Preliminary

Prepared for:

Mekong River Commission

Inflow to the Mekong delta

Discharge rating curves for Pakse, Stung Treng and Kratie

December 2009

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HJM Ogink

February 2009

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1 Introduction

In this report the discharge rating curves of Pakse, Stung Treng and Kratie are reviewed to arrive at reliable inflows to the Mekong delta for use in the hydraulic model for flood hazard assessment. The upstream boundary of the hydraulic model of the delta is formed by the discharge at Kratie. To validate and compliment the data available for Kratie use can be made of station Stung Treng as strong correlation exist between the water levels at the two stations and the discharge at both sites will be almost equal. Pakse is used to validate the flow at Stung Treng and Kratie. Though a large volume of water is entering the Mekong from the Se San and tributaries in between Pakse on the one side and Stung Treng and Kratie on the other, it may be assumed that the ratio of the flows between the up and downstream stations remains approximately the same. The advantage of using station Pakse is that the discharge rating happens to be very stable due to the rocky control section.

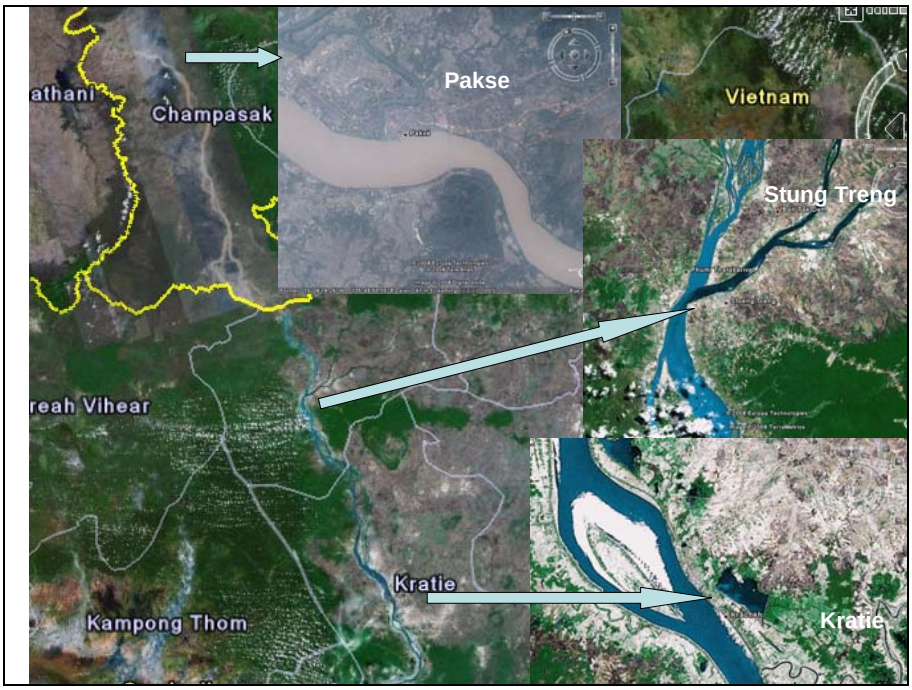

Figure 1.1 Mekong River at Laotian-Cambodian border showing the locations of Pakse, Stung Treng and Kratie

The set up of the report is as follows. The three stations are discussed one by one from upstream to downstream.

- In Chapter 2 the data of station Pakse is discussed, including the station layout, the available water level series and stage-discharge data. The quality of the data is reviewed. Special attention is given to flood plain flow bypassing the station prior to 2002 unmeasured. Data from Khong Chiam, Nam Mun and Se Done have been used to quantify this amount.
- Next, in Chapter 3 the data of station Stung Treng is reviewed similar to Pakse. Different discharge series have been created for Stung Treng for the years 1999-2006 (one based solely on current meter measurements and one based on ADCP-measurements) and validated based on a comparison with the flow at Pakse for the

periods 1960-1969 and 1999-2006. The discharge measurements carried out in 2008 at Stung Treng with ADCP have been compared with the previous rating curves.

- Finally, in Chapter 4 station Kratie is described, its water levels and rating curves reviewed. Water level relation curves with Stung Treng and their development in the course of time are presented to be used to transfer upstream rating curves to Kratie for validation purposes. Recent ADCP-measurements (2008) carried out at Kratie are reviewed and compared with previous ratings. A comparison is made of the assumed discharge rating and the applied discharge rating in calibrating and validating the hydraulic model of the Mekong delta using ISIS.
- In Chapter 5 conclusions are drawn on the quality of the data and recommendations made for improvement.

This report is a revision of and extension to Appendix 8 to Annex 1 of the Stage 1 Evaluation Report.

2 Mekong at Pakse

2.1 Station description

Station Pakse on the Mekong river is located on the right bank of the river, downstream of the mouth of the Se Done and the new bridge across the Mekong, see Figure 2.1. The station is at about 869 km from the sea and covers a drainage area of 545,000 km^2.

Figure 2.1 Location of old and new Pakse gauging station

Before 2003 the gauging station was located upstream of the new bridge across the Mekong at Pakse in front of the Water-borne Transport Office at lat. 15°07' N and long. 105°48'0". This station was equipped with a vertical and inclined staff gauge; the zero of the gauge was at 86.490 masl (Ko Lak datum). From 1960 till 1973 a bubbler gauge was operational at Pakse. Discharge measurements at Pakse were made from a boat some 50 m upstream of the gauge. The bridge was built in the period October 1997 till August 2000 and affects the water level readings by backwater. Therefore, on 4 June 2002 the gauge location was shifted to the right bank downstream of the bridge, equipped with an inclined manual gauge and a Mindata make automatic gauge. Because the latter never functioned, in 2006 under the ANHIP project a new Ott make bubbler gauge was put in operation. The zero of the new gauge is 86.326 masl.

Based on the available historical water level records it is concluded that Pakse gauging station was established around 1902, although records of the first years are very fragmentary. The HYMOS database contains daily water levels as from 1960 onward. The discharge record of Pakse in the database starts in 1923.

2.2 Water level series

2.2.1 Availability in database

The HYMOS database, as available in FMMP-2, contains for Pakse a complete daily water level record for the period 1/1/1960-31/12/2006, relative to the old gauge datum of 89.49 masl.

The data archives according to the hydrological yearbooks for Pakse comprise:

- a complete or nearly complete daily gauge records of the Mekong at Pakse by the Laos Travaux Publics for the periods 1914-1918, 1922-193, 1927, 1932-1944, 1952-1973 and fragmentary records 1902, 1913, 1926 and 1945-1951. The daily records are derived from twice daily measurements from October to June; during the flood season the daily value is based on 11 (daytime?) readings.
- a daily record of bubbler gauge data for the period 1960-1973.

2.2.2 Validation and completion

The daily water level record stored in the HYMOS database has been validated by MRC in 2004 by comparison of hydrographs with nearby stations (MRC, 2004). Some anomalies were discovered then, but without follow up actions. Additional inconsistencies were discovered during this study and the corrections have been implemented in the database.

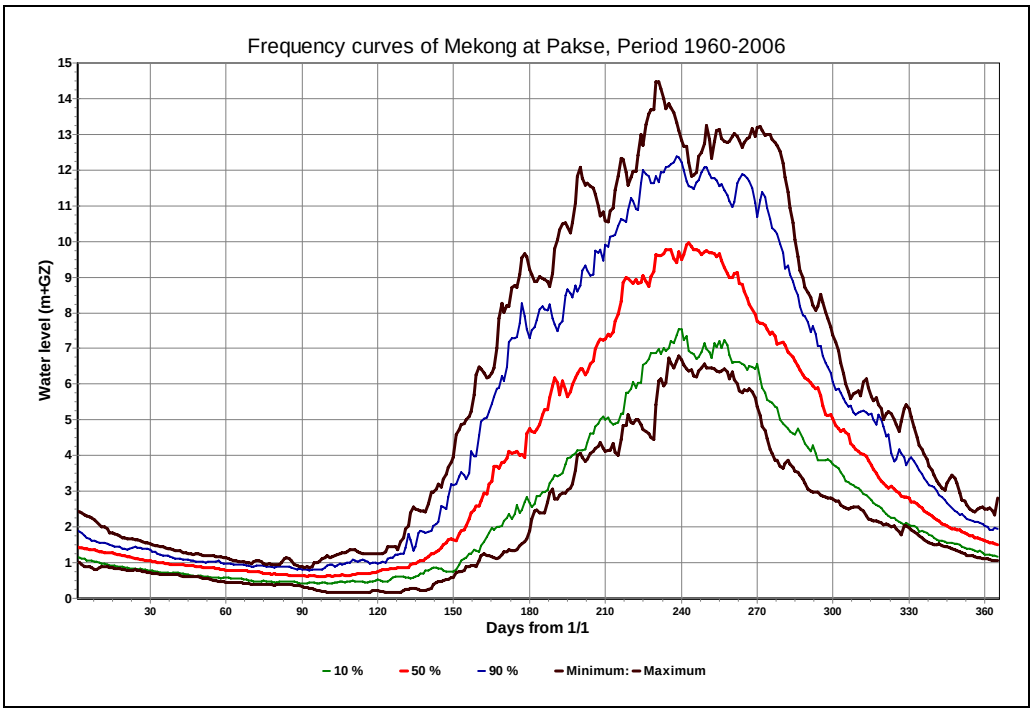

Figure 2.2 Frequency curves of the daily average water level of the Mekong at Pakse, Period 1960-2006

The water level range is seen to be from 0.16 to 14.48 m+GZ, with the lowest levels in April-May and the highest in August-September.

2.3 Stage-discharge measurements

2.3.1 Availability

An overview of the stage-discharge measurements available in the MRC HYMOS database for Pakse is presented in Table 2.1.

Table 2.1 Summary of availability and range of stage-discharge measurements for the Mekong at Pakse

Year	number	h-range (m+GZ)	Q-range (m^3/s)
1960	9	1.30-6.23	3,050-15,800
1961	108	0.30-12.83	1,360-42,800
1967	18	1.03-8.72	2,290-2,3200
1970	1	0.40	724
1971	12	2.08-10.75	3,091-25,824
1973	16	5.65-11.58	14,700-38,600
1986	8	1.30-2.99	2,810-5,970
1987	28	1.30-11.58	2,810-36,400
1990	22	2.01-10.06	4,290-28,870
1991	26	0.69-10.50	1,550-30,800
1997	29	0.80-11.99	1,614-39,989
1998	42	0.61-8.84	1,451-25,174
1999	32	0.46-10.15	1,258-30,291
2000	34	0.86-12.39	2,102-40,980
2001	34	0.96-12.32	1,956-40,782
2002	38	0.84-11.57	1,750-36,042

The total number of stage-discharge measurements is 457, covering a water level range from 0.30 to 12.83 m+GZ with discharges ranging from 724 to 42,800 m^3/s.

2.3.2 Validation

In absence of details of the stage-discharge measurements simple consistency checks were carried out on the applied water level and on outliers in the stage-discharge plot.

The water levels entered with the discharge measurements have been compared with the daily average water level record of Pakse. Measurements were flagged when deviating more than 0.1 m from the daily average water level. When the flagged water levels appeared to be clearly inconsistent with those of the water level series the discharge measurement was eliminated from the data set. In total 12 measurements appeared to be inconsistent.

Next, checks were carried out on outliers in the stage-discharge plot. Reference is made to Chapter 4 for a detailed discussion on outliers. The stage-discharge data of the Mekong at Pakse as from 1960 onward decade-wise are displayed in Figure 2.3.

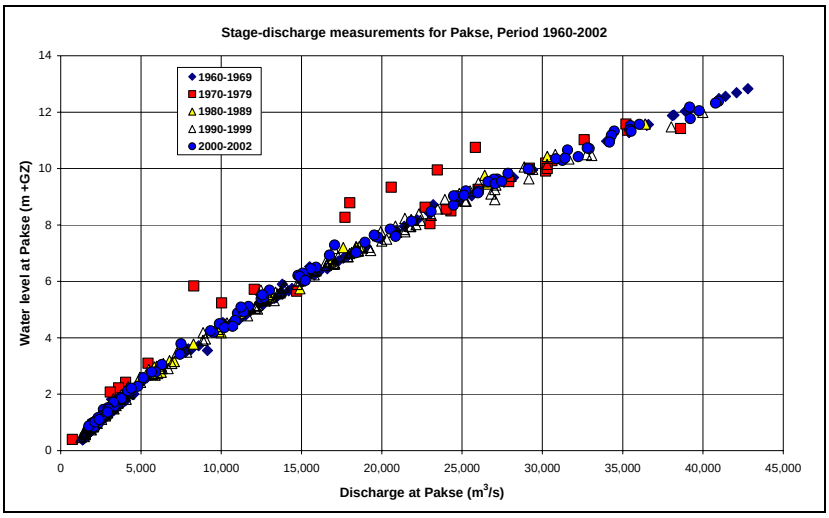

Figure 2.3 Stage-discharge measurements for the Mekong at Pakse in the Period 1960-2002

The graph shows that the stage-discharge relation is, as expected, very stable in view of the rocky control section downstream of Pakse. Only some 16 measurements, particularly those carried out in 1970-1971, appeared to be inconsistent with the rest, and were subsequently eliminated from the data set.

2.3.3 Discharge rating curve for Pakse

Rating curve by MRC

Despite the very stable control section at Pakse it appears that the discharge series stored in the MRC HYMOS database is based on many different rating curves. These curves appear to differ considerably for high water stages, e.g at a level of 12.80 m+GZ, which is within the measured range, the discharges vary from 39,500 to 45,000 m^3/s. The current discharge rating curve for Pakse is presented in the 2006 Mekong Flood Report:

$$Q = 454.7(H + 1.60)^{1.70} \qquad (2.1)$$

with: Q = discharge in m^3/s
H = water level in m+GZ

In Figure 2.4 an analysis is made of the performance of the current rating curve to the available discharge measurements. It is observed that the curve fits the data unbiased for discharges > 20,000 m^3/s. For lower discharges there is a negative bias, ultimately changing to a positive one for the lowest discharges.

It is concluded that a single relation for the full water level range as applied above is insufficient for an unbiased coverage. A revision of the stage discharge relation for Pakse is therefore required.

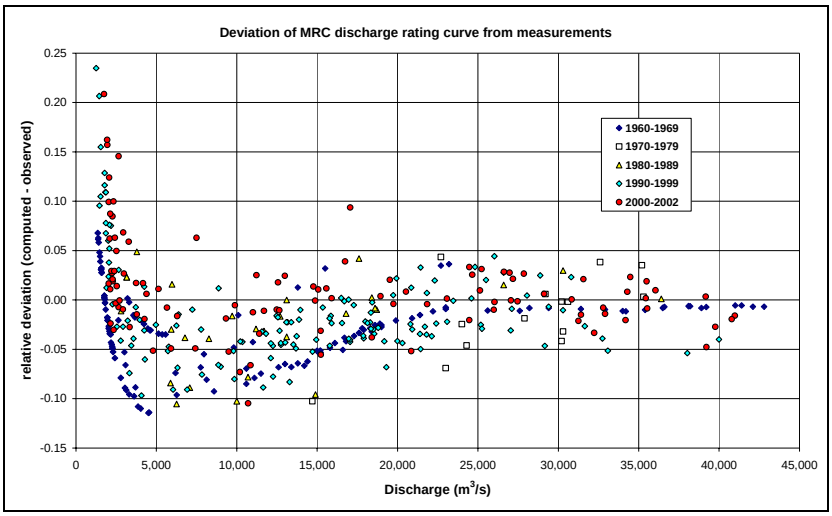

Figure 2.4 Error analysis for MRC rating curve for Pakse

Discharge rating curves for Pakse

In developing discharge rating curves for Pakse the following considerations were taken into account:

- The control section of the Pakse gauging station in view of the rocky river bed is stable; it has only been affected by the construction of the bridge at Pakse;
- The stage-discharge relation based on the measurements at Pakse requires at least two segments to get an unbiased coverage for the full range of discharges, and
- For stages above 12 m+GZ flood plain flow takes place, which is not covered by the measurements; this requires an extra contribution to the measured rating curve.

In the following, first rating curves are developed based on the measured flows, without and with the presence of the bridge. It is noted that on 4th June 2002 the gauging station was moved to a location downstream of the bridge, creating the same control section conditions as prior to the construction of the bridge. The only difference is the fall between the old and the new gauge location, which could be taken care of by adjusting the zero of the gauge. For the same gauge zero it is estimated that the difference will be about 0.01 m.

Period 1960-1999, without flood plain correction

The discharge rating without flood plain flow correction based on the measurements in the period 1960-1999 reads:

$$\begin{aligned} &for \quad 0 < H < 4.96\,m: \quad Q = 757.2(H+1.085)^{1.523} \quad See = 4.60 \; and \; n = 144 \\ &for \quad 4.96 \le H < 14.50m \quad Q = 198.0(H+3.277)^{1.936} \quad See = 2.45 \; and \; n = 170 \end{aligned} \tag{2.2}$$

The fit of the relation to the data and the error analysis is presented in Figure 2.5 and Figure 2.6. From the latter graph an unbiased fit is observed for the all distinguished period between 1960 and 1999. In Figure 2.7 an error analysis of this curve is given with the

measurements in the period 2000-2002. A small positive bias for the median and lower discharges is observed, which indicates that the curve would slightly overestimate the actual flow. This is likely caused by backwater created by the bridge.

The validity of (2.2) beyond the measured range (12.83-14.50 m+GZ) has been investigated by extrapolation of the components of the Manning equation using measured data of the wetted area and hydraulic radius and derived extrapolated data of energy slope and hydraulic roughness. The analysis proved the curve to be in close agreement with the Manning equation.

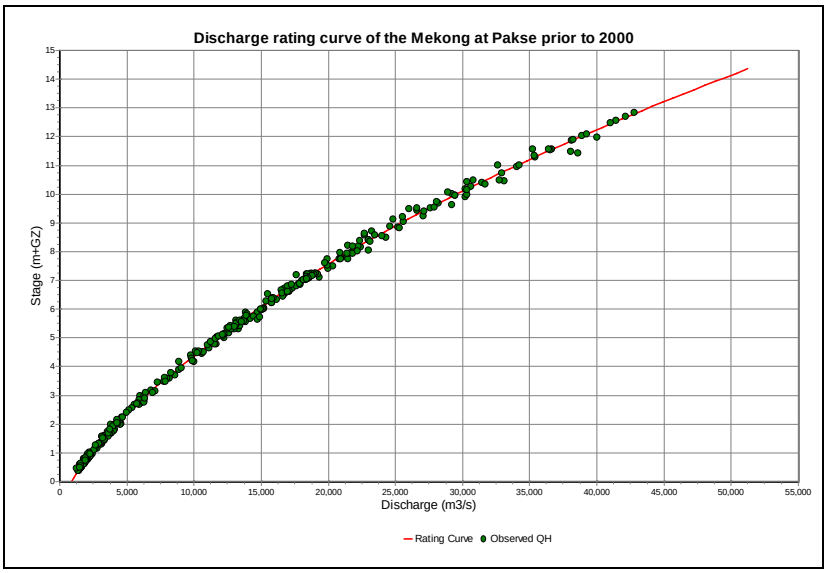

Figure 2.5 Discharge rating curve of the Mekong at Pakse without flood plain flow correction, Period 1960-1999

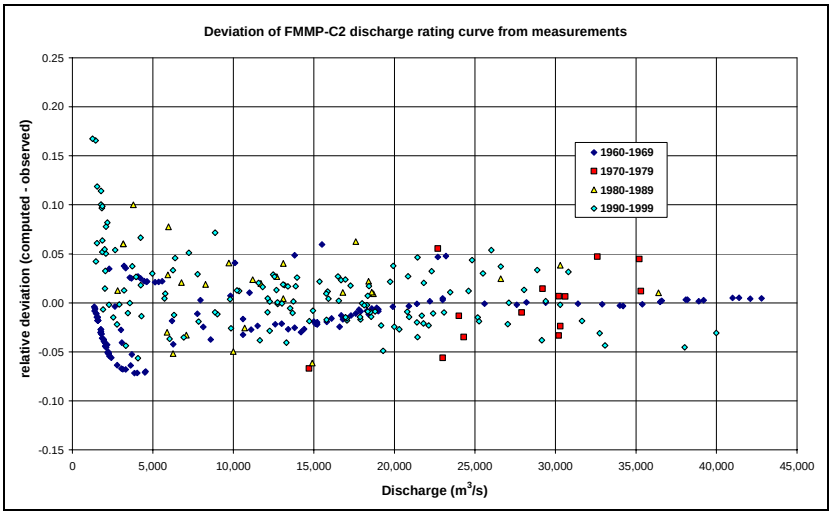

Figure 2.6 Error analysis for 1960-1999 discharge rating curve

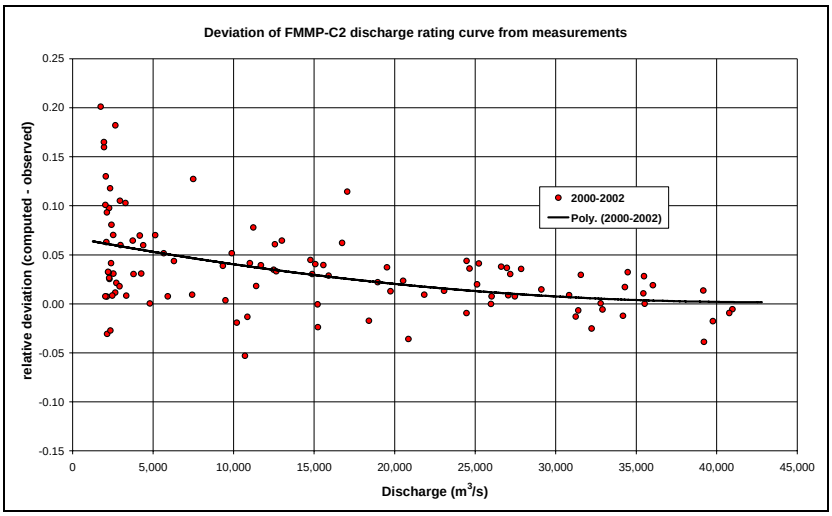

Figure 2.7 Error analysis of 1960-1999 discharge rating to flow measurements in the Period 2000-2002

Period 2000–2002 without flood plain correction

To account for backwater effects created by the bridge across the Mekong built between 1997 and 2000 a separate rating curve has been established for the period 2000-2002, which reads:

$$\begin{aligned} &for \quad 0 < H < 4.49\,m: \quad Q = 552.0(H + 1.286)^{1.664} \quad See = 5.08 \; and \; n = 46 \\ &for \quad 4.49 \le H < 14.50m \quad Q = 66.7(H + 4.797)^{2.257} \quad See = 2.52 \; and \; n = 60 \end{aligned} \tag{2.3}$$

The fit of the measurements to the curve and error analysis are presented in Figure 2.8 and Figure 2.9 respectively. The latter graph shows an unbiased fit. It has been assumed that the 2002 stage-discharge data were as before related to the old gauge location upstream of the bridge.

