelated. It should always be neglected in any test for correlation between data sets.

Concerning the operation of irrigation systems on a river basin scale, these considerations mean that some parts of the scheme might have substantial rainfall while other parts have very little. If water allocations are to be responsive to rainfall, a fairly dense rainfall monitoring network will be required. For irrigation design, poor spatial correlation of rainfall means that a design assumption of drought rainfall everywhere in the critical period might lead to an over-pessimistic design condition. The same is true, by implication, for river flows. However this refers to basins of the scale of Prek Thnot and not necessarily to areas the size of the current Project area.

2.4 Long term rainfall and its seasonal distribution

The time series of wet season rainfalls are shown in Figure I-7 for Phnom Penh and Kompong Speu. Records for the wet season are more complete than the annual series. Apart from the two years 1916 and 1917, there are no unusual features in the time series. These two years had unusually high rainfall in July to November that could have been caused major disturbance to the regional climate. Surprisingly, neither of these years is cited in the flood history of Prek Thnot, possibly because flow records were not kept in those years. There is a tendency for rainfall to have been slightly less variable in recent years, particularly at Kompong Speu.

The general features of the seasonal distribution of rainfall are clear from the data presented above. The stability of the seasonal distribution and particularly the time of onset of the wet season is difficult to generalise. It is well known by farmers that the timing of the start of the wet season is uncertain and can cause problems in the planting of the main rice crop. Transplanting in August reflects, in part, the need to delay planting until enough rainfall has been received.

Using the long rainfall record from Phnom Penh, Figure I-8 shows the time series of the proportion of rainfall that falls in the wet season defined as May to November. The series is smoothed slightly to reveal the underlying variation over the past 90 years. This is a curious result and no explanation is offered, but there might be significant long term variations. The data suggest that in the 1920s over 15 % of the annual rainfall fell in the dry season, whereas by the 1970s the figure had fallen to little over 5 %.

2.5 Statistical description of daily rainfall

Information on the frequency and intensity of rainfall on a daily time scale is used for agricultural planning and irrigation design. The daily rainfall data from Phnom Penh, Kompong Speu and Slakou show that the statistical properties of daily rainfall are reasonably constant over the lowland region. Data from any one station characterises the rainfall likely to be observed elsewhere in the lowland area. There is a relatively small drift in the mean annual rainfall from place to place reflecting the gradual decline in rainfall from west to east. Also, local topography might cause storms to track preferentially over one area rather than another, although there is little evidence of this from the limited data available.

Figures I-2 to I-4, based on monthly data for relatively few years, illustrate the general seasonal pattern of rainfall, number of raindays, and the average intensity of rainfall on wet days. Figure I-9 shows that the correlation between raindays and rainfall is good on a mean monthly basis using the longer period of record for Phnom Penh, Kompong Speu and Slakou. Naturally, in individual months there is some spread around these averages. As the correlation is reasonably linear, the average daily rainfall intensity is about the same in all months.

Figure I-10 extends this analysis by showing the exceedance probability of daily rainfall at the three stations. All daily rainfalls at each station are pooled and the probability of exceedance of daily rainfall of a given amount is estimated from the pooled sample. The result is very consistent among the three stations, suggesting that daily rainfalls anywhere in the region can be regarded as coming from a single statistical distribution. Where mean annual and mean monthly rainfall is comparable from place to place, daily rainfall will have comparable characteristics of frequency and intensity. However, as indicated by the correlation analysis, this does not mean that daily rainfalls will occur everywhere on the same days.

One useful outcome of this analysis is that it confirms that a record from any station, such as Phnom Penh, describes the statistical distribution for other locations within the same general area, including the Project area.

2.6 Extreme short duration rainfalls

Information on rainfall intensities for periods of less than one day is not readily available. However, drainage of the paddy areas is probably insensitive to very short term rainfall, except in the most severe storms. Storm rainfalls will usually surcharge the bunded fields before runoff is seen in the drainage system, and the effect of the storm will be attenuated as water is passed from field to field. Therefore, the daily data from Phnom Penh are used to derive frequency curves for rainfall over periods from one to five days.

As the results are not being extrapolated to return periods beyond the scope of the data, the form of the statistical distribution is not important. The curves plotted in Figure I-11 have been scaled according to the general extreme value function, but any extreme distribution would have been effective. The values listed below are obtained by interpolation for the return periods used for drainage design.

Estimated maximum short period rainfall at Phnom Penh (mm)

	1 day	2 day	3 day	4 day	5 day
Mean annual maxima	80	103	120	137	151
10-year return period maxima	100	142	169	196	212
20-year return period maxima	118	165	184	220	236

3. RUNOFF

3.1 Review of the available data

Records are available from three locations:

a. monthly records exist for a station at the town bridge in Kompong Speu. Although records date back to 1902, continuous records for all months are available only in the period 1926 to 1933,

b. from 1960 to 1970, a water level recorder was operated at Thnuos Luong, a site near the road bridge on Highway 4 just upstream of Kompong Speu town.

c. from September 1963 to February 1970, a staff gauge station was maintained at Anlong Touk, just downstream of the site of the proposed Prek Thnot dam. Daily records for this station were published in the Lower Mekong Hydrologic Yearbooks, (LMHY).

All these stations are rated river sections for which rating curves were derived by discharge measurement for a range of water levels over a period of several years. The quality of the data can be inferred from the form and consistency of the rating curves.

Figure I-12 shows the discharge measurements made in each year for rating the Anlong Touk station. There is no evidence for a shift of rating over the period. The LMHY show that three different ratings were used because the rating was continually revised as new discharge measurements became available. The curve fitted to the data has the form:

$$Q = 12.15 * (H + 0.14)^{1.79}$$

where Q is the discharge in m^3/s and H is the gauge height in m.

Table I-3 summarises the three rating curves used for this station together with the differences between the single curve derived here and the historical curves used in the different periods. These comparisons show good agreement with the final LMHY curve, but suggest that low flows in the years 1963-65 were significantly underestimated.

Figure I-13 shows that the rating curve for Thnuos Luong was also stable for the period covered by the discharge measurements. A 2-part curve is needed to describe the rating:

$$Q = 6.3 * (H + 0.15)^{4.45} \qquad \text{for } H < 1.5 \text{ m}$$

$$Q = 20 * (H + 0.34)^{1.7} \qquad \text{for } H > 1.5 \text{ m}$$

The exponent for the lower section of the curve is unusually large, but no simple physical reason was found. The site is good. There is a single low flow channel between the recorder section (about 300 m upstream of the bridge) and a rock outcrop about 100 m downstream from the bridge. The longitudinal profile of the river shows a large change in slope at this point of flow control. Upstream, the slope is about 1:30,000, whereas downstream, the slope is about 1:2000, typical of the river in the lowland area. Bankfull discharge is unlikely to much more than 600 m^3/s. However, the lower part of the rating curve remains questionable[1].

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1 This is further discussed in Chapter 6 where recent discharge measurements are seen to confirm the historical rating at low flows.

All these records predate the construction of Roleng Chrey diversion weir and it should be possible to infer the inflow from the intermediate catchment area from the difference in flows at Thnuos Luong and Anlong Touk. In practice this procedure is not very reliable due to uncertainties in the flow estimates at the two stations.

The average monthly difference in flow is plotted in Figure I-14, which identifies the separate periods corresponding to the revision of Anlong Touk rating. In the low flow months differences appear to be negative and even for August, a high flow month, the data indicate a negative increment. This demonstrates the practical limits of accuracy of the estimated flows which cannot be used reliably to indicate small differences.

Euroconsult compared discharge measurements made on the same day at both stations. They concluded that there is a 10% increase in flow between the stations. However, the difference is certainly smaller and is almost entirely in the months of September and October. There is no real indication of significant increments to flow in other months. In a summary of an earlier study, SMHEA[2] concluded that, in view of the low runoff from the area downstream of the dam, the runoff at each station is equivalent to that at the dam site. This view is generally supported by the data except in the months of very high flow.

The Anlong Touk daily record has been used in much of the analysis presented here. It represents runoff from the higher mountain areas of the basin without the complications of the intensely farmed and very much flatter lowland areas. The extension of this record with reference to rainfall in previous studies is reviewed below.

3.2 The annual hydrograph

Figure I-15 shows the six complete annual hydrographs of daily flow at Anlong Touk. While there are obvious differences in the shape and magnitude of the hydrographs in different years, there a number of important similarities which characterise the hydrological response of the basin. Flows during December to April form a very small proportion of the annual total. From May through the remaining months of the wet season, floods can occur at any time in response to intense rainfall, but the highest floods tend to occur towards the end of the wet season, usually in September or October. Rarely, high floods have occurred unseasonably such as the highest flood of memory or record which occurred in March 1922. The hydrograph declines rapidly at the end of the wet season with a characteristic decay curve which is similar in all years shown.

Plotting a typical annual hydrograph on a logarithmic scale (Figure I-16) shows that baseflow increases from about April to October. This indicates that natural retention of water in the basin increases throughout the wet season, and this storage provides the recession flow that is seen usually from November to the end of March. The recession curves are very similar and can be described very well by the sum of two exponential curves. The time constants of 10 and 45 days suggest that the runoff is derived from interflow and baseflow storage in the basin. At the beginning of the recession, typically at a total flow of about 150 m^3/s, the storage amounts to about 30 mm and 12 mm respectively expressed as a depth over the basin,. This is relevant to the modelling of runoff discussed below.

Flow duration statistics are derived from the daily data for Anlong Touk for the complete record and for seasons representative of the periods when water might be required to be diverted for irrigation. The numerical data are given in Table I-4; Figure I-17 shows typical curves.

