Flood hazard assessment in the Mekong Delta

Report

Preliminary

Prepared for:

Mekong River Commission

Boundary conditions

December 2009

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Contents

1 Introduction 1

2 Upstream boundary condition 2

2.1 General 2

2.2 Derivation of discharge boundary 2

2.3 Flow statistics 5

3 Tributary inflow to Tonle Sap Lake 13

3.1 Layout of the basins 13

3.2 Historical inflow 14

3.3 Creation of inflow series 18

4 Additional tributary inflow to the Mekong 21

5 Rainfall 22

5.1 Overview of stations and series availability 22

5.2 Extension of rainfall series 24

6 Evaporation 28

6.1 Overview of stations and series availability 28

6.2 Series completion and extension 28

7 Water demands 31

8 Downstream boundary condition 32

8.1 Overview of stations and data availability 32

8.2 Extension of the tidal boundary 36

9 Literature 38

1 Introduction

Flood hazard assessment in the Mekong Delta involves the determination of flood levels for distinct return period from 2 to 100 years with the duration and time of occurrence of the flood. For this purpose simulation runs with the ISIS and the VRSAP models of the delta, one-dimensional hydraulic models, are carried out, covering 97 years of historical floods from 1910 to 2006. In this Report the determination of the boundary conditions are described. This includes:

1 upstream boundary condition at Kratie,
2 tributary inflow to Tonle Sap Lake,
3 tributary inflow to Mekong,
4 rainfall,
5 evaporation,
6 water use, and
7 downstream boundary condition at Gulf of Thailand and South China Sea.

2 Upstream boundary condition

2.1 General

The Mekong Delta Model for flood hazard assessment requires a long discharge time series at Kratie as upstream boundary condition. A 97 year long discharge time series for Kratie have been developed based on observations made at Stung Treng, covering the period 1910-2006. The derivation of this series is dealt with in the next sub-section. Next the statistical characteristics of this series including frequency curves, monthly flow statistics and frequency distributions of peak flow and (early) flood volumes are presented.

2.2 Derivation of discharge boundary

The water level series, stage-discharge measurements and discharge series of the Mekong at Pakse, Stung Treng and Kratie have been reviewed in Report: "Inflow to the Mekong delta. Discharge rating curves for Pakse, Stung Treng and Kratie" of February 2009. Water levels at Kratie are available since 1933. It appears that at several occasions gauge shifts have taken place and that a number of periods are of doubtful quality. Furthermore, stages at Kratie have gradually changed in the course of time, due to developments downstream. This implies that the stage-discharge relation will have changed with time. Unfortunately, between 1969 and 2002 no discharge measurements were carried out at Kratie and those carried out since 2002 with ADCP are biased relative to the current meter measurements in the past, due to referencing to bottom tracking. Also, the hydraulic control at Kratie is complicated and difficult to describe with shifted type power relations. This makes extrapolation beyond the measured range cumbersome. Finally, the stage-discharge relation for Kratie is affected by backwater from the Tonle Sap: for a particular water level at Kratie during rising stages when water is flowing into the Tonle Sap the discharge at Kratie is higher then during falling stages when water is flow out of the Tonle Sap. So, summing up, though the sensitivity of the gauge at Kratie is high (large dh/dQ), a number of factors make the conversion of stages into discharge uncertain.

In view of these difficulties and because for Stung Treng longer series is available (since 1910), preference has been given to the discharge series of Stung Treng. The basin area at Stung Treng measures 635,000 km^2, whereas at Kratie the upstream area is 646,000 km^2, i.e. only 1.7 % larger than at Stung Treng. In the flows measured at both locations this difference is not visible, and regarding peak flows it is further diminished by attenuation between Stung Treng and Kratie. For a correct reproduction of the flow at Kratie the flow at Stung Treng has to be shifted with 1 day to account for travel time between the two sites. Extensive flow measurements have been carried out at Stung Treng from 1959-1966 and from 1991-1993, covering the full water level range. It appears that the ratings for the high flows did not change in this period, indicating a stable control for the larger discharges. Also these stage-discharge measurements could easily be described by a shifted power type rating curve with an acceptable value for the power. For low flows the ratings vary. In 1999-2000 the last flow measurements were carried out at Stung Treng for a limited water level range with discharges less than 13,500 m^3/s. These data have been combined with the high flow rating applied previously to arrive at a discharge rating curve for 1999-2007. This relation fits

unbiased to the GPS referenced ADCP-measurements made in 2008 at Stung Treng. The discharge rating for high flows that have been applied for Stung Treng reads:

$$1910-2006: \quad Q = 536.8(H+0.51)^{1.92} \qquad (2.1)$$

where: Q = discharge in the Mekong at Stung Treng (m^3/s)
H = gauge reading at Stung Treng (m+GZ)

It appears that the discharge generated by above equation exceeds the flows used for the calibration of the ISIS-based Delta model for the highest stages. With respect to flood volumes the inflow used for the model calibration is on average 8% lower than derived from the Stung Treng series. 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 by jba Consulting), 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 exceeded. A comparison between the maximum water levels in the delta obtained with the following upstream boundary conditions has therefore been carried out:

- Discharge as used for model calibration
- Discharge based on Stung Treng rating curves
- Discharge based on Stung Treng rating curves with 8% reduction

A summary of the results of this comparison for selected locations is presented in Table 2.1 to Table 2.3 and Figure 2.1 to Figure 2.3. From the tables and figures it is observed that the model as calibrated on average underestimates the observed water levels with margins from -0.44 m to +0.18 m. At the river stretches where the effect of developments are being investigated (the last 4 mentioned in the tables) average absolute error is 0.23 m for the Period 2000-2006, with 0.15 m for the flood year 2000 and 0.33 m for the dry year 2003. Using the Stung Treng discharge as boundary condition the water levels are substantially overestimated. If this inflow is reduced with 8% on average the observed stages are slightly overestimated with for the reaches of interest an average absolute error of 0.19 m for the Period 2000-2006, with 0.21 m for the flood year 2000 and 0.27 m for the dry year 2003, i.e. results comparable to the boundary condition used for the calibration of the model.

Table 2.1 Years 2000-2006 average annual maximum water levels at selected locations as observed and computed with different upstream boundary conditions

Average 2000-2006	River/Lake	Observed	Model-calibration	Stung Treng	92% Stung Treng	MC-Obs	ST-Obs	92%ST-Obs
Kampong Cham	**Mekong**	14.52	14.08	15.05	14.61	-0.44	0.53	0.09
Phnom Penh	**Mekong**	9.40	9.41	9.92	9.54	0.01	0.51	0.14
Prek Kdam	**Tonle Sap**	9.46	9.53	10.06	9.63	0.08	0.61	0.17
Kampong Luong	**Tonle Sap Lake**	9.47	9.61	10.08	9.64	0.13	0.61	0.17
Neak Luong	**Mekong**	7.20	6.77	7.11	6.85	-0.43	-0.09	-0.35
Tan Chau	**Mekong**	4.50	4.69	4.93	4.73	0.18	0.43	0.22
Koh Khel	**Bassac**	6.59	6.39	6.85	6.66	-0.20	0.26	0.06
Chau Doc	**Bassac**	4.12	4.22	4.49	4.26	0.10	0.37	0.14
Average difference						-0.07	0.40	0.08
Standard deviation						0.25	0.23	0.18
Max-negative						-0.44	-0.09	-0.35
Max-positive						0.18	0.61	0.22

Table 2.2 Maximum water levels of year 2000 (large flood volume) at selected locations as observed and computed with different upstream boundary conditions

Year 2000	River/Lake	Observed	Model-calibration	Stung Treng	92% Stung Treng	MC-Obs	ST-Obs	92%ST-Obs
Kampong Cham	**Mekong**	14.98	15.14	15.60	15.24	0.15	0.62	0.26
Phnom Penh	**Mekong**	10.13	10.36	10.60	10.25	0.23	0.47	0.12
Prek Kdam	**Tonle Sap**	10.34	10.59	10.81	10.35	0.25	0.47	0.01
Kampong Luong	**Tonle Sap Lake**	10.36	10.65	10.81	10.32	0.29	0.45	-0.04
Neak Luong	**Mekong**	7.79	7.45	7.61	7.38	-0.34	-0.18	-0.41
Tan Chau	**Mekong**	5.04	5.19	5.30	5.10	0.15	0.26	0.06
Koh Khel	**Bassac**	6.94	6.96	7.38	7.09	0.01	0.44	0.15
Chau Doc	**Bassac**	4.89	4.79	4.90	4.68	-0.10	0.01	-0.21
Average difference						0.08	0.32	-0.01
Standard deviation						0.21	0.27	0.21
Max-negative						-0.34	-0.18	-0.41
Max-positive						0.29	0.62	0.26

Table 2.3 Maximum water levels of year 2003 (small flood volume) at selected locations as observed and computed with different upstream boundary conditions

Year 2003	River/Lake	Observed	Model-calibration	Stung Treng	92% Stung Treng	MC-Obs	ST-Obs	92%ST-Obs
Kampong Cham	**Mekong**	13.95	13.37	14.52	13.97	-0.58	0.57	0.02
Phnom Penh	**Mekong**	8.62	8.50	9.18	8.82	-0.12	0.56	0.20
Prek Kdam	**Tonle Sap**	8.41	8.35	9.05	8.63	-0.06	0.64	0.22
Kampong Luong	**Tonle Sap Lake**	8.26	8.39	8.86	8.46	0.13	0.60	0.20
Neak Luong	**Mekong**	6.65	6.17	6.58	6.32	-0.48	-0.07	-0.33
Tan Chau	**Mekong**	4.03	4.22	4.50	4.32	0.19	0.47	0.29
Koh Khel	**Bassac**	6.37	5.93	6.32	6.22	-0.44	-0.05	-0.15
Chau Doc	**Bassac**	3.48	3.68	3.99	3.79	0.20	0.51	0.31
Average difference						-0.15	0.40	0.09
Standard deviation						0.32	0.29	0.23
Max-negative						-0.58	-0.07	-0.33
Max-positive						0.20	0.64	0.31

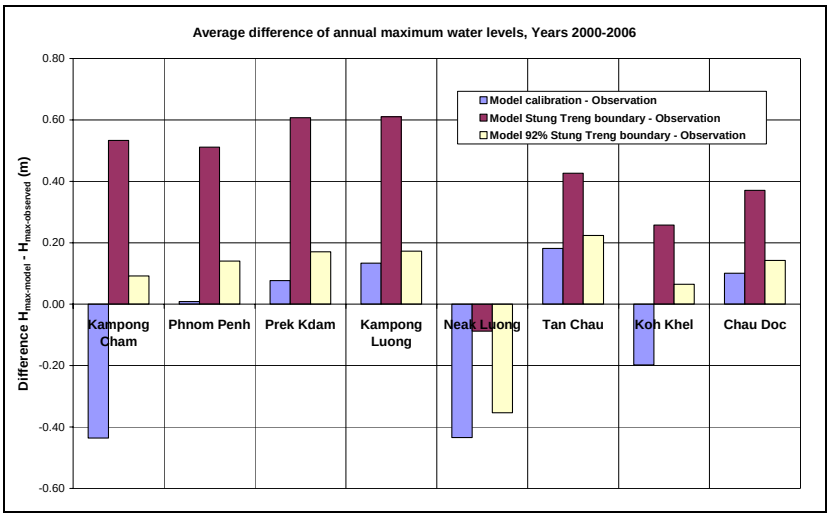

Figure 2.1 Average differences of annual maximum water levels for different upstream boundary conditions, Years 2000-2006

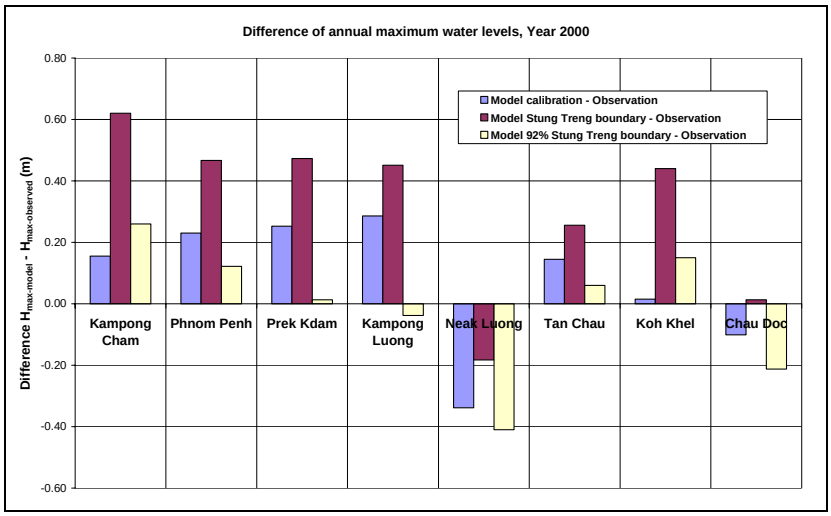

Figure 2.2 Differences of annual maximum water levels for different upstream boundary conditions, Year 2000

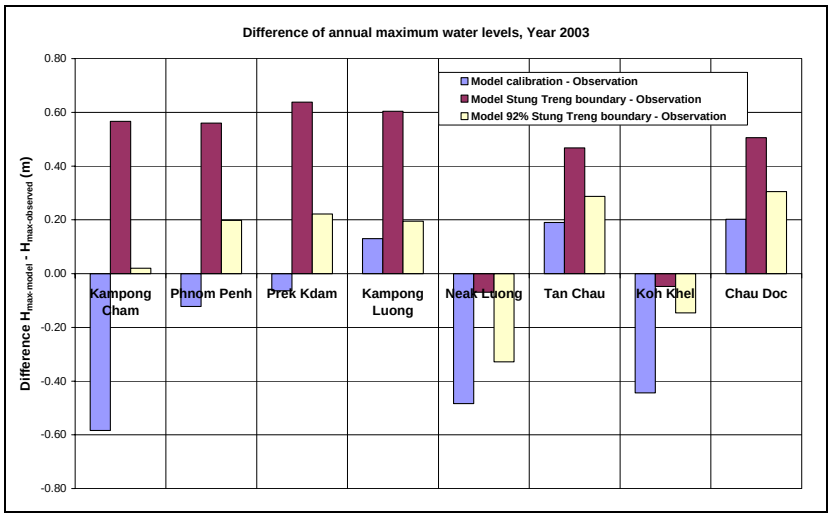

Figure 2.3 Differences of annual maximum water levels for different upstream boundary conditions, Year 2003

Based on this analysis, it is concluded that the use of either the calibration boundary or the reduced Stung Treng boundary will give comparative results with on average a small negative bias using the former and a similar positive bias using the latter.