An error analysis of the 2000-2002 discharge rating with the discharge measurements from the Period 1960-1999 is shown in Figure 2.10. A negative bias is now observed for the median and lower discharges. This is consistent with the observations made above when discussing the fit to the 1960-1999 discharge rating curve.

Since the deviation of equations (2.2) and (2.3) for the higher stages is minimal, the validity test on the extrapolation by means of the Manning equation as presented above also holds here.

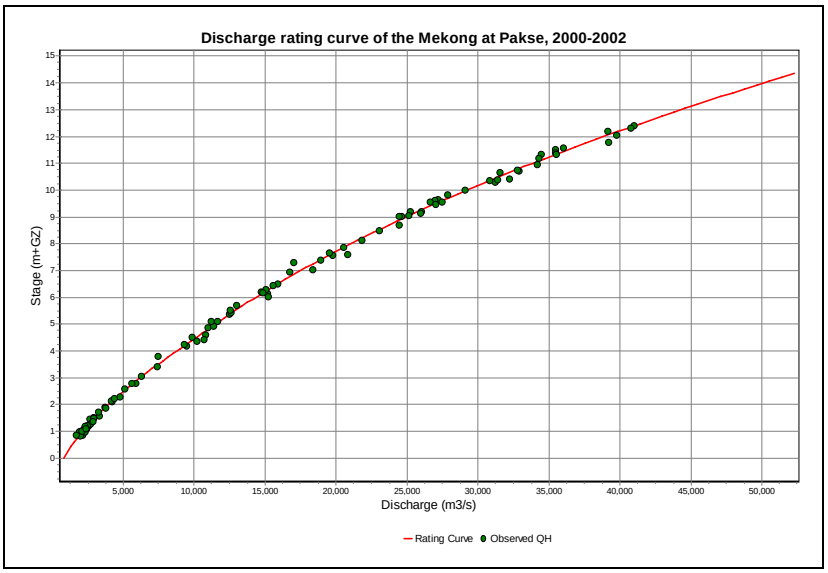

Figure 2.8 Discharge rating curve of the Mekong at Pakse no flood plain flow correction, Period 2000-2002

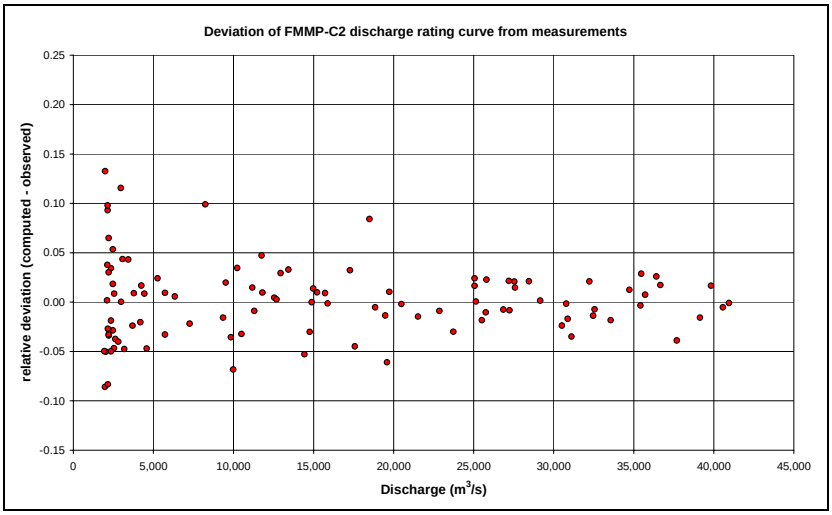

Figure 2.9 Error analysis for 2000-2002 discharge rating

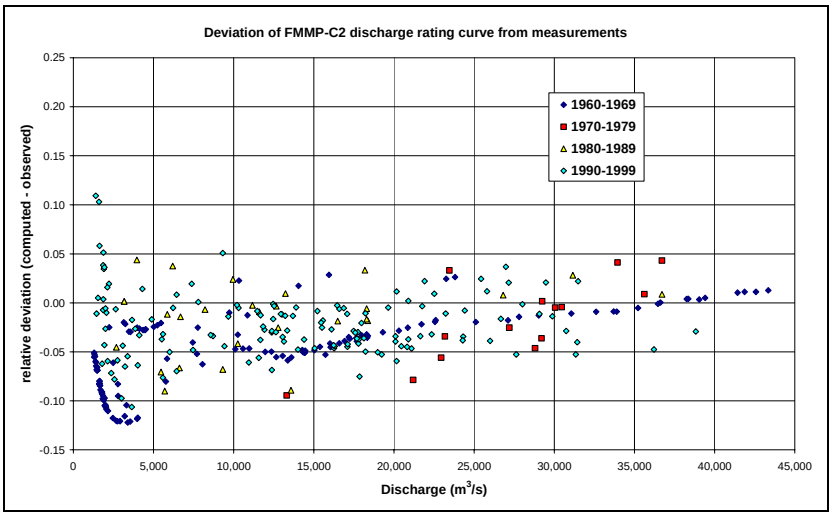

Figure 2.10 Error analysis of 2000-2002 discharge rating to 1960-1999 discharge measurements

Correction to discharge rating curves for flood plain flow

In the past, part of the flood flow was conveyed via the left bank flood plain. This flooding started for stages above 98.50 masl or 98.50-86.49 = 12.01 m+GZ. Since this part was not measured a correction had to be applied. An assessment of the flow bypassing the Mekong at Pakse before 2002 can be obtained from flow measurements made at Khong Chiam, augmented with the discharge of the Nam Mun and Se Done. Highest flows at Khong Chiam were measured in 1974. Therefore, the measurements around this year 1973-1975 have been considered. The measurements at Khong Chiam, increased with the Nam Mun discharge at Ubon (taken from the daily discharge series) are presented in Figure 2.11 and Figure 2.12.

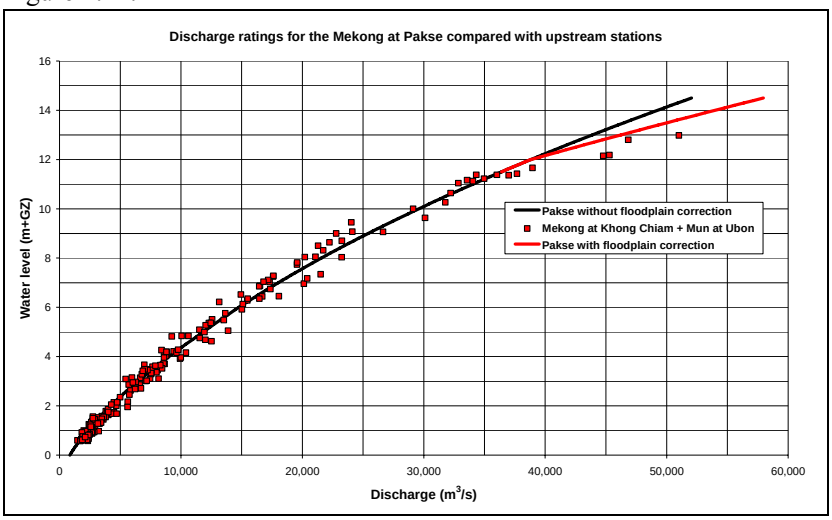

Figure 2.11 1960-1999 discharge rating for Pakse with and without flood plain correction compared with observed flows at Khong Chiam on Mekong river and Ubon on Nam Mun

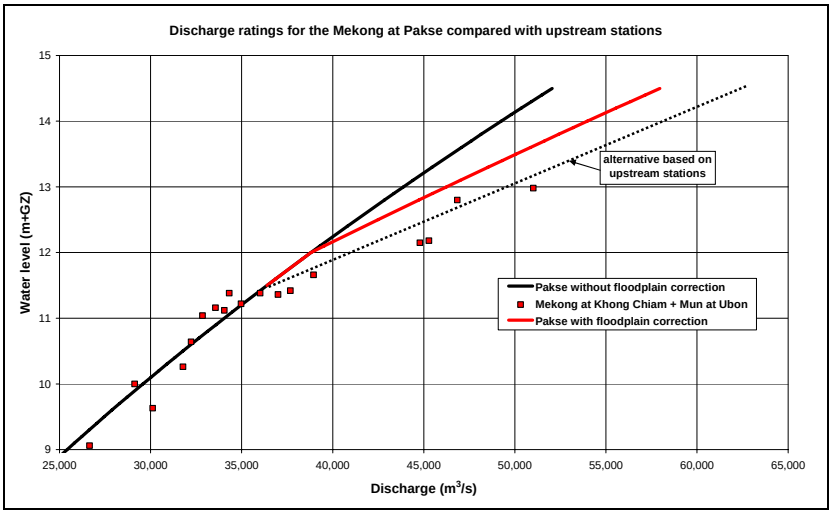

Figure 2.12 Upper part of 1960-1999 discharge rating for Pakse with and without flood plain corrections compared with observed flows at Khong Chiam on Mekong river and Ubon on Nam Mun

Note that for this period no measurements are available for Se Done. The latter can generate for the high flow period a discharge generally in the order of 400 m^3/s, but occasionally it may be 10 times as large, see Figure 2.13.

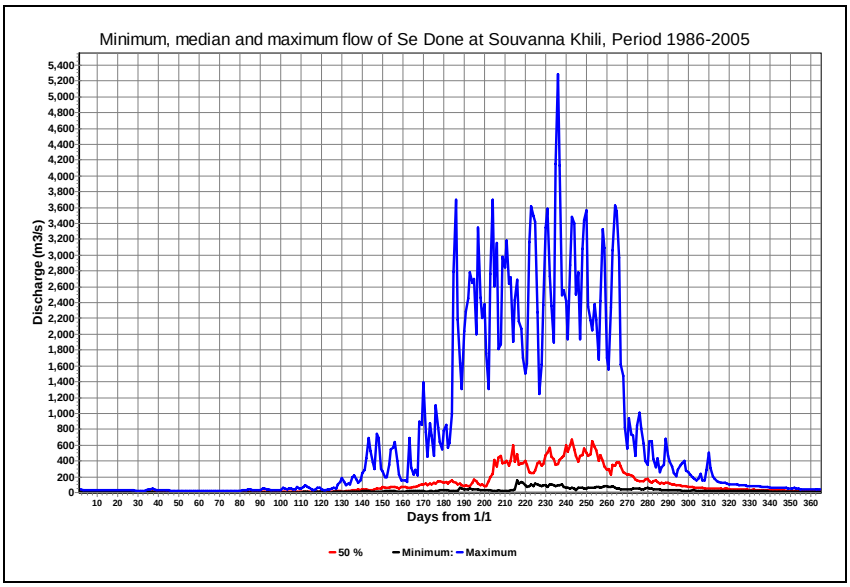

Figure 2.13 Minimum, median and maximum daily flows in the Se Done at Souvanna Khili, Period 1986-2005

From Figure 2.11 and Figure 2.12 it is observed, that the combined Mekong flows at Khong Chiam and Nam Mun at Ubon plotted against the water level at Pakse for the same day fit well to the discharge rating curve without flood plain correction up to a level of 11.5 to 12.0 m+GZ. Above that level the measurements deviate considerably from the curve. In the figures a red line has been drawn based on a linear increase in flood plain flow from a level of 12.00 m+GZ and matching with the flow of 57,800 m^3/s as presented in the available historical discharge records for the 14.48 m+GZ level. This line closely represents the assumed rating curve applied for 1974, which formed the basis for the discharge series in the MRC HYMOS database. From Figure 2.12 it becomes clear that this red line underestimates the combined Khong Chiam and Ubon flows, the more so as the Se Done contribution is not included yet. The dashed line shown in the figure gives a better approximation to the measurements. This would result in a peak flow on 17th August 1978 of approximately 62,500 m^3/s. But the actual amount remains speculative as no proper hydraulic model with adequate flood plain representation is available for the reach of the river. Therefore to avoid confusion, the MRC estimate of 57,800 m^3/s is assumed to be the best estimate at present.

To deal with flood plain flow for the conditions the following discharge is to be added to discharge rating curves (2.2) and (2.3):

$$for \quad H > 12.0, \quad Q_{floodplain} = 2366(H - 12) \qquad (2.4)$$

In 2002, under the ADB funded Secondary Towns Urban Development Project some 5 km of flood control dike and water gates have been constructed along the Mekong River at Pakse and on the left bank of the lower Se Done. It may be assumed that this embankment makes the left bank flood plain flood free. Hence, at present all Mekong flood water is conveyed through the main river, but prior to 2002 a flood plain flow correction has to be applied for Pakse.

2.4 Discharge series

2.4.1 Stage-discharge transformation

Using the rating equations (2.2), (2.3) and (2.4) the discharge series of Pakse was recomputed as follows:

- 1923-1959: no change in absence of water level data;
- 1960-1999: new series using equations (2.2) and (2.4);
- 2000-2001: new series using equations (2.3) and (2.4);
- 1/1/2002-3/6/2002: new series using equation (2.3), and
- 4/6/2002-2006: new series using equation (2.2).

It is likely that for the discharge series of the period 1923-1959 previously a rating curve similar to equation (2.2) has been applied. In that case it would mean that the discharges for stages above 12 m+GZ have been underestimated. Requests were made on the 1923-1959 water levels via MRC to Laos. Unfortunately, no data were received.

2.4.2 Extremes

Peak flows

The series of annual maximum discharges of the Mekong at Pakse based on the original and adjusted flow series are displayed in Figure 2.14. It is observed that the adjusted series generally have higher peak values, with a maximum difference of almost 6,000 m^3/s on 26/9/1996. The Gumbel (EV1) and General Extreme Value (GEV) distributions fitted to the adjusted annual extremes of Pakse are shown in Figure 2.15.

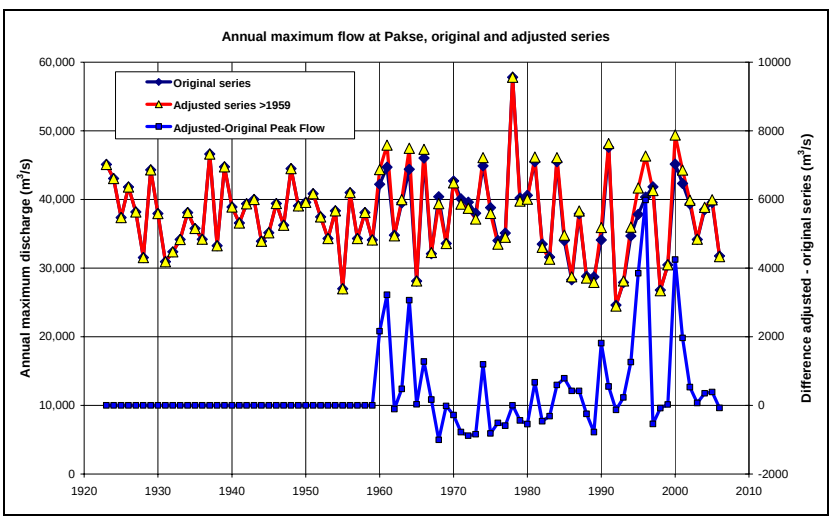

Figure 2.14 Annual maximum discharge of the Mekong at Pakse, original and adjusted series

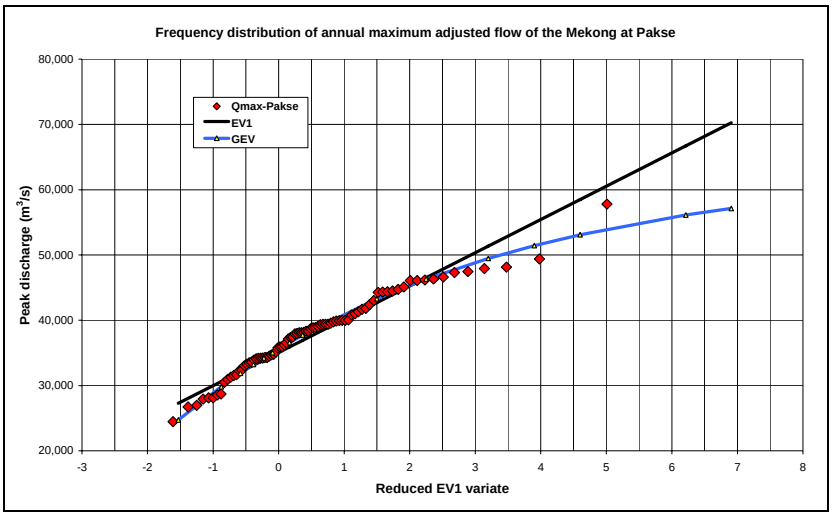

Figure 2.15 Frequency distribution of adjusted annual maximum discharge of the Mekong at Pakse

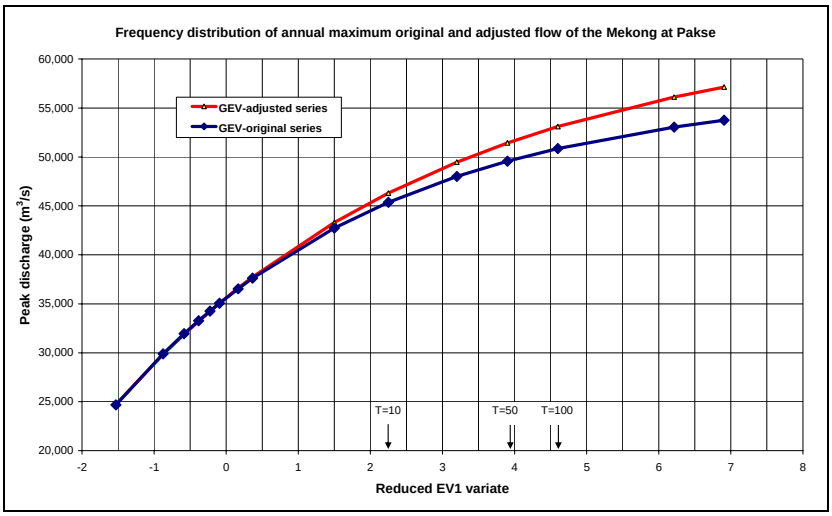

Figure 2.16 GEV-distributions of adjusted and original annual maximum discharge series of Pakse

Note that the Gumbel distribution poorly fits to the data. A better fit is obtained with the GEV distribution. A comparison between the GEV distributions before and after the adjustment is shown in Figure 2.16. It is observed that the 100 year design flood has increased from 50,800 to 53,100 m^3/s. This implies that design levels based on a 100 year flood would increase with 0.40 m.

(It is noted that the GEV fitted to the original annual maximum series leads to an upper limit, which is lower than the 1978 flood peak discharge. Such anomalies are not encountered in the application to the adjusted series.)

Flood volumes

Flood volumes of the Mekong in the MRC are determined as the flow volume between the upcrossing and the downcrossing of the discharge hydrograph with the average flow as threshold level. Here, however, the flood volume is determined as the flow volume between

annually fixed dates as it is used for comparisons with the flood volume at other stations to investigate possible changes in the discharge ratios.

So, the annual flood volume is defined here as the flow volume from 1 June till 30 November. These volumes of the original and adjusted series are displayed in Figure 2.17. The flood volume in the original series on average is slightly higher then the one according to the adjusted series, but the differences are small (absolute differences on an annual basis are all < 3%)

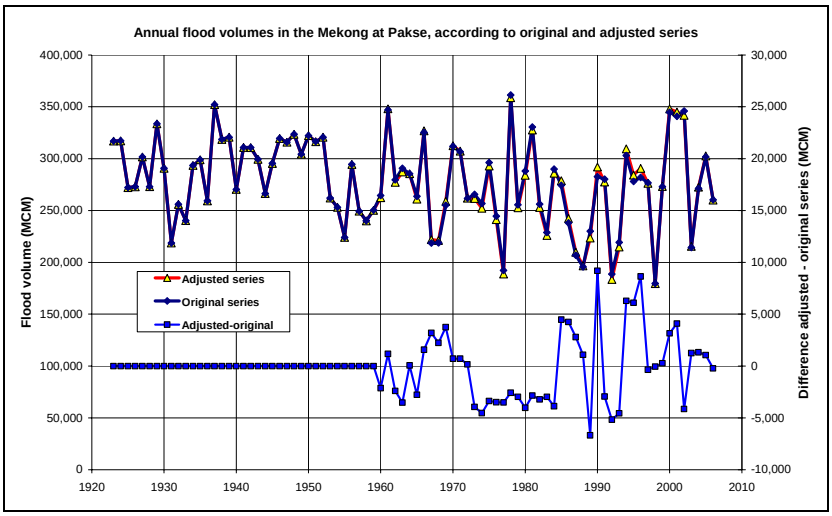

Figure 2.17 Annual flood volumes in the Mekong at Pakse, 1923-2006, according to the original and the adjusted series

3 Mekong at Stung Treng

3.1 Station description

Stung Treng gauging station is located on the left bank of the Mekong at lat 13°32.0'N and long 105°56.7'E, just downstream of the confluence of the Mekong with Se San and according to the hydrographic atlas about 683 km from the sea, see Figure 3.1. The station is located near the municipal slaughter house at the end of a dirt road leading west from Stung Treng town. The operation of the station is the responsibility of the Department of Hydrology and River Works under the Ministry of Water Resources and Meteorology of Cambodia.

Figure 3.1 Location of Stung Treng gauging station

At present the station consist of a slope gauge with zero elevation of 36.79 masl (Hatien datum). The manual gauge is observed by the provincial staff twice daily (07.00 and 19.00 hrs) in the dry season and in the flood season three times per day (07.00, 13.00 and 19.00 hrs). Apart from the manual gauge the station is equipped with a bubbler gauge, installed in 2003. The flood alarm level for Stung Treng is at 11.7 m+GZ and the flood level at 12.0 m+GZ.

The first Stung Treng gauging station was established in 1901 by the Section de l'Hydrologie of the Direction de l'Hydraulique at de la Navigation, Ministère des Travaux Publics (T.P.) at two locations (Harza, 1961):

- a staff gauge at the light vehicle bridge across the Se San, 1400 m east of the present gauge location to monitor floods, with the zero of the gauge at 37.64 m, and
- a staff gauge for low flow some 400 m further east near the municipal water supply pumping station, which was re-installed each year to the same datum as the high stage gauge. In the early sixties another low stage gauge was painted on a channel marker in the Mekong River about 800 m upstream of the present gauge location.

When the measurements at the present gauge location (see Figure 3.1) started is not well documented. Data reports from the early sixties mention the existence of an inclined staff gauge at the present location and the installation of a bubbler gauge in 1960. Harza (1961) starts referencing discharge measurements as from 19 October 1960 onward to the current gauge zero (0.85 m below former zero level). Observations at Stung Treng stopped on 22 April 1970 to resume only on 1 January 1991 from a re-established slope gauge. In 2002 when the JICA-team visited the site defects to the minimum slope gauge were reported and neither a recorder nor a logger were available.

The cross-section of the Mekong at the gauging station is presented in Figure 3.2. The river is seen to be about 1 km wide, with a depth of 45 to 55 m. At a gauge height of 12.29 m+GZ the right bank will be overtopped, whereas the left bank (Stung Treng side) will overtop at a level of 12.50 m+GZ.

