Flow diversion to Tonle Sap

Appendix 11 to the Annex 1 to the
Draft Stage 1 Evaluation Report

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1 Introduction

This Appendix 11 to Annex 1 describes a simple mass balance model for the Mekong delta. The modelled area covers the Mekong river downstream of Kampung Cham, the Tonle Sap river and the Tonle Sap lake. Furthermore it contains a possible diversion channel from the Mekong river (between Kampong Cham and Phnom Penh) to the Tonle Sap lake. This shortcut is considered for the following reasons:

- to limit the flows in the Mekong river downstream of Phnom Penh in the early flood season (June - August) to prevent farmlands with unharvested crops being flooded, and
- to increase the water content of the lake, which has the following benefits:
  - increased wet surface area, which has a positive effect on the fish population.
  - increased water availability in the dry season, which can be beneficial for farmland and “flushing” the delta for desalinisation purposes.

A period of 97 years was simulated with the model to quantify the effects this diversion channel will have on discharges, water levels and water distribution in the system. The main boundary condition of the model consists of historical daily discharges in the Mekong at Kampong Cham over the period 1910-2006. For the same period, discharges of relevant tributaries were reconstructed (see Appendix 9 of Annex 1).

Chapter 2 of this report describes the simulation model, while Chapter 3 describes the main simulation results with a fully controlled and an uncontrolled diversion channel.

2 Model description

2.1 Model with fully controlled diversion channel

Figure 2.1 shows a schematic view of the modelled area. On the right it shows Kampong Cham which is the main upstream boundary of the model. For this location a discharge series over the period 1910-2006 is available. This series is derived from observed discharges in Stung Treng and discharges of the two main tributaries between Stung Treng and Kampong Cham: Prek Chlong and Prek Te. Furthermore, the combined flow of the tributaries of the Tonle Sap lake (not including the Tonle Sap river) is taken into account.

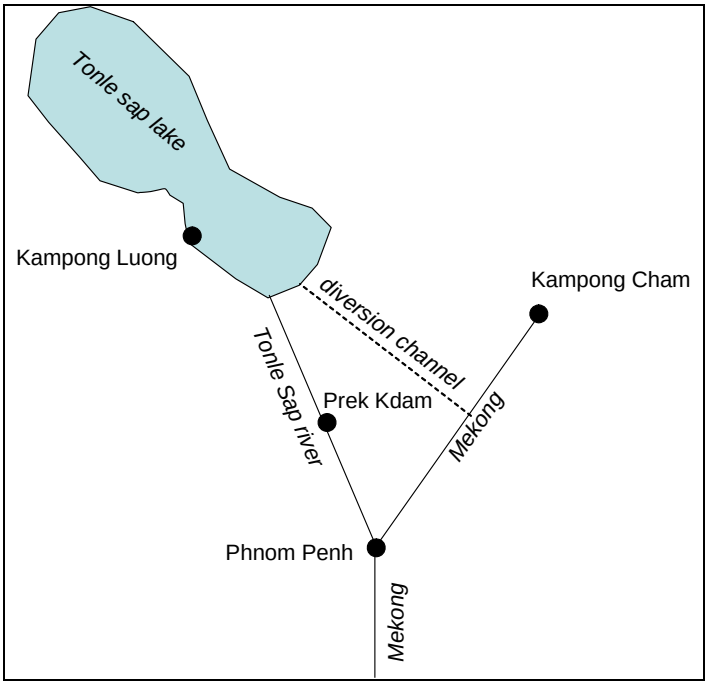

Figure 2.1 Schematic view of the modelled area.

Figure 2.2 again shows a schematic view of the area, this time including the following symbols:

Q_{KC}:	Mekong river discharge at Kampong Cham	[m^3/s]
Q_{div}:	flow through the diversion channel	[m^3/s]
Q_{PP} :	Mekong river discharge upstream of Phnom Penh	[m^3/s]
Q_{delta}:	Mekong river discharge downstream of Phnom Penh	[m^3/s]
Q_{TLS}:	flow through the Tonle Sap river (positive direction towards the lake)	[m^3/s]
Q_{trib}:	combined flow of tributaries of Tonle Sap lake	[m^3/s]
h_{KC}:	water level in the Mekong river at Kampong Cham	[m+MSL]
h_{div}:	water level in the Mekong at offtake diversion channel	[m+MSL]
h_{PP}:	water level in the Mekong river at Phnom Penh	[m+MSL]
h_{PK}:	water level in the Tonle Sap river at Prek Kdam	[m+MSL]
h_{KL}:	water level in the lake at Kampung Luong	[m+MSL]
A_{lake}:	surface area of the Tonle Sap lake	[km^2]
V_{lake}:	volume of the Tonle Sap lake	[BCM]

Note that the flow in the Tonle Sap river can be in both directions. A positive value of Q_{TLS} means that water is flowing towards the lake, a negative value means the water is flowing from the lake towards Phnom Penh. Besides flows and water levels there are some capacity limitations that play a vital role in the model:

C_{div} :	flow capacity of the diversion channel	[m^3/s]
C_{delta}:	flood free flow capacity of the Mekong downstream Phnom Penh	[m^3/s]
C_{TLS}:	flow capacity of the Tonle Sap river	[m^3/s]
V_{max}:	maximum content of the Tonle sap lake	[BCM]

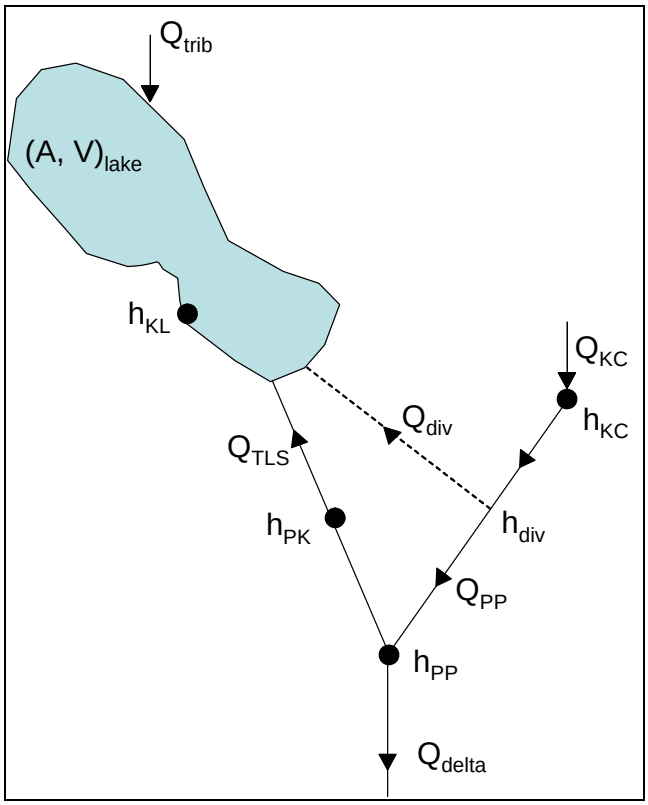

Figure 2.2 Schematic view of flows and water levels in the modelled area.