2.3 Flow statistics

Frequency curves of daily flows

The frequency curves of daily Mekong discharges at Stung Treng is presented in Figure 2.4. The flows are highest in August and September, with the peak value occurring around 1 September, and lowest discharges in April and early May. Note that from these graphs no information is obtained about the true shape of the hydrographs in a particular year as sequential information is not contained in the frequency curves.

Statistics of monthly flows

The monthly flow volume statistics of the Mekong at Stung Treng, including the mean, standard deviation and range is presented in Figure 2.5. This picture is apart from the scale very similar to the frequency curves of daily flows.

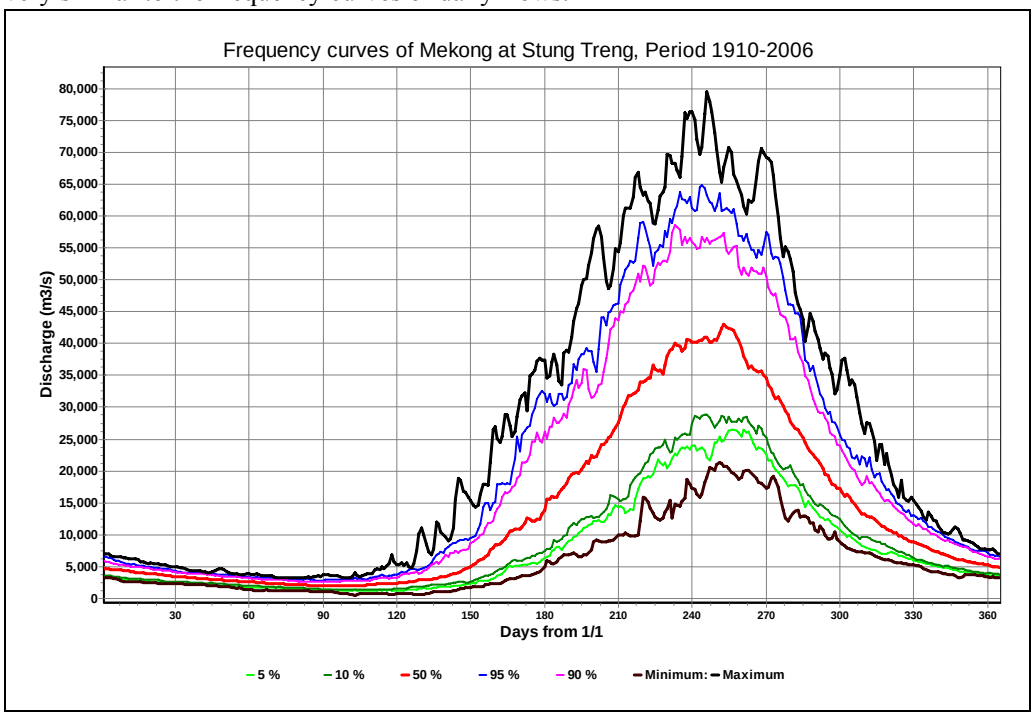

Figure 2.4 Frequency curves of the Mekong discharge at Stung Treng, Period 1910-2006

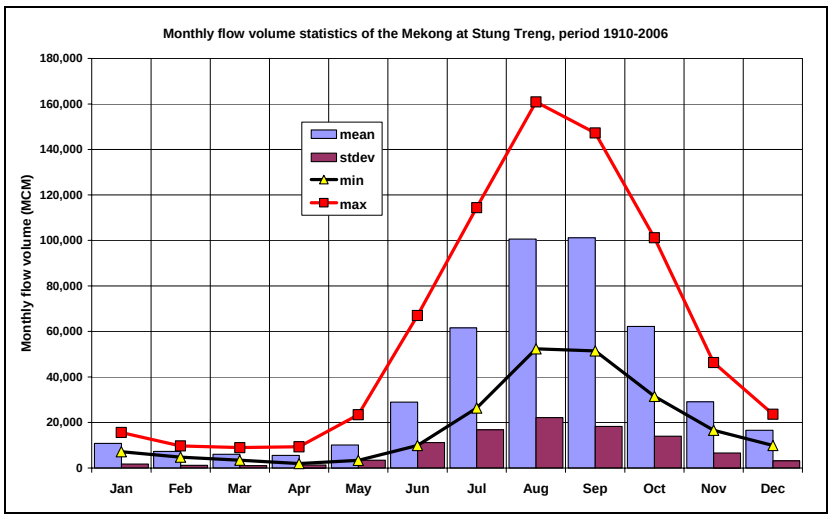

Figure 2.5 Monthly flow volume statistics of the Mekong at Stung Treng, Period 1910-2006

Table 2.4 Monthly flow volume statistics of the Mekong at Stung Treng, Period 1910-2006

Var	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mean	10,850	7,301	6,108	5,564	10,113	29,017	61,609	100,603	101,190	62,197	29,095	16,584	440,231
stdev	1,788	1,155	1,082	1,358	3,415	11,188	16,818	22,124	18,341	14,016	6,622	3,203	61,508
cvar	0.165	0.158	0.177	0.244	0.338	0.386	0.273	0.220	0.181	0.225	0.228	0.193	0.140
min	7,205	4,780	3,426	1,931	3,391	9,922	26,355	52,390	51,462	31,474	16,584	9,945	285,292
max	15,596	9,740	8,957	9,329	23,476	67,019	114,411	160,875	147,218	101,193	46,386	23,618	567,996

Peak flows and flood volumes

The time series of annual peak discharges and flood volumes of the Mekong at Stung Treng (flow volume between up-crossing and down-crossing of the annual mean according to the definition as applied at MRC) with an 11-year moving average are presented in Figure 2.6 and Figure 2.7. It is observed that prior to the nineteen fifties the peaks as well as the flood volumes were generally higher then thereafter, except for the last decades.

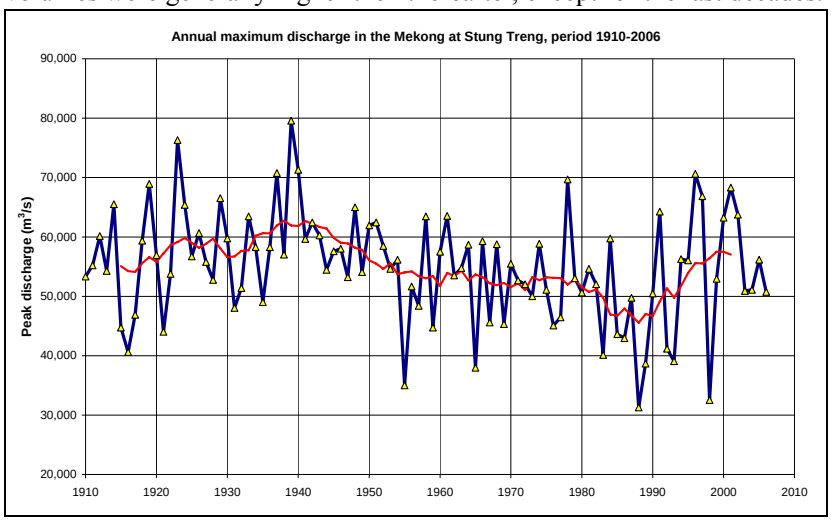

Figure 2.6 Annual maximum discharge in the Mekong at Stung Treng with 11 year moving average, period 1910-2006

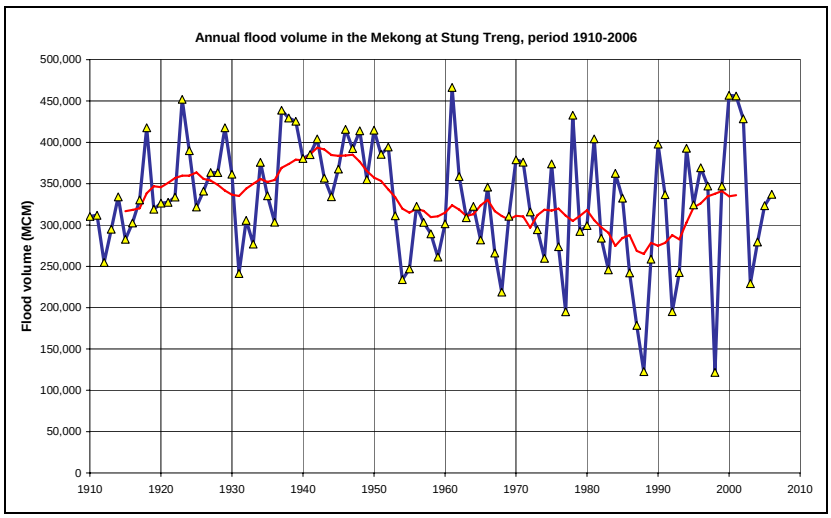

Figure 2.7 Annual flood volume in the Mekong at Stung Treng with 11 year moving average, period 1910-2006

The marginal distributions of peak discharge and flood volumes in the Mekong at Stung Treng are well described by General Extreme Value (GEV) distributions as shown in Figure 2.8 and Figure 2.9. The distribution function F(x) of the GEV has the following form:

$$F(x) = \exp\left\{-\left(1-k\left(\frac{x-u}{\alpha}\right)\right)^{1/k}\right\} \qquad (2.2)$$

where: u, α, k = parameters of the distribution

The parameters (u, α, k) can be estimated from probability weighted moments as follows (Cunnane, 1989):

$$M_{1j0} = \frac{1}{N}\sum_{i=1}^{N} F_{(i)}^{j} x_{(i)} \quad with: \quad F(i) = \frac{i-0.35}{N}$$

$$C = \frac{2M_{110} - M_{100}}{3M_{120} - M_{100}} - \frac{\log 2}{\log 3}$$

$$k = 7.8590\,C + 2.9554\,C^2 \qquad (2.3)$$

$$\alpha = \frac{(2M_{110} - M_{100})\,k}{\Gamma(1+k)\left[1-2^{-k}\right]}$$

$$\hat{u} = M_{100} + \frac{\alpha}{k}\left[\Gamma(1+k) - 1\right]$$

The parameter values of the distributions are presented in Table 2.5.

Table 2.5 GEV-parameters estimates of peak discharge and flood volume of the Mekong at Stung Treng

Parameter	Peak discharge (m^3/s)	Flood volume (MCM
u	51,868	307,084
α	9,532	74,182
k	0.3217	0.3684

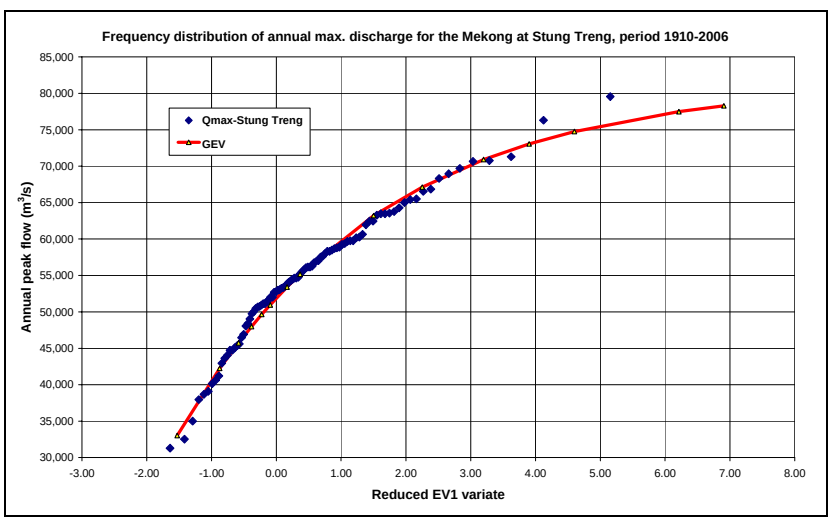

Figure 2.8 GEV distribution fitted to annual maximum discharge at Stung Treng

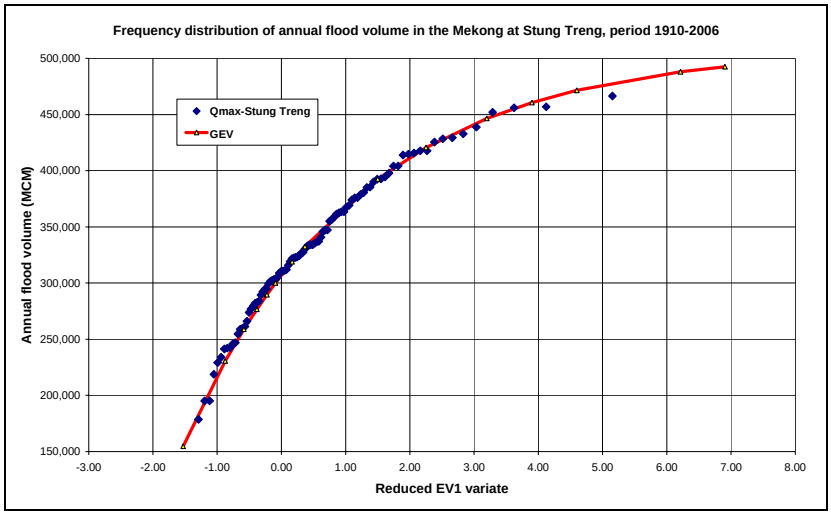

Figure 2.9 GEV distribution fitted to annual flood volume at Stung Treng

The peak values and flood volumes for distinct return periods T follow from:

$$x = u + \frac{\alpha}{k}\left\{1 - \left[-\ln\left(1 - \frac{1}{T}\right)\right]^{k}\right\} \tag{2.4}$$

and are presented in Table 2.6. The flood volumes may vary considerably for similar peak flows as can be observed from Figure 2.10.

The bivariate extreme value distribution of flood peaks and flood volumes has been described by Adamson et al. (1999). The joint probability can be generated by the Gibbs sampler Monte Carlo procedure. This technique requires that annual flood peaks (X) and annual flood volumes (Y) are regressed against each other:

$$\begin{aligned} X &= a_{x,y} + b_{x,y} Y \\ Y &= a_{y,x} + b_{y,x} X \end{aligned} \tag{2.5}$$

and the GEV distributions are used to model the residuals of flood peaks and flood volumes with parameters respectively (u_x, α_x,,k_x) and(u_y, α_y,,k_y). The Gibbs procedure then reads with uniform distributed random numbers R and the generated values marked with #:

$$\begin{aligned} X_j^{\#} &= a_{x,y} + b_{x,y} Y_j^{\#} + u_x + \frac{\alpha_x}{k_x}\left\{1 - (-\ln(R_1))^{k_x}\right\} \\ Y_{j+1}^{\#} &= a_{y,x} + b_{y,x} X_j^{\#} + u_y + \frac{\alpha_y}{k_y}\left\{1 - (-\ln(R_2))^{k_y}\right\} \end{aligned} \tag{2.6}$$

Application to the peak flows and flood volumes at Stung Treng leads to the parameter values as displayed in Table 2.7. The fits are presented in Figure 2.11 to Figure 2.14.

