

ONLINE SUPPLEMENT

S1 Reservoir optimisation method

To define reservoir operation, a linear programming optimisation was used to define monthly outflows for each reservoir separately. The target of the objective function was to maximise annual outflow from a reservoir through hydropower turbines, using the reservoir active storage, estimated monthly inflows, minimum outflow and optimal outflow from the reservoir as parameters. The problem was defined as follows:

Variables:

| | | |
|----|-------------|---|
| | q_i | monthly outflow from reservoir |
| 10 | o_i | monthly overflow from reservoir |
| | q_{in_i} | estimated monthly inflow, $i=1..12$ |
| | s_i | reservoir active storage, $i=1..12$ |
| | q_{min_i} | minimum value for outflow, $i=1..12$ |
| | q_{opt} | maximum flow through turbines |
| 15 | s_{max} | reservoir active storage |
| | k | parameter for storage water level |
| | $sign(x)$ | function, returns -1 if $x < 0$, else +1 |
| | nd_i | days in month i , $i=1..12$ |

Objective ($i=1..12$):

$$20 \quad \text{Max } \Sigma (q_i + k \text{ sign}(q_{opt} - q_{in_i}))$$

Constraints ($i=1..12$):

- 1) $s_i + s_{i+1} + nd_i (q_{in_i} - q_i - o_i) = 0$;
- 2) $q_i > q_{min_i}$
- 3) $q_i < q_{opt}$
- 25 4) $s_i < s_{max}$
- 5) $q_m = q_n$; $m, n = 1,2; 2,3; 3,4; 4,5$.

The above optimisation problem can be solved using standard linear programming methods. As results, optimised monthly outflows q_i and reservoir storage values s_i are obtained for each month. The term starting with coefficient k in the objective function aims to maximise reservoir storage when the inflow is larger than optimal flow (wet season), and minimise storage when the inflow is lower than optimal flow (dry season). This forces the filling of the reservoir during wet season, and emptying of the reservoir during dry season. Additional equality constraints (5) were added to keep the reservoir outflow constant during the dry season. Coefficient k can be adjusted, but here k was set to average inflow to reservoir times 10^{-6} .

To regulate the daily outflow of a dam, the computed data were used as follows:

Variables:

- c current active storage
- q_{out} current outflow
- 40 q_{id} interpolated outflow
- s_{id} interpolated storage

Algorithm:

- if $c > s_{id}$ then $q_{out} = q_{id}$
- if $c < s_{id}$ then $q_{out} = q_{id} (c/s_i)^2$

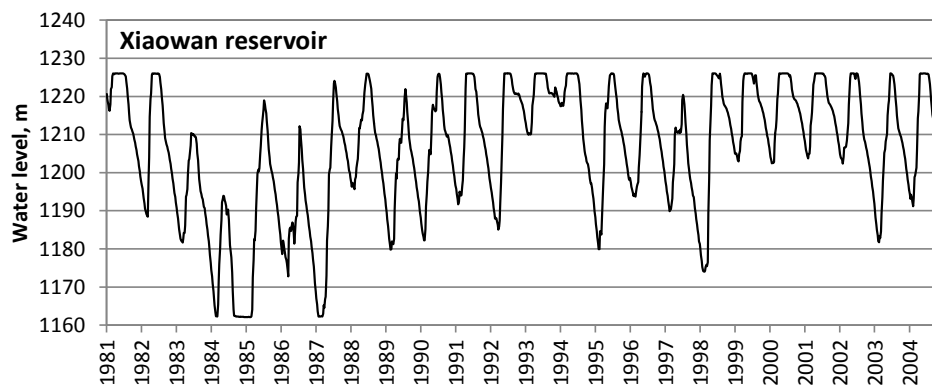
- 45 The monthly inflows to each reservoir were estimated from computed 24-year time series (1981-2005) for each reservoir. These monthly inflows were then reduced by multiplying the data with coefficient r , in order to reduce the amount of years when the reservoir would not completely fill up due to lack of water. Coefficient r was computed as $(a - 0.75 s)/a$, where a is the average annual inflow, and s the standard deviation of average annual flows. The
- 50 minimum flow for each month was set to be 0.25 times the average annual flow, but no larger than 0.25 times the average monthly inflow.

Using the above defined operation rules the reservoir storages typically fill up about every second year. Normal reservoir operation rules are more careful and aim to make certain that the reservoir is filled up to full capacity each year. Here, however, the aim was to

55 overestimate the reservoir usage and find an upper limit to the possible effect of reservoirs on Mekong discharges.