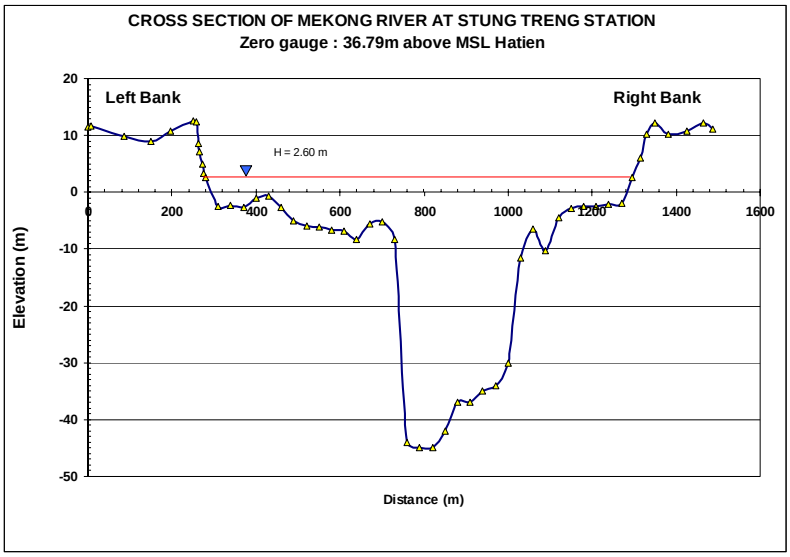

Figure 3.2 Cross-section of the Mekong at Stung Treng gauging station

3.2 Water level series

3.2.1 Availability in database

The HYMOS database, as available in FMMP-2, contains for Stung Treng a complete average daily water level record from 1 January 1910 till 31 December 2006. This record is adjusted and completed for several periods as follows.

Data prior to 1960 were available from data archives as:

- daily tabulation from the Office of Fluvial Navigation, Travaux Publics, Saigon, Vietnam,
- plotted hydrographs for available data after 1940 in the Office of the Port Engineer, Phnom Penh, Cambodia.

These archives covered complete or nearly complete stage records of 1902, 1903, 1905-1907, 1910-1913, 1915-1918, 1921-1931, 1933-1937, 1939-1948, 1950-1960 and fragmented records for 1901, 1904, 1908, 1914, 1920, 1932, 1938 and 1949. A hard copy of the stage record held at the Mekong Secretariat in Bangkok in the sixties covered the period from 1910 to 1960, which was presumably partly corrected and completed. In 2004 at the MRC the Mekong stage records have been reviewed. For Stung Treng the record was almost continuous from 1 January 1910 till 22 April 1970 and from 1 January 1991 onward.

It follows that the stage record of Stung Treng 1910-2006 is based on measurements for the entire period apart from the above mentioned years with fragmented record and the period 23-04-1970 up to and inclusive 31-12-1990.

3.2.2 Validation and completion

In 2004 MRC screened the Stung Treng stage record from 1910-2003 on 10 by 10 years basis (MRC, 2004), with the following observations:

- 1910-1919: data from 01-01-1919 till 31-12-1919 increased with 1 m to adjust for lowering of gauge zero with 1 m during that period. Plots show that the observed data during this period is of good quality.
- 1920-1949: plots show acceptable quality.
- 1950-1959: plots shows greater dispersion throughout whole data range indicating lower data quality.
- 1960-1969, some portions of 1961 and 1969 data set are doubtful, other years are good.
- 23-04-1970 to 01-01-1991 missing
- 1991-2003: in the dry year 1998 the data shows for a few days appreciable discrepancy with the record of Pakse.

According to the review made by Harza (1961) the low stage recordings are of doubtful quality, also due to the annual reinstallation of the low flow gauge before 1960.

The gap 23-04-1970 to 01-01-1991 in the Stung Treng stage record was filled in by MRC as follows:

- for the period 23-04-1970 to 01-01-1980, in absence of a record at Kratie in this period, by linear regression on Pakse, based on the period 1960-1969.
- for the period 01-01-1980 to 01-01-1991 by non-linear regression (3rd degree polynomial) on Kratie, established for the rising and falling stages separately to cope with the looped relationship between the two stations, caused by backwater of the Tonle Sap on the stages at Kratie.

For this study a comparison was made between the average daily water levels and the instantaneous 07.00 hrs PM values stored in the forecast database for the period 2000-2006 and no anomalies were found. Also graphical comparisons (hydrographs and relation curves) were made between the water levels at Stung Treng and Kratie for the years for which also discharge measurements are available for Stung Treng. Based on this comparison the record of 08-12-1966 to 02-01-1967 has been adjusted.

The range of the stage records at Stung Treng can be read from the water level frequency curves displayed in Figure 3.3. The water level range is from 1.27 m to 13.00 masl, i.e. a

range of nearly 12 m. Lowest values are recorded in April-May, whereas in August-September the maximum water levels generally occur.

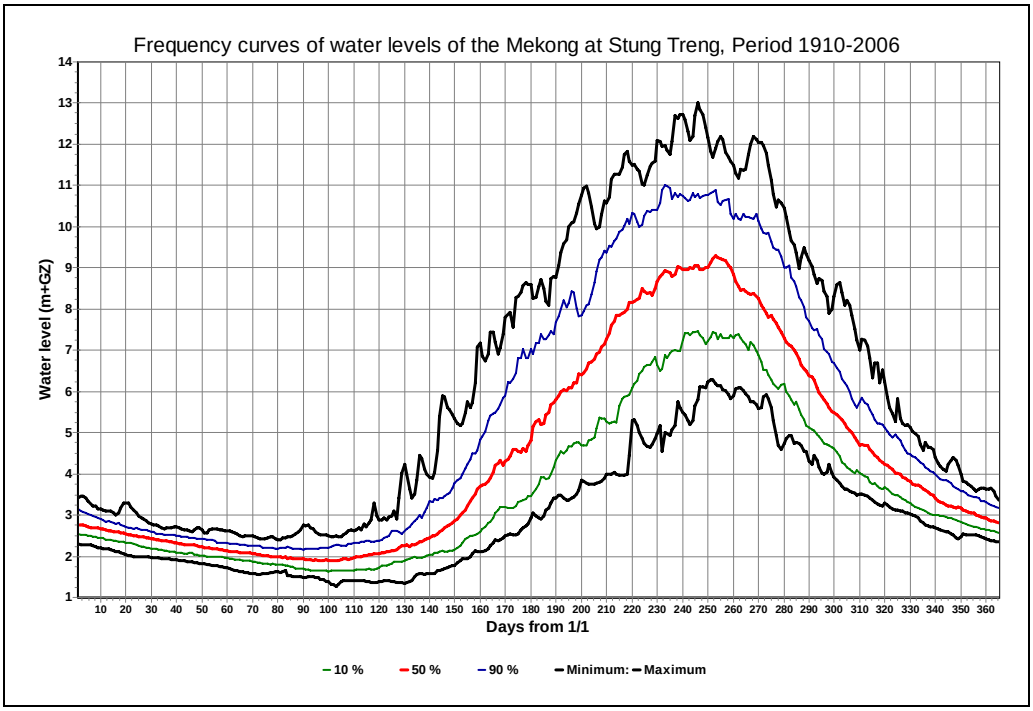

Figure 3.3 Frequency curves of water level of the Mekong at Stung Treng, period 1910-2006.

3.3 Stage-discharge measurements

3.3.1 Availability

Discharge measurements at Stung Treng on the Mekong are available for four periods: from 2 November 1959 to 16 September 1966, from 2 April 1991 to 20 March 1993, from 19 November 1999 to 3 February 2000 and for the year 2008. The measurements up to 2000 were made in a cross–section about 3 km downstream of the Se San-Mekong confluence with a current meter suspended from a boat, using the 0.2-0.8 method in verticals distanced some 40 m apart. An overview of the data availability is presented in Table 3.1. The measurements in 2008 were carried out with an ADCP according to a fixed schedule: two measurements per month during the lean season and four in the flood season.

Table 3.1 Summary of availability and range of stage-discharge measurements for the Mekong at Stung Treng

Year	number	h-range (m+GZ)	Q-range (m^3/s)
1959	1	4.96	14,000
1960	36	1.90 – 9.05	1,890 - 43,000
1961	45	1.45 – 11.03	1,590 - 57,000
1963	1	2.25	3,544
1964	8	1.60 – 8.46	1,480 – 34,960
1965	11	1.95 – 8.57	1,728 – 39,440
1966	4	1.94 – 11.06	1,564 – 57,600

Year	number	h-range (m+GZ)	Q-range (m^3/s)
1991	11	1.98 – 11.54	1,930 – 63,500
1992	9	1.94 – 2.36	1,950 – 3,130
1993	10	1.94 – 2.50	1,950 – 3,130
1999	7	3.33 – 4.98	6,192 – 13,373
2000	4	2.47 – 3.08	2,930 – 4,675
2008	35	2.28-9.60	2,369 -37,821*) (1,455-41,463)**)

*) Range of measurements with ADCP ref..Bottom Tracking
**) Range of measurements with ADCP ref. GPS

Details are available for the stage-discharge data of 1959-1961 from measurement sheets of Harza. For the remaining current meter measurements no further information could be traced. Two sets of discharges are available from the ADCP measurements of 2008, one set GPS referenced and another set Bottom Tracking referenced.

3.3.2 Validation

From the discharge measurement sheets of Harza it is observed that the first 20 discharge data (2-11-1959 to 12-10-1960) have been entered against the water level read from the old gauges at Stung Treng (at the bridge across the Se San and the municipal water supply pumping station, where a different gauge zero applies). From a comparison of the documented stage of the discharge measurements and the daily average water level record of Stung Treng it appeared, that apart from the first 20 measurements, also the remaining data for the year 1960 needed a (smaller) correction to the documented water level, see Figure 3.4. Therefore, the water levels recorded with the discharges for 1959 and 1960 have been replaced with the average water level for the day of measurement as obtained from the water level series, leading to a much closer stage-discharge relation as can be observed from Figure 3.5. No anomalies were found in the discharge measurements of 1961 till 1966 and of 1991.

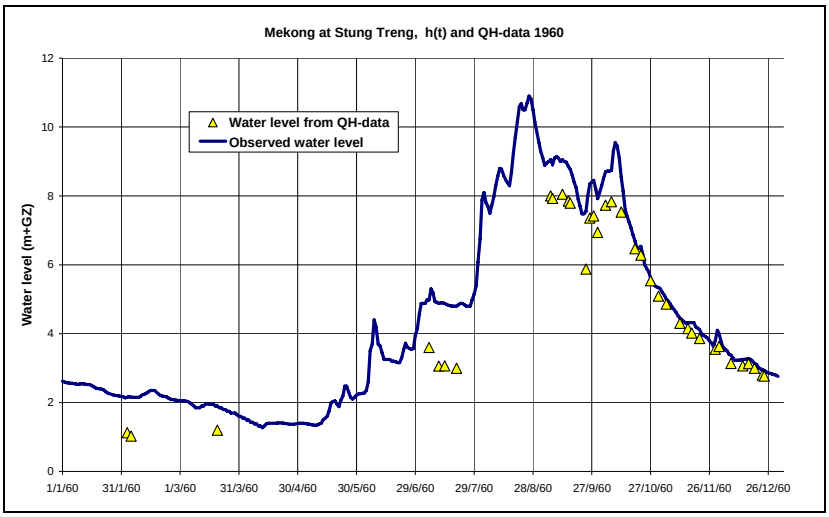

Figure 3.4 Comparison of stages of discharge measurements at Stung Treng with the water level record for the year 1960

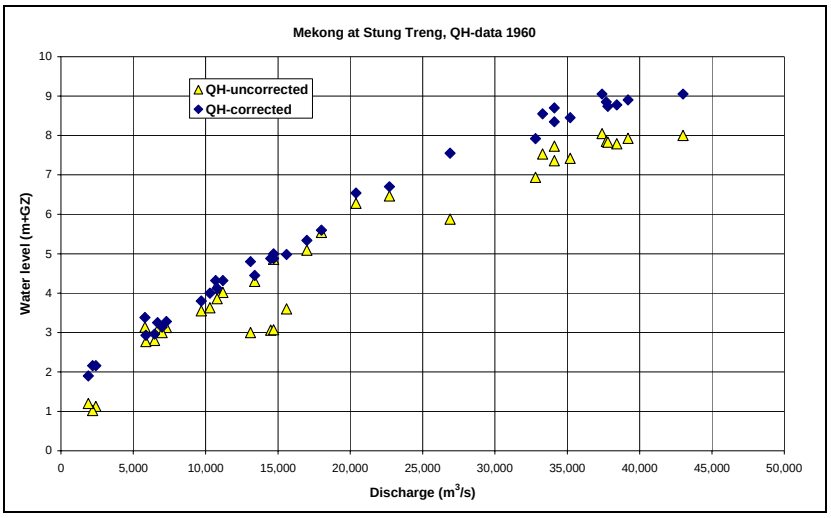

Figure 3.5 Effect of adjustment of water levels on the stage-discharge relation for Stung Treng, year 1960

With respect to the 9 discharge measurements for 1992 as stored in the HYMOS database, it is noted that the discharge values appeared to be exactly the same as those for 1993, whereas the water levels deviated considerably from the stage record of 1992. Apparently, at some moment in time erroneous dates were added to those measurements. The 1992 stage-discharge data were therefore deleted from the database.

3.3.3 Discharge rating curves for Stung Treng

Ratings based on current meter measurements

The stage-discharge data made by a current meter as available for Stung Treng are displayed in Figure 3.6 and Figure 3.7. The following observations can be made.

- The low flow control of the station appears to be unstable as may be observed from the considerable scatter in discharges through the years for a particular water level as displayed in Figure 3.6. Before October 1960 these changes could at least partly be attributed to shifts in the setting of the low water gauge near the municipal pumping station on the Se San, if flow measurements from that date would have been available. But since a new slope gauge was erected along the Mekong by Harza late 1960 such sources of errors are less likely. The figure shows that for stages around 2 m+GZ the discharge varies from 1,500 to 3,000 m^3/s, with the higher ones in 1961. Between 2 to 5 m the measurements of 1999-2000 also deviate from the rest of the sample with a lower discharge for the same water level than before. Different discharge ratings have therefore been assumed through the years.
- Regarding the high flows, above a level of 6 m+GZ little variation without a specific trend is observed in the stage-discharge measurements in the period 1960-1991. Apparently, the high flow control of the station, contrary to the low flow, is very stable.

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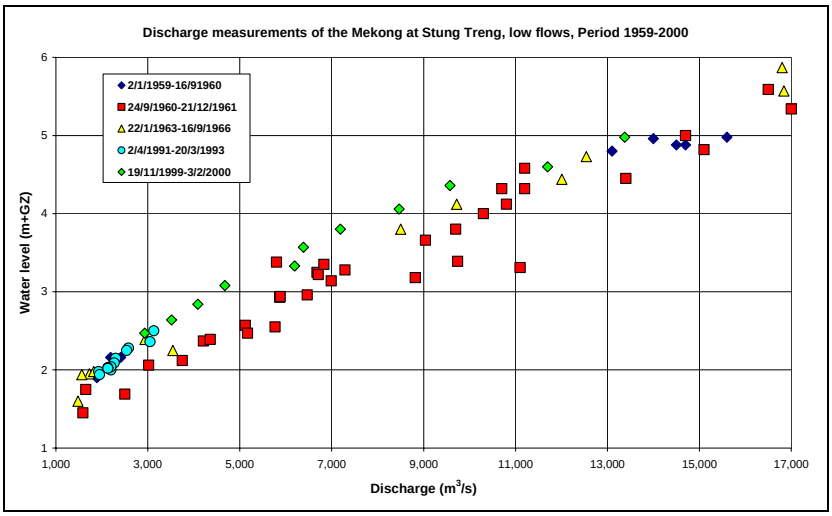

Figure 3.6 Stage-discharge measurements for the Mekong at Stung Treng, low flows, Period 1959-2000

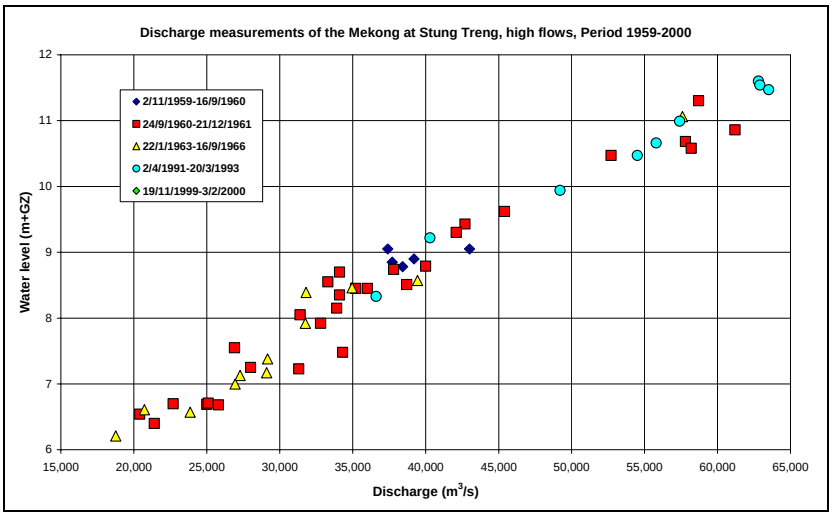

Figure 3.7 Stage-discharge measurements for the Mekong at Stung Treng, high flows, Period 1959-1991

In the development of the rating curves for Stung Treng the following approach has been used:

- The low flow measurements before the flood season of 1960 and those of 1963 till 1993 have been combined to arrive at one relation for the low flow segment of the periods 1/10/59 – 20/9/1960 and 1/10/1962-31/12/1998. A separate low flow segment has been developed for the periods 21/9/1960 – 30/9/1962 and for 1/1/1999-1/1/2008 using the measurements in those periods. Note tha for the latter period only current meter measurements are available for 1999-2000. Prior to 1/10/1959 the low flow segment has been based on all measurements from 1959-1993, to account for possible similar variability in the past as observed thereafter.
- Since the control downstream of Stung Treng appeared to be very stable for discharges larger than 15,000 to 20,000 m^3/s a single relation for the high flows has been assumed throughout, based on the discharge measurements at Stung Treng between 1960 and 1991.

The resulting rating equations now read:

- Period 01/01/1910-30/09/1959:

$$\begin{aligned} &for \quad 1.20m < H < 7.25m: \quad Q = 1926(H - 0.84)^{1.43} \\ &for \quad H \geq 7.25m: \quad Q = 536.8(H + 0.51)^{1.92} \end{aligned} \tag{3.1}$$

- Period 01/10/1959-20/09/1960:

$$\begin{aligned} &for \quad 1.20m < H < 5.11m: \quad Q = 1442(H - 0.75)^{1.58} \\ &for \quad H \geq 5.11m: \quad Q = 536.8(H + 0.51)^{1.92} \end{aligned} \tag{3.2}$$

- Period 21/09/1960-30/09/1962:

$$\begin{aligned} &for \quad 1.20m < H < 7.04m: \quad Q = 1734(H - 0.48)^{1.44} \\ &for \quad H \geq 7.04m: \quad Q = 536.8(H + 0.51)^{1.92} \end{aligned} \tag{3.3}$$

- Period 01/10/1962-31/12/1998:

$$\begin{aligned} &for \quad 1.20m < H < 5.11m: \quad Q = 1442(H - 0.75)^{1.58} \\ &for \quad H \geq 5.11m: \quad Q = 536.8(H + 0.51)^{1.92} \end{aligned} \tag{3.4}$$

- Period 01/01/1999-01/01/2008:

$$\begin{aligned} &for \quad 1.20m < H < 6.18m: \quad Q = 835.5(H - 0.52)^{1.85} \\ &for \quad H \geq 6.18m: \quad Q = 536.8(H + 0.51)^{1.92} \end{aligned} \tag{3.5}$$

The curves are shown in Figure 3.8 and an error analysis is presented in Figure 3.9.

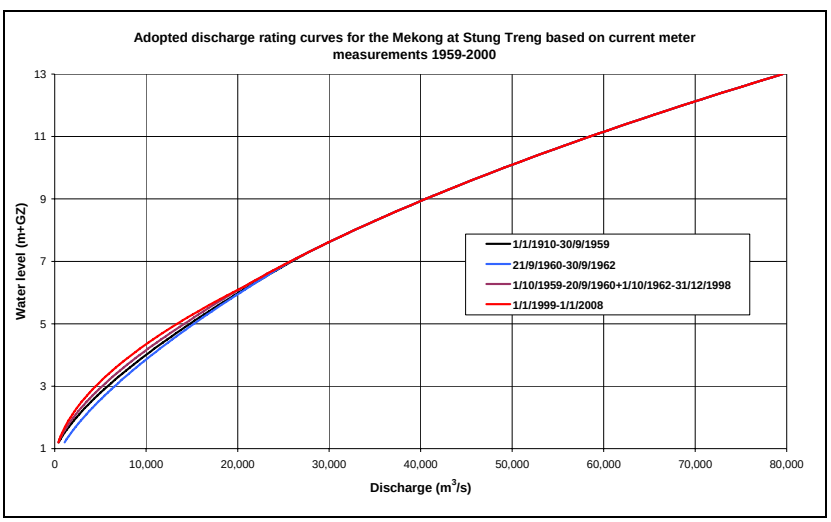

Figure 3.8 Adopted rating curves for the Mekong at Stung Treng

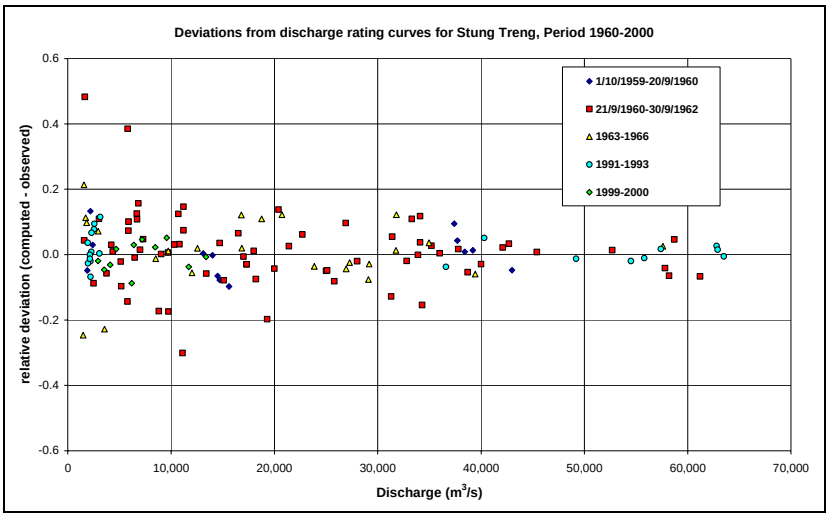

Figure 3.9 Error analysis of discharge rating curves for Stung Treng, Period 1959-2000

The latter graph shows that for the relative error ((calculated–observed)/observed) decreases with increasing discharge. An overall unbiased fit is observed throughout the full measured range.