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2 Snowy Mountains Hydro-electric Authority, Paper to an Engineering Seminar, Phnom Penh, Nov 1965.

3.3 Drainage areas

Table I-5 shows the drainage areas and the proportion of each area comprising higher land as distinct from the low, flat land predominantly used for rice cultivation. The topographical maps show that the basin above the dam site contains very little of the low flat land. The drainage area of O Krang Ambel is the only other basin that has the major part of its area in the higher land. All other tributaries, including Stung Toch and Stung Tonle Bati are predominantly in the low flat areas.

The area on the right bank of Prek Thnot downstream of the O Krang Ambel confluence drains primarily to Stung Toch. A further large area to the south drains to Stung Tonle Bati. The discussion of the geomorphology of the area (Annexe II) suggests that Stung Toch was formerly an old course of Prek Thnot. When Prek Thnot migrated northwards, perhaps in response to regional tilting of the land surface, the present Stung Toch retained this part of the former Prek Thnot drainage area. SMEC[3] report that Stung Toch acts as a distributary of Prek Thnot during major floods. Part of the flood crosses into Stung Toch and thereafter follows the course of Stung Toch towards Boeng Cheung Luong.

Much of the low flat land contains numerous small ponds and some lakes that are marked as seasonal storage on the 1:50,000 scale maps.

3.4 Estimation of long term runoff

In their review of the proposed dam on Prek Thnot, Euroconsult extended and in-filled the monthly flow record to cover 1901-1972. The in-filled record has a mean annual flow of 1270 mcm with a coefficient of variation (CV) of 0.40. This is equivalent to a mean annual runoff of about 350 mm at the dam site.

For the years of largely observed data (a much smaller sample), the mean is 1388 mcm with a CV of 0.61. Comparison with the in-filled series is strongly affected by the very high runoff in 1922 which is included in both series. The average for the in-filled series excluding 1922 is 1227 mcm with a CV of 0.27, and the corresponding figure for the largely observed period is 1243 with a CV of 0.42. Thus, the in-filling procedure has had little effect on the mean, but the CV has been reduced significantly. This suggests that the tendency for regression methods to reduce the variance of the estimated series has not been fully corrected.

Extension of runoff records using longer rainfall records is a commonly used procedure, but it does rely on there being a good correlation between rainfall and runoff. In this area the correlation is poor because of the poor spatial correlation of rainfall, and the only long rainfall records are from Phnom Penh and Kompong Speu, both some distance from the basin. Thus the additional information introduced from the long rainfall record is equivalent to very few years runoff record. The mean of the extended series is only marginally more reliable than the mean of the observed data.

An annual average runoff from the upper basin of 1227 mcm (335 mm) is probably the best estimate of the long term runoff currently available. It accords with the observed data and with the mean of the in-filled series excluding 1922. However, any estimate from a such a short period of real information has wide confidence limits. If the CV of annual runoff is about 0.4 and there are about 20 years of real information in the combined records, the 95% confidence limits for the mean are about $^{+}/_{-}$ 200 mcm. It is worth noting that the differences discussed above are small compared with the range of estimates from earlier studies.

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3 Snowy Mountains Engineering Corporation, Report on the Rehabilitation of the Kompong Tuol Road Dike, Feb 1993.

The typical drought year selected by Euroconsult for their analysis of irrigation potentia is based on an 80 % probability of exceedance for the months December to April. The year 1964 fitted this criterion. It is irrelevant that the year as a whole has more than average runoff provided that the critical period in the cropping studies is always in these months.

3.5 Runoff modelling

A rainfall-runoff model is seen as the best way to estimate runoff from the lower tributaries and the smaller rivers. The model could be used to extend the runoff record at the dam site if better rainfall data were available. A monthly model is used because of data limitations. Input rainfall is derived from four stations, Kirirom, Phnom Sruoch, Kompong Speu and Phnom Penh. These four stations define a reference rainfall series representing the basin as a whole; the rainfall station network is too sparse to define rainfall on each drainage area separately. The spatial averaging ensures that variability of the monthly rainfall series is appropriate to areal estimates, and that storms missed at one station will be probably represented in the record at other stations.

(1) Definition of the model

Initially, rainfall is reduced by a fraction, **A**, of the potential transpiration loss because part of the rainfall in each month falls in small daily amounts that do not contribute to runoff. The remaining rainfall is partly transformed to runoff and partly used to increase catchment storage by the equations:

$$QA = 0 \quad \text{for } R < A * Et$$

otherwise

$$QA = (R - A * Et) * (B + C * CS / SM)$$

where **QA** is the runoff, **R** the reference rainfall, and **Et** the potential transpiration, **CS** is the contents of the catchment storage, maximum value **SM**, and **A**, **B**, **C**, and **SM** are parameters of the model.

This function represents a number of features that are seen in the runoff record, and also corresponds with ideas of the physical processes involved. Runoff occurs quite early in the wet season, well before the catchment storage, largely represented by soil storage, is filled. The parameter **B** allows for this. As the catchment becomes wetter during the wet season, the proportion of rainfall that is transformed to runoff increases. This is represented by the parameter **C** which scales the additional runoff. When the storage is full, any remaining excess net rainfall is also added to the runoff total for that month. This function, relating the runoff fraction to storage, is usually non-linear, but the extra parameter needed could not be defined with the poor rainfall data available. Runoff is also produced by drainage of the catchment storage to provide a notional base flow component according to:

$$QB = D * CS$$

where **QB** is the baseflow runoff, and **D** is a parameter of the model.

Runoff is routed through further notional storages with an approximate form of exponential decay typical of the observed flows. These storages are unlimited in capacity, the gross runoff amounts **QA** and **QB** are added to these storages and the final runoff **QT** is given by:

$$QT = CA * KA + CB * KB$$

where **CA** and **CB** are the current contents of the stores receiving the gross runoff amounts **QA** and **QB** respectively, and **KA** and **KB** are parameters of the model.

Finally the remaining potential transpiration is taken from the catchment storage unless there is no more water available, and the storage is updated for the start of the next month.

Lowland effects are represented in the model by an additional storage equivalent to the surcharge that can be held in paddy fields and other natural depressions. All runoff is routed through this storage and the net runoff is the excess after the storage has been filled. The storage is depleted only when there is unsatisfied evaporation demand. More sophisticated infiltration concepts might be appropriate, but there is simply no data with which to calibrate this part of the model independently.

(2)Fitting the model using data from Anlong Touk

The model parameters are adjusted until the best fit results between the simulated and observed runoff during the period chosen for model calibration. Goodness of fit is measured by the sum of squares of differences between observed and simulated monthly runoff. Use of linear and log scales ensures that emphasis is not unduly placed on the high flows.

From considerations of the rainfall distribution discussed previously, and of the known runoff and expected losses from the upper part of Prek Thnot basin, a mean annual rainfall about 1800 mm is realistic. This would result in about 335 mm mean annual runoff and 1465 mm of transpiration losses compared with a potential loss of 1857 mm based on the Phnom Penh meteorological data. The potential losses might be lower in the mountain region but use of a lower figure and a correspondingly lower rainfall would not materially alter the outcome. Both the rainfall and potential transpiration are regarded as realistic indices of the unknown true values.

By trial and error the following parameter values were found to give a reasonably good simulation of observed runoff:

A=0.37, B=0.082, C=0.463, D=0.008, SM=420,
KA=0.94 and KB=0.62

With these parameter values the model explains just over 83% of the initial base line variance in normal terms and nearly 89% in log terms[4]. Experience in similar regions of the world suggests that 90 % can be regarded as good for a monthly model of this type.

Figures I-18 and I-19 compare the observed and simulated runoff for the six year period of observed flows at Anlong Touk at normal and log scales. The model is calibrated on the four years, 1966-1969 and the other two years are a test period. The shape of the annual hydrograph is reproduced reasonably well given the approximations made, particularly in the derivation of a monthly reference rainfall series. No model could reproduce the first of the floods in 1967, the rainfall record does not show a major storm at that time. Rainfall undoubtedly occurred in the mountains, but there was no commensurate rainfall at any of the four stations used to construct the reference rainfall series.

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4 Taking the sum of squares of monthly runoff about the mean of all months (either in normal or log terms) provides a base line variance against which the performance of the model can be judged. The difference between this and the residual sum of squares remaining after model fitting can be regarded as the amount of variation in the monthly runoff series that has been explained by the model.

3.6 Resource estimates for irrigation planning

The model is used to predict runoff for 1964-1970 for the lower tributaries and the small rivers. Table I-6 shows the estimated mean annual rainfall on each catchment, and the additional lowland storage, which is based on the proportion of low, flat land in each catchment.

Table I-7 summarises the results in terms of depth and volume of runoff for each area under these assumptions. Figure I-20 shows how the shape of the annual hydrograph changes with lower rainfall and additional retention in paddy field storage. The effect of the storage is indicated by hatched lines on the lower hydrograph. There is no information to test the reliability of these results, but they conform to reasonable expectations and simple observations of the hydrological behaviour of the area. Runoff from all but the upper basin is severely curtailed in the dry season, the major part being concentrated in the months of September and October. The rapid decline of flow during December and January accords with field observations that flow ceases during the dry season in all the rivers except Prek Thnot.

For irrigation planning, these series have been extended to the 10 years covered by the combined record for Prek Thnot from Anlong Touk and Thnuos Luong. The additional data for Thnuos Luong is adjusted to the dam site by monthly factors derived from the model results[5]. For the four additional years, tributary and small river flows are derived by scaling runoff at the dam site by monthly factors derived from the modelled period. These approximations are acceptable given the relatively small runoff volumes from the lower basin, and the benefits of including more information at the dam site.