The optimisation of all reservoirs was performed so that before optimising a reservoir all the upstream reservoirs were optimised. The inflows to the reservoir to be optimised were then computed with the upstream reservoirs active. An example of reservoir regulation result is

60 shown in Fig. S1, which displays the water level of Chinese Xiaowan reservoir. The reservoir reaches full capacity on 17 of the 24 simulated years, and goes to bottom regulation level three times.



65 *Figure S1: An example of reservoir operation rule result: computed Xiaowan reservoir water level for years 1981-2005.*

S2 Comparison of climate change and hydropower development impact studies

70 In this section we compare the results of our climate change and reservoir operation
assessment to the existing assessment done in the basin. First we compare the climate change
assessments, then we compare hydropower development assessments, and finally we compare
the combined climate change and hydropower development assessments. The comparison has
been carried out on flow changes at Chiang Saen and Kratie on monthly or seasonal scales
depending on the data availability. The section complements the Discussion Sections 6.1 – 6.3
75 of the main article.

S2.1 Climate change impacts

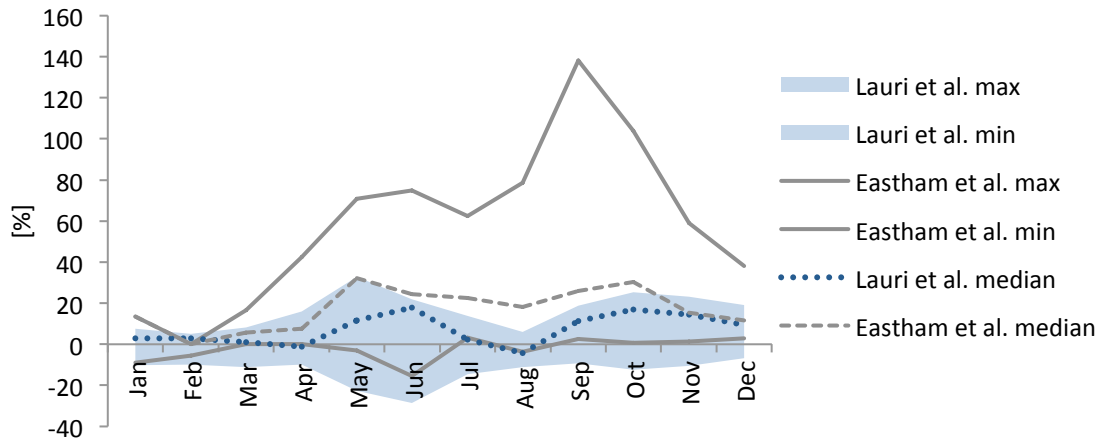
Climate change impacts on the flows of the Mekong have been estimated by Eastham *et al.*
(2008), Västilä *et al.* (2010), Hoanh *et al.* (2010), Mekong River Commission (2010b) and
Kingston *et al.* (2011). In this section we compare our climate change impact estimates for the
80 flows at Chiang Saen and Kratie with the aforementioned studies. The estimates of Kingston
et al. (2011) and Mekong River Commission (2010b) could not be directly compared due to
different scenario formulations. Eastham *et al.* (2008) used in their estimations 11 GCMs and
the A2 scenario; we compared to these our results from five GCMs and the A1b scenario (Fig.
S2). Furthermore, our future climate projection was for the years 2032-2042 and the
85 projection of Eastham *et al.* (2008) was for the year 2030. Västilä *et al.* (2010) and Hoanh
et al. (2010) used in their estimations the ECHAM4 GCM and scenarios A2 and B2, and
therefore we compared our results only from the ECHAM5 GCM and A1b and B1 scenarios.
The future climate projection of Västilä *et al.* was for the years 2030-2049, the projection of
Hoanh *et al.* (2010) for the years 2010-2050.

90 The comparison of the assessments at Kratie shows that all studies in general suggest an
increase in flows (Fig. S2, Fig. S3C and S3D), although few climate models suggest also
decrease in flows (Figure S2). The earlier assessments suggested changes in annual flows
between -2-82% and whereas our estimate with five GCM's suggests changes between -12-
16% in annual flows. In general the estimates of Eastham *et al.* (2008) and Hoanh *et al.*
95 (2010) suggest the larger changes than our estimates, but the median of 11 GCM's in the
assessment of Eastham *et al.* (2008) shows similarities with the median of five GCM's used in
our study (Figure S2). Interestingly the medians of our estimate and the estimate of Eastham
et al. (2008) suggest that the largest changes in flows will occur during the first (May-June)
and last months (September-October) of the monsoon season.