Comparison with current meter measurements at Kratie

It may be assumed that the high flows at Stung Treng and Kratie are about equal as the lateral inflow between the two stations is small and cancels out against attenuation on the reach. Hence, using stage-relation curves with one day time shift to account for travel time between the two locations, discharge measurements and ratings on either side may be transferred to the other and vice versa. Reference is made to Table 4.1 for an overview of stage-relation curves. The discharge ratings of Stung Treng thus transferred to Kratie, appear to match very well with the current meter measurements at Kratie made in the nineteen sixties. Even up to the maximum measured discharge of 70,000 m^3/s it fits well, as can be observed from Figure 4.14 and Figure 4.15. This confirms the validity of the discharge ratings for Stung Treng. Unfortunately, after the nineteen sixties no current meter measurements have ever been carried out again at Kratie.

MRC rating

MRC has used the following rating curve for Stung Treng (indicated as the old curve in MRC (2007)):

$$Q = 1839(H - 0.94)^{1.49} \qquad (3.6)$$

The fit of this relation to the measurements can shown to be somewhat biased, due to the use of only one equation. Figure 3.10 presents a comparison between the MRC rating curve and the average one (equation 3.1) established in this study. It shows that the present curve gives slightly lower discharges for the middle stages and higher values for the largest water levels, see also Figure 3.11.

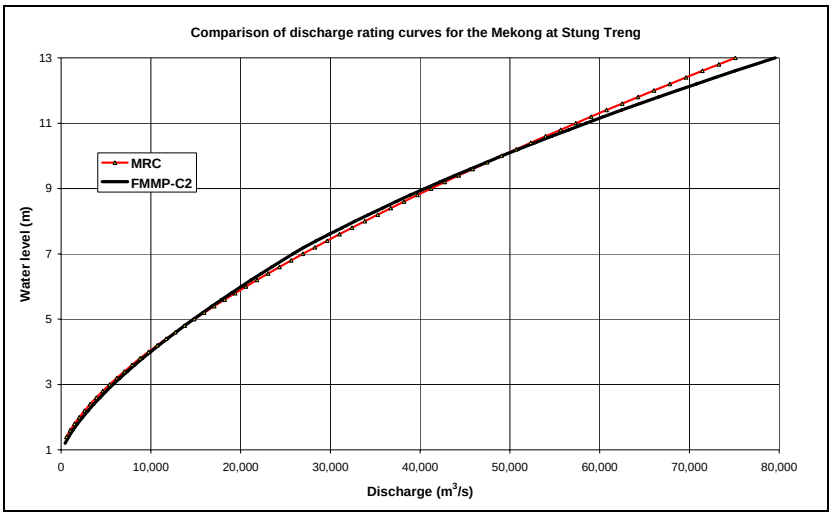

Figure 3.10 Comparison of discharge rating curves of the Mekong at Stung Treng from MRC and FMMP-C2.

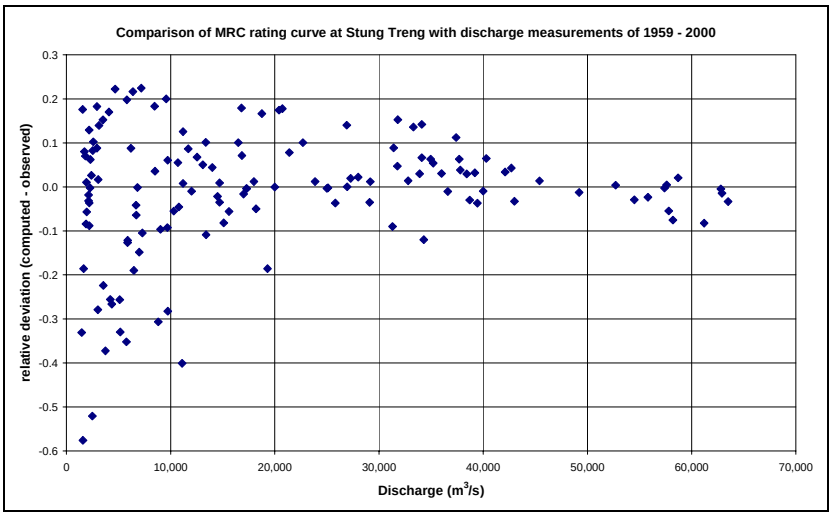

Figure 3.11 Error analysis for MRC discharge rating curve to 1959-2000 discharge measurements at Stung Treng

For the highest water level observed at Stung Treng of 13.00 masl the MRC curves gives 75,100 m^3/s against 79,500 m^3/s for the present curve, the latter being almost 6% higher. Though these values are beyond the measured range as the highest water level with a measured discharge reached only to a value of 11.54 masl with a discharge of 63,500 m^3/s, it is noted that the present curve gives a proper unbiased fit to the highest discharges, with a realistic value for the power of the rating equation. For a final proof of the validity of the curve a mathematical hydraulic model of this river reach will be required, which, unfortunately, is not available.

Stung Treng rating based on ADCP-measurements at Kratie 2002-2007

From 2001 up to 2007 no discharge measurements were carried out at Stung Treng. In Kratie, though, in 2002 and 2003 and then in 2007 a large number of discharge

measurements were made by JICA with an ADCP, which have been transferred to Stung Treng by putting them against the water level on the previous day in Stung Treng. These discharges comprise bottom tracking referenced ADCP measurements. Combining the low flow discharge measurements of 1999-2000 at Stung Treng with the ADCP measurements at Kratie for 2007 the following discharge rating for Stung Treng is obtained:

$$Q = 1631(H - 0.98)^{1.493} \qquad (3.7)$$

The match of this curve with the data is shown Figure 3.12. To validate this curve it has been compared with the bottom tracking referenced ADCP measurements at Kratie in 2002-2003 in Figure 3.13. A good match to these measurements is observed. A distinct difference between the ADCP-curve and the current meter based rating is observed for the higher flows increasing with the flow velocity up to about 15%, see also Figure 3.14. This phenomenon has also been experienced elsewhere. E.g. in the EU sponsored River Survey Project for the major rivers in Bangladesh in the mid nineties (WL|Delft Hydraulics and DHI, 1996), an extensive discharge measuring campaign with ADCP and current meters was carried out. The results showed a similar difference between the two discharge measurement techniques: bottom tracking referenced ADCP discharges were lower than those measured with conventional current meters, where the relative difference increased with increasing flow velocity. The difference was attributed to the bottom tracking procedure applied in the flow measurements with the ADCP, where the flow velocities were measured relative to the moving sediment near the river bed. This led to an underestimation of the ADCP measured flow velocity, increasing with the velocity. ADCP-measurements using DGPS eliminate such errors, whereas the result can be compared with conventional current meter measurements to make the relation with the past discharge curves. To eliminate this error from the 2002-2007 measurements at Kratie a velocity dependent correction is to be implemented.

Iwona Conlan (2009, pers comm..) mentions an additional reason why the bottom tracking referenced ADCP measurements underestimate the actual discharge as bottom tracking often drops out during high flows (observed a.o. by the Cambodian measurement teams who often experienced this problem). When this happens, there are missing ensembles and flow in that portion of the channel is not included in the final discharge measurement.

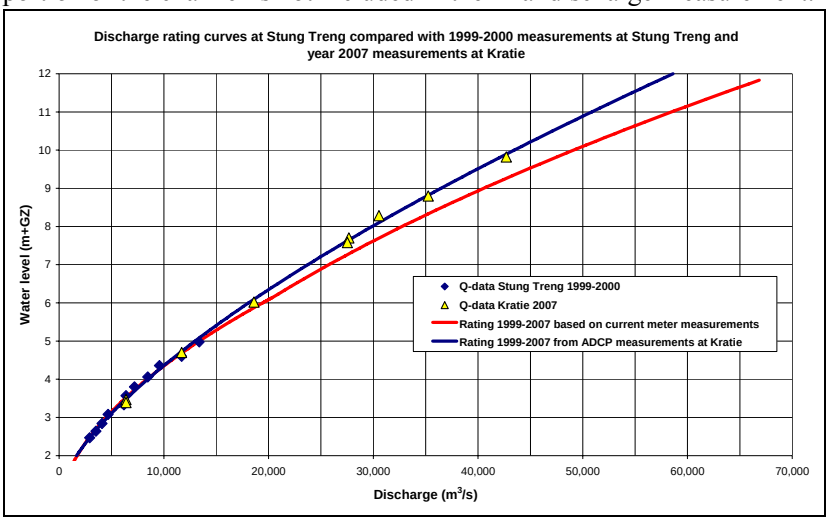

Figure 3.12 Discharge rating curves of the Mekong at Stung Treng with low flow current meter measurements at Stung Treng (1999-2000) and bottom tracking referenced ADCP measurements at Kratie (2007)

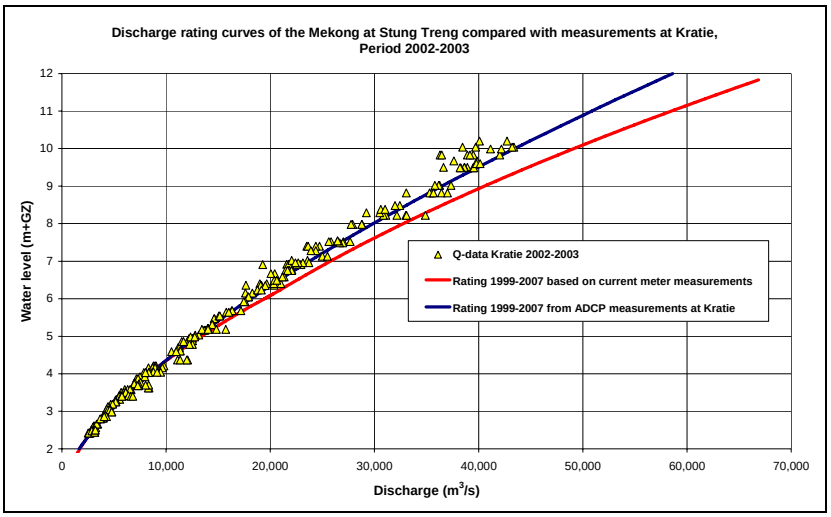

Figure 3.13 Discharge rating curves of the Mekong at Stung Treng compared with bottom tracking referenced ADCP measurements at Kratie (2002-2003)

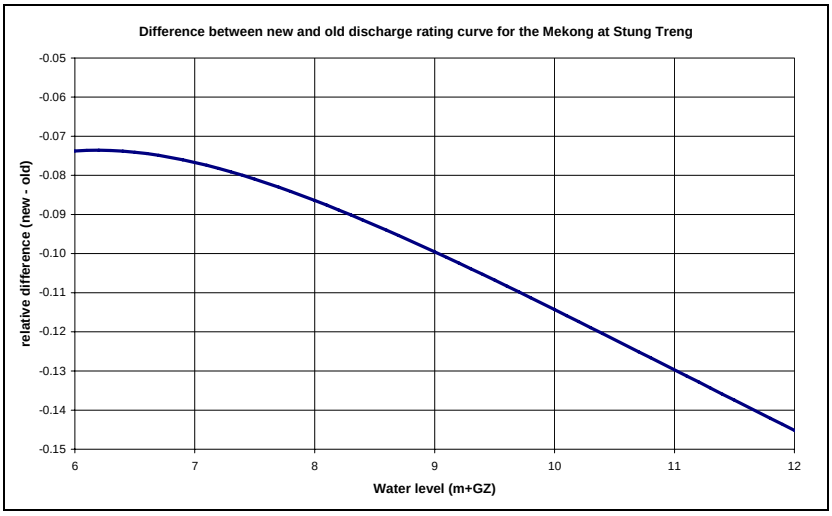

Figure 3.14 Relative difference between bottom tracking referenced ADCP and current meter based discharge rating curves for the Mekong at Stung Treng, Period 1999-2007

3.3.4 Discharge measurements in the Mekong at Stung Treng in 2008

In 2008 DHWR carried out large scale discharge measurements on the Mekong in Cambodia using an ADCP. The results where not only referenced to bottom tracking (Q_{BT}) but also to GPS (Q_{GPS}), using a handheld GPS. At Stung Treng 35 discharge measurements were carried out. The measurements are shown in Figure 3.15 and Figure 3.16 for Q_{BT} and Q_{GPS} respectively.

- It is observed that the Q_{BT} data fit very well up to a gauge reading of about 5 m (13,000 m^3/s) to both curves. From 5 to 8 m the data show a close match with the ADCP-based 1999-2007 discharge rating. Beyond 8 m (30,000 m^3/s) the ADCP-curve gives slightly higher and the current meter based rating considerably higher discharges.
- The Q_{GPS} data fit better to the 1999-2007 current meter based discharge rating, though the spread is much larger than for the Q_{BT} data.
- The difference between the two approaches is presented in Figure 3.17. For discharges in excess of 10,000 m^3/s (approx. 4 m at the gauge of Stung Treng) the GPS data exceed the BT estimates with 10 to 20 %. This tendency is in agreement with moving bed conditions. For the low flows the opposite holds, with differences up to 40%. These differences are not understood and are indicative for the poor quality of the use of hand held reference method. Overall, the observed differences are unacceptably large.

In Figure 3.15 and Figure 3.16 also the ADCP measurements at Kratie related to the gauge at Stung Treng (via the stage-relation curves shown in Figure 3.18 and Figure 3.19 applying a shift of 1 day) are presented.

- It is observed that the Kratie BT-referenced measurements fit well to the 1999-2007 Stung Treng ADCP-rating. In itself this is not remarkable, as the upper part of the curve has been based on the same referenced ADCP-measurements at Kratie of 2007 as described in the previous sub-section. Note that the highest BT-referenced measurements at Kratie slightly exceed those at Stung Treng for the same gauge reading at the latter; for flows up to 30,000 m^3/s the measurements at the two locations show a very close match.
- The GPS-referenced discharges at Kratie differ considerably from those at Stung Treng for the same gauge reading at the latter, as can be observed from Figure 3.16: the Kratie estimates lead to much higher values than those of Stung Treng. Note that the Kratie estimates also exceed the current meter discharge rating at Stung Treng by far.

From the above it follows that the BT-referenced data at Stung Treng and Kratie are mutually fairly consistent, but underestimate the flow due to moving bed. The GPS-referenced measurements at the two locations are mutually strongly inconsistent. Particularly the GPS-referenced discharge measurements at Kratie likely overestimate the actual discharge considerably. Hence, the present ADCP measurements are not helpful in creating a reliable discharge rating for Stung Treng as well as for Kratie.

To illustrate the present uncertainties with the ADCP discharge measurements referenced to BT and GPS Iwona Conlan, in reviewing in 2008 the discharge measurements along the Mekong for IKMP, commented to the large difference between the discharge estimates by the two references at Kampung Cham on 17/9/08 as follows:

> *"The GPS-referenced measurement is likely the more accurate of the two due to the moving bed, which affects only the bottom tracking. However, due to the overall poor accuracy of a handheld GPS, even this value is likely to be significantly different from the true discharge. This example highlights the importance of correcting for moving bed-effects using standard international methods (Differential GPS or the Loop Method)".*

To this comment a strong recommendation is added that conventional current meter measurements should also be carried out together with the ADCP measurements to ascertain the historical connection.

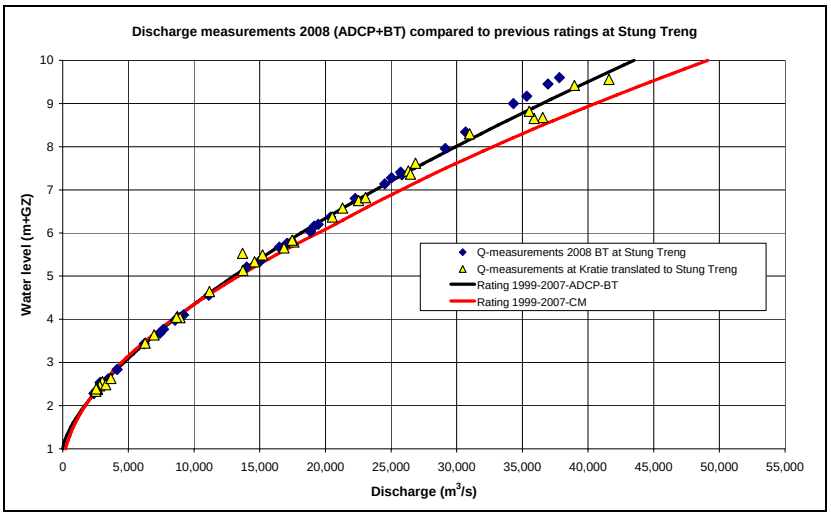

Figure 3.15 Comparison of bottom tracking referenced discharge measurements with ADCP at Stung Treng and Kratie in 2008 against the gauge reading in Stung Treng with discharge ratings of 1999-2007

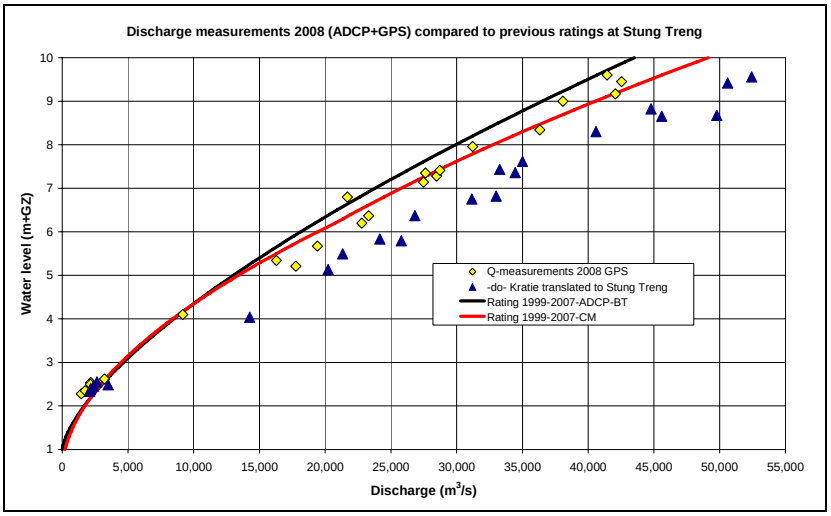

Figure 3.16 Comparison of GPS referenced discharge measurements with ADCP at Stung Treng and Kratie in 2008 against the gauge reading in Stung Treng with discharge ratings of and 1999-2007

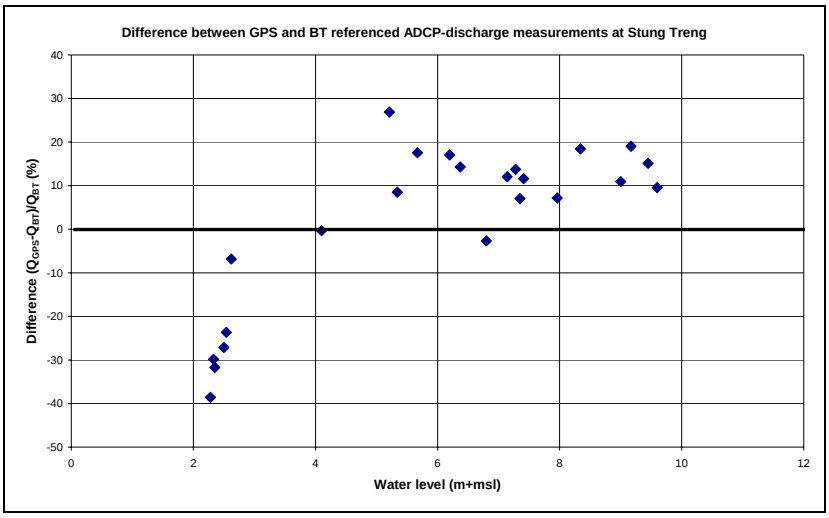

Figure 3.17 Difference between GPS and BT referenced discharge measurements with ADCP at Stung Treng

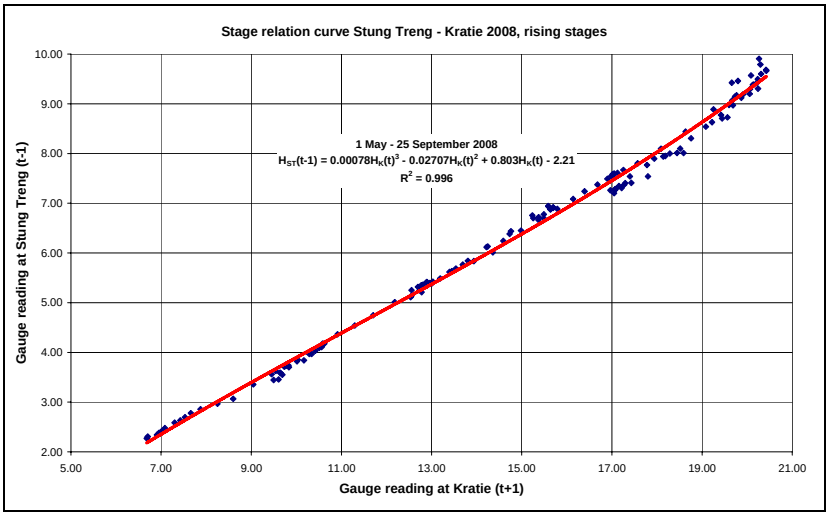

Figure 3.18 Stage relation curve Stung Treng-Kratie for rising stages in Kratie, year 2008

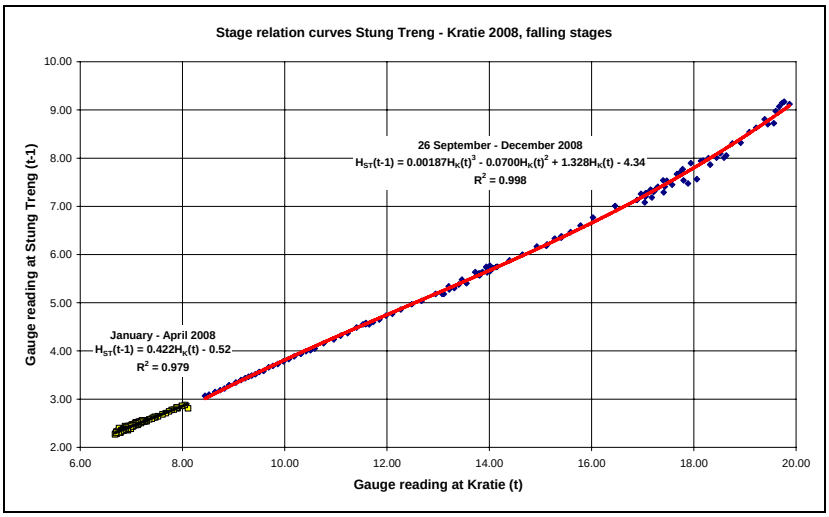

Figure 3.19 Stage relation curve Stung Treng-Kratie for falling stages in Kratie, year 2008

3.4 Discharge series

3.4.1 Stage-discharge transformation

Using equations (3.1) to (3.5) and the completed and corrected water level record of Stung Treng a discharge series was obtained for the period 1910-2006, hereafter referred to as series A. To show the effect of the ADCP-based discharge rating a series B has been created using equations (3.1) to (3.4) for the years 1910 to 1998 and equation (3.7) for the period 1999-2006.

The flood volumes (June-November flows) derived for the series A and B are presented in Figure 3.20. From 1999 onward series A gives about 9% higher flood volumes than series B.