Table 2.6 Annual maximum discharge and flood volume in the Mekong at Stung Treng, period 1910-2006

T	Reduced EV1-var	Peak flow (m^3/s)	Flood volume (MCM)
2	0.37	55,200	333,000
5	1.50	63,200	393,000
10	2.25	67,100	421,000
25	3.20	70,900	446,000
50	3.90	73,100	461,000
100	4.60	74,800	471,000

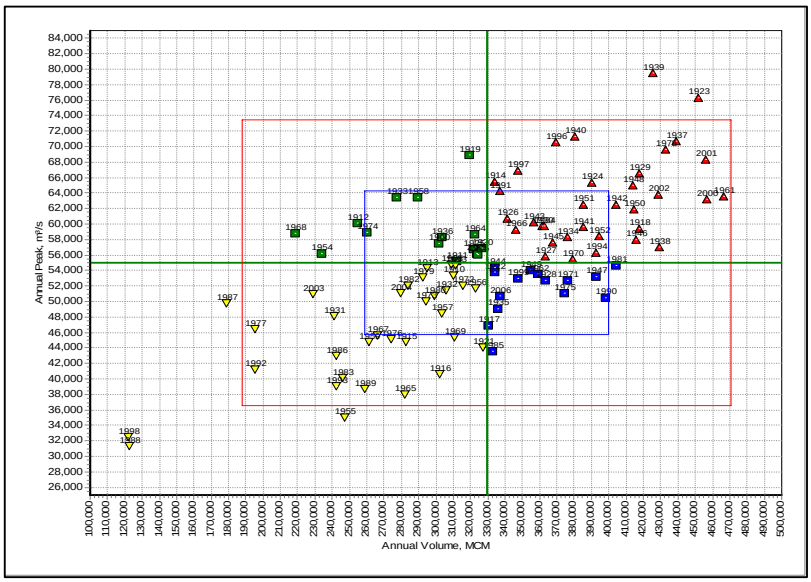

Figure 2.10 Annual peak discharge against flood volume in the Mekong at Stung Treng period 1910-2006

Table 2.7 Regression parameters and parameters of GEV distributions of regression residuals for the peak flows and flood volumes of the Mekong at Stung Treng

Regression	Regression parameters		GEV parameters of regression residuals		
Peak on volume	$a_{y,x}$=25,130	$b_{y,x}$=0.0907	u_y= -2,754	α_y= 5,987	k_y=0.1328
Volume on peak	$a_{x,y}$=37,146	$b_{x,y}$=5.3131	u_x=-13,990	α_x=53,830	k_x=0.4394

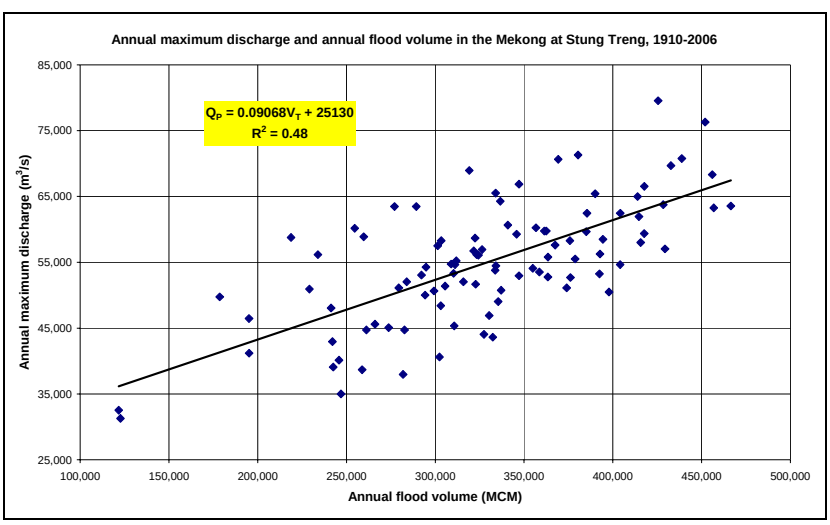

Figure 2.11 Regression of peak discharge on flood volume of the Mekong at Stung Treng

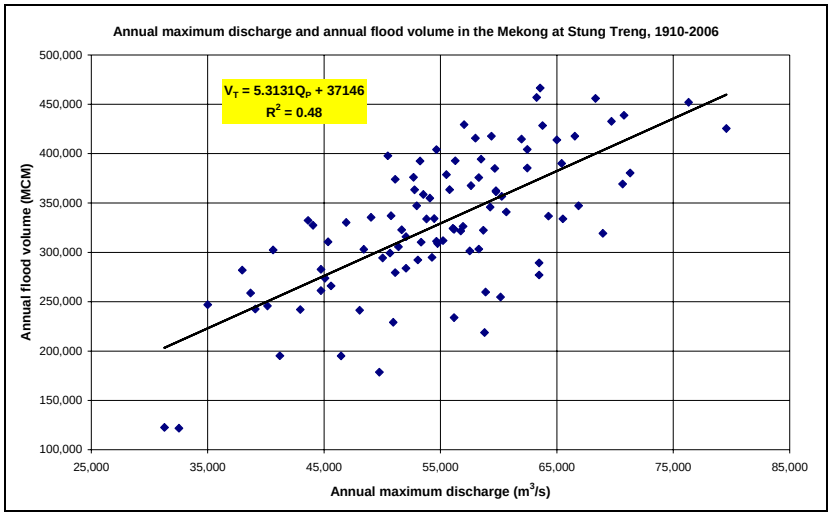

Figure 2.12 Regression of flood volume on peak discharge of the Mekong at Stung Treng

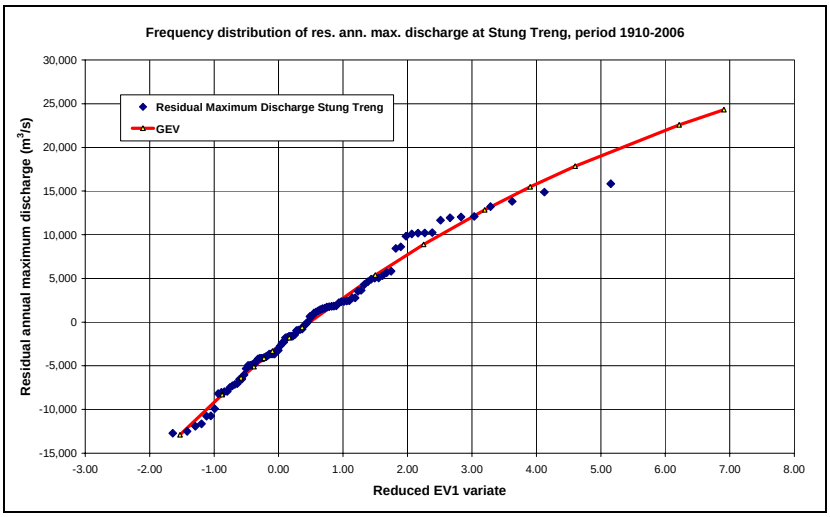

Figure 2.13 GEV-fit to regression residuals of annual maximum discharge at Stung Treng

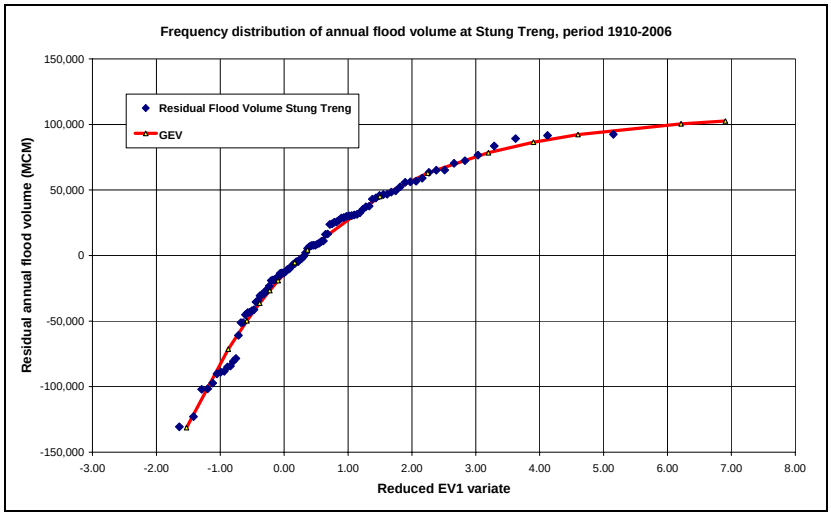

Figure 2.14 GEV-fit to regression residuals of annual flood volume at Stung Treng

In the paper by Adamson et al. (1999) also contours of recurrence interval for the joint distribution are presented obtained with the above mentioned Gibbs sampler procedure. The return period attached to the contours is said to refer to the reciprocal of the proportion of the bi-variate density that lies outside of the contour. Two kinds of return period for two correlated random variables X and Y can be formulated (Yue, 2001):

1 T(x,y) is the joint return period of the event that either X or Y or both is exceeded, and
2 T'(x,y) is the joint return period of the event that both X and Y is exceeded:

$$T(x,y) = \frac{1}{1-F(x,y)} \quad with: \quad F(x,y) = \Pr\left[X \le x, Y \le y\right]$$
$$T'(x,y) = \frac{1}{1-\left\{F_x(x)+F_y(y)-F(x,y)\right\}} \tag{2.7}$$

Note that none of the definitions apply to the elliptic contours presented in the paper and in MRC (2005).

3 Tributary inflow to Tonle Sap Lake

3.1 Layout of the basins

The tributary inflow to Tonle Sap is runoff from the following rivers draining in the lake:

- Stung Chinit,
- Stung Sen,
- Stung Staung,
- Stung Chikreng,
- Stung Siem Reap,
- Stung Sreng,
- Stung Mongol Borey, including Stung Sisophon,
- Stung Battambang,
- Stung Sangker,
- Stung Dauntri, including stung Svay Donkeo,
- Stung Pursat, and
- Stung Baribor.

The locations of the tributaries, with their principal flow measuring stations are shown in Figure 3.1.

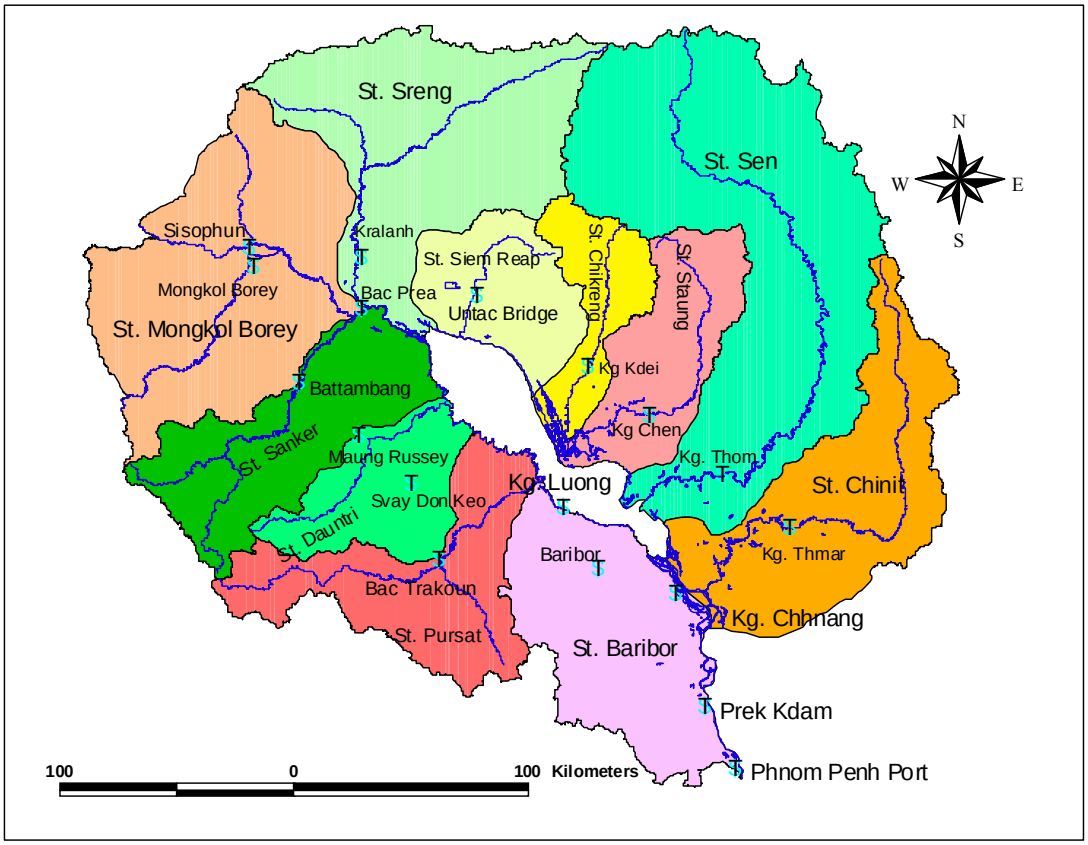

Figure 3.1 Layout of tributaries draining to Tonle Sap Lake

Different definitions of basin are of the tributaries have been used. Generally, the areas are defined from source up to Tonle Sap Lake at low level. In the hydraulic model, however, the basin areas are taken from the source up to the ring roads (highways nrs 5 (SW) and 6 (NE)) around Tonle Sap. These areas are presented in Table 3.1. The total area of the tributaries amounts 68,830 km^2 of which some 72% is gauged, (see last columns of the table)