The model will be described with the symbols as introduced above. The first equation describes the mass balance at the off-take between Kampong Cham and Phnom Penh:

$$Q_{KC} = Q_{PP} + Q_{div} \tag{2.1}$$

The following equation describes the mass balance at Phnom Penh:

$$Q_{PP} = Q_{TLS} + Q_{delta} \tag{2.2}$$

The mass balance of the lake is as follows:

$$\Delta V_{lake} = k\left[Q_{TLS} + Q_{div} + Q_{trib}\right] \tag{2.3}$$

where Δ means "increase of". Factor k is introduced to convert discharges, expressed in m^3/s, to volume, expressed in BCM. This means k equals:

$$k = \frac{86400}{10^9} \tag{2.4}$$

The value of the numerator in eq. (2.4) is the number of seconds in a day, required because the model simulations are performed on the daily time scale.

The flow in the diversion channel is assumed to be fully controlled. It will be controlled in such a way that the discharge downstream of Phnom Penh will not exceed its flood free capacity, C_{delta}:

$$Q_{delta} \leq C_{delta} \tag{2.5}$$

The combination of eqs (2.1), (2.2) and (2.5) gives:

$$Q_{KC} - Q_{div} - Q_{TLS} \leq C_{delta} \;\Rightarrow\; Q_{div} \geq Q_{KC} - Q_{TLS} - C_{delta} \tag{2.6}$$

Eq (2.6) can be considered as the operation rule for the diversion channel. In the simulations the value of C_{delta} is set equal to 30,000 m^3/s. This is approximately the flow capacity of the Mekong river, downstream of Phnom Penh.

Note that eq. (2.5) and (2.6) may not hold at all times. During periods of (extremely) high flows the capacities of the diversion channel and the lake may be insufficient to divert and store the desired amount of flow, which means the flow downstream of Phnom Penh will exceed C_{delta} and floods will occur. One of the main outputs of the simulations as presented in Chapter 3 is the frequency with which these undesired events occur.

According to Forsius (2007) the flow (discharge and direction) in the Tonle Sap river is determined by the water levels in Prek Kdam, Kampong Luong and Phnom Penh:

$$Q_{TSL} = \begin{cases} -8.581 f^2(h) + 691.35 f(h) & ; h_{PP} \geq h_{KL} \\ -6.608 f^2(h) - 476.21 f(h) & ; h_{PP} \leq h_{KL} \end{cases}$$

with: (2.7)

$$\mathrm{f}(\mathrm{h}) = h_{PK}{}^{1.2} \left| h_{PP} - h_{KL} \right|^{0.5}$$

This means the water levels in these three locations need to be derived from the flow conditions and, in case of Kampong Luong, the volume of the lake. The relation between the lake volume and the water level at Kampong Luong is as follows:

$$V_{lake} = 0.73248 h_{KL}^2 - 0.031375 h_{KL} + 0.68578$$

or : (2.8)

$$h_{KL} = \frac{0.031375 + \sqrt{(0.031375)^2 - 4*0.73248*(0.68578 - V_{lake})}}{2*0.73248}$$

The water level at Phnom Penh is related to the water level at Kampong Cham, as can be seen in Figure 2.3:

$$h_{PP} = 0.62 h_{KC} - 0.34 \tag{2.9}$$

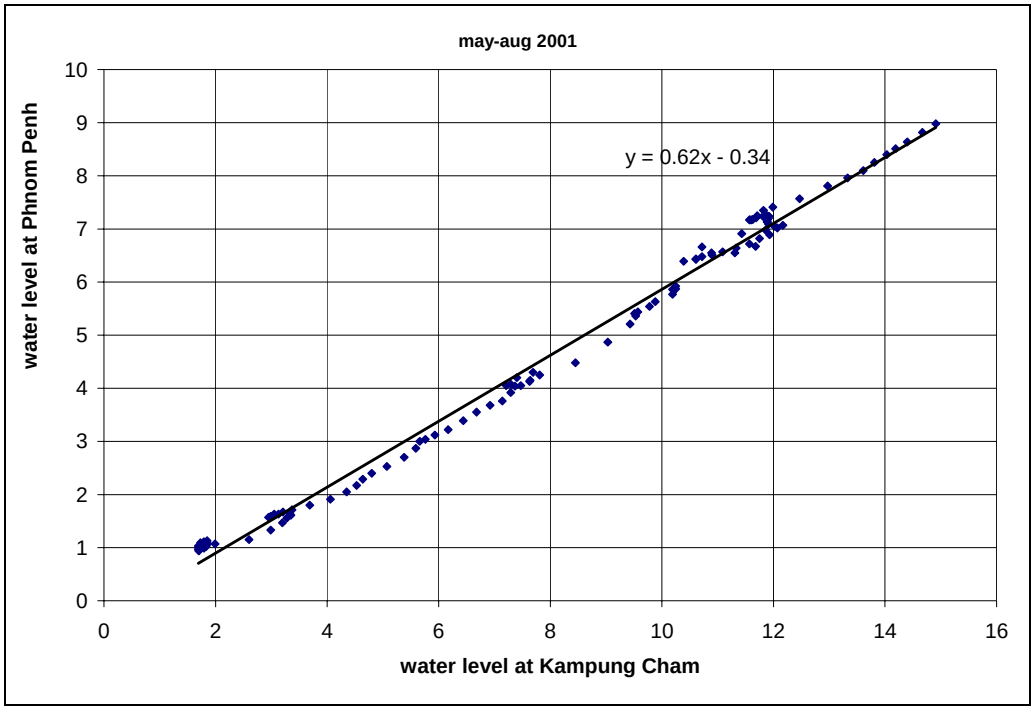

Figure 2.3 Water level at Phnom Penh as a function of the water level in Kampong Cham

With regard to eq. (2.9) it has to be emphasised that

- this relation only holds for the early flood season, i.e. from May until August;
- this relation is derived for the current situation, i.e. without diversion channel.

For Kampong Cham there is a stage-discharge relation available:

$$h_{KC}^{*} = \left(\frac{Q_{KC}^{*}}{28.42} \right)^{(1/2.62)} - 3.91 \tag{2.10}$$

The reason to use the asterisk (*) is because the combination of eqs (2.9) and (2.10) only holds for the current situation without flow diversion. If the flow diversion channel is realized and used, part of the flow in Kampong Cham will not reach Phnom Penh. Therefore, the water level of Kampong Cham will be related to the remainder of the flow:

$$h_{KC} = \left(\frac{Q_{PP}}{28.42} \right)^{(1/2.62)} - 3.91 \tag{2.11}$$

Even though this does not represent the real water level at Kampong Cham, this relation suffices for the model since it is only used to derive the water level at Phnom Penh through the combination of eqs (2.9) and (2.11).