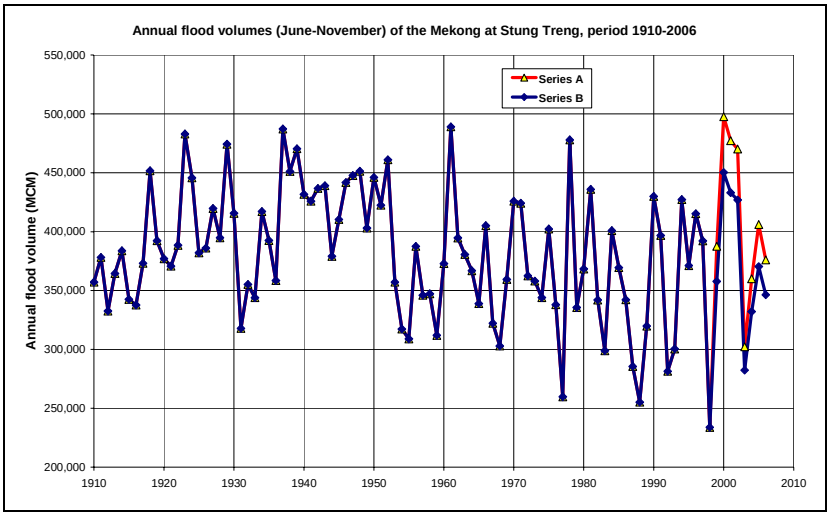

Figure 3.20 Annual flood volume (June-November) in the Mekong at Stung Treng for series A & B, period 1910-2006

These flood volumes have been compared with those estimated for Pakse. The comparison is made for the periods 1960-1969 and 1999-2006. The first period was chosen as it is entirely based on conventional current meter measurements (series A and B) and the latter for series B is for its upper part based on the ADCP-BT measurements at Kratie in 2007. Figure 3.21 shows an insignificant difference in the relationship for series A: for the same flood volume in Pakse for the period 1999-2006 only a 2% higher flood volume at Stung Treng is computed. Had the ADCP-based curve been applied to the levels in Stung Treng for the period 1999-2006 (see Figure 3.22) then a negative bias of about 7 % is obtained. It follows that only series A leads to consistency with the pre-1999 records.

For the flood volume of the Se San and tributaries the effect of the different discharge ratings is more severe. Since reliable data for the Se San at mouth are not available the flood volume is determined as the difference of the volumes at Stung Treng and Pakse. The average for the period 1960-1969 is 98,000 MCM. According to the ADCP-based series the estimate for 1999-2007 would be 80,000 MCM, whereas a continuation of the old rating curve would give for 1999-2007 about 115,000 MCM, i.e. 1.4 times as much. The average annual flood volume at Pakse for the periods 1960-1969 and 1998-2006 was respectively 275,000 MCM and 295,000 MCM. Hence, one would expect a value for the Se San in the

period 1999-2006 to be larger than 98,000 MCM, which makes a continuation of the application of the current meter based curve likely. On the other hand, however, data for the period 1960-1969 indicate, that there is little correlation between the flood volume of the Mekong at Pakse and the Se San at mouth ($R^2 = 0.32$).

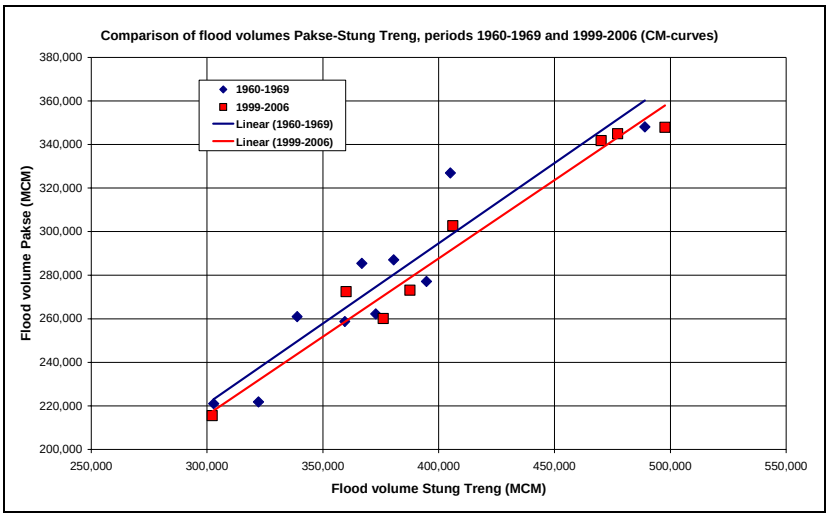

Figure 3.21 Relations between flood volumes (June-November) at Pakse and Stung Treng for the periods 1960-1969 and 1999-2006, series A

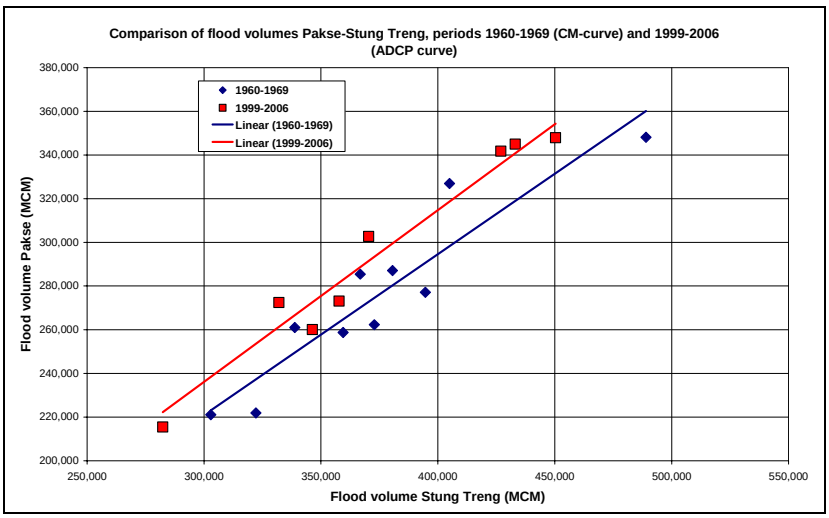

Figure 3.22 Relations between flood volumes (June-November) at Pakse and Stung Treng for the periods 1960-1969 and 1999-2006, series B

From this comparison it may prudently be concluded that the bottom tracking referenced ADCP measurements nowadays create a distinct break in the discharge series. This once more stresses the need for improved ADCP measurement procedures using DGPS simultaneously with current meter measurements.

In the following the series derived from the relations (3.1) to (3.5) will be used as the best estimate for now (= series A). A comparison with series B will be made.

3.4.2 Extremes

Peak flow

The annual maximum discharge of series A and B (defined in sub-section 3.4.1) are presented in Figure 3.23. The peak values of series A as from 1999 onward are about 13% larger than those of series B.

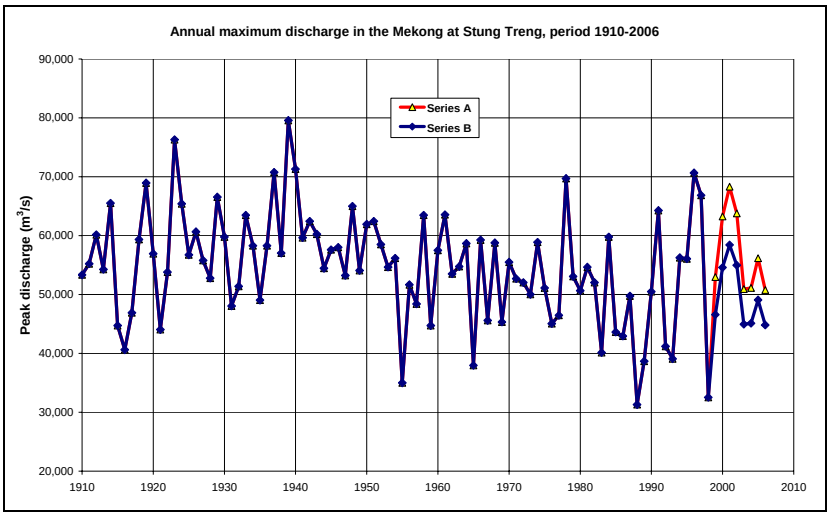

Figure 3.23 Annual maximum discharge in the Mekong at Stung Treng for series A and B, period 1910-2006

The EV1 and GEV distributions have been fitted to the annual maximum flows. The results for series A are presented in Figure 3.24. An acceptable match is obtained with the GEV distribution, whereas the applicability of the EV1 did not pass the test. A comparison of the GEV distributions to the annual maximum flow of series A and B is given in Figure 3.25. It is observed that both series lead to the same results, see also Table 3.2.

Finally, in Figure 3.26 the frequency distribution of the time of occurrence of the annual peak discharge in the Mekong at Stung Treng is observed. Though it may be anywhere in the months August or September, on average it occurs around 1 September. There is no significant correlation between the size of the flood peak and the day of occurrence in the year.

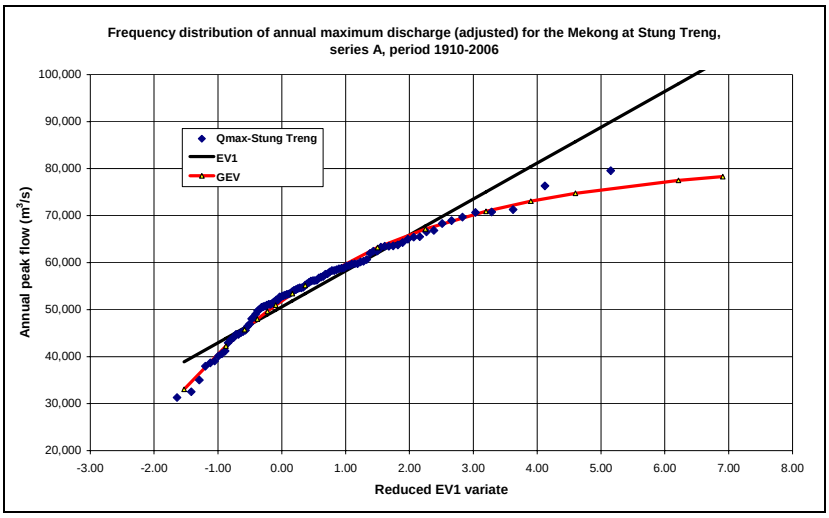

Figure 3.24 Frequency distributions (EV1 and GEV) of annual maximum discharge in the Mekong at Stung Treng for series A, period 1910-2006

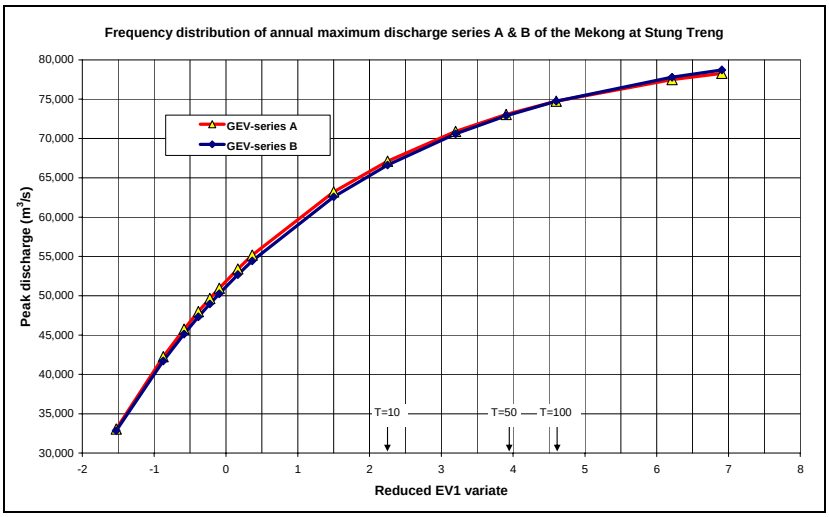

Figure 3.25 GEV distributions of annual maximum discharge in the Mekong at Stung Treng for series A and B, period 1910-2006

Table 3.2 Annual maximum discharge in the Mekong at Stung Treng as a function of the return period for series A and B, period 1910-2006

T	Series A	Series B
2	55,200	54,400
5	63,200	62,600
10	67,100	66,600
25	70,900	70,600
50	73,100	72,900
100	74,800	74,800

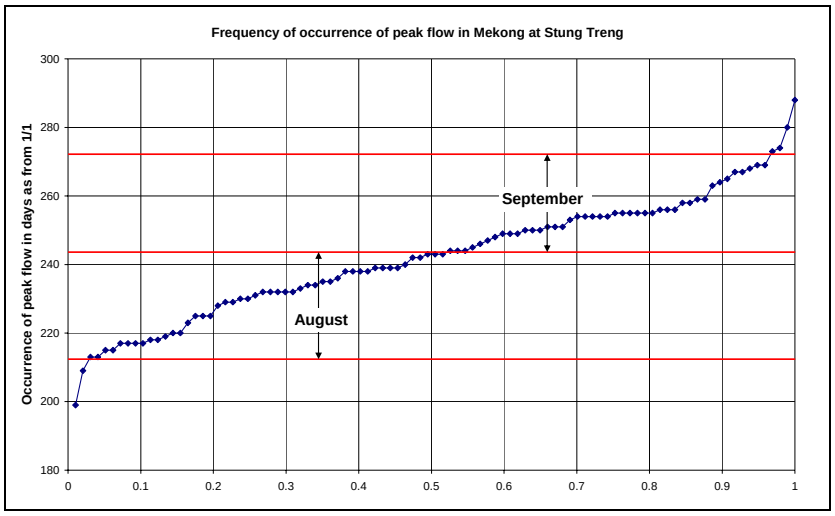

Figure 3.26 Frequency distribution of the day of occurrence of the annual maximum discharge in the Mekong at Stung Treng, period 1910-2006

Flood volume

An important variable for flood hazard assessment in the Mekong Delta is the annual flood volume, determined between the up- and down-crossing of the hydrograph with the mean. The flood volume rather than the flood peak determines the maximum stages in most parts of the Delta. The EV1 and GEV distributions have been fitted to the annual flood volumes. The result for series A are presented in Figure 3.28. The GEV distribution fits the annual flood volume well, whereas the applicability of EV1 did not pass the test. A comparison of the GEV distributions to the annual flood volumes derived from series A and B is given in Figure 3.29. It is observed that series A gives slightly higher values, though the differences are small, see also Table 3.3. Hence, the uncertainty in the discharge rating for Stung Treng for the period 1999-2008.

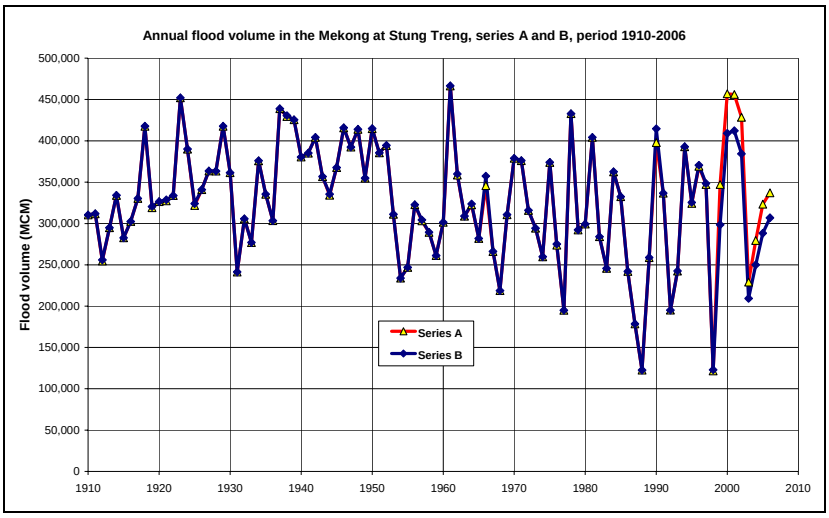

Figure 3.27 Annual flood volume determined between up- and down crossing of the hydrograph with the mean for series A and B', period 1910-2006

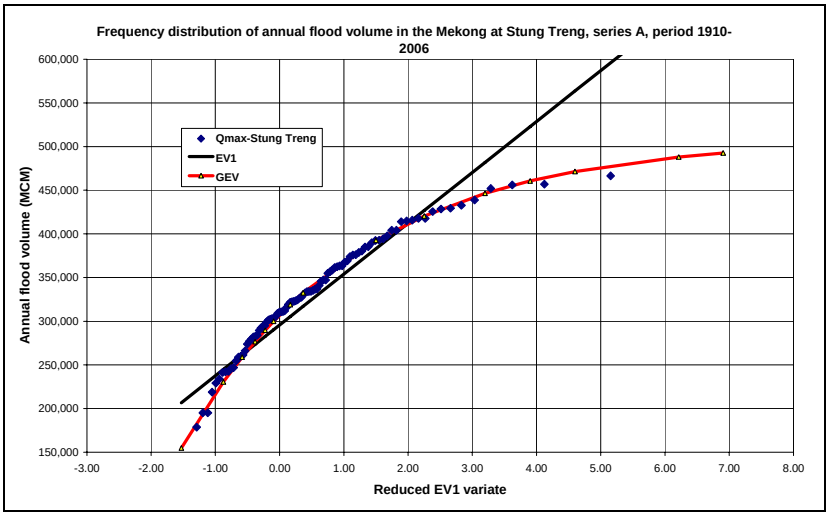

Figure 3.28 Frequency distributions (EV1 and GEV) of annual flood volume in the Mekong at Stung Treng for series A, period 1910-2006

Table 3.3 Annual flood volume in the Mekong at Stung Treng as a function of the return period for series A and B, period 1910-2006

T	Series A	Series B
2	333,000	331,000
5	393,000	389,000
10	421,000	416,000
25	446,000	440,000
50	461,000	453,000
100	471,000	463,000

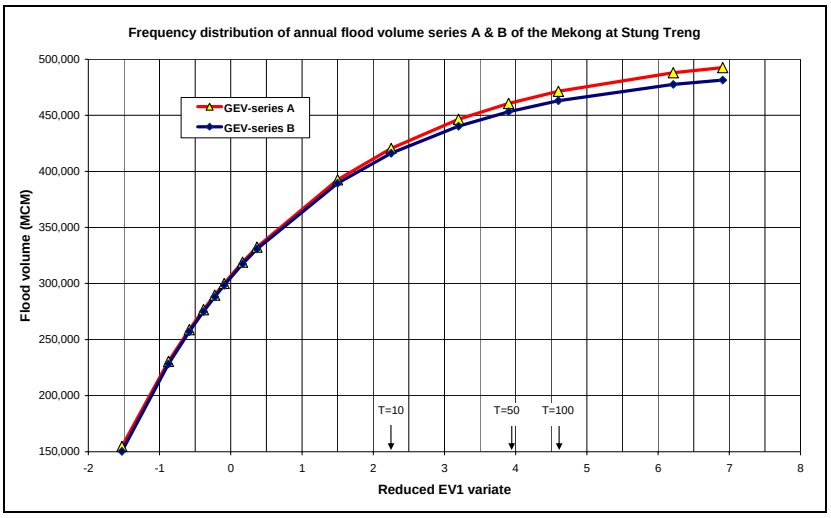

Figure 3.29 GEV distributions of annual flood volume in the Mekong at Stung Treng for series A and B', period 1910-2006

The combined annual flood peak and flood volumes for the Mekong at Stung Treng are presented in Figure 3.30 and Table 3.4. From the figure it is observed that for a flood peak of 65,000 m^3/s, the flood volume may vary from about 275,000 to 460,000 MCM. In the table the historical series of peak discharges and annual flood volumes is presented as well as sorted in descending order according to peak discharge and flood volume.

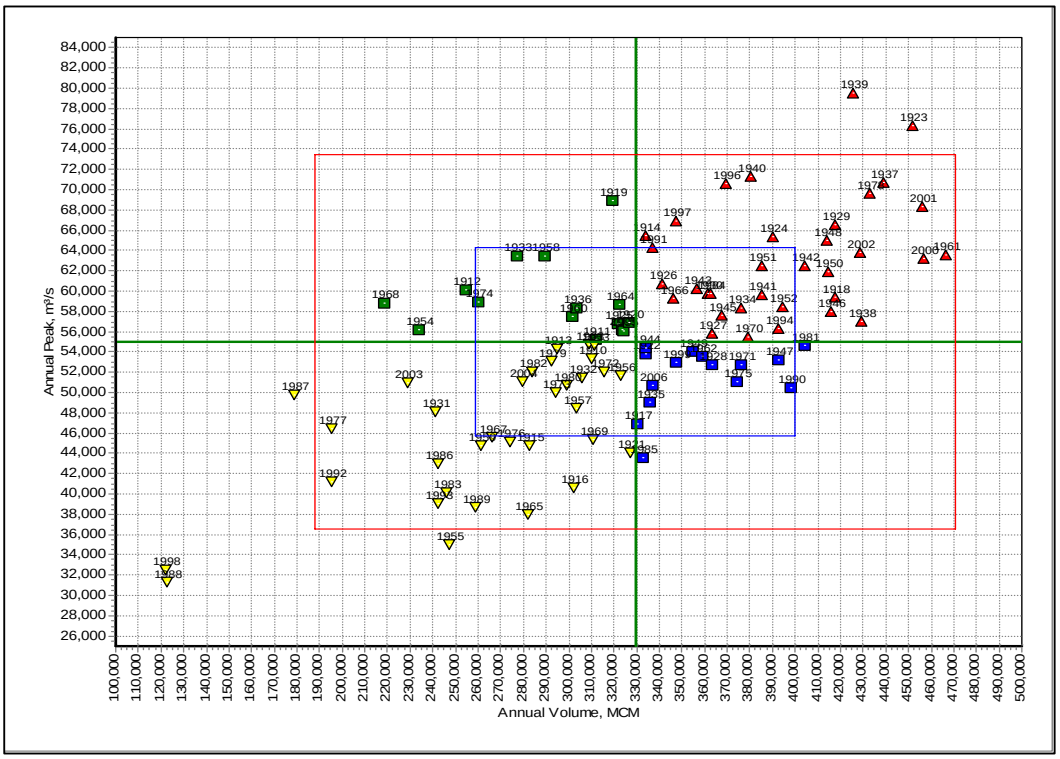

Figure 3.30 Annual maximum discharge against annual flood volume (according to MRC flood volume definition) in the Mekong at Stung Treng for series A, period 1910-2006

Table 3.4 Historical peak discharges and flood volumes of the Mekong at Stung Treng, Period 1910-2006