Table 3.1 Overview of main tributaries draining to Tonle Sap

Nr	Tributary	Basin area upstream ringroad (km^2)	Gauging station	Observed area (km^2)	Factor station to basin
1	Stung Chinit	6,106	Kompong Thmar	4,130	1.478
2	Stung Sen	15,024	Kompong Thom	14,000	1.073
3	Stung Staung	3,258	Kompong Chen	1,895	1.719
4	Stung Chikreng	1,984	Kompong Kdei	1,920	1.033
5	Stung Siem Reap	2,504	Bot Chhivear/UNTAC br	670	3.738
6	Stung Sreng	9,112	Kralanh	8,175	1.115
7	Stung Sisophon*)	4,310	Sisophon	4,310	1.000
8	Stung Mongkol Borey	8,974	Mongkol Borey	4,170	2.152
7+8	Mongkol Borey basin	**13,284**			
9	Stung Sangker	4,044	Battambang	3,230	1.252
10	Stung Dauntri	1,186	Maung Russey	730	1.624
11	Stung Svay Donkeo*)	1,313	Svay Donkeo	810	1.620
10+11	Dauntri basin	**2,498**			
12	Stung Pursat	4,969	Bak Trakuon	4,440	1.109
13	Stung Baribor	6,046	Baribor	869	6.965
	Total	68.830		49,349	

Notes: Stung Sisophon is within Stung Mongkol Borey basin
Stung Svay Donkeo is within Stung Dauntri basin

3.2 Historical inflow

Historical discharge series have been created for the period 1997-2004 (Sopharith Tes, 2007) using the water levels series of the stations mentioned in Table 3.1 in combination with the following discharge rating equations:

Stung Chinit at Kompong Thmar

$$Q = 15.49 - 36.8088 H_{KT} + 36.3032 H_{KT}^2 - 8.5957 H_{KT}^3 + 0.7869 H_{KT}^4 \qquad (3.1)$$

where: H_{KT}= gauge reading at Kompong Thmar

Stung Sen at Kompong Thom

$$\frac{Q}{F^{0.72}} = 1.3x10^{-5}\left(H_{KTh} - 1.21\right)^{6.8178} \quad with: F = H_{KTh} - H_{KL} \qquad (3.2)$$

where: H_{KTh}= gauge reading at Kompong Thom
H_{KL}= gauge reading at Kompong Luong

Stung Staung at Kompong Chen

$$\frac{Q}{\sqrt{F}} = 0.8554 H_{KC}^{2.7794} \quad with: F = K_{KC} - H_{KL} + 0.7 \tag{3.3}$$

where: H_{KL}= gauge reading at Kompong Luong
H_{KC}= gauge reading at Kompong Chen

Stung Chikreng at Kompong Kday

$$\frac{Q}{\sqrt{F}} = 0.1017 H_{KD}^{3.3034} \quad with: F = K_{KD} - H_{KL} + 0.7 \tag{3.4}$$

where: H_{KL}= gauge reading at Kompong Luong
H_{KD}= gauge reading at Kompong Kdey

Stung Siem Reap at UNTAC Bridge

$$\begin{aligned} &for\ H_{UB} > 0.0936m: \quad Q = 4.1059\left(H_{UB} - 0.0936\right)^2 \\ &for\ H_{UB} \le 0.0936m: \quad Q = 0 \end{aligned} \tag{3.5}$$

where: H_{UB}= gauge reading at UNTAC Bridge

Stung Sreng at Kralanh

$$\frac{Q}{\sqrt{F}} = 1.2989x10^{-2} H_{KK}^{4.3665} \quad with: F = K_{KK} - H_{BP} + 4.0 \tag{3.6}$$

where: H_{KK}= gauge reading at Kralanh
H_{BP}= gauge reading at Bak Prea

Stung Sisophon at Sisophon

$$\begin{aligned} &for\ H_S \le 2.20: && Q = 0.3029 + 0.2626 H_S \\ &for\ 2.21 \le H_S \le 5.40: && Q = 0.06855 H_S^{3.5191} \\ &for\ H_S \ge 5.41: && Q = 147.03 - 115.0262 H_S + 17.1329 H_S^2 \end{aligned} \tag{3.7}$$

where: H_S = gauge reading at Sisophon

Stung Mongkol Borey at Mongkol Borey

$$\frac{Q}{\left(F + 6.09\right)^{0.69}} = -0.5665 + 2.212 H_{MB} - 0.8243 H_{MB}^2 + 0.1796 H_{MB}^3 \tag{3.8}$$

$$with: F = H_{MB} - H_{BP}$$

where: H_{BP}= gauge reading at Bak Prea
H_{MB}= gauge reading at Mongkol Borey

Stung Sangkar at Battambang

$$\frac{Q}{(F-0.3)^{0.18}} = -28.2541 + 33.8995H_{BB} - 9.5551H_{BB}^2 + 0.8092H_{BB}^3 \qquad (3.9)$$

$$with: F = H_{BB} - H_{BP}$$

where: H_{BP}= gauge reading at Bak Prea
H_{BB}= gauge reading at Battambang

Stung Dauntri at Maung Russay

$$for\ H_{MR} > 1.24: \quad Q = 12.4(H_{MR} - 1.2439)^2$$
$$for\ H_{MR} \le 1.24: \quad Q = 0 \qquad (3.10)$$

where: H_{MR}= gauge reading at Maung Russay

Stung Svay Donkeo (tributary of Stung Dauntri) at Svay Donkeo

$$Q = 0.0963 + 0.5268H_{SD} + 0.3.7212H_{SD}^2 \qquad (3.11)$$

where: H_{SD}= gauge reading at Svay Donkeo

Stung Pursat at Bak Trakuon

$$for\ H_{BT} > 0.0856: \quad Q = 25.5(H_{BT} - 0.0856)^2$$
$$for\ H_{BT} \le 0.0856: \quad Q = 0 \qquad (3.12)$$

where: H_{BT}= gauge reading at Bak Trakuon

Stung Baribor at Baribor

$$Q = 37.16H_B^{1.62} \qquad (3.13)$$

where: H_B = gauge reading at Baribor

The discharge rating equations as applied here differ for the following stations from the curves applied in the discharge series stored in the MRC HYMOS database: Siem Reap, Kralanh, Sisiphon, Mongkol Borey, Battambang and Baribor. The new ratings are based on measurements carried out in the period 1998-2000.

Series completion

For all stations water levels were available for the period 1997-2004, except for Stung Baribor, which missed data for the period January 1997 – May 1998. The total inflow for this period based on the runoff from the basins without Baribor have been corrected by multiplying the monthly values with the monthly average ratio of the observed series with and without Baribor (1998-2004).

Monthly and annual flow characteristics

The statistical characteristics of the combined observed inflow to the Tonle Sap Lake from the tributaries for the period 1997-2004 are presented in Figure 3.2.

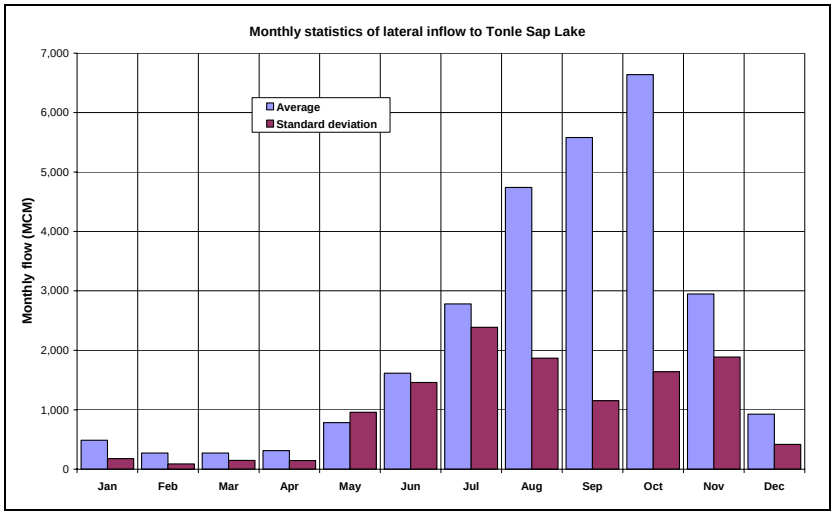

Figure 3.2 Average and standard deviation of monthly inflows to Tonle Sap Lake, Period 1997-2004

From the graph it is observed that on average the inflow is largest in October, in response to the highest monthly rainfall. In comparison with the Mekong, as shown in Figure 2.5, it follows that the inflow regime to the Tonle Sap is shifted by about one month, see Figure 3.3. This gives excellent opportunities to use the Tonle Sap Lake for temporary storage of the early flood of the Mekong to reshape the regime downstream of Phnom Penh for harvesting in late August. On the other hand, as shown in Figure 3.4, during the year 2000, when the flood volume of the Mekong was large, the inflow to Tonle Sap Lake from its tributaries was also large. The annual inflows are correlated with the flow volume in the Mekong upstream of the Delta, see Figure 3.5. More than half of the variance on the inflow is explained by the Mekong flow volume.

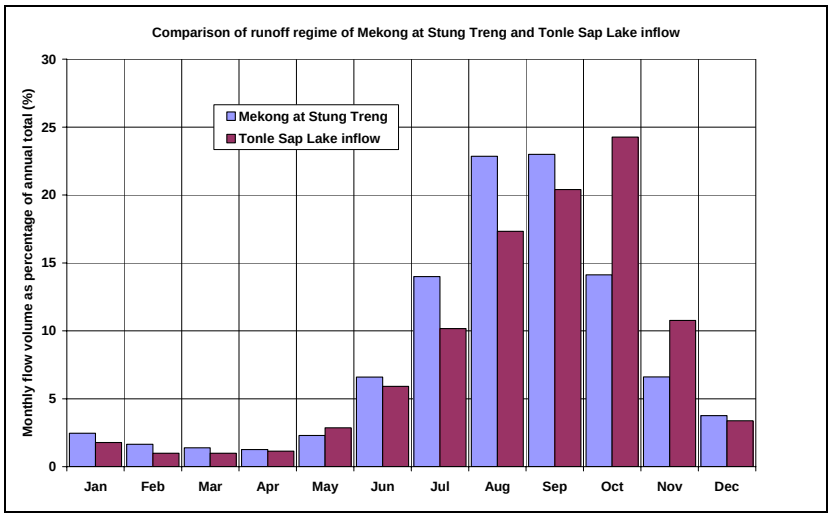

Figure 3.3 Average monthly flow regime of Mekong at Stung Treng and of Tonle Sap Lake inflow expressed as percentage of annual total

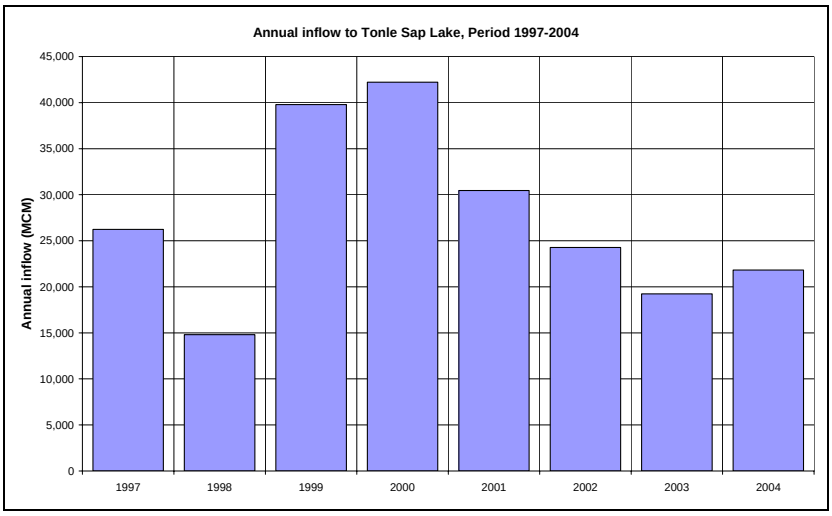

Figure 3.4 Annual inflow to Tonle Sap Lake, Period 1997-2004

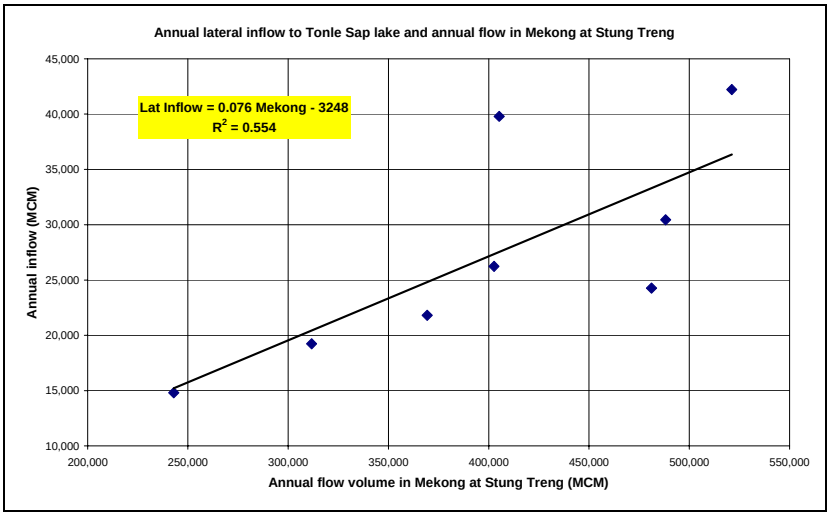

Figure 3.5 Comparison of annual lateral inflow to Tonle Sap Lake and in the Mekong at Stung Treng

3.3 Creation of inflow series

For the creation of inflow series to Tonle Sap Lake focus was on the inflow in the flood season from May to November. First monthly series have been created maintaining the correlation with the delta inflow at Stung Treng and the serial correlation with inflow in the previous month. A random component was added to the monthly inflows to reproduce the variability of the original observed 8 year series 1997-2004. The monthly total inflow series was then replaced by monthly adjusted total daily inflow series from the observed years. The observed years were selected according to the rank of the seasonal flow. These total daily inflows were finally disaggregated to 12 daily inflow series according to the historical contribution in the selected year.

In detail the following steps were applied:

1 Establishment of multiple regression equations for monthly inflows with the monthly flow at Stung Treng in the same month and with the lateral inflow in the previous month.
2 Generation of monthly inflow series of the months May to December for the years 1910-1996 and 2005-2006, using the regression equations of step 1 with a random component for the unexplained part.
3 Adjustment of the generated monthly inflows. Values below a threshold were replaced by a likely minimum values for the months.
4 To eliminate a possible bias by the adjustment in step 3 and the addition of the random component in step 2, the values for each month have been multiplied by the observed monthly mean divided by the generated monthly mean.
5 Creation of flow classes based on the total observed inflow in the period May-November in a particular year. The class limits are the averages of successive ranked seasonal flows. Hence the daily flow pattern of the year selected for a class is considered representative for that class
6 Classification of each generated year of monthly flows to a flow class.
7 Replacement of the generated monthly series of a particular year by the representative daily series of the class, with a monthly adjustment so that the monthly total of the daily series match with the generated monthly value.
8 Dis-aggregation of the total generated daily inflow into the Tonle Sap Lake into 12 series according to the daily ratios in the observed series.