The water level at Prek Kdam is assumed to be the mean of the water level at Kampong Luong and the water level at Phnom Penh:

$$h_{PK} = 0.5 * \left(h_{PP} + h_{KL} \right) \tag{2.12}$$

Furthermore, the water level at the off-take of the diversion channel, h_{div}, is required to know the head of the diversion channel. This water level is derived from linear interpolation between the water levels at Kampong Cham and Phnom Penh, based on the distance to those two locations:

$$h_{div} = 0.4 * h_{PP} + 0.6 * h_{KC} \tag{2.13}$$

Finally, there is a relation between the wet surface area of the lake and the water level at Kampong Luong:

$$A_{lake} = 30.053 h_{KL}^2 + 1094.19 h_{KL} + 716.65 \tag{2.14}$$

Equation (2.14) does not influence the state of any of the other variables. The reason why it is shown here is that the wet surface area is one of the relevant outputs of the simulations, because this area influences the fish population.

To summarize, the model for the **fully controlled** diversion channel is as follows:

the model consists of the following equations:

$$Q_{KC} = Q_{PP} + Q_{div} \quad (2.1)$$

$$Q_{PP} = Q_{TLS} + Q_{delta} \quad (2.2)$$

$$\Delta V_{lake} = \frac{86400}{10^9}\left[Q_{TLS} + Q_{div} + Q_{trib}\right] \quad (2.3)$$

$$Q_{TSL} = \begin{cases} -8.581 f^2(h) + 691.35 f(h) & ; h_{PP} \geq h_{KL} \\ -6.608 f^2(h) - 476.21 f(h) & ; h_{PP} \leq h_{KL} \end{cases}$$

with: (2.7)

$$\mathrm{f}(\mathrm{h}) = h_{PK}^{1.2} \left| h_{PP} - h_{KL} \right|^{0.5}$$

$$h_{KL} = \frac{0.031375 + \sqrt{(0.031375)^2 - 4*0.73248*(0.68578 - V_{lake})}}{2*0.73248} \quad (2.8)$$

$$h_{PP} = 0.62 h_{KC} - 0.34 \quad (2.9)$$

$$h_{KC} = \left(\frac{Q_{PP}}{28.42}\right)^{(1/2.62)} - 3.91 \quad (2.11)$$

$$h_{PK} = 0.5*(h_{PP} + h_{KL}) \quad (2.12)$$

$$h_{div} = 0.4*h_{PP} + 0.6*h_{KC} \quad (2.13)$$

$$A_{lake} = 30.053 h_{KL}^2 + 1094.19 h_{KL} + 716.65 \quad (2.14)$$

Flow through the diversion channel is regulated in such a way that, if possible, the following requirements are fulfilled:

$$Q_{div} \geq Q_{KC} - Q_{TLS} - C_{delta} \quad (2.6)$$

This is only realised of none of the following limitations is violated:

C_{div} :	flow capacity of the diversion channel	[m^3/s]
C_{TLS}:	flow capacity of the Tonle Sap river	[m^3/s]
V_{max}:	maximum content of the Tonle Sap lake	[BCM]

2.2 Model with uncontrolled diversion channel

In case of an **uncontrolled** diversion channel, the off-take acts as a fixed weir on the right bank of the Mekong river. The following dimensions and flow parameters have been applied:

Channel width: 2500 [m]
Discharge coefficient: 1.85 ($m^{1/2}/s$]
Level of the sill: 8.0 [m+MSL]
Weir formula exponent: 1.5 [-]

The flow into the diversion channel is then equal to:

$$Q_{div} = \begin{cases} 0 & h_{div} \leq 8.0 \\ 2500 * 1.85 * \left(h_{div} - 8.0\right)^{1.5} & h_{div} > 8.0 \end{cases} \tag{2.15}$$

This equation replaces equation (2.6) in the model version of the controlled diversion channel.

3 Simulation results

3.1 Simulations with controlled diversion channel

In the first simulation we assumed the following capacities:

C_{delta}: = 30,000 [m^3/s]
C_{div} : = 20,000 [m3/s]
C_{TLS}: = 10,000 [m^3/s]
V_{max}: = 85.86 [BCM] (related to water level h_{KL} = 11 m+MSL)

The water content of the lake at the beginning of the simulation period (May 1st) was taken equal to 1.7 BCM. Each year in the period 1910-2006 was simulated. Figure 3.1 shows an example of a year (1976) in which the flow diversion channel could have been successfully used to keep the flow in the delta below the threshold of 30,000 m^3/s. First the various lines in the figure will be explained

Upper plot

- red line: water level in the Mekong at Kampong Cham (h^*_{KC})
- black line: water level in the Mekong at the offtake (h_{div})
- cyane line: water level in the Mekong river at Phnom Penh (h_{PP})
- magenta line: water level in the Tonle Sap lake (h_{KL})
- dark blue line: head of the flow diversion channel (h_{div}-h_{KL})

lower plot

- red line: discharge of the Mekong at Kampong Cham (Q_{KC})
- black line: flood free capacity of the Mekong, downstream Phnom Penh (C_{delta})
- cyane line: flow in the Tonle sap river (Q_{TSL})
- magenta line: flow in the diversion channel (Q_{div})
- dark blue line: discharge of the Mekong, downstream Phnom Penh (Q_{delta})

As can be seen from the figure, the diversion channel is used from early August onwards (magenta line, lower plot). As a result, the discharge in the Mekong downstream of Phnom Penh (blue line, lower plot) remains at a level of 30,000 m^3/s. Without the diversion channel, this discharge would have been higher and it would have caused flooding downstream of Phnom Penh. The flow in the diversion channel remains below its assumed capacity of 20,000 m^3/s, which means in this case the capacity sets no limits on the use of the diversion channel. The same holds for the capacity of the lake, since the water level of the lake (black line upper plot) remains far below the maximum water level of 11 m+MSL. There's one downside though: the head between the off-take of the diversion channel and its outlet at the lake drops in August to a level of even below zero. This means near the end of August the flow of the diversion channel, as computed with the model, cannot actually be driven by gravity. Near the end of August the model basically loses its validity and should be considered as an optimistic scenario.