Historical			Sorted according to Qpeak			Sorted according to Fvolume		
Year	Qpeak (m^3/s)	Fvolume (MCM)	Year	Qpeak (m^3/s)	Fvolume (MCM)	Year	Qpeak (m^3/s)	Fvolume MCM)
1910	53,335	310,333	1939	79,556	425,563	1961	63,567	466,495
1911	55,217	311,867	1923	76,309	452,039	2000	63,262	456,905
1912	60,159	254,656	1940	71,293	380,450	2001	68,319	456,062
1913	54,272	294,825	1937	70,757	438,838	1923	76,309	452,039
1914	65,510	334,017	1996	70,651	369,262	1937	70,757	438,838
1915	44,735	282,720	1978	69,692	432,767	1978	69,692	432,767
1916	40,625	302,352	1919	68,952	319,206	1938	57,035	429,390
1917	46,905	330,339	2001	68,319	456,062	2002	63,770	428,437
1918	59,371	417,683	1997	66,856	347,141	1939	79,556	425,563
1919	68,952	319,206	1929	66,544	417,769	1929	66,544	417,769
1920	56,938	326,404	1914	65,510	334,017	1918	59,371	417,683
1921	44,051	327,395	1924	65,407	390,045	1946	58,003	415,692
1922	53,802	333,816	1948	64,996	413,956	1950	61,952	414,723
1923	76,309	452,039	1991	64,279	336,650	1948	64,996	413,956
1924	65,407	390,045	2002	63,770	428,437	1942	62,454	404,238
1925	56,746	321,672	1961	63,567	466,495	1981	54,649	404,118
1926	60,655	340,922	1933	63,465	277,012	1990	50,478	397,854
1927	55,788	363,489	1958	63,465	289,327	1952	58,489	394,424
1928	52,776	363,413	2000	63,262	456,905	1994	56,266	392,770
1929	66,544	417,769	1942	62,454	404,238	1947	53,241	392,478
1930	59,764	361,496	1951	62,454	385,454	1924	65,407	390,045
1931	48,052	241,303	1950	61,952	414,723	1951	62,454	385,454
1932	51,392	305,593	1926	60,655	340,922	1941	59,666	385,105
1933	63,465	277,012	1943	60,258	356,713	1940	71,293	380,450
1934	58,294	375,829	1912	60,159	254,656	1970	55,502	378,827
1935	49,034	335,426	1930	59,764	361,496	1971	52,683	376,116
1936	58,294	303,351	1984	59,764	362,494	1934	58,294	375,829
1937	70,757	438,838	1941	59,666	385,105	1975	51,117	374,006
1938	57,035	429,390	1918	59,371	417,683	1996	70,651	369,262
1939	79,556	425,563	1966	59,272	345,823	1945	57,614	367,559
1940	71,293	380,450	1974	58,880	259,704	1927	55,788	363,489
1941	59,666	385,105	1968	58,782	218,762	1928	52,776	363,413
1942	62,454	404,238	1964	58,685	322,470	1984	59,764	362,494
1943	60,258	356,713	1952	58,489	394,424	1930	59,764	361,496
1944	54,460	334,186	1934	58,294	375,829	1962	53,521	358,680
1945	57,614	367,559	1936	58,294	303,351	1943	60,258	356,713
1946	58,003	415,692	1946	58,003	415,692	1949	54,084	354,938
1947	53,241	392,478	1945	57,614	367,559	1999	52,962	347,156
1948	64,996	413,956	1960	57,518	301,418	1997	66,856	347,141
1949	54,084	354,938	1938	57,035	429,390	1966	59,272	345,823
1950	61,952	414,723	1920	56,938	326,404	1926	60,655	340,922
1951	62,454	385,454	1925	56,746	321,672	2006	50,752	337,125
1952	58,489	394,424	1994	56,266	392,770	1991	64,279	336,650
1953	54,649	311,197	1954	56,170	233,902	1935	49,034	335,426
1954	56,170	233,902	2005	56,170	323,324	1944	54,460	334,186
1955	35,008	246,895	1995	56,075	324,353	1914	65,510	334,017
1956	51,667	322,756	1927	55,788	363,489	1922	53,802	333,816
1957	48,408	303,113	1970	55,502	378,827	1985	43,626	332,388
1958	63,465	289,327	1911	55,217	311,867	1917	46,905	330,339
1959	44,735	261,258	1963	54,744	308,941	1921	44,051	327,395
1960	57,518	301,418	1953	54,649	311,197	1920	56,938	326,404

Historical			Sorted according to Qpeak			Sorted according to Fvolume		
Year	Qpeak (m^3/s)	Fvolume (MCM)	Year	Qpeak (m^3/s)	Fvolume (MCM)	Year	Qpeak (m^3/s)	Fvolume MCM)
1961	63,567	466,495	1981	54,649	404,118	1995	56,075	324,353
1962	53,521	358,680	1944	54,460	334,186	2005	56,170	323,324
1963	54,744	308,941	1913	54,272	294,825	1956	51,667	322,756
1964	58,685	322,470	1949	54,084	354,938	1964	58,685	322,470
1965	37,965	281,896	1922	53,802	333,816	1925	56,746	321,672
1966	59,272	345,823	1962	53,521	358,680	1919	68,952	319,206
1967	45,597	266,085	1910	53,335	310,333	1972	52,035	315,864
1968	58,782	218,762	1947	53,241	392,478	1911	55,217	311,867
1969	45,337	310,680	1979	53,055	292,254	1953	54,649	311,197
1970	55,502	378,827	1999	52,962	347,156	1969	45,337	310,680
1971	52,683	376,116	1928	52,776	363,413	1910	53,335	310,333
1972	52,035	315,864	1971	52,683	376,116	1963	54,744	308,941
1973	50,025	294,281	1972	52,035	315,864	1932	51,392	305,593
1974	58,880	259,704	1982	52,035	283,916	1936	58,294	303,351
1975	51,117	374,006	1956	51,667	322,756	1957	48,408	303,113
1976	45,079	273,811	1932	51,392	305,593	1916	40,625	302,352
1977	46,467	195,080	1975	51,117	374,006	1960	57,518	301,418
1978	69,692	432,767	2004	51,117	279,456	1980	50,660	299,250
1979	53,055	292,254	2003	50,934	229,146	1913	54,272	294,825
1980	50,660	299,250	2006	50,752	337,125	1973	50,025	294,281
1981	54,649	404,118	1980	50,660	299,250	1979	53,055	292,254
1982	52,035	283,916	1990	50,478	397,854	1958	63,465	289,327
1983	40,135	245,767	1973	50,025	294,281	1982	52,035	283,916
1984	59,764	362,494	1987	49,754	178,613	1915	44,735	282,720
1985	43,626	332,388	1935	49,034	335,426	1965	37,965	281,896
1986	42,950	242,070	1957	48,408	303,113	2004	51,117	279,456
1987	49,754	178,613	1931	48,052	241,303	1933	63,465	277,012
1988	31,293	122,675	1917	46,905	330,339	1976	45,079	273,811
1989	38,682	258,841	1977	46,467	195,080	1967	45,597	266,085
1990	50,478	397,854	1967	45,597	266,085	1959	44,735	261,258
1991	64,279	336,650	1969	45,337	310,680	1974	58,880	259,704
1992	41,201	195,156	1976	45,079	273,811	1989	38,682	258,841
1993	39,083	242,568	1915	44,735	282,720	1912	60,159	254,656
1994	56,266	392,770	1959	44,735	261,258	1955	35,008	246,895
1995	56,075	324,353	1921	44,051	327,395	1983	40,135	245,767
1996	70,651	369,262	1985	43,626	332,388	1993	39,083	242,568
1997	66,856	347,141	1986	42,950	242,070	1986	42,950	242,070
1998	32,534	121,732	1992	41,201	195,156	1931	48,052	241,303
1999	52,962	347,156	1916	40,625	302,352	1954	56,170	233,902
2000	63,262	456,905	1983	40,135	245,767	2003	50,934	229,146
2001	68,319	456,062	1993	39,083	242,568	1968	58,782	218,762
2002	63,770	428,437	1989	38,682	258,841	1992	41,201	195,156
2003	50,934	229,146	1965	37,965	281,896	1977	46,467	195,080
2004	51,117	279,456	1955	35,008	246,895	1987	49,754	178,613
2005	56,170	323,324	1998	32,534	121,732	1988	31,293	122,675
2006	50,752	337,125	1988	31,293	122,675	1998	32,534	121,732

4 Mekong at Kratie

4.1 Station description

Kratie water level gauging station is located on the left bank of the Mekong in the south-western corner of Kratie town at lat 12°28.6'N, long 106°00.09'E and according to the hydrographic atlas 561 km from the sea (see Figure 4.1), covering a catchment area of 646,000 km^2. The positioning of the station downstream of the Kratie loading ramp/port and the layout with the inclined manual gauge are shown in Figure 4.2.

Figure 4.1 Mekong at Kratie d/s Sambor Rapids (left) with location of Kratie gauging station (right)

Figure 4.2 View on Kratie gauging station downstream of loading ramp (left) and station layout with slope gauge (right)

Alongside the staircase with the manual slope gauge the pipe connecting the water body with the Ott Nimbus bubbler gauge can be observed, see Figure 4.3. The Ott Nimbus replaced the failing Mindata equipment; the latter is now only used as a data logger.

Figure 4.3 Inclined manual gauge with gauge pipe for Ott Nimbus bubbler gauge with Mindata data logger (right) at Kratie gauging station

The manual gauge is observed twice daily (07.00 and 19.00 hrs) in the dry season and in the flood season three times per day (07.00, 13.00 and 19.00 hrs) by the staff of the Kratie Provincial Department of Water Resources and Meteorology. The operation of the station is the responsibility of the Department of Hydrology and River Works under the Ministry of Water Resources and Meteorology of Cambodia.

The gauging station at Kratie was established in 1933. Harza (1961) describes the gauge as a painted slope gauge on the downstream side of a disused concrete loading ramp. The gauge zero has ever since its establishment been 0.4822 masl (Hatien) (note that the documented -1.08 masl in the hydrological yearbooks is based on a wrong level of the benchmark near the station). The yearbook of 1961 mentions the existence of a bubbler gauge in Kratie at least since 13 August 1960 when the record of this gauge starts. The gauging station at Kratie has replaced station Sambor, about 10 kilometres upstream of the city), just downstream of the rapids where stages were measured as from 1924 onward until 1966.

When the JICA-team visited the Kratie site in 2001 an insecure minimum slope gauge was found with a broken gauge support, while further no recorder nor did a data logger exist at the site. The team recommended to re-inforce the slope gauge. The site was visited on 28th January 2008 by Consultants and was found in good condition.

Characteristic water levels at Kratie are following:

- Flood alarm level = 22.0 masl
- Flood level = 23.0 masl
- Station staff indicated that at a level of 22.05 m+GZ (= 22.53 masl) the Kratie market starts flooding through the sewer system
- At 19.0 m+GZ (= 19.5 masl) at Kratie flooding starts between Chhlong and Kampong Cham.

The cross-section of the Mekong at Kratie is presented in Figure 4.4. At the station the river is split in two branches by the island in the river opposite Kratie, see also Figure 4.1. Note that at a level of 22.52 m+GZ the left bank (Kratie side) will be overtopped. The right bank reaches to 21.60 m+GZ in the graph, but this may not be the maximum elevation.

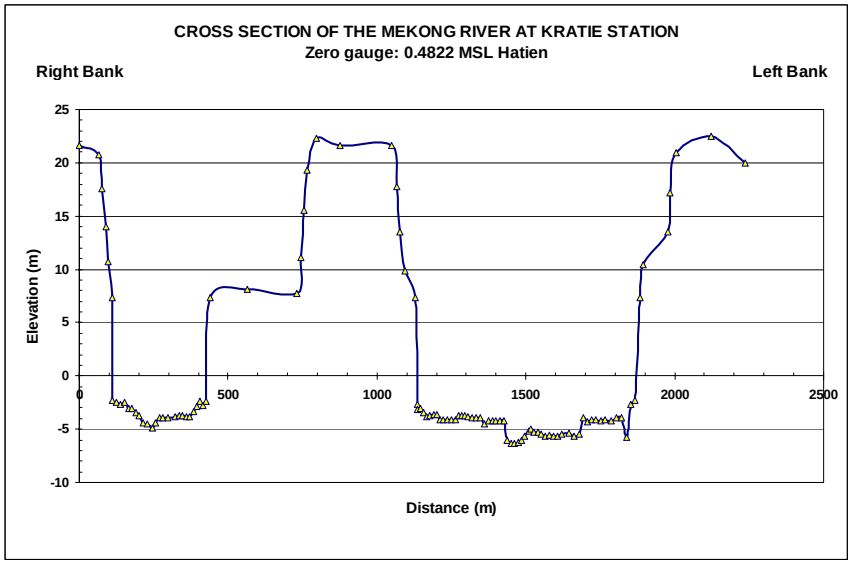

Figure 4.4 Cross-section of the Mekong at Kratie gauging station

4.2 Water level series

4.2.1 Availability in database

The HYMOS database at MRC contains for Kratie a water level record from 7 January 1933 till 31 December 2006 with the following missing periods:

- 1933: 22-31 December
- 1934: 1-3 January
- 1936: 1-6 July
- 1938: 1 June – 31 October
- 1945: 9 March – 31 April
- 1950: 6 January – 23 February
- 1967: 27 February – 31 March
- 1969: 24 November -31 December
- 1970: 15 January – 22 March
- Major gap: 1 April 1974 – 31 December 1979
- 1996: 13 - 31 December

4.2.2 Validation and completion

No original record of the water level series of Kratie was reported to be available (MRC, 2004). The series have been validated by inspection of the natural variation and by

comparison with the record of Stung Treng. Also a comparison was made between the average daily water levels and the instantaneous 07.00 PM values stored in the forecast database for the period 2000-2006.

The following anomalies are observed:

- Gauge shifts on 16/3/1933, 8/12/1953, 12/11/1957, 1/1/1960, 1/4/1970 and 1/1/1989.
- Doubtful periods: 7/1/-15/3/1933, 1/12/1953-31/12/1959, 1/1/-26/5/1960, 15/11/-17/11/1964, 24/3/-18/4/1965, 9/12/1966-3/1/1967, 29/11/1967, 24/1/-16/4/1968, 29/11/1968-21/4/1969, 4/11/-31-12/1969 and 23/3/1970-31/3/1974. Origin of the data of the latter period is not clear and the water level range is too small. The record of minimum and maximum water levels available at the gauging station indicates that the period 1970-1979 is entirely missing. Above periods have been omitted from the analyses.
- Harza (1961) states that the records of Kratie are of good quality for medium and high stages, but questionable for stages below a gauge height of 6.00 m as prior to 26/5/1960 the gauge height was estimated below the bottom graduation mark on the ramp. It mentions that the record from sometime in the dry season of 1957 till 26 May 1960 must be corrected for wrongly painted graduation of the slope gauge by the formula: $h_{corr} = 4.25+0.793\ h_{record}$. Reference is made to the comments in the Harza Report on the water level record as footnotes to the discharge series of 1933-1953, where for each year the doubtful water level data have been specified. At several occasions the discharge series for Kratie was estimated based on Pakse and Mukdahan.
- After a period of interruption in the seventies the daily gauge records resumed again on 1/1/1980. MRC (2004) reports that from 1/1/1980 till the end of 1996 the gauge datum was 2.0 m lower than the current zero gauge datum. This statement seems to be incorrect as:
  - a shift was introduced on 1/1/1989, and
  - from the hydrograph it can be deduced that a shift of 2.42 m is more appropriate then a shift of 2.00 m.

Our analysis of the hydrographs shows that particularly the water level records for the low stages are doubtful. This observation is consistent with the findings of Harza as far as the record prior to 1960 is concerned. Note, however, that these findings are partly based on a comparison with the levels at Stung Treng, which were considered to be doubtful in a number of occasions prior to 1960 as well.

4.2.3 Stage-relation curves

To be able to make a comparison between water level and discharge measurements at Stung Treng and Kratie stage-relation curves have been established for different periods. A distinction has been made between rising and falling stages to account for backwater effects on the water levels at Kratie by the flow direction in the Tonle Sap. Relation curves have been described as polynomials of the following general form:

$$h_{Kratie,t} = a + b\,h_{Stung\,Treng,t-1} + c\,h^2_{Stung\,Treng,t-1} + d\,h^3_{Stung\,Treng,t-1} \quad [m+GZ] \qquad (4.1)$$

By comparison of the annual relations for rising and falling stages separately, a grouping of relations appeared to be possible. The distinguished periods and the parameters of the

polynomials per period are presented in Table 4.1. Note that the equations should not be used beyond the indicated range in the table as no physics is included in the equations.

Table 4.1 Kratie-Stung Treng stage-relation parameters of equation (3.1) for rising and falling stages.

Period	Stage	Range (m)	a	b	c	d
1960-1969	rising	2.00 - 11.60	1.856	1.877	0.0772	-0.0077
	falling	1.40 - 10.80	1.713	1.982	0.0792	-0.0084
1989-1999	rising	2.00 – 12.20	1.697	1.992	0.0573	-0.0067
	falling	1.40 - 4.00	1.807	1.854	0.0784	-
		4.01 – 10.80	0.173	2.791	-0.0367	-0.0031
2000-2006	rising	2.00 – 12.00	2.585	1.597	0.1099	-0.0085
	falling	1.40 – 6.00	1.322	2.410	-0.0280	-
		6.01 – 10.20	-4.826	4.260	-0.1669	-

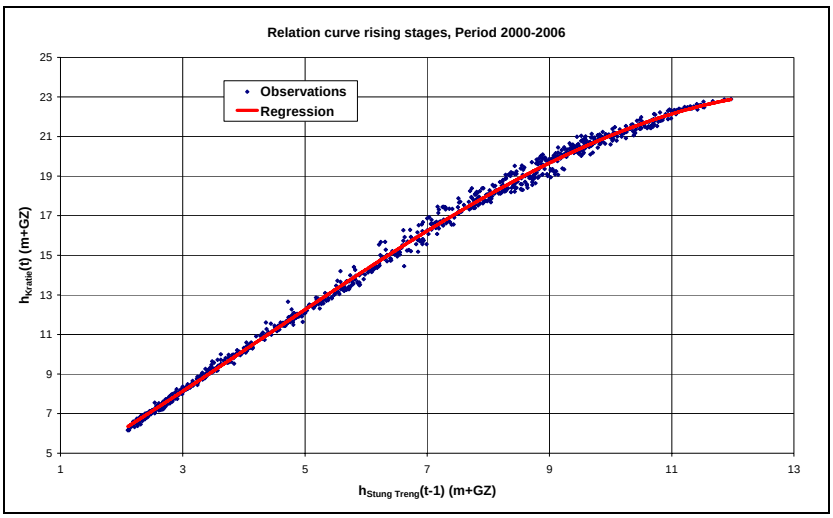

Figure 4.5 Fit of Kratie-Stung Treng relation curve to rising stages in period 2000-2006

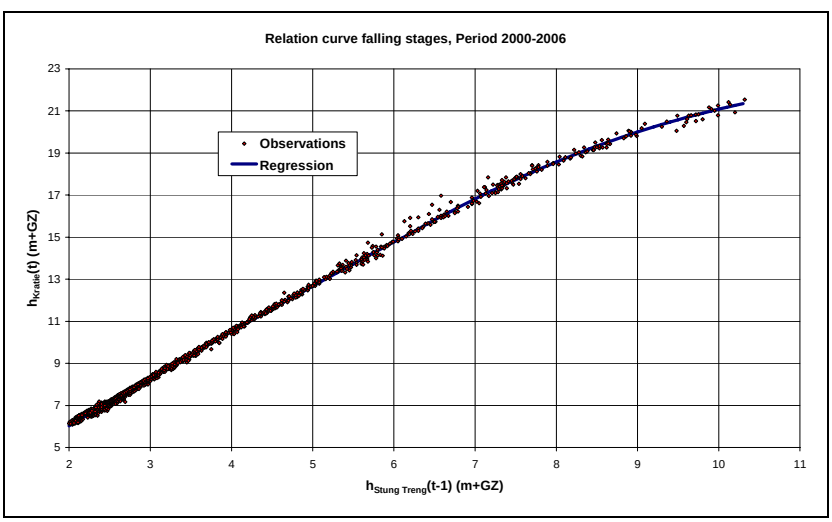

Figure 4.6 Fit of Kratie-Stung Treng relation curve to falling stages in period 2000-2006

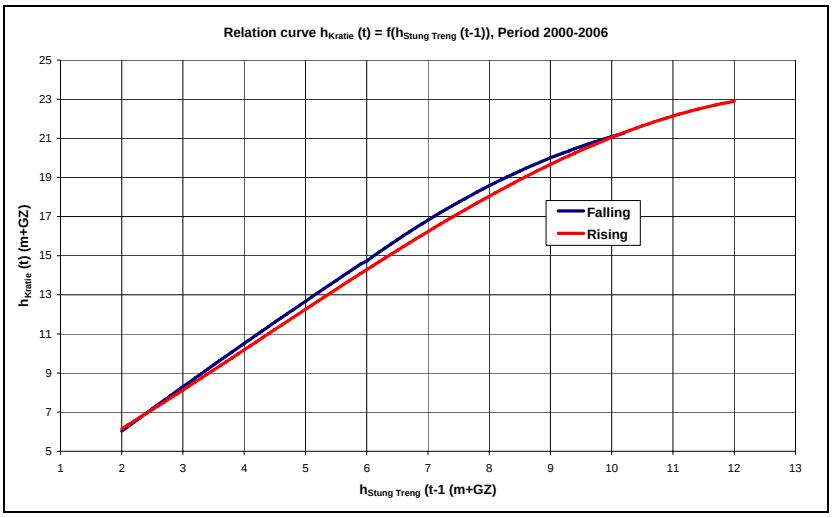

Figure 4.7 Kratie-Stung Treng stage relation curves for all rising and falling stages, period 2000-2006

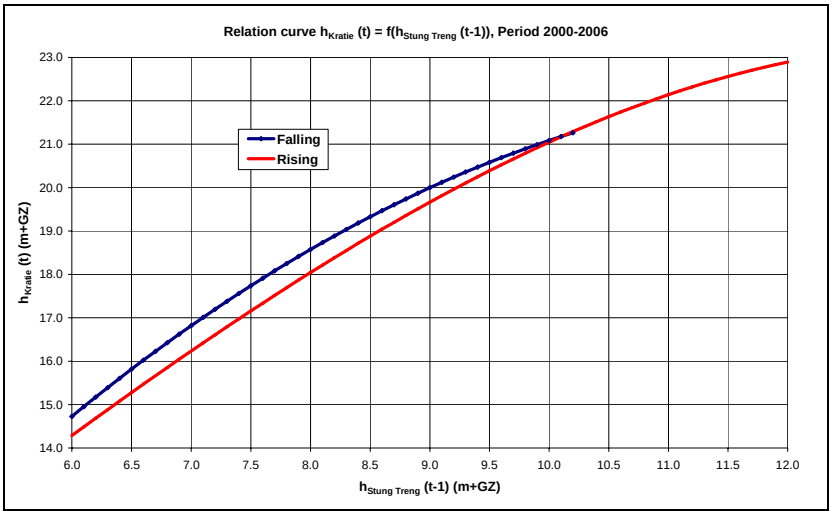

Figure 4.8 Kratie-Stung Treng stage relation curves for higher rising and falling stages, period 2000-2006

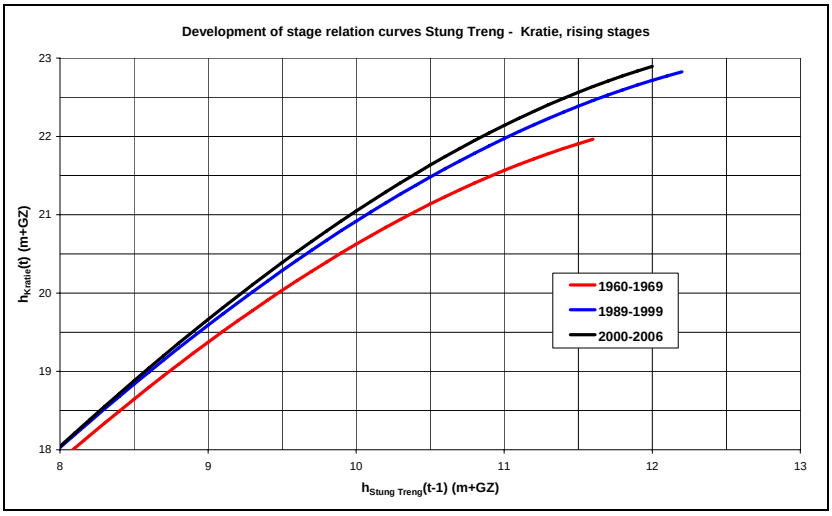

Figure 4.9 Comparison of Kratie-Stung Treng stage-relation curves for 1960-2006

The relations for the period 2000-2006 are displayed in Figure 4.5 to Figure 4.8. It shows that the rising and falling stages at Kratie and Stung Treng with a time shift of 1 day are well correlated. The looping in the relation is due to backwater effect on the water levels of Kratie by inflow to and outflow from the Tonle Sap.