The regression equations used for the generation of the monthly series have the following general form:

$$I_{i,j} = a_i M_{i,j} + b_i I_{i-1,j} + c_i + \varepsilon_{i,j} S_{e,I_i} \qquad (3.14)$$

where: $I_{i,j}$ = inflow in month *i* of year *j* (MCM)
$M_{i,j}$ = Mekong flow at Stung Treng in month *i* of year *j* (MCM)
a_i, b_i, c_i = regression coefficients
$\varepsilon_{i,j}$ = normal random deviate for month *i* in year *j*
$S_{e,Ii}$ = standard deviation about regression in month *i*

The regression coefficients are summarised in Table 3.2. It is observed that the value for May is solely derived from the flow in the Mekong in that month, and that the value for December is solely derived from the inflow in the previous month. All other months are derived from the flow at Stung Treng in the same month and the inflow in the previous month, to preserve cross- and serial correlation.

Table 3.2 Regression coefficients used in generation of monthly inflow series to Tonle Sap Lake

Coefficient	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a	0.119	0.041	0.052	0.034	0.041	0.141	0.182	0.000
b	0.000	0.978	0.758	0.359	0.074	-0.278	0.158	0.218
c	-731	-508	-2094	198	949	808	-2916	284
S_e	739	493	1246	1219	656	927	800	73
R^2	0.41	0.89	0.73	0.57	0.68	0.68	0.82	0.97

Standard normal random number times the standard error of regression has been added to the regression estimates to preserve the series variance.

The seasonal flow (May to December) from 1910-1996 and 2005-2006 generated in this way, and the observed flow in the period 1997-2004 is presented in Figure 3.6. The

frequency distribution of the seasonal flow is shown in Figure 3.7. It is observed that the range of the generated values does not exceed the observed one. The range of the observed series has been very large as it incorporates the extreme dry year 1998 and the very wet year 2000.

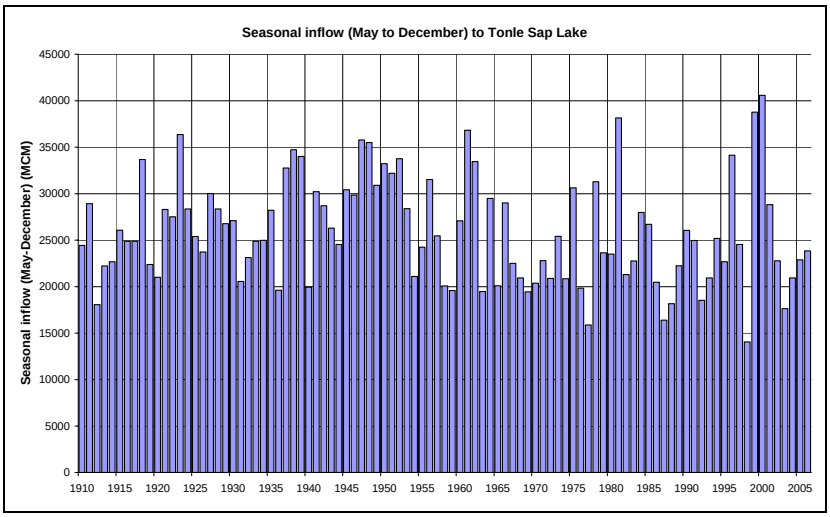

Figure 3.6 Created and observed seasonal inflow to Tonle Sap Lake, Period 1910-2006, 1997-2004 observed

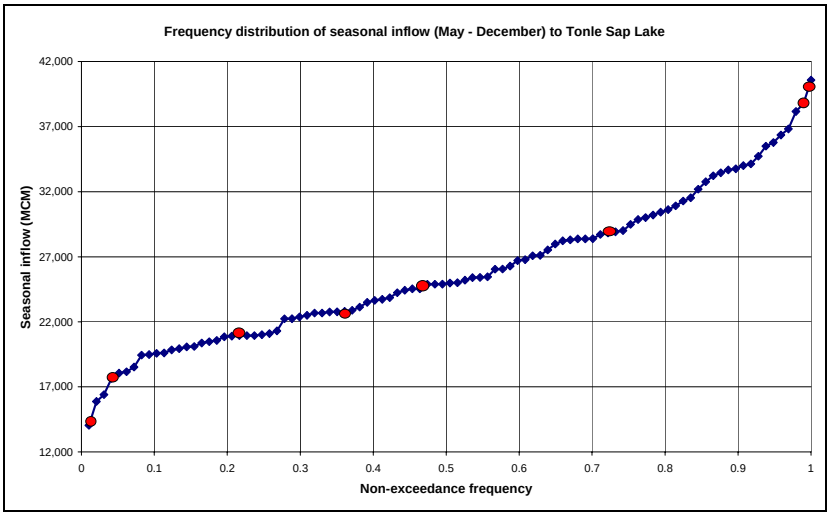

Figure 3.7 Frequency distribution of generated and observed (red dots) inflow to Tonle Sap Lake

4 Additional tributary inflow to the Mekong

Apart from the inflow to the Tonle Sap Lake the Delta Model also requires inflow series for the following tributaries:

1 Prek Te
2 Prek Chhlong
3 Prek Thnot
4 East Vaico River, and
5 West Vaico River.

The daily flow series for the period 1985-2006 are available from the DSF files created by the SWAT model. The mean monthly flows in MCM of these series are presented in Table 4.1.

Table 4.1 Mean monthly and annual flows of additional tributaries of Mekong River downstream of Kratie

Tributary	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Prek Thnot	77.5	58.0	39.6	88.3	192.0	235.6	335.7	395.0	504.8	674.6	299.0	153.4	3,054
Prek Te	114.3	60.4	33.9	27.1	42.0	87.1	159.9	368.9	632.7	585.6	357.9	201.2	2,671
Prek Chhlong	84.4	43.6	32.2	25.8	42.6	79.0	83.8	162.7	278.2	339.7	227.5	133.4	1,533
East Vaico	140.3	56.3	26.8	12.0	8.2	73.1	161.7	229.7	396.8	529.9	402.8	267.9	2,305
West Vaico	6.3	3.9	1.2	6.0	16.9	25.0	36.6	46.0	76.7	69.5	20.5	7.7	316

Since the SWAT-series show no correlation with the flow in the Mekong and the contributions of the above mentioned tributaries are small (about 20-30% of the total inflow to Tonle Sap Lake discussed in the previous chapter) their influence on the extreme stages will be limited. Therefore, a pragmatic approach by applying a block-wise repetition of the series 1985-2006 for the years 1910-1984 is justified

5 Rainfall

5.1 Overview of stations and series availability

Daily series of the following 14 rainfall stations are input into the Delta Model

1. From Kratie to Phnom Penh:
   a. Snuol
   b. Kampong Cham
   c. Oudong
   d. Ponchentong
2. Around Tonle Sap Lake
   a. Pursat
   b. Siem Reap
   c. Kampung Thom
3. Downstream Phnom Penh
   a. Prey Veng
   b. Kampot
4. Vietnam from border to sea
   a. Chau Doc
   b. Moc Hoa
   c. Rach Gia
   d. Can Tho
   e. Ca Mau

Daily rainfall, covering at least the period 1985-2006, is available for above stations with the following remarks:

- Station Snuol has insufficient data and the data of Kampong Cham is used instead
- Series of Kampong Cham has been completed with the series of Thbong Khmum (ID 10428)
- Series of Oudong completed with the series of Ponchentong
- Series of Prey Veng completed with series of Svey Rieng (ID 110503)
- Series of Kampot completed with WUP-JICA filling technique (WUP-JICA, 2003).
- Daily rainfall series of stations Tri Ton, Cao Lanh, Nui Sap, Hau My Bac and Cai Be as from 1983 onward were also made available. However, in the calibration of the Delta model only the series Chau Doc, Moc Hoa, Rach Gia, Can Tho and Ca Mau as listed above have been used. In order not to change the model calibration and validation results the additional stations have not been introduced in the Delta model.

Annual maximum daily rainfall

The annual maximum daily rainfall of these series is presented in Figure 5.1 to Figure 5.4. Annual maximum values generally are in the order of 100 to 200 mm, with occasionally larger values, particularly in the Vietnamese delta. In 1985 a daily value of 400 mm has been recorded in Can Tho. It is also observed that the extremes of the series Tri Ton, Cao Lanh, Nui Sap, Hau My Bac and Cai Be are of the same order of magnitude than the model series.

Therefore, extreme rainfall in the Vietnamese part of the Mekong delta is well represented by the series Chau Doc, Moc Hoa, Rach Gia, Can Tho and Ca Mau.

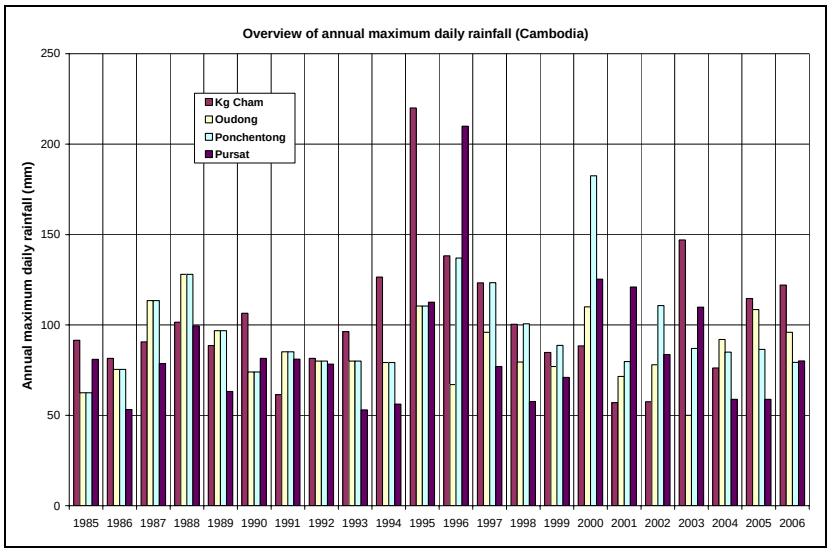

Figure 5.1 Annual maximum daily rainfall of stations selected for the Delta Model, Cambodia

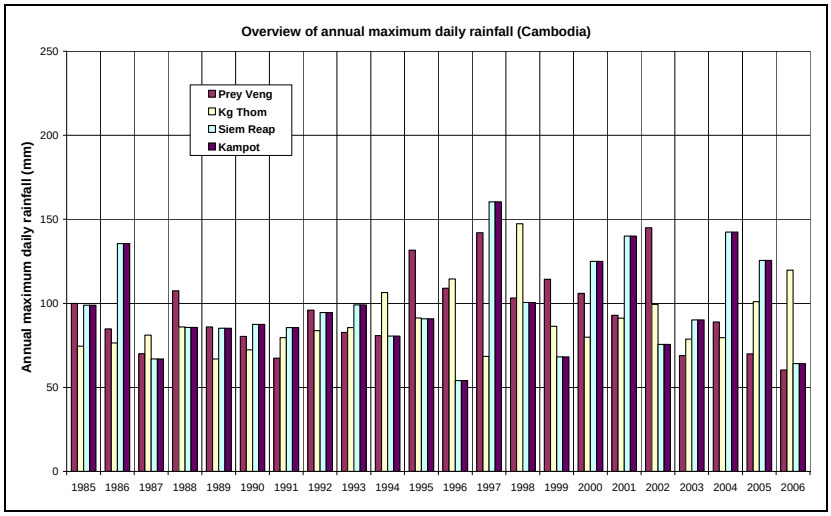

Figure 5.2 Annual maximum daily rainfall of stations selected for the Delta Model, Cambodia (cntnd)

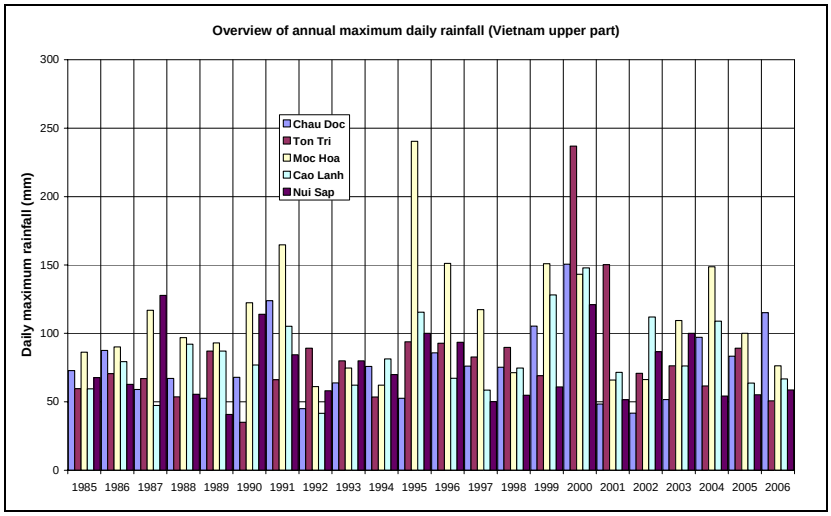

Figure 5.3 Annual maximum daily rainfall of stations selected for the Delta Model, Vietnam upper part of delta

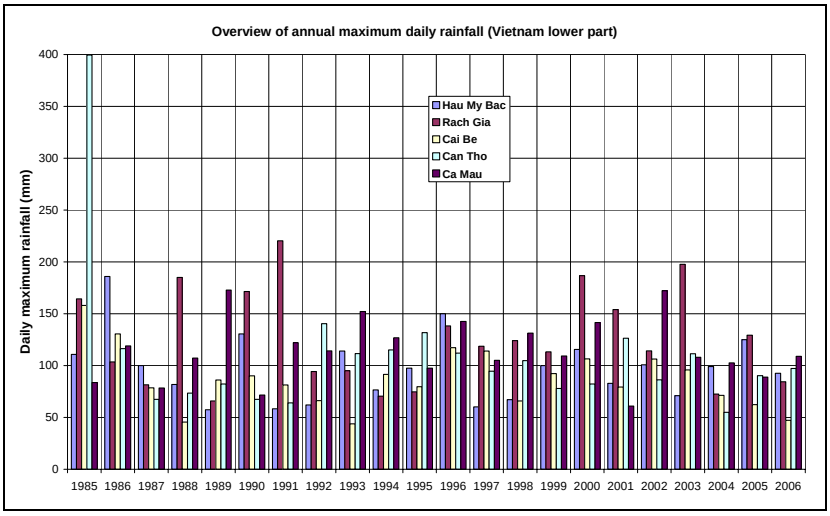

Figure 5.4 Annual maximum daily rainfall of stations selected for the Delta Model, Vietnam lower part of delta

5.2 Extension of rainfall series

Extension of the series backward in time requires historical records for the period 1910-1984. Long historical records are available in the MRC HYMOS database for the following stations:

- Ponchentong
- Kampong Spau
- Kampong Tralanh
- Pursat
- Kampong Chhnang
- Kampong Thom
- Kampong Cham
- Kratie
- Battambang
- Siem Reap
- Chau Doc
- Can Tho

A long historical record also exists for Takeo (Ville) but the record proved to be inconsistent with surrounding stations and has therefore not been considered any further. Inspection of the other records learns that a proper distinction between missing values and rainless days is often not made. In many instances data were clearly missing, where a zero was entered. This reduces the quality of the data considerably. After elimination of the obvious erroneous data, the remaining series have been compared with the inflow to Tonle Sap Lake en Mekong flow on a seasonal basis (May-November). If correlation exists, this has to be taken into consideration when completing the series backward in time. The seasonal rainfall is displayed in Figure 5.5 to Figure 5.8.