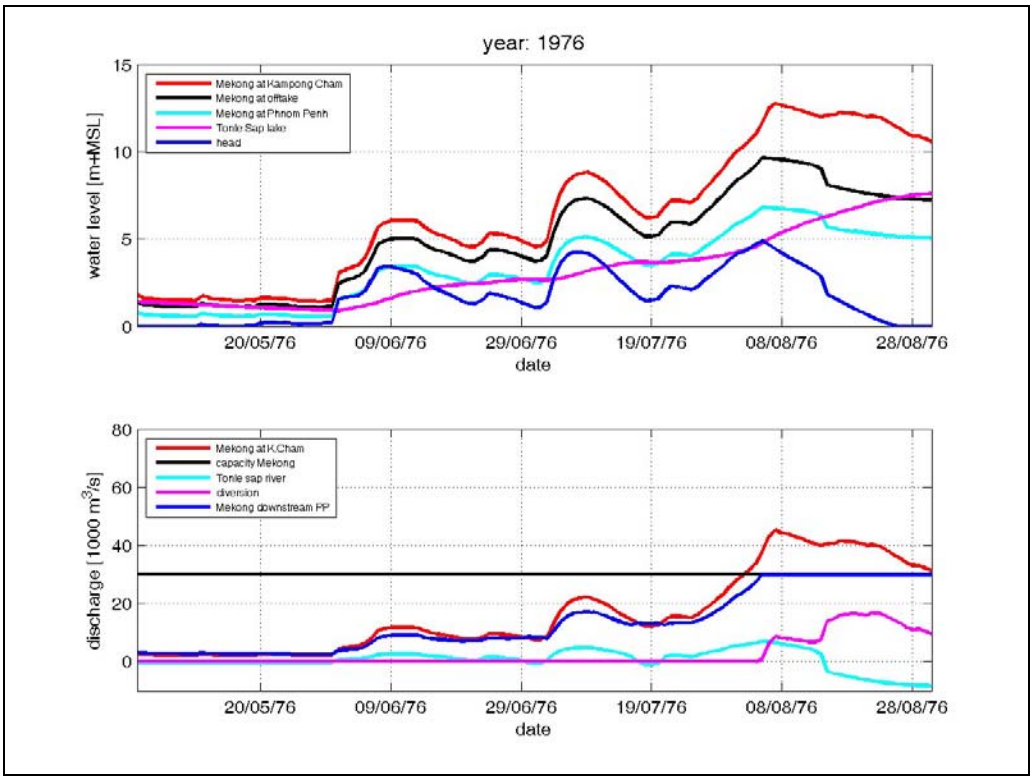

Figure 3.1 Overview of water levels (above) and discharges (below) in the simulation of the year 1976

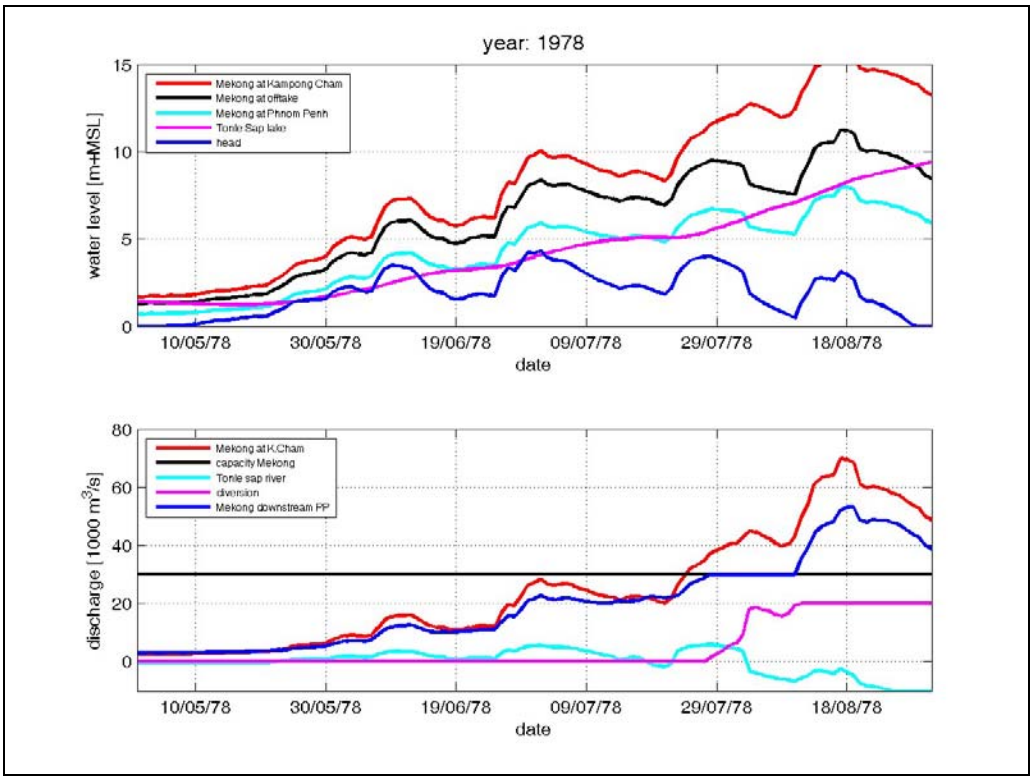

Figure 3.2 Overview of water levels (above) and discharges (below) in the simulation of the year 1978

For each of the simulated years, the water level in the lake remained below its maximum level, which means the maximum storage capacity of the lake didn't put any limit on the use

of the diversion channel. The maximum flow capacity of the diversion channel, on the other hands, did limit the use of the flow diversion channel. Figure 3.2 shows a typical example of a year in which the diversion channel is used successfully for a while, until the upstream discharge becomes too large to handle completely. So for a while the downstream discharge is kept at 30,000 m^3/s, but for the last three weeks of August this threshold is exceeded, causing floods downstream of Phnom Penh.

From the previous figures it is clear that the benefits of the diversion channel will vary from year to year, depending on the flow conditions upstream. Figure 3.3 gives an impression of the "success rate" of all simulated years combined. It shows the percentage of days in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s. These percentages are given for each day in the period May-August (horizontal axis). The dark blue line shows the situation without flow diversion, the cyane line shows the situation with flow diversion, assuming a flow capacity of 20,000 m^3/s. For example, Figure 3.3 shows that "without flow diversion" (dark blue line) the exceedance rate at August 11 (11/08) is equal to 60%. This means that in a "random" year, there is a 60% probability that the flow downstream of Phnom Penh on August 11 exceeds 30,000 m^3/s. Figure 3.4 shows two curves that are directly derived from the curves of Figure 3.3. They represent the average cumulative number of days (up to the date shown on the horizontal axis) in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s. For example, in the case "without flow diversion" (dark blue line) the average cumulative number of days at August 11 (11/08) is approximately equal to 8. This means on average, there are 8 days in the period 1 May – 11 August during which the flow downstream of Phnom Penh exceeds 30,000 m^3/s.