100 The comparison of the assessments at Chiang Saen shows less agreement in the direction of
the flow changes (Fig. S3A and S3B). In A-scenarios our assessment agrees with the
assessment of Hoanh *et al.* (2010) that the seasonal and annual flows will increase, but in the
B-scenarios our assessment suggests a relatively small decrease in flows whilst that of Hoanh
et al. (2010) suggests an increase. Furthermore, the assessment of Hoanh *et al.* (2010)
105 suggests larger flow changes in both scenarios.

Mekong River Commission (2010b) used only emission scenario B2 and one GCM
(ECHAM4). However, as it considered climate change as part of its long-term development
scenarios (including hydropower, irrigation and water supply), climate change impacts on

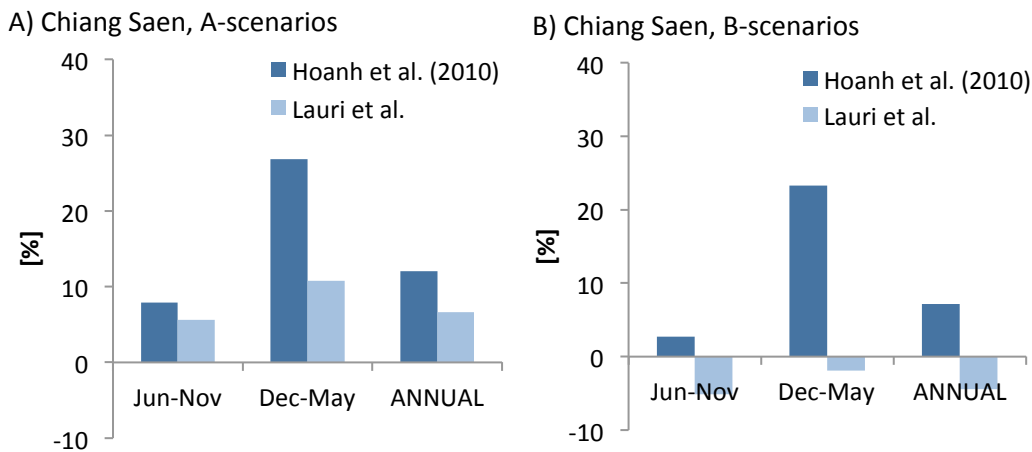
110 hydrology are visible only as part of the development scenarios. At more general level, however, the report concludes that climate change is likely to bring clearly more variable conditions within the basin as well as increase runoff. The report also reminds that the likely increase of sea level rise is likely to bring remarkable impacts to the Mekong Delta in Vietnam.



115

Figure S2. Comparison of climate change impact estimates on flows at Kratie A) on monthly scale and B) on seasonal scale. The compared estimates are ranges and medians of the results from five GCMs of our study and 11 GCMs from Eastham et al. (2008) using A-scenarios. Lauri et al. refers to this study.

120



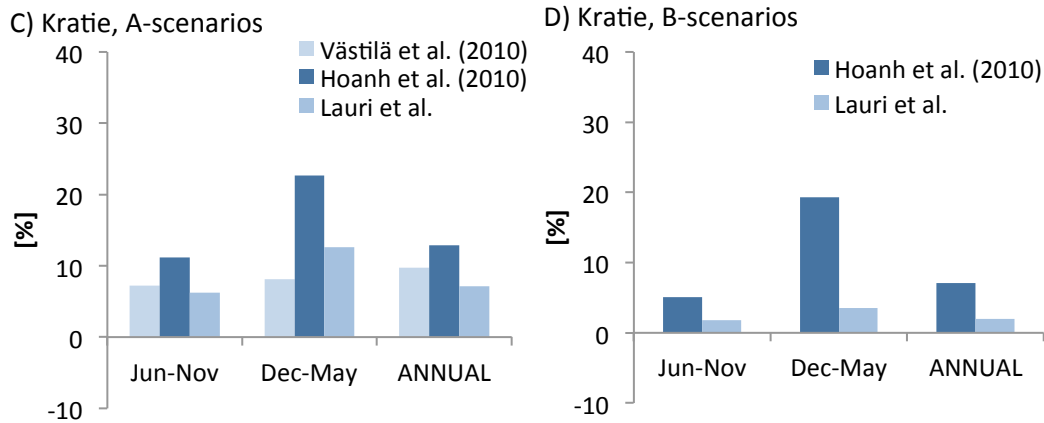


Figure S3. Comparison of climate change impact estimates on flows: A) Chiang Saen, A-scenario B) Chiang Saen, B-scenario, C) Kratie, A-scenario and D) Kratie, B-scenarios. Our assessment is based on GCM ECHAM5 and assessments of Västilä *et al.* (2010) and Hoanh *et al.* (2010) are based on GCM ECHAM4. Lauri *et al.* refers to this study.