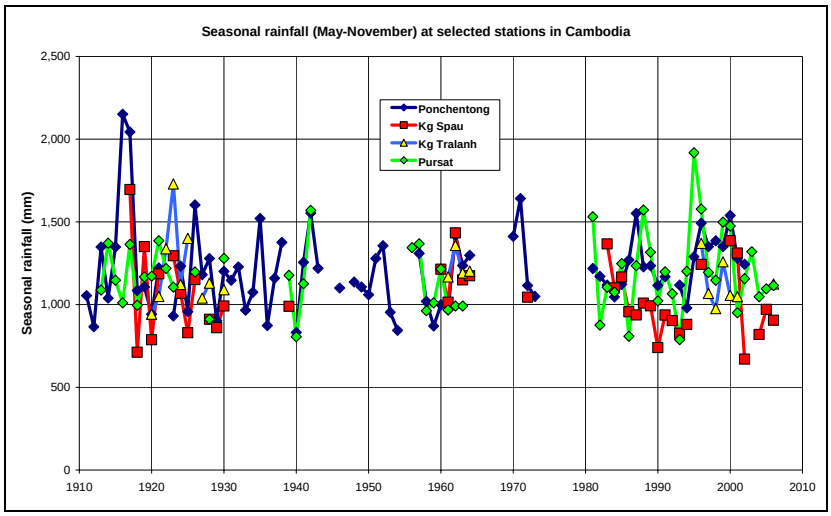

Figure 5.5 Seasonal rainfall (May-November) at selected stations in Cambodia (1)

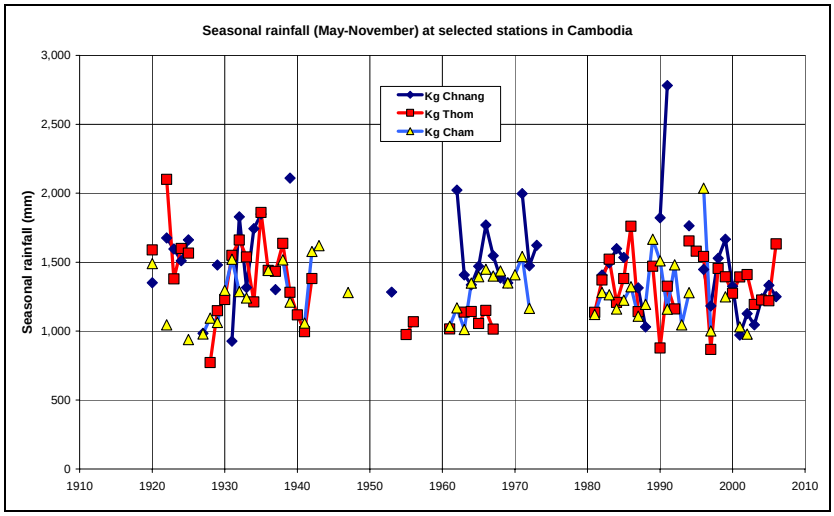

Figure 5.6 Seasonal rainfall (May-November) at selected stations in Cambodia (2)

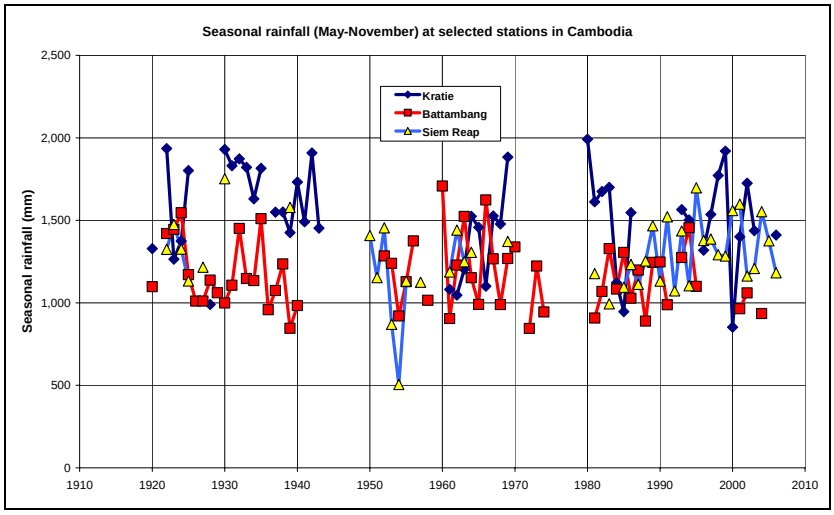

Figure 5.7 Seasonal rainfall (May-November) at selected stations in Cambodia (3)

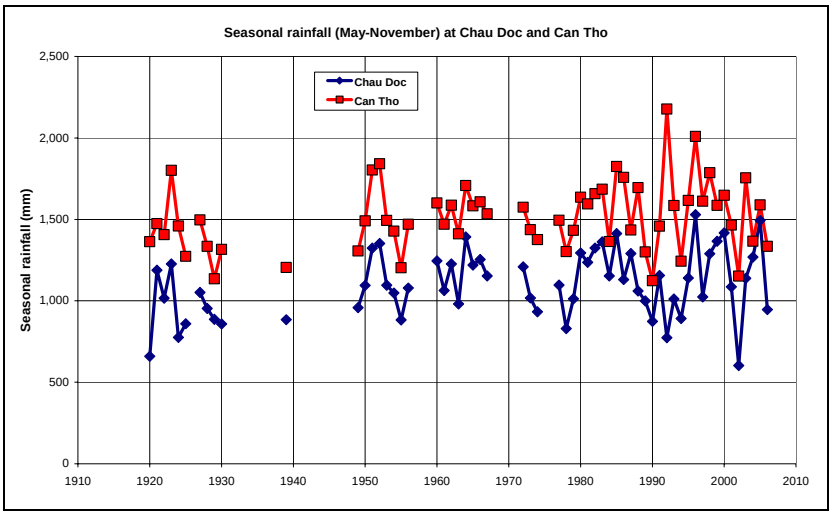

Figure 5.8 Seasonal rainfall (May-November) at selected stations in Vietnam

The results of the correlation analysis is presented in Table 5.1 and Figure 5.9. The 95% critical t-value for zero correlation is 1.67-1.68 for N = 40-60 and 1.78 for N = 20. It is observed that only in a few cases a non-zero correlation is significant. But, when existing, the correlation coefficient is small. The overall conclusion is that rainfall of the selected stations (which fully represent the area covered by the Delta Model) is surprisingly hardly correlated to Tonle Sap inflow and not at all with the Mekong flood volume. This gives full freedom in distributing the observed rainfall to the years 1910-1984. Therefore, the observed daily rainfall of the years 1985-2006 has been applied block-wise to the years without records or with doubtful records in the period 1910-1984.

Table 5.1 Results of correlation analysis of seasonal rainfall and inflow to Tonle Sap Lake and Mekong flow at Kratie

			Rainfall vs Lat.Inflow Tonle Sap				**Rainfall vs Mekong at Kratie**			
Rainfall station	**N**	**rain*)**	**R^2**	**R**	**t-value**	**Sign.**	**R^2**	**R**	**t-value**	**Sign.**
Ponchentong	72	1210	0.002	0.047	0.39	no	0.003	0.050	0.02	no
Kg Spau	38	1052	0.104	0.322	2.04	yes	0.002	0.042	0.01	no
Kg Tralanh	20	1183	0.213	0.462	2.21	yes	0.125	0.354	0.72	no
Pursat	53	1182	0.036	0.189	1.37	no	0.005	0.071	0.04	no
Kg Chhnang	46	1497	0.073	0.270	1.86	yes	0.075	0.274	0.58	no
Kg Thom	52	1331	0.002	0.045	0.32	no	0.003	0.057	0.02	no
Kg Cham	48	1281	0.007	0.082	0.56	no	0.006	0.080	0.05	no
Kratie	46	1523	0.120	0.347	2.45	yes	0.089	0.298	0.73	no
Battambang	57	1165	0.025	0.157	1.18	no	0.005	0.069	0.04	no
Siem Reap	43	1286	0.053	0.231	1.52	no	0.111	0.334	0.81	no
Chau Doc	46	1099	0.030	0.174	1.17	no	0.013	0.116	0.10	no
Can Tho	42	1504	0.000	0.000	0.00	no	0.059	0.243	0.37	no

*) seasonal rainfall (May-November) in mm

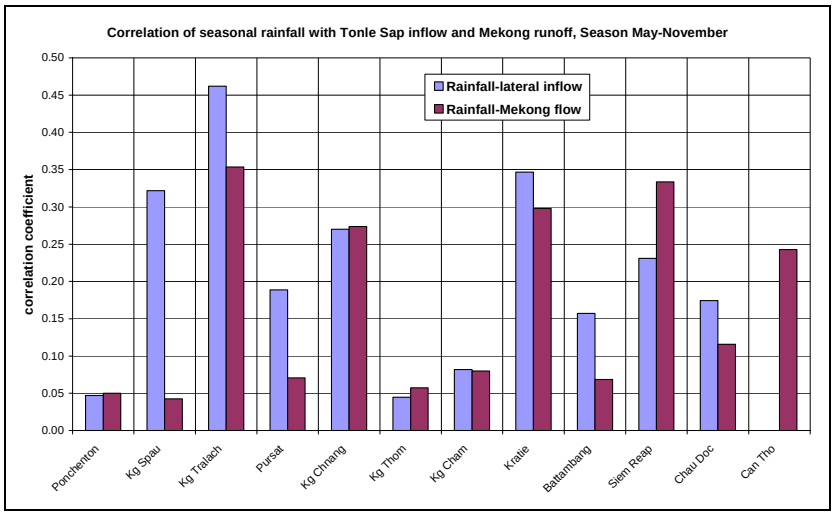

Figure 5.9 Correlation of seasonal rainfall with Tonle Sap inflow and Mekong flood volume

6 Evaporation

6.1 Overview of stations and series availability

In the Delta model at 14 locations daily evaporation data is to be applied, for which observations at the stations mentioned in Table 6.1 is used.

Table 6.1 Overview of applied evaporation stations in Delta model with annual evaporation totals

Country	Station	Data availability	Annual observed (mm)	Long term annual average (mm)
Cambodia	Snuol	-	-	1657
	Kampong Cham	-	-	1890
	Ponchentong	1985-2006, partly	1634	1621
	Oudong	-	-	1621*)
	Kampong Thom	-	-	1621*)
	Siem Reap	1997-2006, partly	1637	1725
	Pursat	1997-2006, partly	1341	1355
	Prey Veng	1997-2006, partly	1765	1756
	Kampot	-	-	1649
Vietnam	Chau Doc	1985-2006, except 2002	1226	1273
	Can Tho	1985-2006, except 2002	982	938
	Rach Gia	1985-2006, except 2002	1363	1230
	Moc Hoa	1985-2006, except 2002	1338	1206
	Ca Mau	1985-2006, except 2002	1102	1064

*) no data, Ponchentong data used instead

From the table it is observed that for the Vietnamese stations 21 years of daily observations is available as from 1985 onward. The data availability for the Cambodian stations is less promising. Only for Ponchentong a fairly long daily evaporation record is available. For 3 stations 3 to 6 years of record is present and for 5 stations no daily record is found. All records refer to pan-evaporation data.

6.2 Series completion and extension

In case no data daily evaporation series is available, monthly averages (in mm/day) are applied. The monthly averages for the various locations are presented in Figure 6.1 to Figure 6.4. The annual totals are presented in Table 6.1. A distinct difference is observed between the values applied in Cambodia and those in Vietnam; the latter are generally lower.

All evaporation data as used in the Delta model for calibration refer to pan-evaporation measurements and a pan-coefficient of 1.0 has been applied. Since pan-evaporation data generally overestimate potential and open water evaporation in view of its exposure, a comparison has been made between these data and the ET_0 values according to Penman-Monteith method (FAO-climwat database). For Cambodia it appears that for the relevant months May to November the differences for most stations are small (pan-evaporation data are 1-5% higher); only for Siem Reap and particularly Kampong Cham the differences are substantial (9 and 17% higher). In all, however, the differences for the delta are small.