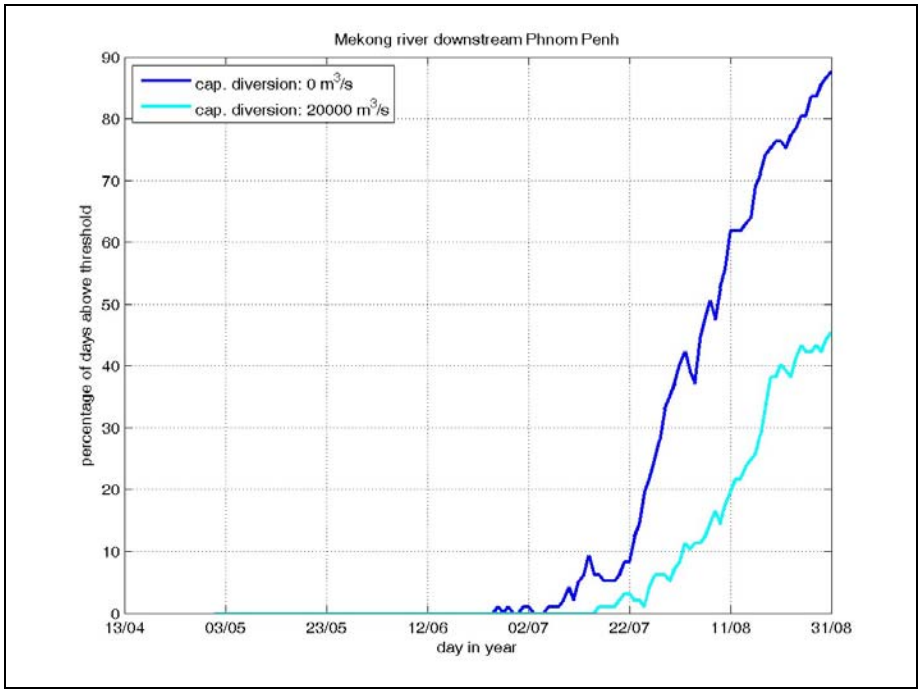

Figure 3.3 Percentage of days in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s; depending on the available flow capacity of the diversion channel.

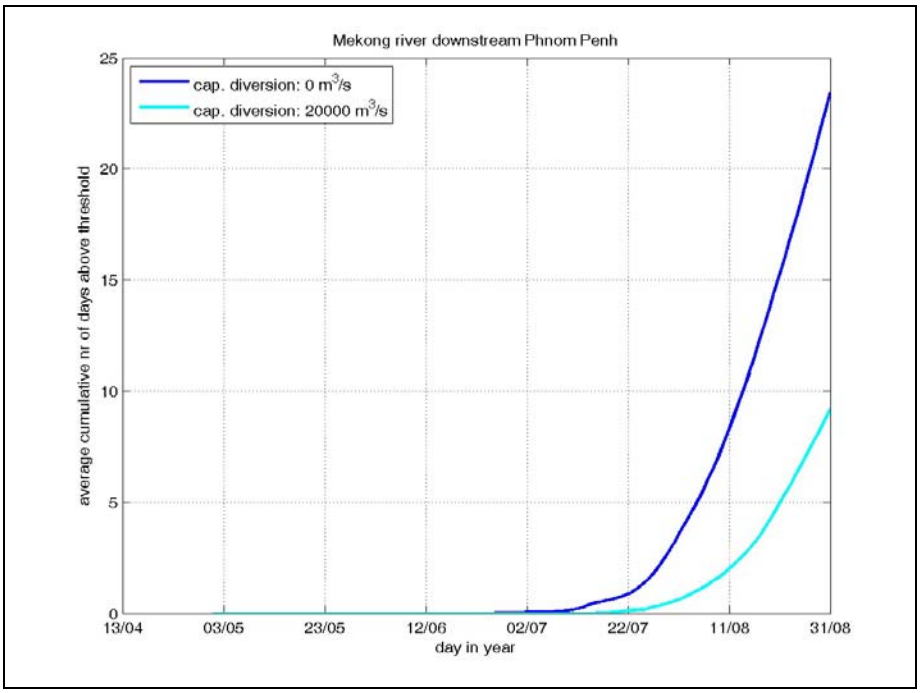

Figure 3.4 Average cumulative number of days (up to the date shown on the horizontal axis) in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s; depending on the available flow capacity of the diversion channel.

From Figure 3.3 and Figure 3.4 it can be seen that the number of days during which the flow downstream of Phnom Penh exceeds 30,000 m^3/s is reduced by at least a factor 2 as a result of the flow diversion channel.

Effect of diversion capacity

Since the assumed flow capacity of the diversion channel sets a limit on the "success rate" it is interesting to verify what happens if other values for the flow capacity are assumed. Figure 3.5 shows the results for 7 different capacities, ranging from 0 (no diversion channel) to 100,000 m^3/s ("infinite" capacity). With the latter, the flow capacity sets no limits on the use of the diversion, which means the flow downstream of Phnom Penh will almost never exceed the threshold of 30,000 m^3/s. This only happens when the lake is filled to capacity. In the simulation with a capacity of 20,000 m^3/s this never happened, but with increased capacity of the diversion channel more water is diverted to the lake, which in some cases means the lake is filled to capacity before September 1st.

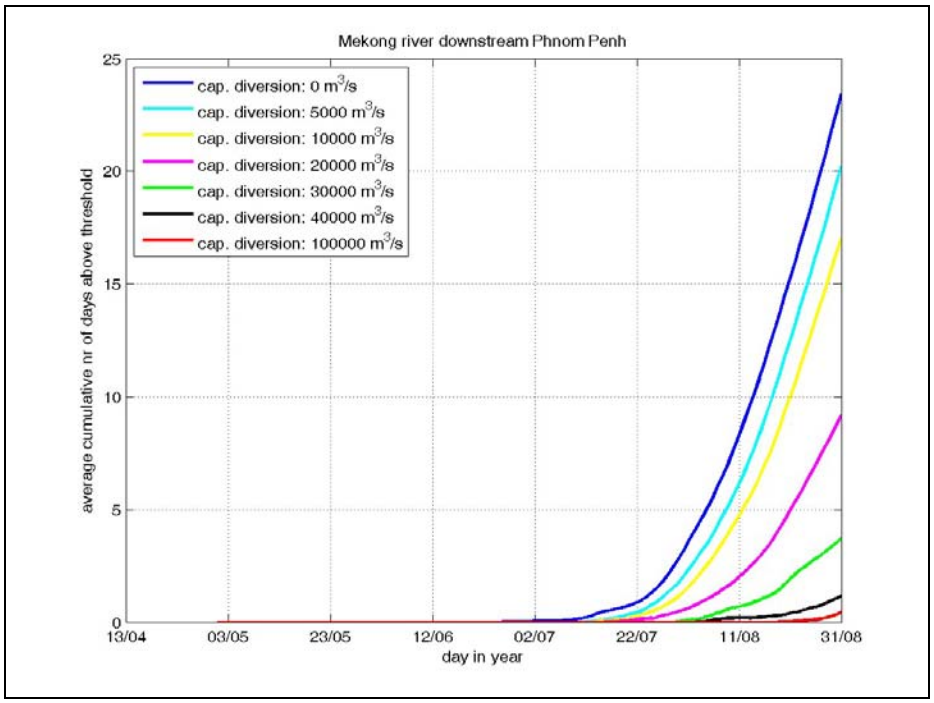

Figure 3.5 Average cumulative number of days (up to the date shown on the horizontal axis) in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s; depending on the available flow capacity of the diversion channel

Figure 3.6 shows the mean wet surface area of the lake for different values of the flow capacity of the diversion channel. It shows the area increases with increasing capacity. Generally, an increase in the wet surface area has a positive effect on the fish population.