The following table summarises the river flows for the 10-year design period, 1961-1970. Flows in all the tributaries below the dam site have been combined into a single series.

Average river flows for the 10-year design period (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Dam site	9.3	5.2	4.5	9.5	38.0	78.9	130.0	187.2	292.2	383.2	131.3	64.0	1334.0
Tributaries	0.9	0.1	0.0	0.0	0.0	2.7	13.5	15.3	31.0	52.5	19.6	9.6	145.2
Stung Toch	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.8	7.0	2.5	1.2	14.6
Stung Tonle Bati	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.4	3.9	9.6	3.5	1.6	20.1

This 10-year period has a slightly higher mean flow than the best estimate of the long term average. It also contains two of the drier years on record (1963 and 1968) and one very wet year (1970). This is consistent with a higher coefficient of variation (0.32 compared with the expected value of about 0.21). The choice of a fully representative period for irrigation design is bound to be difficult given the short period of observed data. This sequence will probably give conservative estimates of irrigation potential, which is a realistic precaution given the uncertainty of the estimates.

3.7 Comparison with the Euroconsult estimates

Euroconsult used a non-linear relationship between rainfall and runoff to estimate monthly runoff from the tributaries and small rivers. This approach neglects the effect of catchment storage and the relationship between rainfall and runoff is assumed to be the same in all months. When used with the reference rainfall series described above, the Euroconsult equation predicts annual runoff of 338 mm and 474 mm for 1300 mm and 1500 mm rainfall

[5] The average adjustment predicted by the model is equivalent to 4.3% of the flow at Anlong Touk compared with an average factor of 3.8% from contemporary data for the same period.

respectively. In both cases these runoff figures are more than is observed in the higher rainfall mountain basin of the upper Prek Thnot. It is realistic to expect the runoff in the lower rainfall areas to be much less than in the mountainous headwaters.

In an analysis of run-of-river irrigation potential this overestimation of runoff does not affect the analysis because the runoff in the critical months is negligible. Arguably there is no need to predict runoff from the lower basin. But when storage is included in the system, such as at Tonle Bati or the possible Saba or Koktel reservoirs, the estimation of seasonal runoff is necessary and the Euroconsult equations cannot be regarded as a reliable input for this purpose.

In a preliminary evaluation of the irrigation potential in the with-dam case, Euroconsult defined the average monthly water availability as the sum of controlled releases from Prek Thnot, uncontrolled releases (seepage and spill), and tributary inflow and return flow between the dam and Tuk Thla. The tributary inflows[6] were based on an assessment of the 80% reliable flows which are about 25% of their estimated average flows, or about 116 mcm over the year. By inference, the return flows are about 32 mcm over the year.

The following table summarises the figures derived in this study and by Euroconsult. The 80% low flows derived by Euroconsult are based on the statistics of flows in each month considered independently. Thus the result appears to be very extreme when viewed in terms of the annual total. In any case it is not appropriate to use the 80% figures for the with-dam case as the reservoir will provide virtual storage of tributary flows. Use of the mean is more justifiable. By chance the Euroconsult 80% flows are about the order of magnitude expected for the average.

Comparison of estimates of tributary runoff (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
JICA STUDY													
1961-70 average	0.9	0.1	0.0	0.0	0.0	2.7	13.5	15.3	31.0	52.5	19.6	9.6	145.2
EUROCONSULT													
average	0.0	0.0	8.2	3.1	40.4	24.7	49.4	39.4	109.3	148.1	34.7	1.5	458.8
80% low flow	0.1	0.0	0.0	0.0	1.1	1.7	8.2	7.3	44.5	50.5	2.8	0.0	116.1

3.8 Water levels in Tonle Bassac

Seasonal flood levels in the Mekong/Tonle Bassac system influence drainage from the lowland areas including parts of the Project area for the duration of the flood peak. Levels at Phnom Penh can rise to 10 m above mean sea level, higher in exceptional years. Typical hydrographs based on data for 1960-69 are shown in Figure I-21. The timing of the recession of water levels in Tonle Bassac also governs the date from which a recession rice crop is possible on land previously inundated. Water levels in the lower reaches of Prek Thnot are affected by backwater effects from Tonle Bassac for several months, the effects being seen further upstream in Prek Thnot as flow declines rapidly in November and December.

Linear interpolation between daily levels at Phnom Penh and Chaudoc is used to estimate levels 30 km downstream of Phnom Penh. The earliest, average and latest dates at which the level falls below a number of thresholds are shown in Table I-8. It is interesting that the spread between earliest and latest dates is approximately constant at about one month for levels above 2.5 m.

6 The derivation of the figures used by Euroconsult in their irrigation analysis is not fully explained. The figures quoted here are based on an interpretation of their published tables using a catchment area of 1122 km^2 between the dam and Tuk Thla.

4. TRANSPIRATION AND EFFECTIVE RAINFALL

4.1 Meteorological data

Monthly values of maximum and minimum temperature, humidity, sunshine hours and wind speed are available from the meteorological station at Pochentong. This is the nearest station with historical data to the Project area and these data are representative of conditions there. From 1960, the station was within the perimeter of the airport, but it was moved to its present location in the Bureau of Hydro-Meteorology compound in the late 1980s. The exposure is not as good at the present site, but there appears to be no significant change in the time series. Some apparent changes in wind speed are due to different instrumentation discussed below.

The monthly data for 22 years covering 1961-1970 and 1981-1992 are largely complete except for short gaps for some variables from time to time due to instrument failure or breakage. Comparisons of the monthly means for the two periods show very consistent values except for wind speed. In this case, monthly average values for the later period are found to be about 75% of those for the earlier period. This is due to differences in the method of measurement. Up to 1970, the data are true averages of wind run; from 1981, the data are averages of a few measurements each day of instantaneous wind velocity from a deflection anemometer. Conventional anemometers are now installed at the site. Data for the later period have been increased by 33% to obtain a consistent record of wind run for the whole period. Pan data are available from several stations for a number of years mainly in the 1960s.

4.2 Estimation of reference crop transpiration

The estimation of reference crop transpiration is based on the modified Penman method recommended by FAO. Estimates are derived for each month that has a complete record of the five variables. The results, shown in Table I-9, are very consistent from year to year; mean values for the two periods of data are very close, and the coefficients of variation for the calendar months are small. On this evidence, it is reasonable to use monthly average values in the assessment of crop water requirements.

The seasonal variation is illustrated in Figure I-22, which also shows the consistent results between the two data periods and the range between maximum and minimum values. High values in March and April, the hotter and less humid months, are exceptions to a pattern of much less variation over the rest of the year. Comparison with other reported estimates shows some marked differences illustrated in Figure I-23. Although the monthly variation is very similar, the Euroconsult estimates are significantly lower in all months. The overall difference of 209 mm is around 12% of the annual total. This is within the tolerance of the estimation procedure, but the reason for the differences lies in the different data used.

Table I-10 shows the differences in the average values for the meteorological data used in the two studies. Euroconsult used averages for the different variables drawn from different periods indicated in the footnotes to the table. Temperature and sunshine hours are significantly higher in the 1960-92 data used in this study. Also the humidity is significantly lower. The data used for wind speed are more difficult to compare directly. The data used in this study are based on wind speed measured at 10 m above the ground, whereas the Euroconsult estimates are based on wind speed at 0.5 m. The Penman program converts wind speed to the equivalent at 2 m by a power law function. Even after conversion of the wind data to 2 m, the current estimates exceed significantly those used by Euroconsult.

The differences in estimated transpiration are large because all the small differences in the data are similar in their effect. Higher temperature and sunshine hours, lower humidity and wind speed all contribute to a higher estimate of transpiration. It is impossible to comment effectively on the differences in the data; details of the measurements in the 1930s and earlier years are not available. Also Euroconsult give no detail about their choice of data. On balance, it seems reasonable to prefer the longer contemporary records used in this analysis.

Comparison of the estimates of potential transpiration with the pan data and a comparison of pan data between stations is shown in Figures I-24 and I-25. With the exception of Kirirom (altitude 680 m), where evaporation would be expected to be lower, the pan data are reasonably consistent between stations. This supports the view that the data from Phnom Penh are representative of the Project area.

Differences between the estimated potential transpiration and the pan evaporation data for Phnom Penh follow the expected pattern. The difference is a maximum in the dry season when evaporation pans usually overestimate evaporation because of advected energy. The differences are much smaller during the wet season when the pan is surrounded by freely transpiring vegetation. This comparison supports the use of the transpiration estimates derived.

4.3 Estimation of effective rainfall

Net rainfall is very difficult to predict. It is highly dependent on the characteristics of short term rainfall, the crop growing conditions and the state of the crop, and the irrigation regime, particularly the frequency of irrigation. Average factors applied to gross rainfall are often used. A more detailed model is used in this study to derive estimating equations for the calculation of a time series of 15-day irrigation demands.

Euroconsult have used effective rainfall factors in the range 50% to 100%, but there is no explanation for the factors selected other than that they depend primarily on the growth stage of the crop. Their factors were applied to the characteristic drought year rainfall. The model used here simulates the daily operation of a block of rice fields in a cascade. By using a long sequence of daily rainfall, it is possible to derive a consistent relationship between net and gross rainfall over 15-day time intervals. The model is based on the following rules:

a. irrigation water is applied directly to the highest field in the block and water flows down the cascade as each field reaches the target water depth (eg 50 mm),

b. during an irrigation cycle, water is applied at a uniform rate (eg 30 l/s per 20 ha block),

c. an irrigation cycle starts when the water level in the lowest field falls below a threshold value (eg 10 mm), and irrigation ceases when the lowest field reaches the target depth,

d. rainfall below 5 mm in a day is ineffective,

e. when rainfall exceeds 5 mm, each field accepts rainfall as effective up to a maximum defined as the sum of any deficit below the target water level plus any unused part of a surcharge storage (eg 50 mm maximum),

f. effective rainfall is retained in the irrigation block.