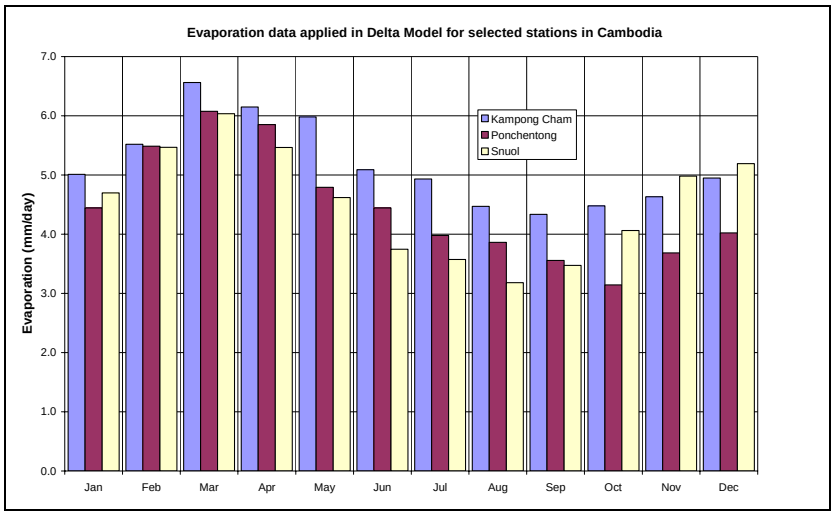

Figure 6.1 Daily evaporation applied in Delta model for selected stations in Cambodia

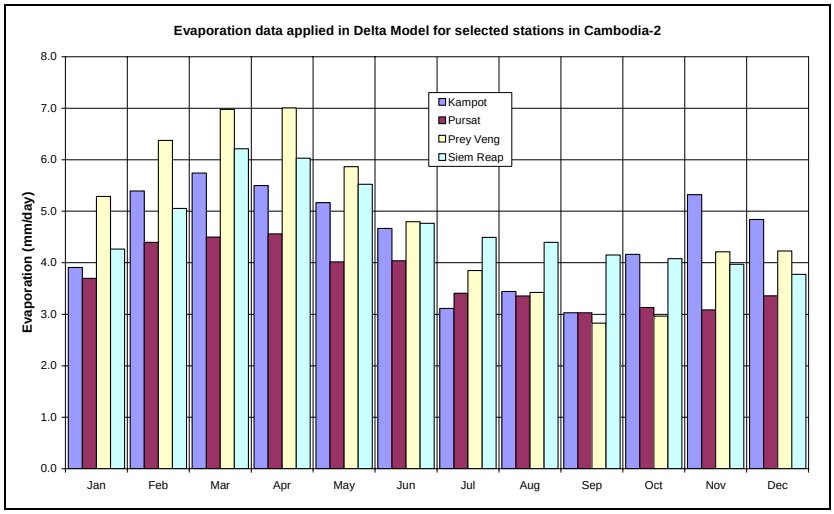

Figure 6.2 Daily evaporation applied in Delta model for selected stations in Cambodia (continued)

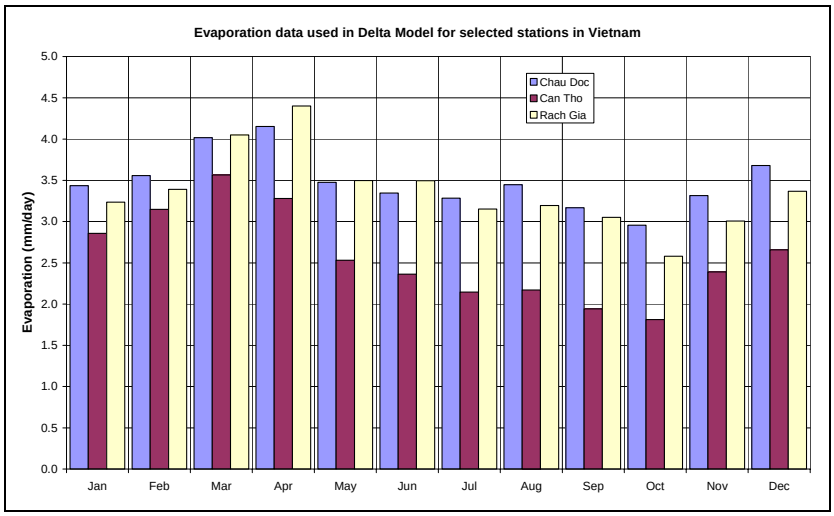

Figure 6.3 Daily evaporation applied in Delta model for selected stations in Vietnam

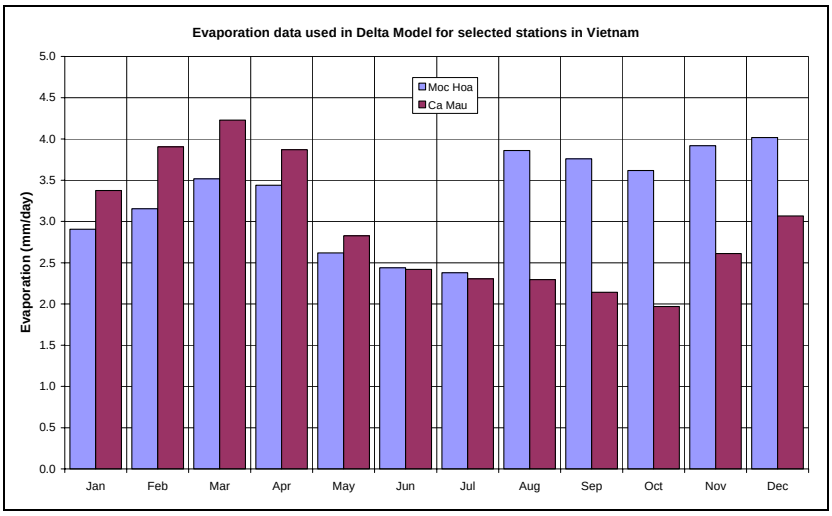

Figure 6.4 Daily evaporation applied in Delta model for selected stations in Vietnam (continued)

7 Water demands

At 128 nodes in the network of the Delta model water is abstracted for agriculture, domestic and industrial use. The variation through the year is displayed in Figure 7.1. It varies from about 0 m^3/s at the end of September till over 1,400 m^3/s in January. A strange doubling of the demand is observed from December 31 till 1 January. The total annual demand amounts 16.5 BCM, whereas during the flood season the demand is about 4.4 BCM in total. This implies an abstraction of less than 300 m^3/s, which is smaller then the error margin in the computed discharge from the Mekong.

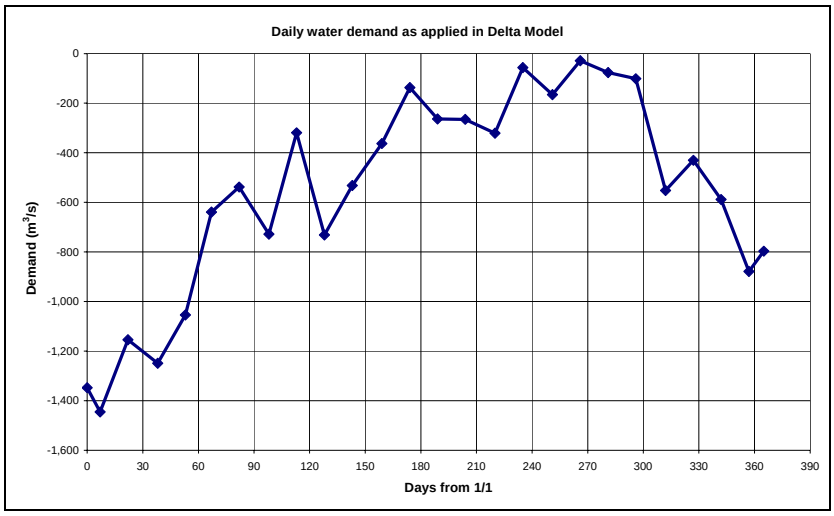

Figure 7.1 Water demand applied in the Delta Model

8 Downstream boundary condition

8.1 Overview of stations and data availability

In total at 19 nodes water level boundaries are defined in the Delta Model. These boundaries are taken from hourly observations made at the 6 stations listed in Table 8.1.

Table 8.1 Overview of water level stations at sea boundaries

Station	River	Province	Remark
Rach Gia	Cai Lon	Kien Giang	Draining to Gulf of Thailand
Song Doc	Song Ong Doc	Ca Mau	-do-
Ganh Hao	Ganh Hao	Ca Mau/Bac Lieu	Draining to South China Sea
My Thanh	Bassac	Soc Trang/Tra Vinh	Draining to South China Sea
Ben Trai	Cua Cung Hau	Tra Vinh/Ben Tre	Southern Mekong outlet, draining to South China Sea
Vam Kinh	Cua Dai	Ben Tre/Tien Giang	Northern Mekong outlet, draining to South China Sea

The hourly observations used in the Delta Model are records of the year 2000. The characteristics of the series are discussed below.

Rach Gia and Song Doc

The rivers Cai Lon and Song Ong Doc discharge to the Gulf of Thailand and the records of their tidal boundaries at Rach Gia and Song Doc show similarity. The characteristics of the records are shown in Figure 8.1 and Figure 8.5. The tide varies from semi-diurnal to diurnal. The range at Rach Gia was from -0.34 to 1.04 masl and at Song Doc from -0.50 to 1.01 masl in 2000. Average levels at Rach Gia are highest in October and in Song Doc in November. The tide at Song Doc is a few hours ahead of Rach Gia, as can be observed from Figure 8.5.

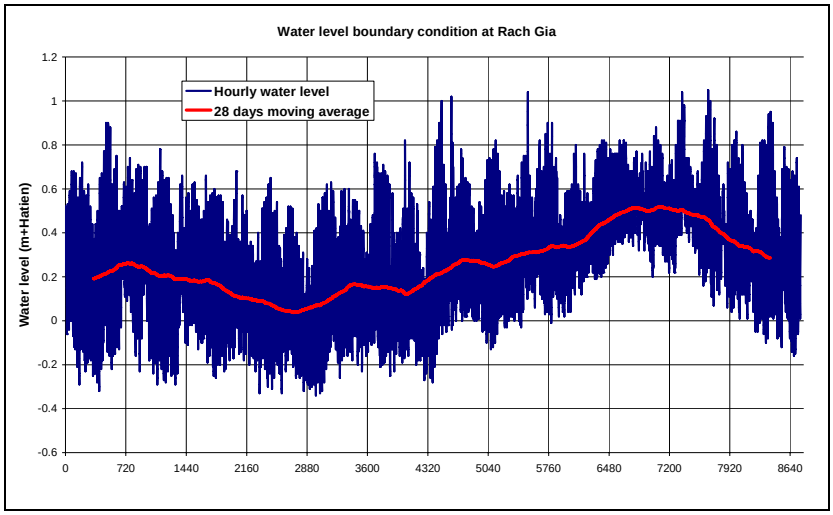

Figure 8.1 Tidal boundary for Delta Model at Rach Gia

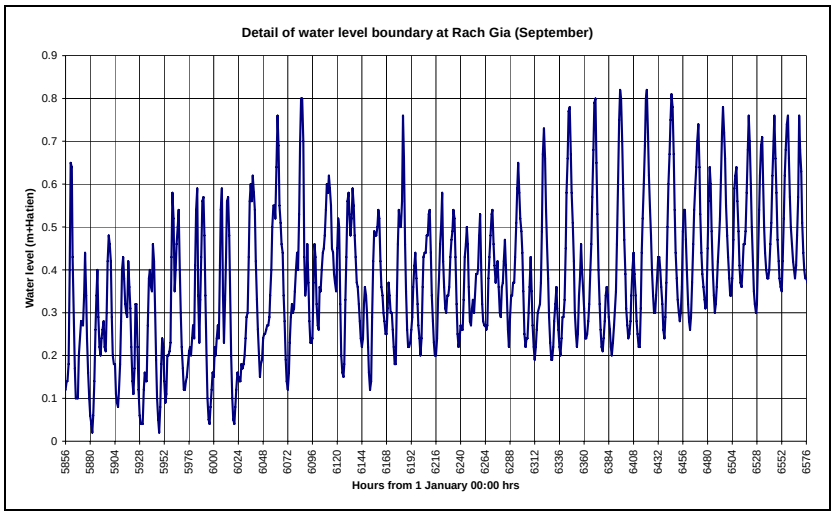

Figure 8.2 Detail of tidal boundary at Rach Gia (September)