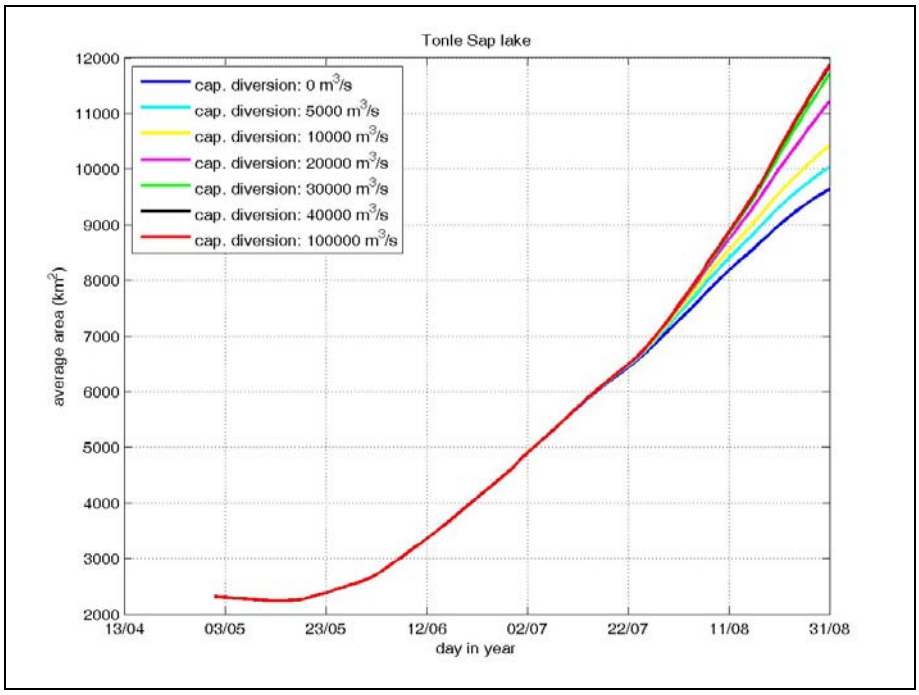

Figure 3.6 Mean wet surface area of the lake for different values of the flow capacity of the diversion.

3.2 Simulations with uncontrolled diversion channel

Similar simulations have been executed with the model that assumes an uncontrolled diversion channel. Figure 3.7 shows the simulation results for the year 1976. In the previous section it was shown that the fully controlled diversion channel was able to keep the flow downstream of Phnom Penh below the threshold of 30,000 m^3/s. With the uncontrolled channel that is not the case anymore. From the beginning of August, when the flow at Kampung Cham exceeds 30.000 m^3/s, the water starts to flow into the diversion channel. As a result, the flow downstream of Phnom Penh is kept more or less equal to 30,000 m^3/s for about a week. But then, as the level of the lake rises, water in the Tonle Sap starts changing direction, which increases the flow downstream of Phnom Penh to a level above 30,000 m^3/s.

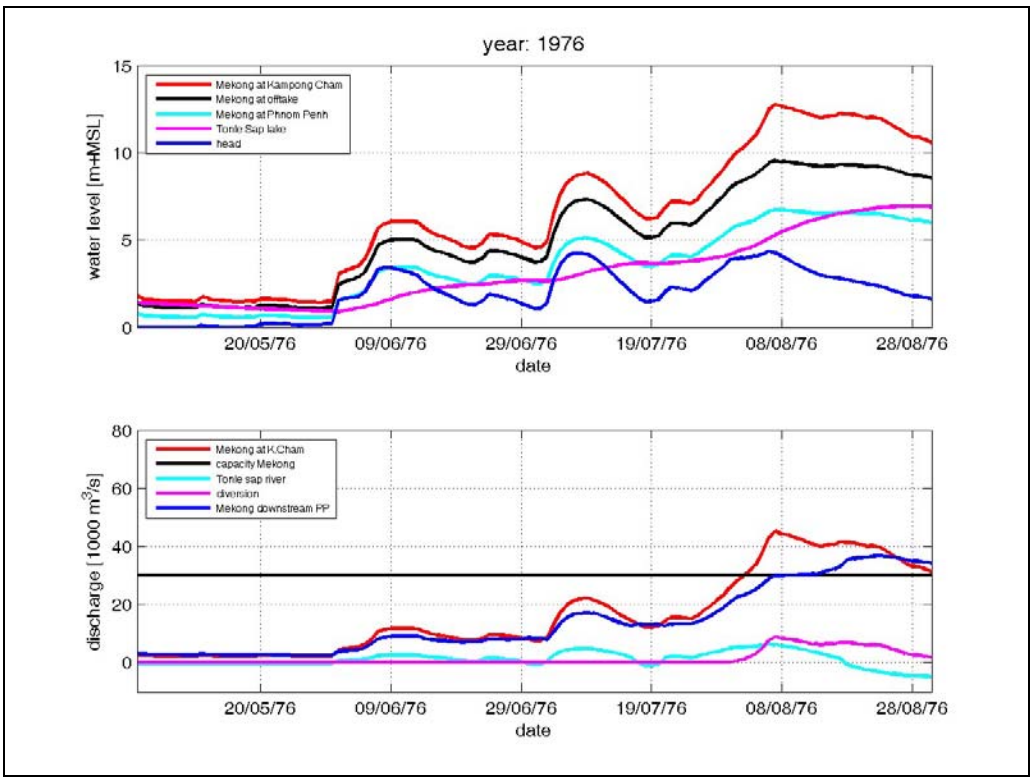

Figure 3.7 Overview of water levels (above) and discharges (below) in the simulation of the year 1976

Figure 3.10 shows, similar to Figure 3.4, the average cumulative number of days (up to the date shown on the horizontal axis) in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s. From this figure it can be seen that there is hardly any difference between "no diversion channel" (dark blue line) and an uncontrolled diversion channel with a flow capacity of 20,000 m^3/s. This in contrast to the controlled diversion channel which gave a reduction of at least a factor 2 in the number of days during which the flow downstream of Phnom Penh exceeds 30,000 m^3/s. The reason for this is obvious: the uncontrolled channel does not offer the possibility to keep the flow at exactly 30,000 m^3/s during periods of high flows. Two more examples for the years 2000 and 2006 are shown in Figure 3.8 and Figure 3.9