The model is run with a daily time interval using 21 station-years of rainfall data primarily from Phnom Penh and Slakou. The resulting values of daily effective rainfall are summed over 15-day time intervals, and averaged for small ranges of gross rainfall giving the points shown in Figure I-26. The average effective rainfall is about 60% of gross rainfall throughout the wet season.

For general application, two linear equations describe the results:

$$ER = -3.4 + 0.67 * R \quad \text{for } 5 \text{ mm} < R < 140 \text{ mm}$$
$$ER = 60.6 + 0.21 * R \quad \text{for } R > 140 \text{ mm}$$

Because the frequency distribution of daily rainfall is similar across the lowland region, these equations are used to define effective rainfall throughout the irrigated rice areas.

5. WATER RESOURCES FOR IRRIGATION

5.1 Introduction

The first priority is to maximise the utility of the run-of river flows in Prek Thnot together with the resources of the smaller rivers. Euroconsult[1] studied the potential for staged development before the dam is constructed and concluded that a total of 4200 ha could be irrigated, 2500 ha of which would be in the JICA Project area. The residual flows at Tuk Thla are derived in the context of this plan.

While this study is not primarily concerned with estimation of the irrigation potential of the proposed dam on Prek Thnot, it is clear that full development of the Project area cannot be achieved without the additional timely water resulting from the dam. Thus, it is necessary to review the previous studies of irrigation planning for the Prek Thnot basin and to ensure that sufficient water would be available to meet the needs of Master Plan for agricultural development in Project Area.

Both Tahal[2] and Euroconsult present plans for agricultural development in the Prek Thnot basin. Their results appear to differ significantly in terms of irrigated area and the balance between power and irrigation in the operation of the reservoir. Tahal concluded that a reservoir with a maximum capacity of 1120 mcm could irrigate up to 50000 ha, and as much as 66000 ha if the dam was raised a further 3 m. SMEC and Euroconsult conclude that 34000 ha can be double cropped if irrigation is given priority, but this is reduced to 27000 ha double cropped if power is the priority. They concluded that the benefits of raising the dam, while slightly increasing the irrigated area and producing some firm energy benefits, would have no economic benefit. Triple cropping alternatives are also presented.

This very brief summary shows the range of estimates of the irrigation potential. But the figures are not directly comparable. They refer to different cropping plans at different cropping intensities, and they use different data, assumptions and methods for the calculation of irrigation requirements. Both the Tahal and SMEC analyses were based on simulation of reservoir operation, but the inflow series were different in the two cases.

Most of the differences can be resolved by comparing the results on a consistent basis. But uncertainty about the reliability of the results in terms of reservoir inflows requires further consideration. A reservoir simulation has been made using the 10-year runoff series and the probability of recurrence of the critical years is discussed.

5.2 Resources for run-of river irrigation

Flows in Stung Toch and Stung Tonle Bati are defined in Chapter 3 above. They are available for irrigation without further modification. However, the flow available at Tuk Thla must be derived from consideration of irrigation development upstream. This is assumed to follow the Euroconsult staged plan and to amount to 1700 ha. The flow available at Tuk Thla is therefore the natural flow less the gross irrigation demand upstream based on the Euroconsult cropping plan of double-cropped HYV rice.

These upstream demands have been recomputed using the revised potential transpiration figures and the net rainfall model described in Chapter 4. All other assumptions, including percolation rate (1 mm/day), requirement for puddling water (two applications of 125 mm) and an overall efficiency of 65% are those of Euroconsult. This results in an

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1 Euroconsult, Prek Thnot Multipurpose Project, Reappraisal Report Vol 5 - Irrigation, Jan 1992
2 Tahal, Prek Thnot Pioneer Agricultural Project, Project Preparation, Main Report, Jan 1975

increase of about 11%, and the average annual diversion requirement to irrigate 1700 ha amounts to 34 mcm. The detailed flow balance on a 15-day time interval shows that the average annual shortfall amounts to 0.6 mcm. Shortage of water occurs in only five months in the 10-year series, the months affected being April (twice), June (twice) and December. These small deficiencies can be overcome with local storage such as O Krang Ambel reservoir.

The following table shows the monthly averages derived from the 10-year series of residual flow at Tuk Thla.

Average residual flow at Tuk Thla for the 10-year design period (mcm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Tuk Thla	8.01	5.3	4.5	6.4	33.0	79.0	140.9	199.0	318.6	433.7	147.9	69.2	1445

5.3 Irrigation potential with Prek Thnot dam

Table I-11 shows a summary of the main options presented by SMEC/Euroconsult and by Tahal for the operation of the reservoir. The figures for power, energy and irrigable area taken together define the benefit of the dam, and they illustrate the trade-off between firm power and irrigation potential. Total energy should be comparable between the different cases because most of the irrigation release can be used for energy generation.

Table I-12 compares the gross monthly irrigation requirements for the different cropping plans. The Euroconsult figures refer to double or triple cropping of HYV rice for 200% and 300% cropping intensity respectively. The Tahal figures are based on a wet season rice crop followed by 40% rice and 60% upland crops in the dry season, with a combined cropping intensity of 170%. The other major difference is caused by the overall irrigation efficiencies assumed. The Tahal figure of 70% efficiency is markedly higher than the 55% assumed by Euroconsult on the basis of the extensive distribution network for the basin wide project.

The combination of cropping intensity and efficiency factors means that the Tahal analysis will produce a nominal irrigated area (they refer to it as a project area) 50% larger than the Euroconsult double cropping analysis and 125% larger than the Euroconsult triple cropping plan. There are other differences - Tahal used a higher transpiration rate, and a smaller percolation loss - but they have much less impact on the outcome.

For each case shown in the Table I-12, a trial simulation is carried out using the 10-year reservoir inflow series defined in Chapter 3. This ensures that the options are tested against a common inflow record. In all other respects, the JICA study comparative figures shown in the table are derived using the original irrigation requirements, operating rules and constraints defined by the respective consultants. These comparative figures are not intended to be definitive results; they are for comparison only. The simulation method used is non-iterative and, without more detailed data on the turbine characteristics, the power and energy figures are approximate. Also, the treatment of the tributary inflows is not clear from the consultants' reports, and it is assumed that they are neglected. Thus the JICA study figures underestimate the irrigation potential by about 10%, but the power and energy output is unaffected.

Nevertheless, with few exceptions, the comparison confirms the different consultants' results. The main exceptions are the figures produced by Tahal in the case of the higher dam. The large increase in project area, especially for low firm power, is not substantiated. The reservoir simulation using the 10-year series showed that the additional storage is not filled often enough to offset the impact of the poor inflows in the dry years.

5.4 Comparison of the reservoir inflow series

The storage provided by the proposed reservoir on Prek Thnot is not large relative to the mean inflow. SMEC consider that an active storage of about 1000 mcm (about 80% of mean annual inflow) will be optimal. Tahal think there might be net benefit in a higher dam, but still giving an active storage of the same order as the mean annual inflow. Thus, the reservoir can provide only limited over-year storage capability. From reservoir trials it is seen that failure to meet demand is caused by a single wet season of low inflow, although the failure is more severe and prolonged if inflows at the beginning of the following wet season are also below average.

This means that an annual analysis is almost as reliable as a time series analysis of the response of the reservoir. The key factor is defining the annual inflow with the selected probability of non-exceedance, such as the 1 in 5 year low inflow year. It also means that Tahal's approach, in which non-consecutive years of data are treated as a continuous series, is acceptable. The probability distribution of inflows can only be made more reliable with additional flow measurement, or indirectly with rainfall measurement in the basin. The effect of poor correlation between long rainfall records at Phnom Penh and runoff at the dam site has been discussed already. Rainfall records in the lowland areas add very little useful information, and the extension or in-filling of the flow record needs rainfall data from the headwaters basin.

The Euroconsult 72-year series and the 10-year series from this study have already been described. Tahal combined the records for the old station at Kompong Speu with those from Thnuos Luong to give a 25-year discontinuous record, mainly representing flows in the 1920s and 1960s. They adjusted these data to obtain flows at the dam site by a scaling factor of 0.9. Thus, their inflow series should be comparable with that used by Euroconsult who used the same factor.

Figure I-27 compares the cumulative frequency distributions[3] of the three series discussed here. It is reasonable to conclude that:

a. the inflow for 1922 is an outlier to an otherwise normally distributed series,

b. the three series define roughly the same distribution,

c. there is no direct benefit from extending the series,

For comparison, the 1 in 5 and 1 in 10 low annual flows derived assuming a normal distribution are shown in the following table.

Comparison of sample statistics from the different runoff series (mcm)

	Tahal (1975)	Euroconsult (1992)	JICA study (1994)
Mean annual inflow	1262	1227	1334
1 in 5 low annual flow	882	941	969
1 in 10 low annual flow	684	792	779

Note: Where relevant the data for 1922 have been ignored in these estimates.

There is reasonably good agreement between these figures and especially between those of Euroconsult and those derived in this study. The JICA study estimate of the mean is a little higher for the 10-year period because of the greater influence of the very high runoff in 1970 in

3 The graph is plotted so that data conforming to the normal distribution will plot as a straight line.

the short series. On average the Euroconsult and Tahal figures should be slightly underestimated[4].