A comparison of the stage-relations of rising stages is presented in Figure 4.9. It shows that for a particular flood level at Stung Treng the level at Kratie has grown in the course of time, increasingly for the higher stages. From Figure 4.9 it is observed that e.g. for a water level of 11 to 11.5 m+GZ at Stung Treng the water level at Kratie has increased with about 60 to 70 cm from 1960 to 2000. These changing stage-relations indicate that the control section of Kratie has changed in absolute sense. It shows that the discharge capacity of the river downstream of Kratie is decreasing, which may be attributed to flood plain encroachments in this section; for the same Mekong discharge it leads to higher water levels at Kratie and further downstream. Analysis shows that a similar, but less pronounced, trend as discussed above for the rising stages exists for the falling stages.

The above observations are based on grouping of years. When looking at the individual years, it appears that there is considerable variation in the stage-relations from one year to another, particularly so in the sixties (see also Chapter 3 for variations observed at Stung Treng). But the trend is clear: increasingly higher flood levels. This trend is likely to be aggravated in future as the road from Chhlong to Kratie along the left bank of the river has been elevated to a flood free level (construction completed in 2008). Historically, diversion to the left bank flood plain took place when the level in Kratie exceeded a level of about 19 m+GZ. The new road blocks this diversion, further encroaching the flood plain and backing up the water table at Kratie.

In summary, this analysis shows that the discharge rating curve for Kratie is changing and has to be regularly updated.

4.3 Stage-discharge measurements

4.3.1 Availability

The earliest stage-discharge measurements available for Kratie in the HYMOS database at MRC are from 1960, when measurements were made from a boat some 2,200 m downstream of the gauging station as reported in the hydrological yearbook of the Mekong of 1961. Though a description of the measurements at Kratie is not available, it may be assumed that the USGS procedure with current meter similar to the measurements at Stung Treng (see Chapter 3) introduced by Harza in the early sixties, has been applied here as well. The current meter measurements continued at Kratie till 1969. Particularly in 1960 a large number of measurements have been carried out, though with a limited discharge range. High flows have been measured in 1964 and especially in 1966. After the sixties until late 2002 no measurements were carried out at Kratie.

With support of the Mekong River Commission the Department of Hydrology and River Works resumed stage-discharge measurements at Kratie in October 2002 till November 2003 using an Acoustic Doppler Current Profiler (ADCP). Over 260 measurements were made in a single river section a few kilometres downstream of the gauging station.

Unfortunately, the flood in the year 2003 was moderate, so high discharges were not measured (Q_{max} < 43,400 m^3/s). Another but much smaller series of ADCP-measurements is available for the year 2007.

In 2008 at the major stations discharge measurements with ADCP were carried out by the DHWR with a frequency of 2 per month in the lean season and 4 in the flood season, producing two sets of discharge estimates: one set referenced to bottom tracking and another set referenced to GPS, see also Chapter 3.

A summary of all the measurements is presented in Table 4.2.

Table 4.2 Summary of availability and range of stage-discharge measurements for the Mekong at Kratie

Year	number	h-range (m+GZ)	Q-range (m^3/s)
1960	101	4.77-20.72	661-36,260
1961	9	5.14-19.20	1,581-37,146
1962	11	7.77-18.45	4,646-36,179
1963	2	6.54-15.27	2,491-23,360
1964	12	5.32-21.31	1,965-61,500
1965	13	5.76-18.70	2,065-35,420
1966	11	5.63-22.13	1,850-73,600
1967	1	6.65	2,810
1968	1	6.05	2,095
1969	2	9.91-17.55	7,300-27,300
2002	81	8.64-17.05	4,410-23,534
2003	181	7.00-21.00	2,522-43,377
2007	10	9.11-20.34	6,390-42,696
2008	35	6.76-20.44	2,530-41,590*) (2,095-52,424) **)

*) Range of measurements with ADCP ref..Bottom Tracking
**) Range of measurements with ADCP ref. GPS

4.3.2 Validation

The water levels of the stage-discharge measurements in the Mekong at Kratie have been validated against those presented in the daily average water level series of the station. Differences in excess of 0.10 m were only accepted at times of rapid rises or falls. Else, the measurements were finally deleted from the data set. Examples are shown in Figure 4.10 and Figure 4.11.

Also stage-discharge plots were made using the water levels as reported with the discharge measurements and those from the daily average water level series, first without distinction between rising and falling stage conditions. The measurements made in the period 1960-1969 are shown in Figure 4.12. The figure shows that apart from a few incidental errors a different stage-discharge relation seems to apply until and after 15 September 1960. Comparison with measurements of later years at Kratie and with the discharges at Stung Treng shows that the discharge data from 1/1/-15/9/1960 do not represent the full Mekong flow. It may well be that these measurements have been carried near the gauging station covering only one branch of the Mekong. These data have therefore been eliminated from the database.

Figure 4.12 also shows that the water level to which the largest measured discharge at Kratie of 73,600 m^3/s is referenced differs largely (10.85 m) with the average water level recorded for the measurement day 21/6/1966. It seems that the date attached to the measurement should read 21/9/1966; in that case the level of 21.77 m+GZ attached to the measurement is close to the average water level of 21.85 m+GZ for that day. But it remains speculative and the measurement has been omitted from the data set.

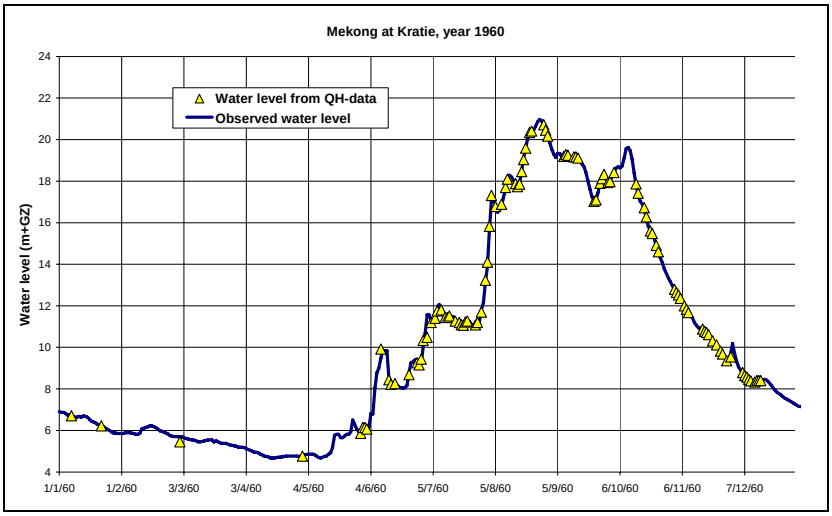

Figure 4.10 Validation of stages of QH-data of the Mekong at Kratie, year 1960

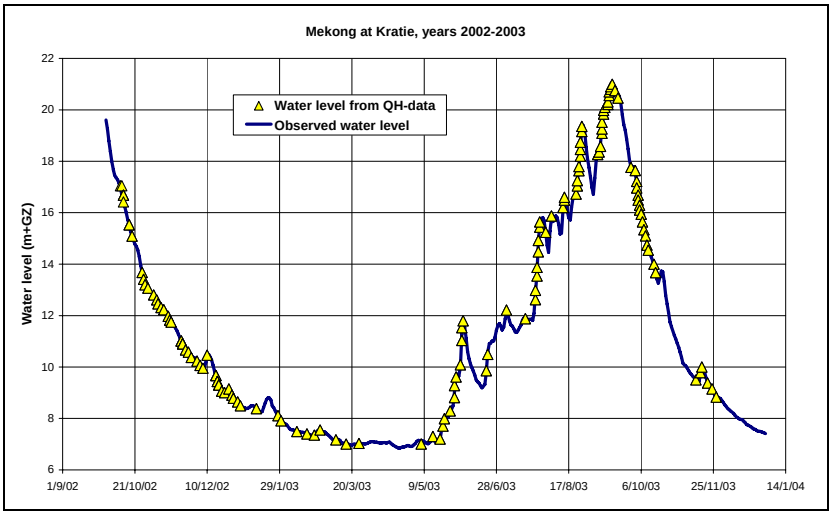

Figure 4.11 Validation of stages of QH-data of the Mekong at Kratie, Period 2002-2003

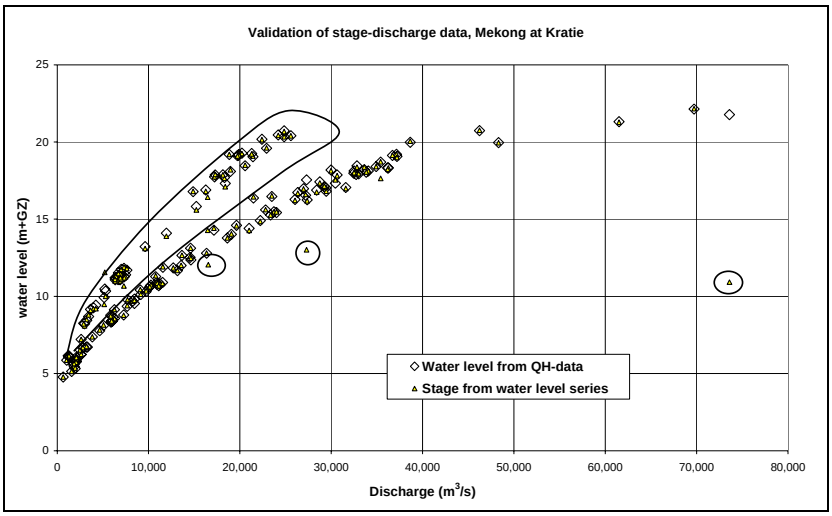

Figure 4.12 Validation of stage-discharge data of the Mekong at Kratie, Period 1960-1969

4.4 Discharge rating curves for Kratie

4.4.1 General

In the introduction to the discharge series of Kratie the following comment is made (Harza, 1961):

> *"Channel subject to shifting especially at time of rapid rises in stage early in flood season when control region downstream of Chhlong shifts and is gradually flooded. Flooding of this control is completed between Kratie gage heights 15.5 m and 16.5 m for rising stages and the control becomes effective again at gage height 11.0 m, for falling stages. At stages above these, the rating is affected by variable slopes indicated by the fall in water surface elevation from Kratie to Kompong Cham gages. The variation in slope is caused by backwater from the Tonle Sap….."*

Generally for sub-critical flow in an open river profile with a natural control, deviations from a unique one-to-one stage-discharge relationship results from:

1. unsteady flow effects,
2. backwater effects from downstream water level conditions,
3. changes in the geometry and/or hydraulic roughness of the control reach (about 3 x characteristic backwater length), and
4. measurement errors.

These effects are elaborated in the following.

Unsteady flow effects

Rapidly rising and falling hydrographs in gently sloped rivers create a looped discharge rating curve. This is a result of differences in energy slopes before and after the passage of

the peak, which are larger respectively smaller than the steady state energy slope. Consequently, for a particular water level, the discharge, when stages are rising, is larger and, when stages are falling, is smaller than for the steady state. This behaviour can generally well be expressed by the Jones equation, which reads:

$$Q_{unsteady} = Q_{steady}\sqrt{1+\frac{1}{S\,c_f}\frac{dh}{dt}} \quad and \quad Q_{steady} = c(h+a)^b \qquad (4.2)$$

with: $Q_{unsteady}$ = actual flow
Q_{steady} = steady state flow for a particular water level
S = slope of the river
c_f = celerity of the flood wave
h = water level at the gauging station
t = time
a,b,c = coefficients in power type steady flow stage-discharge relation

The slope S is basically the steady state energy slope, which may often be approximated by the bed slope of the river. The celerity of the flood wave is 1.67 x average flow velocity in the river when the river is in-bank, to be multiplied by B_r/B_s when the flow is over-bank, with B_r = river width and B_s = total width of the water table, storage and flow. Often, the factor $1/Sc_f$ is expressed as a function of h. It is observed that the term under the root in (3.2) is > 1 when the stage rises (dh/dt > 0) and < 1 for falling stages (dh/dt < 0).

From the daily average water levels available for Kratie it is observed that the values for dh/dt vary generally between 1.5 and -1.0. An example for the time that the first series of ADCP-measurements were made is given in Figure 4.13.

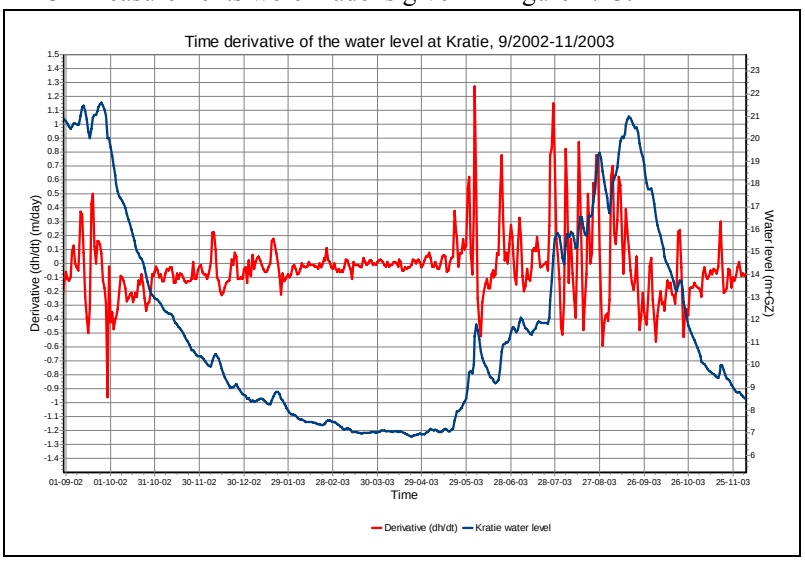

Figure 4.13 Time derivative of the water level at Kratie, Period September 2002 – November 2003

The slope S has been estimated from the stage observations relative to MSL at Kratie and at Kompong Cham, 113 km downstream of Kratie. From average and median levels a slope of about S = 5 x 10^{-5} was estimated. For a flow velocity of 1.5 m/s the celerity for in-bank flow becomes 2.5 m/s. Then the unsteady flow correction ranges from +7% for rising stages till -5% for falling stages. Note that for S = 5 x 10^{-4} the unsteady flow correction would have been < ±1%, i.e. negligible.

It follows, that the unsteady flow effect in the stage-discharge relation for Kratie can be substantial. Runs with the Delta hydraulic model confirm this. However, from daily average water levels an **accurate** value for the time derivative of the water level during the flow measurement is difficult to make. But the effect should certainly be taken into account in future, with dh/dt derived from hourly water levels around the time of execution of the discharge measurement.

Backwater effects

The effect of a disturbance in the steady state water depth h_e at location x = 0 of Δh_0 reduces exponentially further upstream to Δh_L at distance x = L as follows:

$$\Delta h_L = \Delta h_0 \exp\left(-\frac{3S_0 L}{h_e(1-F^2)}\right) \approx \Delta h_0 \exp\left(-\frac{3S_0 L}{h_e}\right) = \Delta h_0 \exp\left(-\frac{L}{L_{BW}}\right) \qquad (4.3)$$

$$with \quad L_{BW} = \frac{1}{3}\frac{h_e}{S_0}$$

where: h_e = equilibrium depth, to be derived from the Manning equation
Δh_0 = initial disturbance to equilibrium depth h_e at x = 0
Δh_L = disturbance to equilibrium depth h_e at x = L upstream of Δh_0
S_0 = slope of the river bed
F = Froude number, assumed to be <<1 in second right hand term of (4.3)
L_{BW} = characteristic backwater length

Above equation is a first order approximation to the Bélanger equation and is valid for **single** channels when $\Delta h_0 << h_e$. The effect of a downstream disturbance is reduced to 5% of its original value (i.e. almost negligible) at a distance of about $L = 3L_{BW}$ upstream of the disturbance. For **compound** channels (river with flood plain) h_e in (4.3) is to be estimated with the Engelund procedure, which leads to an L_{BW} which is substantially smaller.

For a bed slope of $S_0 = 5 \times 10^{-5}$ and an equilibrium depth of 15 m L_{BW} = 100 km. It follows that disturbances up to 300 km downstream of Kratie affect the water level at the site in an exponentially decreasing manner. Hence, with above conditions, a stage variation of 10 cm at Phnom Penh (which is 220 km downstream of Kratie) due to flow into/from the Tonle Sap, would give an effect of about 1.1 cm on the stages at Kratie.

Backwater on the stage-discharge relation for Kratie has been investigated by Sogreah (Bertholot, 1964) and has resulted in separate stage-discharge relations for rising and falling stages. These will be discussed in the next sub-section.

Geometry and hydraulic roughness

From the discussion above on backwater effects it follows, that changes in geometry (due to human interventions like sand mining, or due to morphological activities) and hydraulic roughness (dune formation, vegetation) affect the initial equilibrium depth, to an extent to be

determined with the Manning equation. Consequently, this change in the equilibrium depth will affect the water level in a reach up to 3 x L_{BW} upstream of location of the change.

Measurement errors

Discharge measurements are not error free. Individual conventional current meter measurements contain errors in the order of some 5% percent, highly dependent on the number of verticals taken in the cross-section. The **reproducibility** of ADCP-measurements is generally much better than of the conventional measurements and **lead to more precise but not necessarily to more accurate measurements**, as ADCP-measurements may be biased if not properly referenced as discussed in the previous chapter. Concurrent discharge measurements with conventional methods and with ADCP's can shed more light on observed differences.

4.4.2 Rating curve 1960-1969

The discharge measurements carried out at Kratie between 1960 and 1969 for the rising and falling stages have been displayed in Figure 4.14 and Figure 4.15. It shows that the rating curve derived from Stung Treng (equation (3.1)) gives an unbiased fit to the measurements, throughout the measured range for the rising as well as for the falling stages. The fit is seen to be better than with the Sogreah-curve. Particular attention is to be given to the good fit for the highest flows. This fit means that the 1960-1969 series of Stung Treng as derived in Chapter 3 will provide a reliable source for the discharge in Kratie. Since a calibration of the model for the nineteen sixties is not to be considered, a further quantification of the rating in terms of equations for this period has not been carried out.

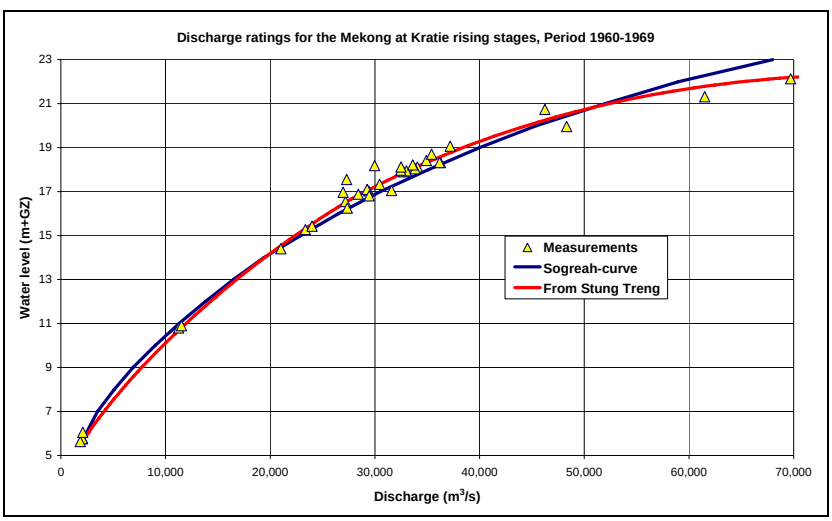

Figure 4.14 Discharge ratings at Kratie derived from Stung Treng and according to Sogreah with the measurements of 1960-1969, rising stages

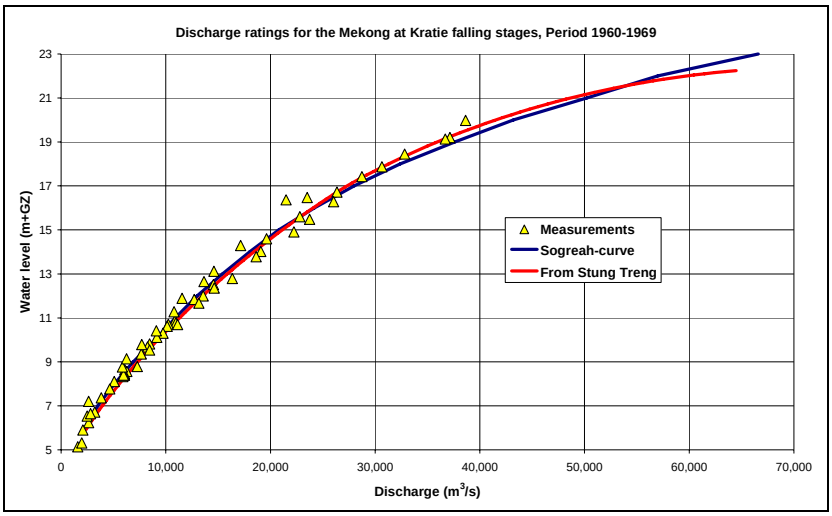

Figure 4.15 Discharge ratings at Kratie derived from Stung Treng and according to Sogreah with the measurements of 1960-1969, falling stages

4.4.3 Rating curve 2002-2008

For the period 2002-2008 bottom tracking referenced ADCP measurements are available for Kratie. Based on the 2002-2003 measurements JICA developed discharge rating curves for the rising and falling stages as follows:

- Rising stages:

$$Q = (8.16H - 10.16)^{2.1} \quad (4.4)$$

- Falling stages:

$$Q = (3.3H + 1.26)^{2.5} \quad (4.5)$$

The curves with the measurements are shown in Figure 4.16 and Figure 4.17 for the rising and falling stages respectively. It is observed that the ADCP-measurements made after 2003 still fit to the JICA discharge ratings. Note, that the water level during the measurements never exceeded 21 m at the gauge of Kratie, while in several years the maximum observed level has been well above 23 m. Hence, the measurements miss a considerable part of the water level reach particularly of importance for flood analyses.