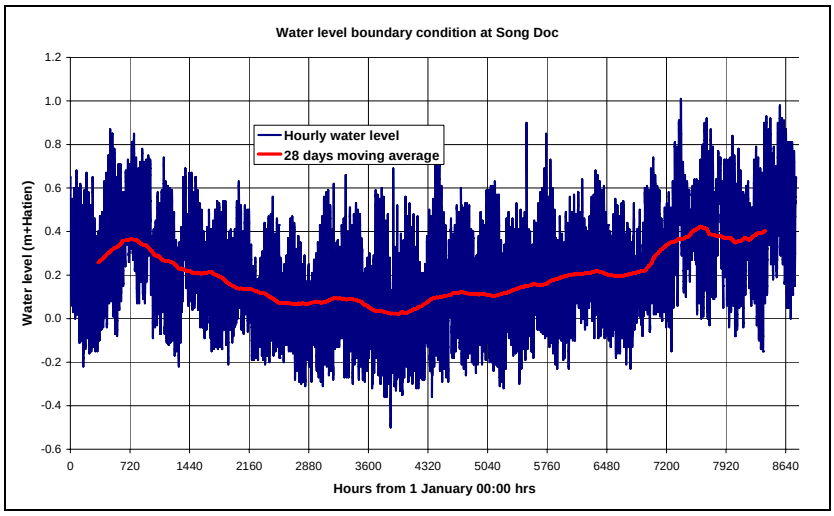

Figure 8.3 Tidal boundary for Delta Model at Song Doc, Gulf of Thailand

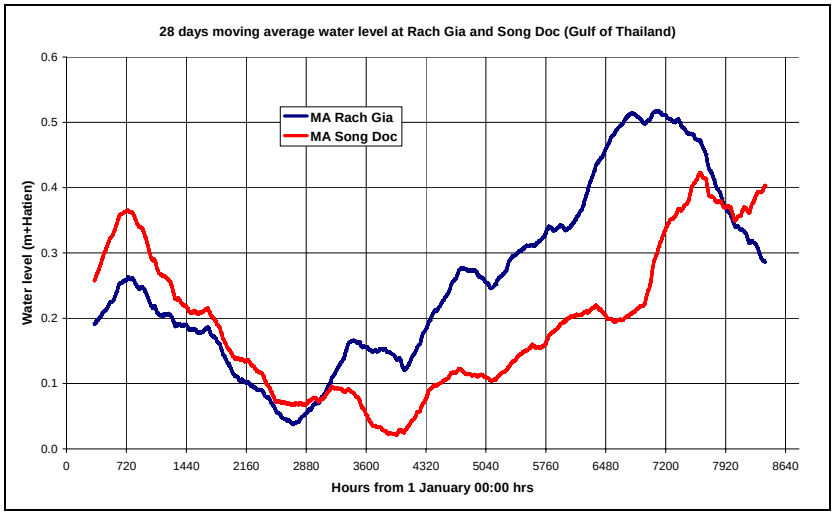

Figure 8.4 28 days moving average of water level at Rach Gia and Song Doc

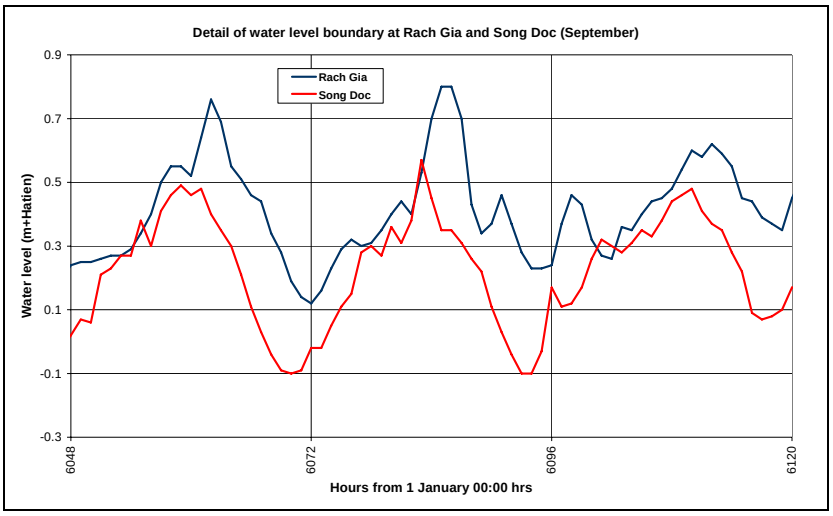

Figure 8.5 Comparison of water level at Rach Gia and Song Doc

Ganh Hao, My Thanh, Ben Trai and Vam Kinh

The characteristics of the tidal boundary of Ganh Hao river at Ganh Hao, east of Ca Mau, the Bassac at My Thanh, and the southern and northern Mekong outlets at respectively Ben Trai and Vam Kinh are very similar. The record of Vam Kinh is displayed in Figure 8.6 and Figure 8.7. The levels vary from -2.09 to 1.73 masl, i.e. a range of 3.83 m. Further southward the range increases till 4.24 at Ganh Hao (-2.21 till 2.03 masl). The tide is basically semi-diurnal, but becomes at times almost diurnal, as can be observed from Figure 8.7. The 28 days moving averages of the 4 tidal stations bordering the South China Sea show a similar pattern, with a sharp increase of about 3 dm in September. From a comparison of the tides at Vam Kinh and Ganh Hao in Figure 8.9 it is observed that the tide at Vam Kinh is a few hours ahead of that at Ganh Hao.

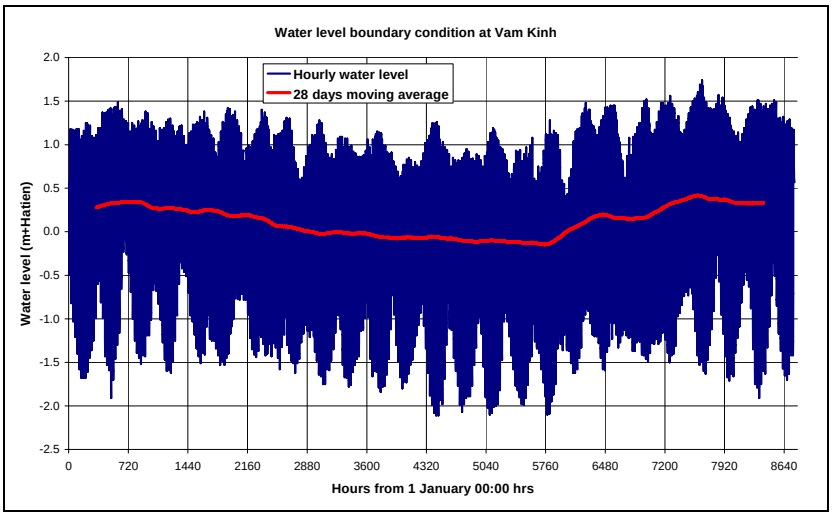

Figure 8.6 Tidal boundary for Delta Model at Vam Kinh

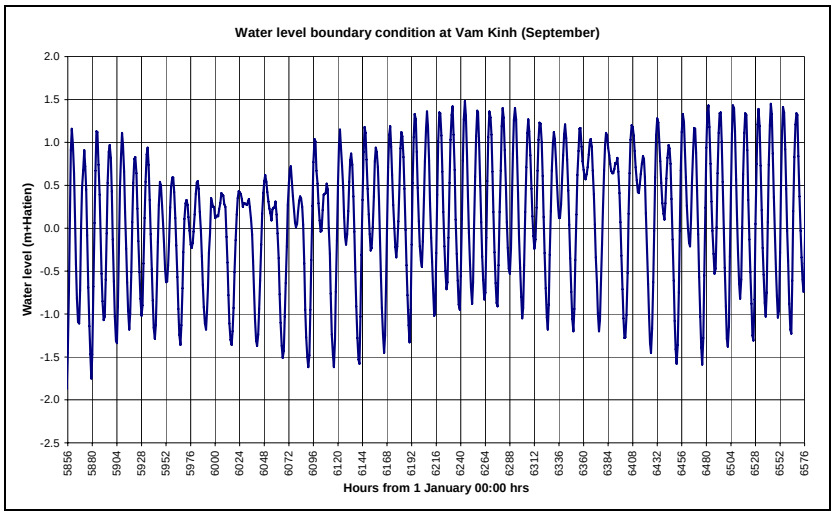

Figure 8.7 Detail of tidal boundary at Vam Kinh (September)

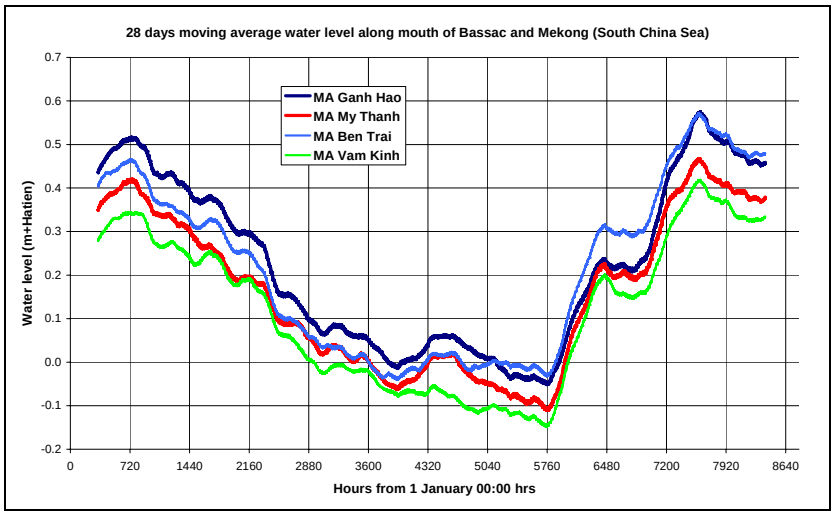

Figure 8.8 28 days moving average of water level at Ganh Hao, My Thanh, Ben Trai and Vam Kinh

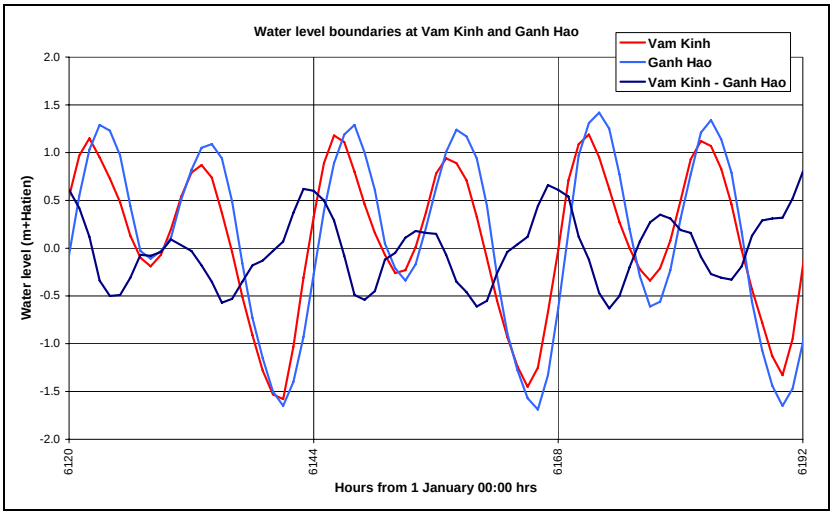

Figure 8.9 Comparison of water levels at Van Kinh and Ganh Hao

8.2 Extension of the tidal boundary

Long time series of daily maximum, mean and minimum water levels are available for a few stations in the delta near the coast. The series have been adjusted for the change in the reference level on 1 January 1995, by adjusting the data prior to 1995 equal to the difference in the annual mean levels before and after the date of the change in reference level. Corrections in the order of 10 to 12 cm were required.

The frequency distribution of the daily maximum water levels (Figure 8.10) indicates that highest stages near the coast may occur from October till March, see also Figure 8.11. This coincides often with the occurrence of the peak water level further upstream, e.g. at Chau Doc near the Vietnamese border. It implies that special attention is required in the selection of the tidal boundary and the variation of the maximum tidal level. From Figure 8.12, which shows the maximum water levels of 3 stations near to the mouth of the Mekong (viz. Tra Vinh, Hoa Binh and My Hoa), it may be observed that the variation in the maximum water level from year to year rather small (about 0.25 m). From an analysis of the annual maximum series it can be deduced that the value for the year 2000 matches exactly with the average value of the annual maximum water level at the selected stations for the period 1985-2006. It follows that the use of the series of the year 2000 to represent the downstream boundary will not introduce a bias regarding peak water levels. The annual maximum daily maximum water levels appear not to be correlated with the annual flood volume flowing into the delta.

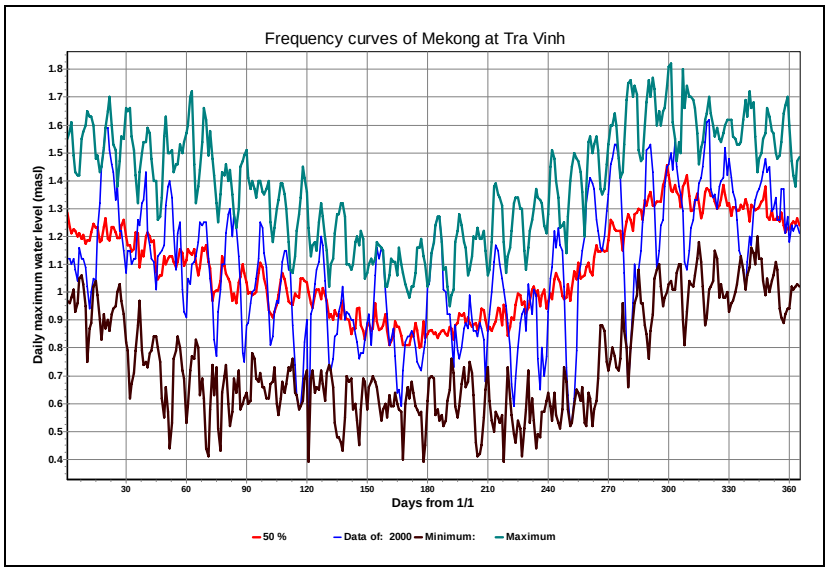

Figure 8.10 Frequency distribution of the daily maximum water level in Mekong at Tra Vinh, 1985-2006

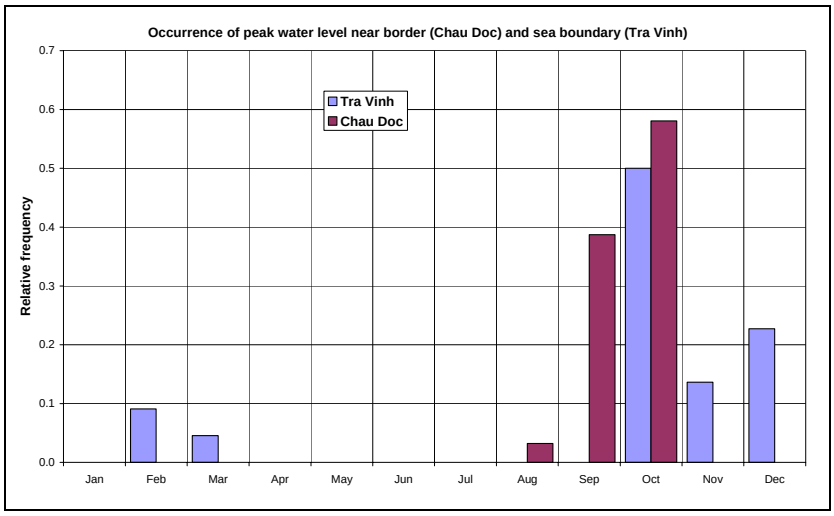

Figure 8.11 Occurrence of maximum water level near Vietnamese border (Chau Doc) and near the coast (Tra Vinh)

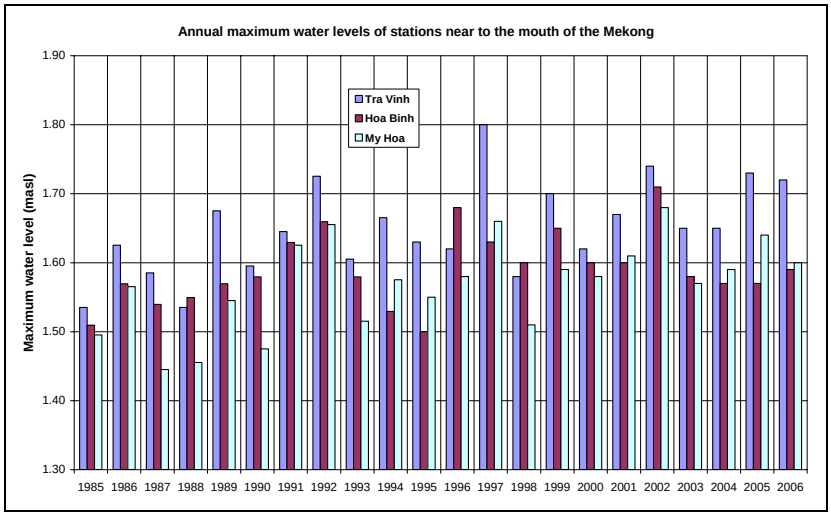

Figure 8.12 Annual maximum water level in Mekong at Tra Vinh, Hoa Binh and My Than, 1985-2006

9 Literature

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