This apparent agreement about the flow regime at the dam site does not necessarily mean that the result is reliable. It means that from a limited amount of data, three alternative approaches have resulted in similar figures. There is no guarantee that the long term (or even flows over the next 50 years) will conform to the same sample distribution. The statistics of the parent distribution (of which present knowledge is a sample) are not known. There are also significant differences between the estimates of flow for the same years in the different series.

5.5 Conclusions

The main result of this analysis is that differences between the irrigable areas with the dam can be explained almost entirely in terms of the different cropping intensities and irrigation efficiencies used by the consultants. If the Euroconsult figure for efficiency of 55% is accepted as the more realistic, then the actual irrigated area (in terms of maximum cropping intensity) is approximately that given by the SMEC/Euroconsult analysis. The benefits of one cropping plan over another are matters for wider considerations than just the water resource issue alone, and they are not discussed here..

The main cause for uncertainty lies in the estimation of the probability of low flows from the limited flow data available. It is known that 1963 and 1968 were dry years. But whether they were the driest years in 10 years indicated by the use of only the best flow data, or the two of the driest three years in 72 as suggested by the Euroconsult record extension, remains an open question. The correlation with rainfall, used by Euroconsult, is not strong enough to give a reliable answer to this question.

In terms of the water balance, the following factors tend to lead to overestimates of irrigable area:

a. not considering the joint probability of high irrigation demands (due to low rainfall) and low inflows,

b. using an inflow series that is less variable than the observed flows suggest.

These factors will lead to underestimation of the irrigable area:

c. reducing flows at Thnuos Luong and Kompong Speu by 10% to estimate inflows to the reservoir,

d. using a short inflow series in which very dry years might be over-represented,

e. not taking account of the significant tributary flows downstream of the dam by virtual storage in cases where maximum firm power is not the primary objective.

The balance between these factors should be evaluated by a more detailed hydrological analysis than has been undertaken so far. While this is not within the scope of this Project, many of the relevant issues have been reviewed here.

For present purposes it is reasonable to accept the SMEC/Euroconsult estimates of irrigable area based on rice cultivation alone. The areas resulting from a different cropping plan, less demanding of water, should be larger. But the increase might not be large if firm power generation is the most beneficial use of the water available.

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4 Euroconsult and Tahal derived flows at the dam site by adjusting flows observed at Thnuos Luong and Kompong Speu in proportion to the difference in basin area. The reduction of 10% is probably too large an adjustment for reasons discussed in Chapter 3.

6. HYDROLOGICAL OBSERVATIONS

6.1 Hydrological stations

It is unusual to attempt to initiate long term hydrological monitoring during studies for a development project. Such work is more often carried out as a separate infrastructure project. The sheer amount of time and effort involved in setting up hydrological stations is not easily reconciled with the demands of a short term investigation. However, the complete breakdown of environmental monitoring in Cambodia over nearly two decades makes it imperative to re-establish measurement of the water resources of the Prek Thnot basin, now that there is some prospect of substantial rural and irrigation development. Continuity with the historical data is achieved by establishing stations at or near to the sites of historical stations; a wider perspective on the operation of the river is gained by adding new stations at other key locations.

Seven hydrological stations have been established at the sites shown on the Location Map. Of these, the station at Peam Khley (dam site) is near the site of the historical station at Anlong Touk, and the station at Thnuos Luong is at the same location as the historical station. These stations, together with one at Prey Phdau, are intended to provide detailed discharge data for Prek Thnot. Two stations on Stung Toch are intended to record the intermittent flows that are expected in about three months of the year. The station on Tonle Bati is intended to provide information on lake levels and outflows through the control gates on Highway 2. The final station on the outlet of Boeng Cheung Luong is intended to monitor lake levels and outflows through the control gates at O Andong.

Construction of the stations was completed in December 1993. They are all equipped with float-operated recorders using continuous paper charts. A slow clock speed of 6 mm/hour means that routine chart changing is necessary only at 3-monthly intervals, although more frequent visits are desirable to ensure that the stations are functioning correctly. In addition, gauge boards have been established by the Bureau of Hydro-Meteorology (BoHM) to monitor upstream and downstream levels at Roleng Chrey and are planned for other locations including Kompong Tuol.

Progress with this element of the project has inevitably met certain difficulties. The field investigation phases have both been largely during the drier months, and flow in the smaller rivers was not observed during these periods. It may be some time before a good rating curve is developed, although it is hoped that the record of water level can be maintained with 3-monthly visits to the site.

The operation of the Roleng Chrey gates (discussed in more detail in Chapter 7) has had the biggest impact on the field work in this period. When the gates are closed, flows in the river downstream are very low. When the gates are opened, the flow increases very rapidly, remains stable for a period of some hours, and returns to low flow quite quickly when the gates are closed again. Water level changes of the order of 1 cm/minute are seen, which makes discharge measurement very uncertain. Also, the lack of communications means that field work cannot be planned properly; there is no way of predicting the likely discharge in the river, and therefore the equipment needed to measure it. On a few occasions it has been possible to arrange for gate operations specifically to ensure a moderately high and relatively constant discharge during a specific period. In these cases, some advantage has been gained from the gate operations.

Establishing new hydrological stations with a view to long-term operation and maintenance is impossible without the support and active participation of the relevant Government departments. Operation and maintenance costs must be met in the future, and skilled staff are needed to carry out discharge measurements for calibration of the stations, and to maintain and process the flow of data so that a useful record can be built up. The staff of the BoHM based at Pochentong have provided invaluable assistance during the period of field investigation, and they are well able to continue the development of the hydrological network.

Valuable training in field measurement and data processing and analysis procedures has been provided by Sok Saing Im from the Mekong Secretariat, and this work should be continued.

6.2 Data collection

Continuity of water level records is now being achieved for most stations. There are gaps in the records in the early months of 1994 when the charts were not changed. However, there has been no flow in Stung Toch (up to the end of July 1994). The recorder at the upstream station on Stung Toch has been disabled frequently by vandals, but there has been no damage to the other stations.

The recorders themselves have functioned well. Time-keeping is accurate and pens and chart motors work reliably despite the hot and humid conditions. There is some evidence of siltation of the inlet pipes and possibly of the float well itself in some cases. Improvements in the geometry of the inlet pipe and the need for regular flushing of the well system to remove sediment has been discussed with the BoHM and Mekong Secretariat staff. The float at the Thnuos Luong station may be sticking at low water levels, and the recorder is being remounted to avoid this problem.

Discharge measurement has been concentrated on the three stations on Prek Thnot. Initially it was intended to carry out same-day discharge measurements at Thnuos Luong, Prey Phdau and at Kompong Tuol to evaluate any changes in discharge down the river. But, the difficulties caused by the operation of the Roleng Chrey gates made this an inappropriate strategy. During gate operations flood waves pass down the river resulting in an apparent increase or decrease in flow due primarily to the relative timing of a flood wave, and this has no relevance in resource terms. Considering the logistics of measurement by boat, it was decided to concentrate available resources on the measurement at one station, Thnuos Luong, and to make measurements at other stations less frequently.

Measurement using wading rods is possible only at low flows. All other measurements have been taken from a boat using the BoHM derrick and cable system. The detail of individual measurements, in terms of number of verticals and number of velocity measurements in each vertical, has depended on the rate of change of discharge discussed above. Comparison of the two different current meters used and of the different propellers for the BoH meter was made and small but acceptable differences were found.

For immediate project needs, the water level data have been processed as required. Routine processing by the BoHM will be carried out using HYMOS software which is compatible with the HYDATA software used by the Mekong Secretariat.

6.3 Provisional rating curves

Provisional rating curves have been defined for the three stations on Prek Thnot. Except for low and medium flows at Thnuos Luong, which can be defined from the discharge measurements, the rating curves have been derived by indirect methods. Manning's equation has been used, based on survey information for river cross-sections and estimates of slope and roughness.

$$Q = \frac{AR^{2/3} S^{1/2}}{n}$$

where Q is the discharge (m^3/s),
A is the area of flow (m^2),
R is the hydraulic radius (area/wetted perimeter) (m),

s is the slope of the river bed, and *n* is a measure of roughness.

Manning's equation works well in straight river reaches of uniform cross-section, conditions that are difficult to find in the lower river below Roleng Chrey. The river section changes markedly over short distances and there are no 'good' sections to use for the indirect estimation of discharge. Sections that appear to be representative of the general river shape at the hydrological stations have been surveyed to provide the area and hydraulic radius curves.

There appear to be two main controls on the morphology of the lower river. One is the bedrock seen in the river just downstream of the Highway 4 road bridge at Thnuos Luong; the other is the level of the Tonle Bassac. Between these two major controls, the river meanders across its flood plain, the low flow channel itself meandering within the wide main channel. The slope is consistent with this general behaviour, but not steep enough to cause braiding.

Slopes have been estimated from known elevations and measurement of river and flood plain length. The data shown in Table I-13 show the variation in these factors along the river. Excluding the upstream basin, slope is a maximum near Kompong Speu, downstream of the bed-rock control. Thereafter, slope declines to the confluence with Tonle Bassac.

At Peam Khley, in the foothills, some gravel and larger rocks are seen in the river bed, but the river flows in a bed of coarse sand in the lower reaches. Finer materials are seen in the banks, which are friable and subject to erosion during intermittent floods. The removal of sand for construction is extensive and is causing changes to the low flow rating of some reaches. There is generally some thick vegetation covering the river banks except where they have been eroded to vertical cliffs, but little in the river bed itself. Generally, the amount of vegetation is less downstream than at the upstream sections. This suggests that it is appropriate to use a variable value of Manning's roughness coefficient (n). Values in the range of about 0.03 for low flows, up to 0.08 high flows, are used depending on water level and local conditions.