In the figures also the Stung Treng current meter measurements based curve (3.5) valid for 1999-2007 is shown, transferred to Kratie using the applicable stage relation curves from Table 4.1. Compared to these transferred ratings the JICA curves lead to lower discharges for a particular water level. This is consistent with the findings at Stung Treng: bottom tracking referenced ADCP-measurements underestimate the flow due to moving bed and drop out of the tracking.

In 2008 at Kratie, similar to other locations, the ADCP measurements were not only bottom tracking referenced but also to GPS, using hand held GPS. The results of the GPS referenced ADCP measurements at Kratie are shown in Figure 4.18 and Figure 4.19. It is observed that the measurements strongly overestimate the discharge according to the current meter measurements based rating. The difference with the bottom tracking referenced

ADCP-measurements is shown in Figure 4.20. Differences vary for the higher discharges from 25 to 60% decreasing for higher discharges, a tendency that is fully inconsistent with effects of moving bed. Apparently, considerable errors have been made in using the GPS.

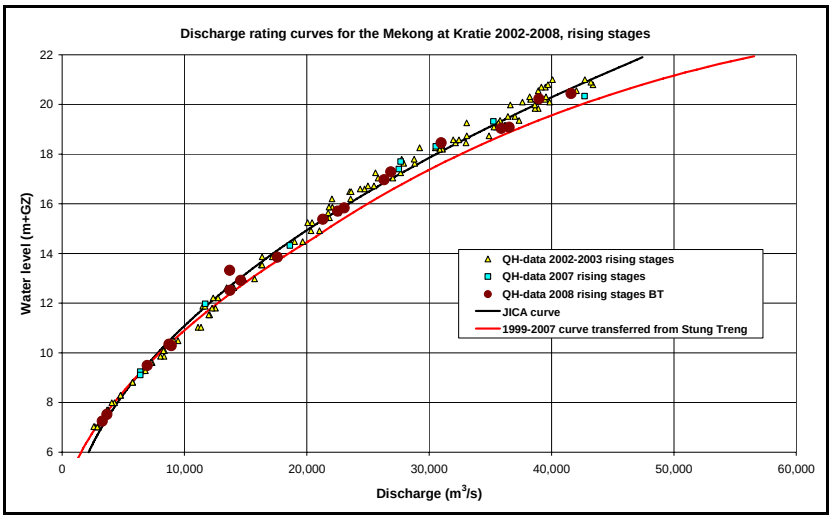

Figure 4.16 Discharge rating curves of the Mekong at Kratie with BT referenced ADCP measurements, rising stages, period 2002-2008

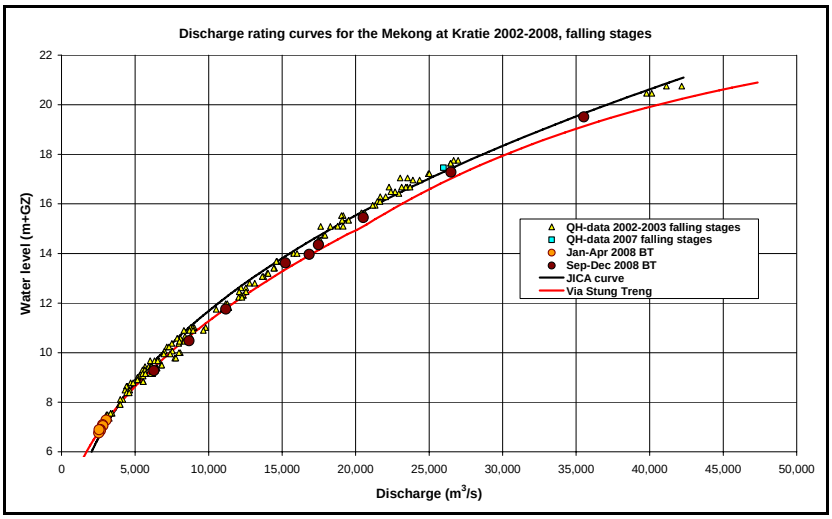

Figure 4.17 Discharge rating curves of the Mekong at Kratie with BT referenced ADCP measurements, falling stages, period 2002-2008

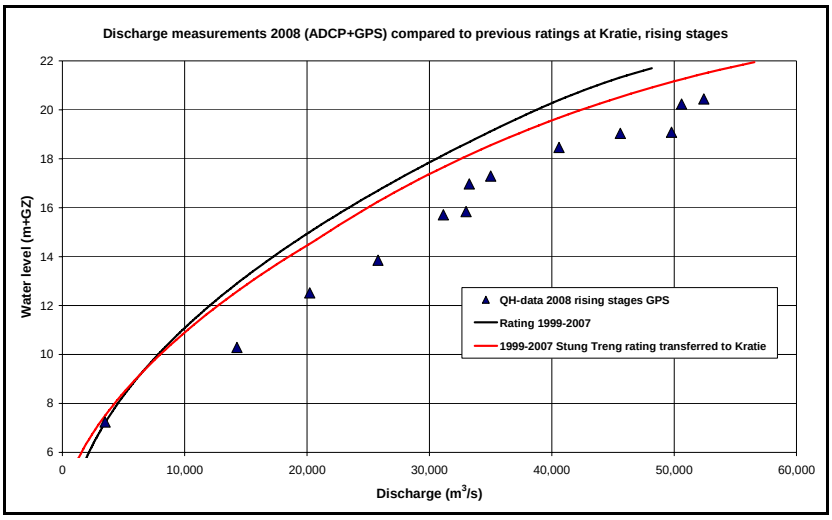

Figure 4.18 Discharge rating curves of the Mekong at Kratie with GPS referenced ADCP measurements, rising stages, year 2008

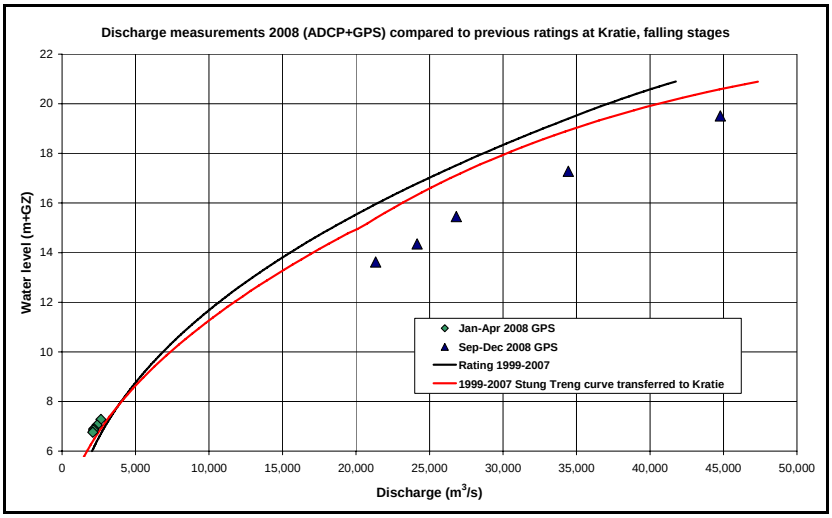

Figure 4.19 Discharge rating curves of the Mekong at Kratie with GPS referenced ADCP measurements, falling stages, year 2008

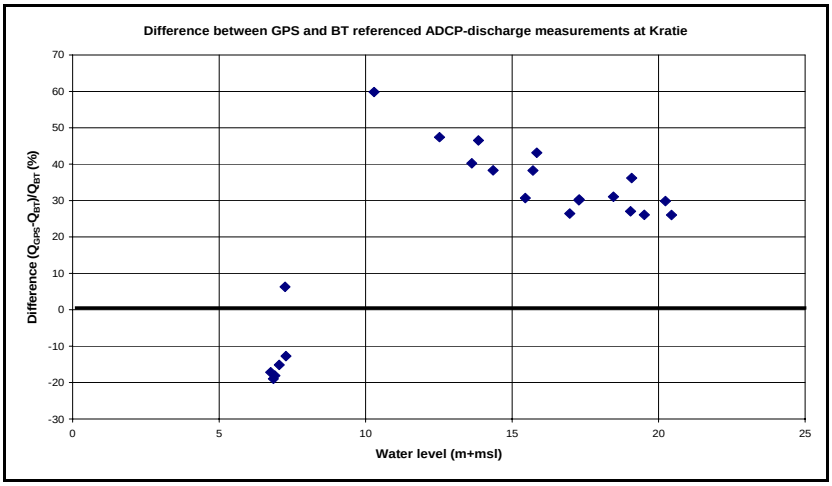

Figure 4.20 Difference between GPS and bottom tracking referenced ADCP discharge measurements at Kratie

4.5 Rating curves used in the Delta model calibration

In the mathematical hydraulic model of the Mekong delta based on ISIS the upstream boundary condition is a discharge time series at Kratie. The discharge rating used to create the boundary condition in the model has been reproduced from the model results and is displayed by the red line in Figure 4.21 for the rising and in Figure 4.22 for the falling stages. These curves are compared with the discharge rating (3.5) of Stung Treng transferred to Kratie. From the figures a close match is observed for the medium stages. At the low stages the model rating gives slightly higher values, while for the high stages (>20 m) the model rating gives lower values (e.g. 11% at a stage of 22.50 m).

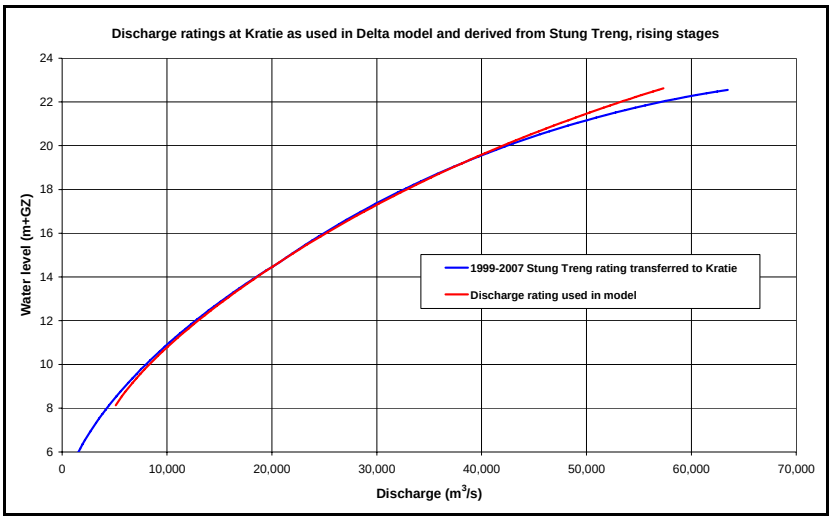

Figure 4.21 Comparison of the discharge ratings for Kratie, rising stages, periods 1960-1969 and 1999-2006

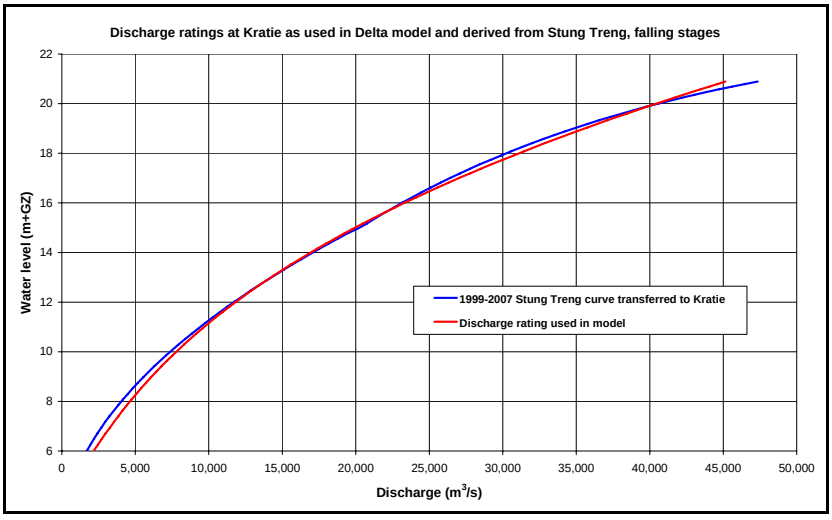

Figure 4.22 Comparison of the discharge ratings for Kratie, falling stages, periods 1960-1969 and 1999-2006

The result of these differences for the discharge hydrograph and the flood volumes (June-November)is shown in Figure 4.23 and Figure 4.24. Figure 4.23 shows consistently higher peaks at Stung Treng, whereas the flood volumes in the period 2000-2006 estimated for Stung Treng are on average 8% larger than applied in the Delta model. Remarkably, the difference in flood volume for the year 2000 is nil.

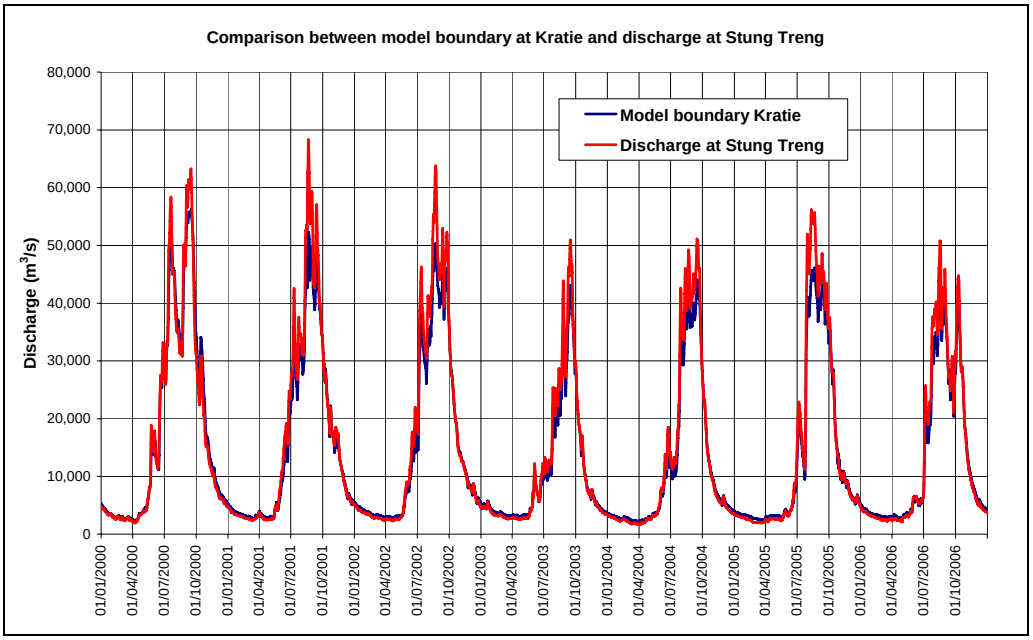

Figure 4.23 Comparison of discharge time series of period 2000-2006 as applied in the Delta model and estimated for Stung Treng

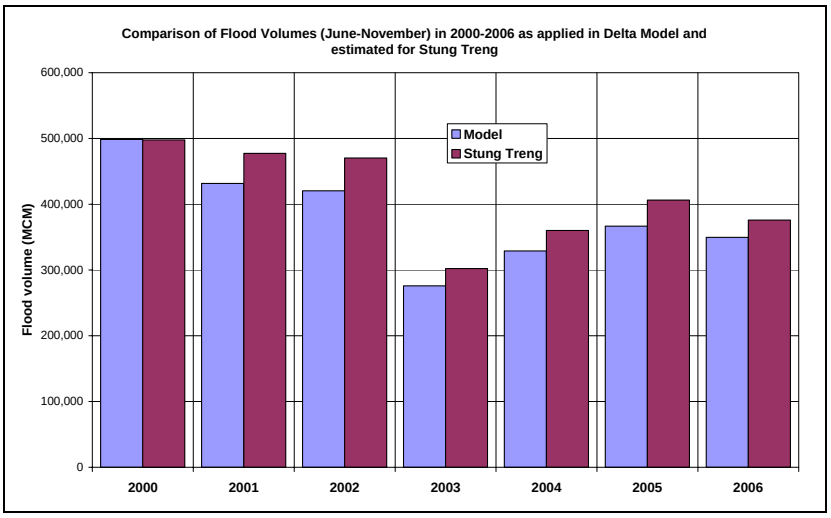

Figure 4.24 Comparison of June-November Flood Volumes of 2000-2006 as applied in Delta model and estimated for Stung Treng

From the above analysis it follows that when using the Stung Treng discharge as upstream boundary condition in the ISIS-model (as recalibrated in September 2008 (jba Consulting, 2008)), the model will compute in general too high flood levels. Since the water levels are generally used in a relative sense in comparison to the baseline conditions (= present day condition) the consequences are limited, unless distinct thresholds are reached, yes or no. A comparison between the maximum water levels in the delta obtained with both upstream boundary conditions is therefore required.

4.6 Discharges

In view of the observed similarity of flow extremes in Kratie and Stung Treng the frequency distribution of discharge extremes and flood volumes of Stung Treng is also applicable for Kratie. Therefore, reference is made to Sub-section 3.4.2 for further details.

5 Conclusions and recommendations

5.1 Conclusions

Based on the analysis presented in the previous chapters the following conclusions can be drawn.

Mekong at Pakse

1. The rocky control section of the Pakse gauging station proved to be stable, as confirmed by the flow measurements carried out between 1960 and 1999.
2. The construction of the bridge across the Mekong at Pakse has affected the water level readings at the former gauge location upstream of the bridge by backwater. This requires an adjustment of the discharge rating equation. The backwater effect is not existing in the readings from the new gauge location downstream of the bridge, which was put in operation on 4th June 2002.
3. In the past, part of the flood flow was conveyed via the left bank flood plain, above a level of 12 m+GZ on the Pakse gauge. This bypass flow has been corrected for in the extreme 1978 flood hydrograph. The estimate likely underestimates the actual discharge as can be deduced from the discharge measurements at Khong Chiam on the Mekong, Ubon on the Nam Mun and Souvanna Khili on the Se Done. Bypass flow corrections for other extreme years were not implemented in the MRC series of Pakse.
4. Since 2002, when a 5 km flood defence was constructed for the city of Pakse and along the lower Se Done, no flow is bypassing the station via the flood plain anymore.
5. The 100 year flood discharge increases from 50,800 to 53,100 m^3/s, when the bypass flow corrections in the Pakse discharge series is included from 1960 onward. This implies that design levels based on the 100 year flood would increase with 0.40 m. A further increase may be expected when this correction is also applied to the series prior to 1960. This will require accessibility to the water levels observed in te period 1923-1959.
6. The bypass correction has no effect on the flood volume statistics.

Mekong at Stung Treng

7. The discharge rating curve of Stung Treng for high flows has shown to be stable between 1960 and 1991. Thereafter no high flow measurements have been carried out at this location to assess the status for present day conditions.
8. The low flow rating for Stung Treng is variable and needs to be regularly updated.
9. Discharge measurements carried out at Kratie with an ADCP from 2002 to 2007 when plotted against the stages at Stung Treng on the previous day show a systematic lower discharge for a particular water level then when derived from discharge ratings based on conventional current meter measurements at Stung Treng for discharges in excess of 15,000 m^3/s.

10. From the measurements with ADCP made at Stung Treng in 2008 referenced to both bottom tracking and to GPS it can be concluded that the measurements from 2002 to 2007 were all bottom tracking referenced.
11. Bottom tracking referenced ADCP measurements will underestimate the discharge in case of moving bed and also because bottom tracking frequently drops out during high flows. Generally, GPS referenced ADCP-measurements show less bias, but the use of a hand held GPS as applied at the Mekong stations in 2008 does not lead to high quality data; a correction procedure using DGPS for moving bed should be used instead.
12. The GPS referenced ADCP-measurements of 2008 at Stung Treng fit reasonably to the rating curve based on low flow measurements in 1999-2000 and high flow measurements in 1960-1991. This current meter based discharge rating is therefore considered as the best estimate for the period 1999-2007.
13. Use of discharge ratings based on bottom tracking referenced ADCP measurements lead to a discontinuity in the historical series. The discontinuity in the discharge series was confirmed by comparison of flood volumes for the periods 1960-1969 and 1999-2006 with those at Pakse. Application of a discharge rating based on current meter measurements at Stung Treng showed minor differences for the same two periods.
14. Sensitivity analysis shows that an ADCP-based discharge rating for Stung Treng as from 1999 onward would have only minor effect on the frequency distributions of peak flow and flood volume at Stung Treng based on a series of 97 years (1910-2006).
15. The frequency distributions for peak flow and flood volume at Stung Treng can also shown to be applicable at Kratie as the lateral inflow in between the two stations is small compared to the main stream flow.

Mekong at Kratie

16. Stages at Kratie are affected by backwater from the Tonle Sap. Stage and stage-discharge relations always need to be established for rising and falling stages separately.
17. Relations developed for different periods between the stages at Kratie and at Stung Treng one day earlier show a gradual increase of the water levels at Kratie.
18. The noise in the stage-discharge relation at Kratie can be reduced by correcting the discharges for unsteady flow effects.
19. Excellent agreement exists between flow measurements carried out at Kratie and at Stung Treng in the nineteen sixties. The full range of flow measurements at Kratie perfectly match to the discharge ratings of Stung Treng transformed to Kratie based on the stage relations for the rising and falling stages.
20. The discharge ratings as developed by JICA based on the 2002-2003 ADCP measurements match with the ADCP measurements in 2007 and 2008. The ratings, however, underestimate the flow for medium and high stages due to the applied bottom tracking referencing procedure, see also conclusion 11 above.
21. The GPS referenced ADCP measurements in Kratie are fully inconsistent with similar measurements at Stung Treng as well as with ADCP or current meter based ratings.
22. The discharge ratings for Kratie gradually change in the course of time. The discharge rating for Stung Treng and the stage relation curves can be used to develop and validate the ratings at Kratie.

5.2 Recommendations

Application of stage-discharge relations at Stung Treng and Kratie based on bottom tracking referenced ADCP-measurements will lead to a discontinuity in the discharge series previously based on current meter measurements. A correction procedure based on the use of DGPS should be introduced to improve the results. The current use of hand held GPS also leads to discharge estimates of poor quality (Conlan, 2008a). The measuring equipment should be also be regularly recalibrated (see also Conlan 2008b). To eliminate uncertainty in the Mekong discharge measurement data it is also strongly recommended to carry out concurrent discharge measurements with both measuring techniques at Kratie (DGPS referenced ADCP and current meter measurements) for the full discharge range, with emphasis on the higher flows. The results can be transferred to Stung Treng by referencing the flows to stages at the latter station of the previous day.

In developing stage-discharge relations for Kratie, the effect of unsteady flow should first be eliminated, by means of the Jones equation.

It is further advised to re-evaluate the size of the flood plain flow at Pakse prior to 2002. The discharge series of Pakse from 1923 onward should be recomputed. For this the water level series of Pakse, as available in the MRC-HYMOS database, should be extended with the period 1923-1959.

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