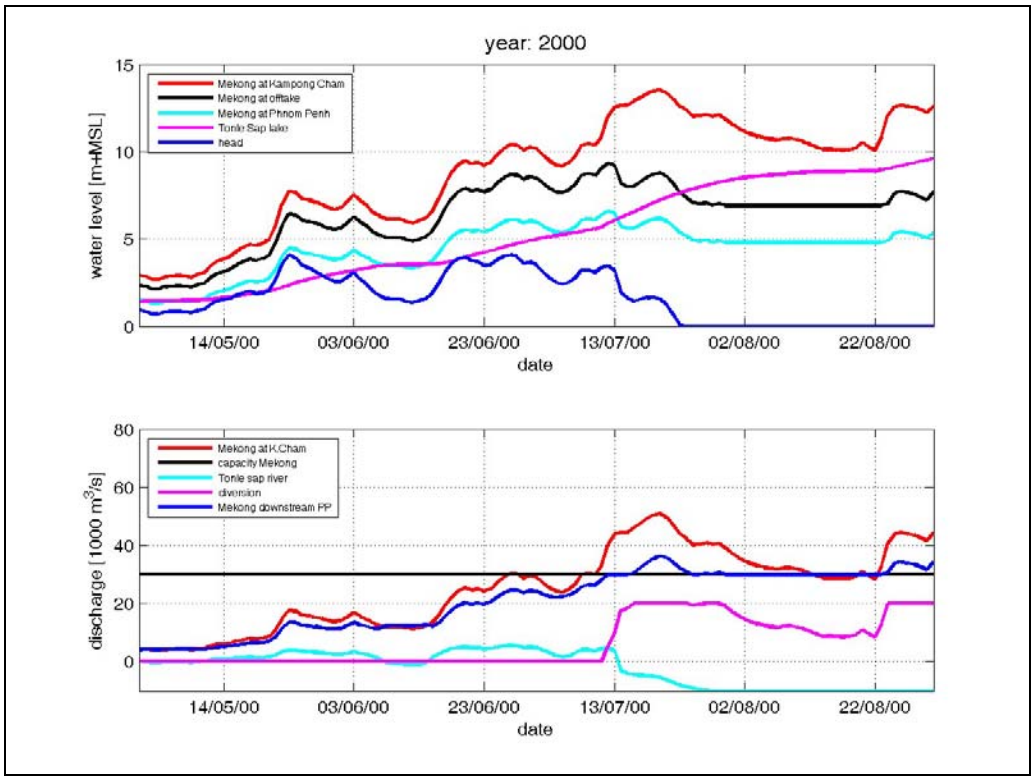

Figure 3.8 Overview of water levels (above) and discharges (below) in the simulation of the year 2000

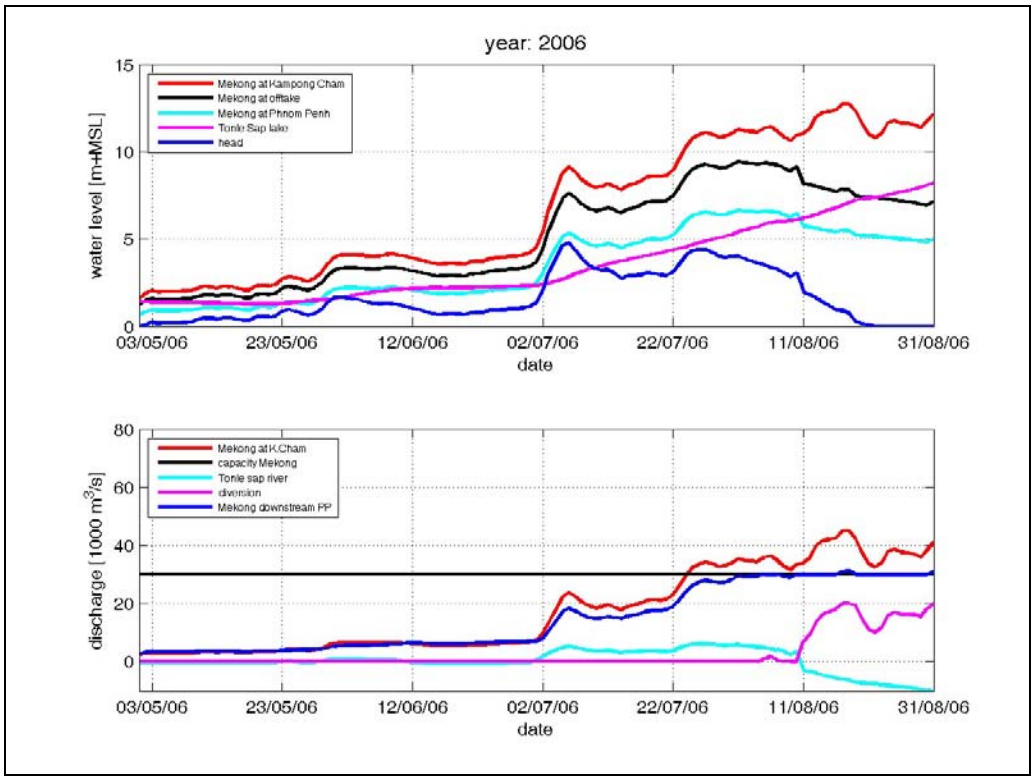

Figure 3.9 Overview of water levels (above) and discharges (below) in the simulation of the year 2006

The benefit of the uncontrolled channel can therefore only be found in the volume of water that fills the flood plain. This volume will be reduced each year the water flows into the diversion channel. For each year in the simulation period 1910-2006 the volume above the threshold of 30,000 m^3/s was derived. Figure 3.11 and Figure 3.12 show the frequency distributions of these volumes as derived on August 1st and August 21st each year. It shows that especially at August 1 there is a large percentage-wise reduction of flood volume, indicating that the diversion channel prevents significant areas of farmland from flooding before the end of the growing season.