Discharge measurements and the shape of historical rating curves where relevant, have been used to help determine suitable values for roughness at each location. The provisional curves used in the flow analysis in this report and the discharge measurements, are shown in Figure I-28 to I-31. The curve derived by indirect methods for Peam Khley has broadly the same shape as the old rating for the Anlong Touk site a few kilometres downstream. The curve for Prey Phdau cannot be checked in this way; this is a completely new station.

The provisional rating curve for Thnuos Luong is defined entirely from the recent discharge measurements. The two measurements of high discharge were made during the August 1994 flood discussed below. A two-part rating is appropriate, and is defined by the curves:

This rating is illustrated in Figure I-30. The old rating was also described by a 2-part curve with the break occurring at a level of 1.5 m on the old gauge. Unfortunately, there are not yet sufficient discharge measurements to judge where the break point should occur, or to judge the accuracy and stability of the new curve.

Continuing discharge measurement by the BoHM, over a wide range of flow conditions, will eventually enable these provisional curves to be replaced by more reliable ones based on sufficient direct measurements to ensure acceptable accuracy, especially at high flows.

The accuracy of flow estimation depends also on the accuracy of the water levels recorded on the charts. Each time a station is visited - for routine checking and chart changing or for discharge measurement - the chart is marked with the date, time and current water level as observed on the staff gauge. Thus the operation of the float and recorder system can be monitored.

Figure I-32 shows a comparison of chart and gauge water levels at the Thnuos Luong station. Most lie on a 1:1 line showing good performance of the recorder. Small differences can be caused by lag in the float well system when water levels in the river are changing rapidly. However, at low water level, there is evidence that the recorder and float system is not recording properly. The float is very near one side of the float well and may be snagged at low water level. Also, there is the possibility of silt in the float well restricting downward movement of the float. The recorder is being re-positioned and further checks will be made. Meanwhile, some correction is necessary to the discharges derived from the water level record for low flows at this station. The rating itself is not affected as it is derived using water level measured on the gauge boards.

6.4 Estimated flows

Given the influence of the operation of Roleng Chrey on the flows in the river downstream, the flow analysis using the new data is directed towards describing the effect of gate operations well enough to allow development of new operating policies for the future. Mean daily flows have been estimated for all periods of water level record, but more detailed hydrographs have been computed for those periods when gate operations have caused flood waves to pass down the river. Simple gate operations were made on 26 May, 10 June and 3 July 1994. The period from 8 July - 27 July 1994 was characterised by a number of moderate flood inflows from the upstream basin, and a series of multiple gate openings resulting in the highest flows in the observed record to date[1]

Comparative hydrographs of mean daily flows are shown in Figure I-33. The more detailed hydrographs are analysed and discussed in Chapter 7. Unfortunately the record from Peam Khley is incomplete. It is known that a significant flood occurred in March 1994, but the records of Roleng Chrey gate operations suggest that there was no other significant flood inflow until May 1994. The records for Thnuos Luong and Prey Phdau are also incomplete, but they confirm the visual evidence that flows in the lower river are little more than the leakage flows from Roleng Chrey for much of the time.

None of these data alter the water resources estimates based on the historical data described in the Chapters 2 to 5 of this Annexe. If the discharge measurements are continued, to provide good rating curves for the stations, it will be possible to update the resources estimates significantly in a few years time.

6.5 Boeng Cheung Luong

While the response of Boeng Cheung Luong is not central to this resources side of this project, the levels could influence drainage from the Priority Project area. The hydrological regime of the lake is complicated and the records available do not yet allow a good description of all the processes involved in its seasonal behaviour. The following description is based on the limited evidence:

_ As water levels in Tonle Bassac fall at the end of the flood season, water drains rapidly from Boeng Cheung Luong towards Tonle Bassac, usually during November, December and January. It is possible that free flow conditions exist at O Andong gate during these high flows when the gate itself acts as a hydraulic control on the rate of outflow. As the upstream level falls, the outflow becomes increasingly controlled by the downstream (possibly Tonle Bassac) level, although water continues to drain slowly out of the lake for a few more months.

a. When the water level begins to rise in Tonle Bassac, usually in May or early June, the flow reverses and water flows into the lake. In years when Tonle Bassac rises

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1 Data up to 27 July 1994 were processed for the analyses in this report, although, for logistical reasons, data from Peam Khley could only be obtained up to 20 July. It is hoped that BoHM will continue to investigate the effect of Roleng Chrey operation during the high flood season.

fast - 1994 is an example - flow into the lake could be substantial through O Andong gate in June and possibly July. But, it is not clear whether Boeng Cheung Luong receives most of its water in this period from the north via the Prek Thnot channel at Takhmau or from the O Andong channel. It is clear that the water must derive from Tonle Bassac as flows in Prek Thnot itself and the smaller rivers are inadequate to cause the rise in lake levels observed.

b. During August, September and October thc variation in lake level depends on the balance between inflows from the upstream basins and the water levels in Tonle Bassac. Generally the flow from upstream Prek Thnot passes into Boeng Cheung Luong via the channel from the Highway 2 bridge upstream of Takhmau, possibly with continuing inflow from Tonle Bassac. Peak water level in Boeng Cheung Luong occurs at roughly the same time as the peak level in Tonle Bassac, usually in September or October.

As yet there is no gauge on the downstream side of O Andong and it is not possible to define the flow history precisely. However, Figure I-34 shows the water level hydrograph from the hydrological station on the upstream side together with the water level in Tonle Bassac from the station operated by the BoHM at Chaktumuk[2]. The Chaktumak record is relative to mean sea level; the O Andong record should be adjusted to true elevation when the datum level is established.

6.6 Meteorological station

A meteorological station for agricultural purposes was established at the Tonle Bati Centre in December 1993, and data are available from February 1994 following training of the observers by staff of the BoHM. The site is well exposed. It is raised on a low platform of soil to avoid flooding, and is surrounded by rice fields and a small pond, an environment that is typical of much of the project area.

A summary of the records to date is given in Table I-14. Except for sunshine hours, these data are comparable to the average figures for Pochentong on which the estimates of crop water requirements are based. Sunshine at Tonle Bati is measured by a special sensor and the output is integrated on a chart using the same format as a tipping bucket raingauge. Records at Pochentong are obtained by manual analysis of a traditional Campbell-Stokes instrument. It is possible that there are real differences between the two stations, but more likely that there is some systematic bias in one or other of the methods of measurement. A longer period of record from Tonle Bati is needed before firm conclusions can be drawn and it would be prudent to install a Campbell-Stokes instrument at Tonle Bati for a period of comparative observation.

6.7 Conclusions

The majority of the hydrological stations are functioning well and providing useful data. There are a number minor problems which can be rectified easily. The station at Tonle Bati should probably be replaced by a series of daily-read staff gauges and the recorder deployed elsewhere. Maintenance, and particularly the removal of silt from the inlet pipes and float wells by flushing, will be carried out by the BoHM who will also take responsibility for data processing using their in-house software. It is understood that some of the data will be passed to the Mekong Secretariat and also made available to other organisations.

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2 This station, established in 1992, is located at UTM 5065 12372.

The data collected so far allow some understanding to be gained of the impact of gate operations at Roleng Chrey. The flood waves can be tracked down river and it should be possible to use this information to define an operating policy for Roleng Chrey that takes account of the future objectives in the distribution of available resources in the Prek Thnot basin.

7. OPERATION OF ROLENG CHREY

7.1 Introduction

Roleng Chrey regulator was completed in 1973, forming part of the multi-purpose project that included the dam on Prek Thnot. Although construction of the dam was halted by the war, the regulator and 4 km of the left bank main canal were completed, and the canal was extended subsequently. The 6.7 m high gates can raise the water upstream to about bank-full level. Consequently the regulator can hold back a substantial volume of water, so much so that Euroconsult concluded that storage over a fairly narrow range of upstream water level would be sufficient to re-regulate the diurnal variation of releases from a dam operated primarily for hydropower. Flows into the left bank main canal are controlled by 4 m high radial gates. Diversion of water into two small canals on the right bank is not controlled other than by a general lowering of the upstream water level.

The operation of the regulator has a major impact on the river downstream. In the dry season, when river flows are naturally low, a substantial part of the flow can be diverted at Roleng Chrey, leaving only leakage flows in the river. Thus, the operation of Roleng Chrey affects the amount of water available at Kompong Tuol in the critical periods for irrigation. In the flood season, the timing of gate opening can influence the peak discharge of moderate floods.

There has been no study of the impact of Roleng Chrey under the existing operating regime; there were few data on which to base such an analysis. Yet improved river management must take account of the existing distribution of water and the constraints under which existing structures operate. Data from the hydrological stations established during this study are used to describe the effect of some recent Roleng Chrey operations. From this work it is possible to define an operational strategy for the future that will allow the natural water resource to be shared between irrigation areas along the river. Other technical issues are reviewed here and the need for improved institutional arrangements is identified.

7.2 Records of operations

The gate operator keeps a partial record of operations both of the main control gates and the gates on the left bank main canal. Data from the current log book are summarised in Tables I-15 and I-16. These cover the period from June 1993. Data for earlier periods have been lost or washed away during the 1991 flood. The records may be reliable; they are certainly incomplete. During the field investigation, it was possible to visit Roleng Chrey regularly and to discuss recent operation with the operator. This is why there is much more information towards the end of Table I-15 than at the beginning. No records are kept of the water level upstream or downstream of the gates; there were no gauge boards. The Bureau of Hydrometeorology has recently installed gauge boards and is organizing daily observation. The gate operator is being requested to keep more comprehensive records including the time of gate adjustment or closure and the upstream water level at the time.