S2.2 Hydropower development impacts

The hydropower development impacts on the Mekong's flows have been assessed at Chiang Saen at least by Adamson (2001), Hoanh *et al.* (2010) and Räsänen (Submitted) and at Kratie by ADB (2004), Hoanh *et al.* (2010). Here, we compare our estimates to these studies. In addition, Mekong River Commission (2010b) included several different scenarios for hydropower (and other) development in the basin. Each study uses different methods to simulate hydropower operations and also the underlying operational assumptions vary: Adamson (2001) used a spreadsheet approach, ADB (2004) used a MikeBasin water resources management tool, Räsänen *et al.* (Submitted) used a combination of VMod hydrological model and CSUDP dynamic programming tool, Hoanh *et al.* (2011) used a combination of SWAT hydrological model and IQQM water allocation model, and we used a combination of VMod hydrological model and a linear optimisation of reservoir operations. Furthermore, each study used hydrological data from different periods. The baseline data periods were in Adamson (2001) 1960-2001, ADB (2004) 1965-1975, Hoanh *et al.* (2010) 1975-2000, Räsänen (Submitted), and in our study 1982-1992.

At Chiang Saen (Fig. S4A), all assessments agree on the direction of the monthly flow changes relatively well, although there are differences in magnitudes. In general the results of Räsänen *et al.* (Submitted) suggest the largest changes and our study the smallest changes. On a seasonal scale (Fig. S4B), all assessments suggest similar changes but the assessment of Räsänen *et al.* (Submitted) suggests the largest changes and the assessment of Hoanh *et al.* (2010) the smallest. Altogether the estimates suggest a 17-22% decrease in June-November flows and 60-90% increase in December-May flows.

At Kratie, our assessment results agree remarkably well, both in magnitude and pattern, with the monthly results of ADB (2004), although some differences exist in May and July (Fig. S5A). On a seasonal scale our results are also well in line with ADB results (Fig. S5B). The results of Hoanh *et al.* (2010) are not fully comparable with the other assessments at Kratie as they also included irrigation in their assessment scenarios. Despite this incompatibility we

155 compared all estimates at Kratie. Altogether the estimates suggest an 8-11% decrease in June-November flows and an 28-71% increase in December-May flows.

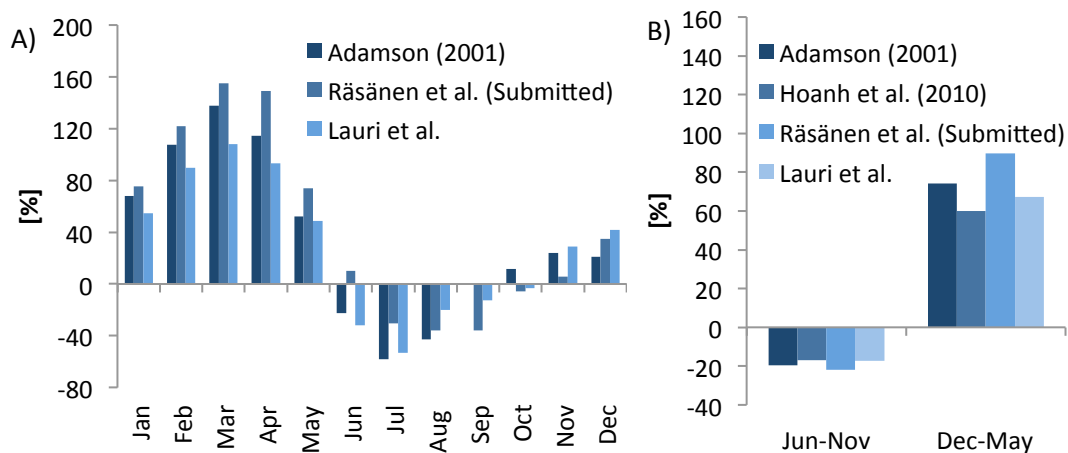
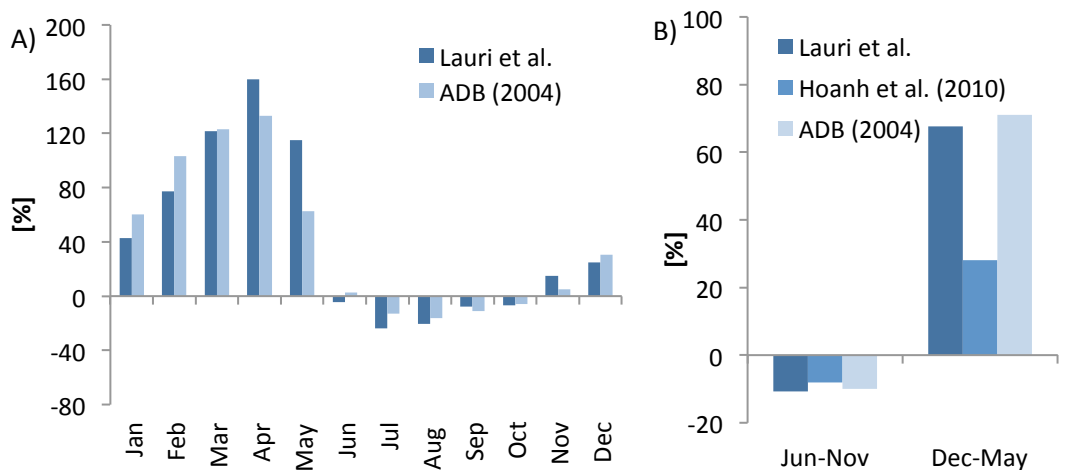