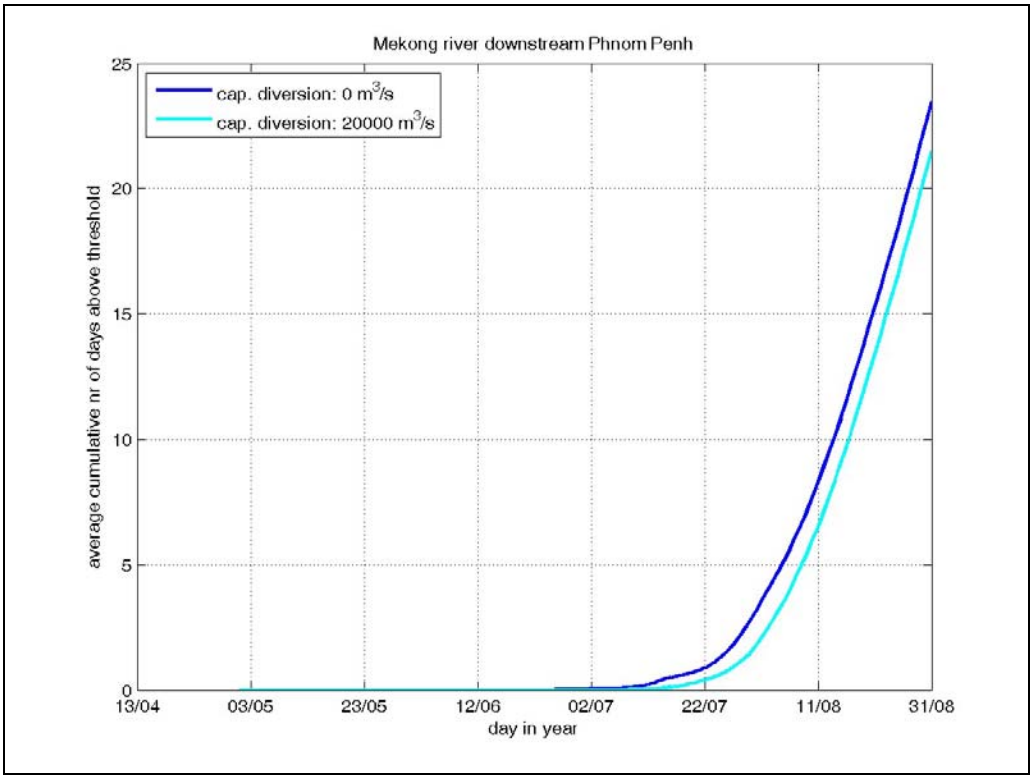

Figure 3.10 Average cumulative number of days (up to the date shown on the horizontal axis) in the simulated period 1910-2006 during which the flow downstream of Phnom Penh exceeded 30,000 m^3/s; depending on the available flow capacity of the diversion channel.

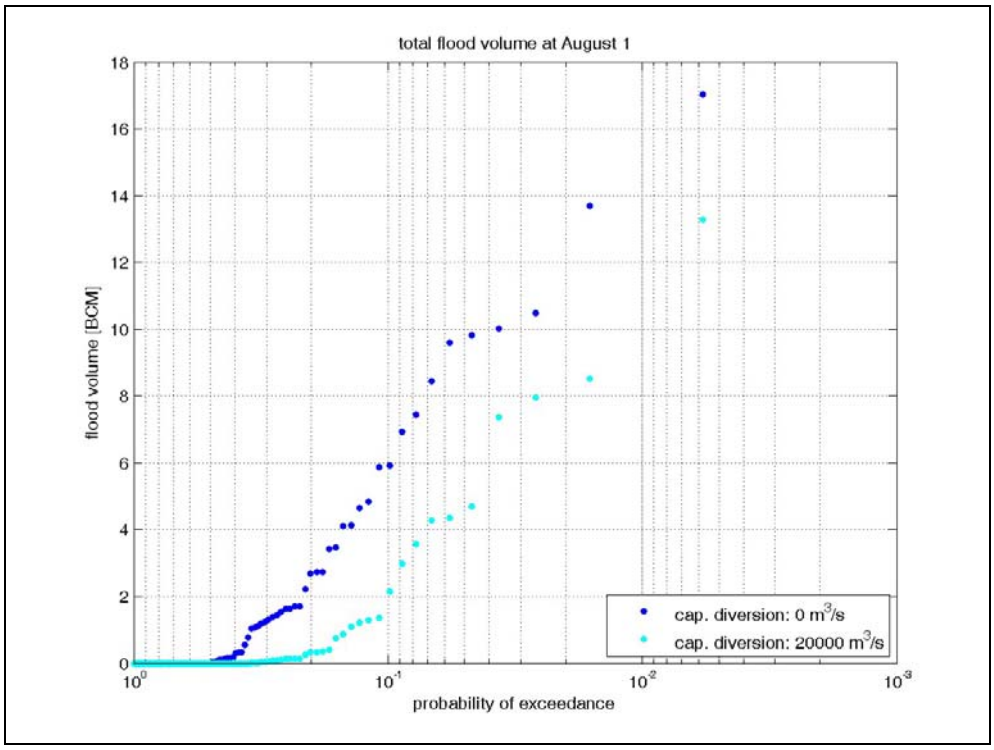

Figure 3.11 Frequency distribution of the total volume above a threshold of 30,000 m^3/s in the Mekong downstream of Phnom Penh until August 1, depending on the available flow capacity of the diversion channel.

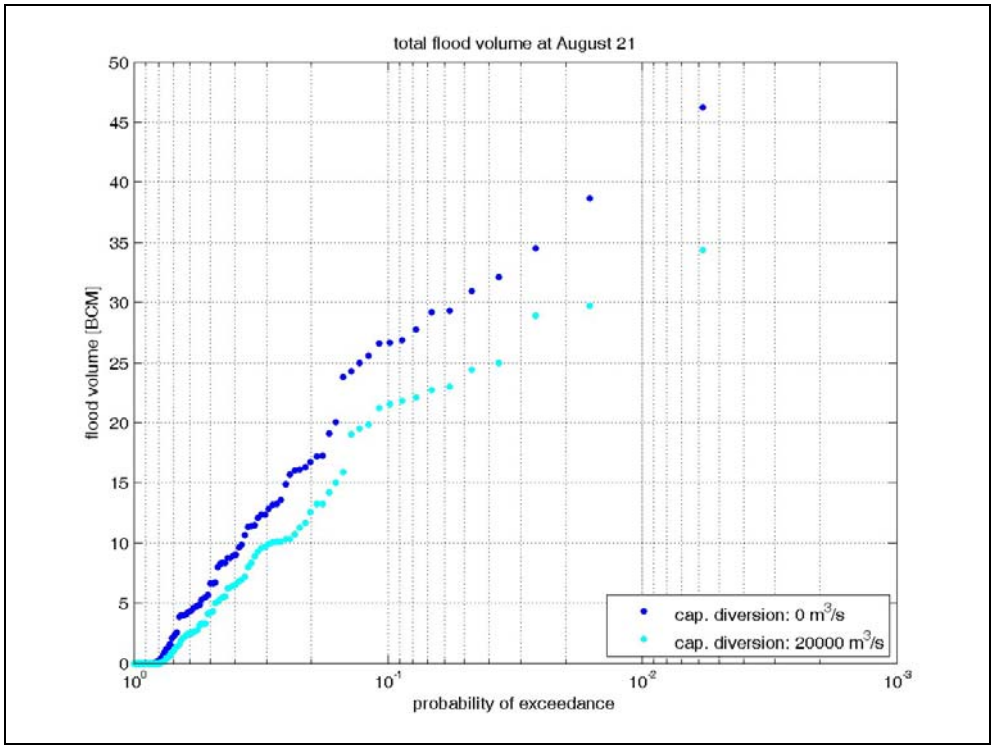

Figure 3.12 Frequency distribution of the total volume above a threshold of 30,000 m^3/s in the Mekong downstream of Phnom Penh until August 21, depending on the available flow capacity of the diversion channel.

4 References

Forsius, 2007: Monitoring the reverse flow at Prek Kdam, MRC report, 2007.

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