As a general rule, the water level at Roleng Chrey is maintained at the level of the top of the closed gates. When there is surplus flow from upstream - in excess of that diverted and leakage past the gates - the operator opens one or more gates an appropriate amount. This may follow a period when water is allowed to spill over the closed gates. Water is released until the upstream level has fallen several metres, when the gate(s) is closed, usually after a period of some hours. This results in the release of a substantial volume of water as the channel storage upstream of the gates is drawn down. Following gate closure, flow from the Prek Thnot catchment causes the upstream water level to return to the operating level, usually after a period of a few days. During the wet season, the operator tries to anticipate flood flows by simple observation of the cloud over the headwaters of the basin. If rain-producing clouds are seen on several successive days, the gates are opened by an amount based on the operator's experience and the season.

There may be some physical constraints that force this method of operation. The gates are well counterbalanced, and it is understood that they cannot be closed when there is full hydrostatic pressure against them. This is probably the reason for substantial drawdown of upstream storage, a procedure that would not otherwise meet the simple objective of maintaining upstream water level.

It should be said that the operator of the structure has long experience of the river and is conscientious in the maintenance and operation of the control equipment. Although the operation appears to be informal - there is little alternative without some knowledge of the river flows from upstream - the operations seen during the field investigation period have been timely and sensible given the present objectives of maintaining upstream water levels and ensuring the safety of the structure. But, little consideration is given to the impact of operations downstream. The gates are usually opened quickly to the extent considered appropriate, much more quickly than the operator's log suggests. From observation of one gate opening, it is clear that one gate can be opened by one metre in less than five minutes. The impact of the flood wave downstream would be significantly reduced if gate opening could be staged, especially in cases where more than one gate needs to be opened.

The operator does not have the means to warn others (downstream of Roleng Chrey) that releases are being made, and whether these are made in anticipation of a significant flood from the headwaters. Consequently, the flood wave arrives at Tuk Thla / Kompong Tuol without warning. The rise in water level can be rapid, and can cause problems for the operators at the downstream location, where the gates can be opened only slowly.

Flows in the left bank main canal are also ungauged. On days when water is requested by the local farmers, the operator opens one gate in the morning by 30 - 40 cm and closes it again after 8 - 10 hours. There is no record of additional gates being opened and the cables required to open them are missing. However, it is possible for the farmers to open the one gate themselves - they are known to do so sometimes for fishing - and their activities are not logged by the operator. During the field survey, it was possible to observe flow conditions when one gate is open. Free flow conditions exist when the upstream water level is at the level of the top of Roleng Chrey gates, and it is possible to estimate the discharge and interpret the operator's log in terms of the volume of water diverted into the canal over the period of record.

There are two small canals taking water on the right bank. They are both uncontrolled and the flow taken depends only on the water level upstream of the Roleng Chrey gates. Direct measurement during the field survey indicates a total flow of about 1 m^3/s when the water level is at the normal operating level at Roleng Chrey. Aerial photography shows that there is a swamp area on the right bank, which is inundated at high water levels. The area is about 4 km^2, but the dynamics of this storage are not known. It does not appear to support flow in the larger of the right bank canals, as that canal is seen to be empty when the water level at Roleng Chrey is drawn down. However, it might act as a modest addition to river channel storage.

Estimates of flow at Peam Khley (upstream of Roleng Chrey) and from the new hydrological stations at Thnuos Luong and Prey Phdau (downstream) are discussed in the previous chapter. While these stations are not yet fully calibrated, the data can be used to help define the probable balance of flows at Roleng Chrey. Some less direct information is available. The small reservoir O Krang Ambel, downstream of Kompong Speu, was full by June 1994, much earlier than might be expected from rainfall during the first half of the year. As unused flows in the left bank canal feed into the reservoir, the high water level is an indication of significant flow in the left bank main canal in the preceding months. During July, the water level in O Krang Ambel fell significantly, probably due to the increased use of water for land preparation. However, there is insufficient information to link these observed changes directly with flows in the left bank main canal.

7.3 Flow analysis

The equations used to estimate releases from Roleng Chrey and the routing of flows downstream are given in Appendix A. Initial calculation showed that a short time step (not exceeding 1 hour) is necessary to compute the rapidly changing outflow from Roleng Chrey. Discharge under the open gates is combined with spill over the closed gates when the water level is above normal gate height.

Table I-17 shows the peak discharge[1] released from Roleng Chrey for combinations of number of gates opened and opening height. Discharges above 600 m^3/s are probably unreliable because it is likely that the water level downstream of the gates rises to a level that precludes free-flow conditions consistent with use of the equations. Under conditions of drowned flow, the discharge will be significantly less, and possibly very much less, than the equivalent free-flow condition.

The timings of events in terms of gate openings and the response of the flood waves at the downstream stations is shown in Table I-18. When a gate is first opened at Roleng Chrey, the flood rise is seen at Thnuos Luong about 1.5 hours later, and at Prey Phdau about 5 hours later still. The river distances are 7.6 and 17.2 km respectively. Thus, the flood wave appears to be slowing as it is attenuated in the empty river channel. This is consistent with the expected response. When a second gate is opened, the supplementary flood wave moves much faster, and the two waves appear indistinguishable at Prey Phdau when the second gate is opened within a few hours of the first being opened. These considerations help define values for K and x in the routing procedure.

Some insight into the present operating strategy can be gained by comparing hydrographs from the new hydrological stations, and simulating the operation of the gates to estimate the routed releases that should be observed at the downstream stations. The period 8 - 20 July is selected for detailed analysis. It includes a small flood from the upper catchment and a complicated series of gate operations. The hydrographs at Peam Khley, Thnuos Luong and Prey Phdau are known for this period, subject only to the limitations of the provisional rating curves.

Leakage is allowed for at a maximum rate of 0.5 m^3/s, and some allowance for diversion is made at a maximum rate of 1.2 m^3/s. Both of these flows are subject to water level constraints. In practice, they are small relative to the flow from upstream during the period considered here.

The result of this gate trial is shown in Figure I-35. The top graph shows the estimated inflow hydrograph from observations at Peam Khley. The other two graphs compare the hydrographs based on observed water levels at Thnuos Luong and Prey Phdau with the estimated routed releases from Roleng Chrey. The comparative daily flows are shown in Table I-19, and a comparison of daily observed flows with the routed gate releases for Thnuos Luong and Prey Phdau is shown in Figure I-36.

Agreement is reasonably good, suggesting that the computation of gate releases is substantially correct. Some errors of timing are inevitable given the imprecise records of gate movements. Also, uncertainty in the provisional rating curves used to derive the observed hydrographs limits the accuracy that can be expected in this analysis. Overall, there appears to

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1 These discharges refer only to flow under the opened gates when the upstream water level is at normal operating level. Spill over the unopened gates will increase these discharges at certain times.

be less water reaching the downstream stations than is seen at Peam Khley. The difference, equivalent to about 5 - 10 mcm over the 13 days is more than can be explained by diversion flows, and must represent the level of uncertainty in the provisional rating curves for the three hydrological stations.

However, it is beyond doubt that current gate operation procedure produces flood waves downstream of the gates that are of greater amplitude than the inflow floods from upstream. The peak at Thnuos Luong in this period was more than double the peak flow at Peam Khley. While it is possible, with hindsight, to criticise the operating policy for over-reacting to possible floods from upstream, it must be remembered that inflows are unknown to the operator; there is no warning system. Also, as events in early August 1994 show[2], a large flood can arrive suddenly, and the safety of the structure is better ensured by a measure of over-reaction.

By the time the flood wave reaches Prey Phdau, attenuation in the river channel has reduced the peak discharge substantially. It is probably a coincidence that the flood peaks of 14 and 16 July at Prey Phdau are almost the same as the inflow flood peak observed at Peam Khley. The channel storage down to Kompong Tuol causes further attenuation of the flood wave, but there are no direct measurements of peak flows downstream to calibrate the routing model.

This analysis demonstrates that, with a little more data, the impact of operations of Roleng Chrey could be defined to a good level of accuracy. More precise records of gate openings and water levels at Roleng Chrey, and more accurate ratings for the hydrological stations are needed. Meanwhile, the present information is sufficient to define a new operating strategy, and this is discussed below.

7.4 Water balance in the dry season

Plans for the development of irrigation in Kandal Stung and Tonle Bati under run-of-river conditions presume water sharing between all the schemes in the Prek Thnot basin. The division of irrigated area as defined in the Euroconsult report[3] is taken as the basis for calculating the run-of-river resource available at Kompong Tuol, and this limits the extent of the Priority Project area. As the upstream developments are not yet in progress, it is necessary to assume both the timing and amount of water to be diverted, so that the residual flows available at Kompong Tuol can be estimated. These estimates are based on the Euroconsult cropping plan for double cropped rice as described in Chapter 5.

Present diversions can be estimated only approximately. Discharge in the left bank main canal was observed at the control gate. Free flow conditions were observed during a period when one gate was open, and was confirmed by hydraulic analysis. The head difference across the gate was estimated to be 1.86 m. For a gate width of 4 m and an upstream water depth above the gate cill of 2.5 m, the discharge would be about 7.4 m^3/s. Over a 9 hour period, this gives a total volume of about 0.24 mcm.

The discharge in the right bank canals was measured at a time when the water level upstream of Roleng Chrey was about 5 cm below the top of the closed gates. The larger of the two canals carried about 0.55 m^3/s, the smaller one carried about 0.45 m^3/s, although there were also some small diversions into adjacent fields at that time. Leakage from the Roleng Chrey gates is estimated to be about 0.5 m^3/s at full operating level.

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2 The major flood of 3 August 1994 is discussed in Chapter 8.

3 Euroconsult, Prek Thnot Multipurpose Project, Reappraisal Report Vol 5 - Irrigation, Jan 1992.

Using this information, the monthly diversions are estimated for the dry season months (December to July) and compared with the expected demand that would apply under the Euroconsult plan. The latter figures are those defined in Chapter 5, but reduced to allow for only 1400 ha of the 1700 ha being upstream of Roleng Chrey. The results are shown in Table I-20. It is assumed initially that the right bank canals flow for 90 % of the time subject to the availability of water and the maintenance of sufficient head at the gates. Under these conditions, and the present operating policy, it is not expected that the gates would be opened at all.

This comparison suggests that present diversions are greater than the design assumptions based on the Euroconsult cropping plan for the upstream areas in some months, notably February, March, April and June. This comparison is subject to a wide margin of error as there are no firm data on present diversions. Nevertheless, it strongly suggests that the water expected in the lower river will not be available unless there is a change of operating strategy at Roleng Chrey, and the control of releases for use downstream is made a priority. Otherwise, only leakage water will be available downstream during the critical months, and the planned water sharing will not be realised.

7.5 Operation for water sharing

Given the uncertainties of present diversions, it is not easy to define an optimum operating strategy for the Roleng Chrey gates, but several important considerations can be identified:

a. during the critical periods (assumed to occur 1 year in 5 on average) there will be periods when there is insufficient water to meet the planned irrigation demand. In these times, water shortage should be shared equitably between upstream and downstream users;

b. water level upstream of the gates must be maintained at a high level, at least for part of the time, to allow water to enter the canals, principally the left bank main canal;

c. releases to meet downstream requirements must be distributed in time such that, given the attenuation of the hydrograph in the river channel and the small amount of storage available above Kompong Tuol, the flows meet the irrigation schedule required in the Priority Project area;

d. diversions by the right bank canals can be controlled only by lowering the upstream water level unless and until gates are constructed;

e. operation during periods of surplus flow can be, and may need to be, different from those during periods of low flow (including critical periods);

f. the operation must always be sensitive to weather conditions and the need to pass excess flows from the upstream basin;

g. allowance should be made for the leakage of the gates under present conditions.

In addition there are several operating constraints, some inherent in the design of the structure:

a. there is presently no monitoring of available discharge, and the operation of the gates is not formally documented; therefore, the resource is not known and the release from the gates is not known;

b. accurate control of small releases is impossible, the gates were not designed for this purpose;

c. there may be some difficulty in closing a gate unless the hydrostatic pressure is reduced by allowing the upstream water level to fall substantially below the top of gate level;

d. there is not, and cannot be, an adequate warning system for flood flows from the upstream basin while poor security conditions persist.

Until there is more information available on the use of irrigation water in the upstream areas, it is not worthwhile trying to optimise the gate operation to meet the stringent requirement of water sharing during critical periods. The result would be hypothetical as the upstream farmers do not know about and are not following the Euroconsult cropping plan. The present idea of water sharing is therefore a more broad principle that cannot be interpreted directly on a short time scale. It is therefore proposed to consider an operation procedure that approximates the general idea by providing the known, required river discharge to the downstream area in the supposed critical year.

It is possible to rule out a strategy of continuous operation, particularly in the dry season for the following reasons:

a. the gates are too insensitive to ensure a small constant discharge;

b. a small discharge risks erosion at the foot of the tailwater channel if the hydraulic jump forms further away from the gates;

c. it might not be possible to maintain upstream water levels under constant discharge conditions during critical periods of low inflow.

Thus, a realistic strategy should be based on dynamic operation of the gates. The following sequence is envisaged over a seven-day period:

a. the upstream water level is maintained for a few days (gates closed) while diversions are made to the existing canals feeding the upstream irrigation areas;

b. one gate is opened to send water downstream as a low flood wave, the upstream water level falls, and the upstream canal flows cease;

c. when sufficient water has been released downstream, the gate is closed, and the upstream water level slowly rises, allowing diversions upstream to recommence.

This cycle can be defined to share the water equitably. Variation in the timing and scale of releases downstream can be made for the changing demands for water through the irrigation seasons, and in response to the different inflow regimes[4]. The cycle could be interrupted at any time by the need to pass a flood, and the cycle would normally be suspended or modified during the main part of the wet season when the distribution of water for irrigation is not at issue. Operation of the gates during flood periods is discussed in the next section.

Figure I-37 illustrates a result of a cyclical operating strategy, in this case the objective is to share equally an average inflow of 2 m^3/s (equivalent to 5.2 mcm/month) between releases/leakage to the river downstream and diversions into the upstream canals. This calculation has involved making assumptions about the relationship between water level upstream of Róleng Chrey and the diversion flow, particularly into the uncontrolled right bank canals. Balance is achieved by finding an operating level (by trial and error) that achieves the intended balance of outflows, while ensuring that the water level at the end of the cycle returns to the starting level so that the procedure can be considered to be sustainable. The release due

4 During the critical low flow periods, the rate at which the water level rises behind the gates is a measure of the inflow and provides useful information in the interpretation of an operating strategy.

to gate opening can be varied to suit the requirements of irrigation scheduling at the downstream location. It will always be substantially attenuated so that it appears as a longer, flatter flood wave at Kompong Tuol.

If this strategy is adopted - and there does not seem to be a realistic alternative given the constraints identified above - more detailed data are needed to define more accurately the relationships between diversions and water level, and the characteristics of the river channel storage above Roleng Chrey. Given this information, the strategy can be interpreted for each week of the dry season in response to the changing balance between upstream and downstream demands.

Inevitably, the introduction of planned water sharing and formal operation of Roleng Chrey gate will require some changes in the irrigation regime in the areas currently benefitting from free water flowing in the canals. The approximate flow balance described above suggests that less water will be available in some periods than is presently distributed, resulting in some economic impact in those areas, attributable to the changed water regime. There is also the danger that downstream demands will be given priority without regard to the existing upstream users. The institutional implications of a more formal operating policy are self evident and the needs for policy formation, technical support, measurement and communications are examined elsewhere in this report.

7.6 Operation during floods

The upper limit to the capacity of the gates is not known. If free-flowing conditions are assumed, the nominal gate capacity is several thousand cubic metres per second. But this is far more than the capacity of the river channel both upstream and downstream of the structure, and free-flow conditions could not exist at very high flows. The true limit to the gate capacity is probably of the same order as the channel capacity, something less than 1000 m^3/s.

It is unlikely that the timing of gate opening would significantly increase the flood peak further down the river during a major flood; the storage commanded by the gate is too small, and there would be substantial flow around the structure on the flood plain. However, the safety of the structure itself would be at risk if the gates were not opened in reasonable time. There are no substantial impediments to flow down the flood plain near Roleng Chrey, and this benefit is discussed further in Chapter 8. Detailed analysis of the operation under severe flood conditions is not possible until much more information is assembled on the topography of the area and flood levels experienced[5].

For minor floods, there is some limited opportunity to use the channel storage upstream of the gates to delay and reduce the peak flows that would have occurred downstream. For example, a storage of only 3 mcm can be used to reduce a 200 m^3/s, 24 hour flood[6] to a peak flow of less than 100 m^3/s. But this requires a sophisticated gate operating procedure and implies advance knowledge of the shape and volume of the flood from the upstream basin. Such a flood warning system is completely impractical now for security reasons. The gates must be operated 'blind' and there is some evidence that present operations increase rather than reduce flood peaks downstream during moderate floods.

The analysis of gate operations described above shows that floods of significant magnitude can be generated just by the release of upstream channel storage. If the two gates are opened quickly to 2 m, a flood peak of over 300 m^3/s would be created. This flood hydrograph would be attenuated quite quickly if the flood wave was released into a

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5 A recommendation for detailed flood studies has been made in Snowy Mountains Engineering Corporation, Report on the Rehabilitation of the Kompong Tuol Road Dike, Feb 1993.

6 A triangular inflow hydrograph is assumed.

downstream channel carrying only a limited baseflow. Nevertheless, such a flood wave could cause some problems at structures downstream if it arrived without warning. However, some simple restrictions on the rate of opening of the gates, especially when there is no visible flood threat from upstream, would go a long way to limit the potential problems downstream. Radio communication between operators would allow precautionary lowering of water levels at Kompong Tuol when substantial flood releases are made at Roleng Chrey.

A dynamic (cyclical) operating regime, discussed above in the context of fair distribution of the waters, will mean that the average storage level upstream of Roleng Chrey is lower than now, at least for the dry season and during the early months of the wet season. This should make it easier to respond to moderate flood flows from the basin, and may result in some reduction in the impact of these floods downstream.

7.7 Conclusions

The present operating policy for the Roleng Chrey gates does not produce sufficient flow in the lower river to meet the expected diversion requirements of the project in the critical low flow months. Preliminary consideration of the changes in operating strategy, needed to ensure the timely availability of a fair share of Prek Thnot water at the downstream irrigation schemes, suggests that a cyclical operation plan is appropriate. It may be the only feasible option given the constraint of supplying the farmers in the upstream areas from the existing canals. More detailed data and analysis is necessary to interpret the strategy in terms of week to week operation.

It is inevitable that the water available to upstream farmers may have to be reduced or at least supplied in a more systematic way than has been the case in past years. This issue needs to be addressed and a feasible operating strategy defined, together with the institutional arrangements to ensure coordinated operation of Roleng Chrey and Kompong Tuol structures.

While flood warning from the upstream basin of Prek Thnot would be a great benefit to the safe operation of structure on the river, it is recognised that it is infeasible at present. However, it should be given high priority when security conditions allow. Meanwhile, policies that imply advance knowledge of inflows should be avoided, and it must be accepted that moderate flood peaks can be fully attenuated by gate operations.