Figure S4. The estimated flow changes at Chiang Saen caused by hydropower development on A) monthly and B) seasonal scale. Lauri et al. refers to this study.

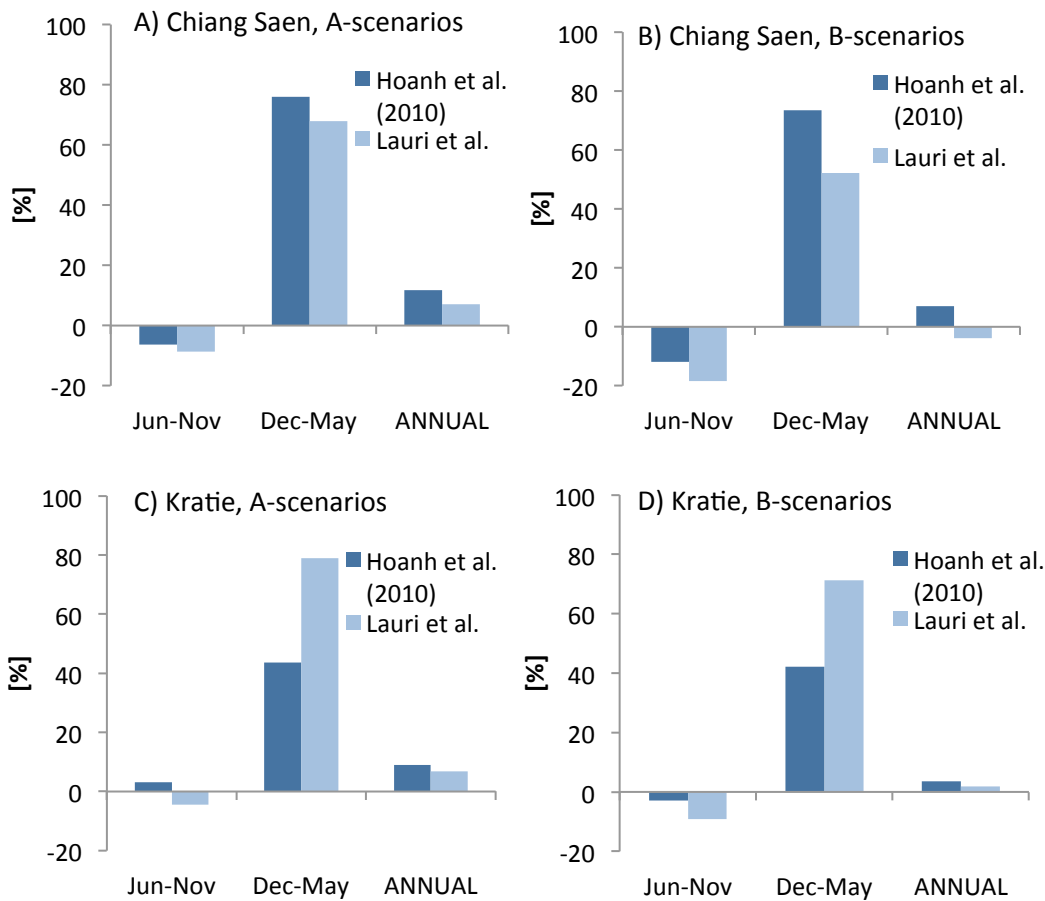


160 Figure S5. The estimated flow changes at Kratie caused by hydropower development on A) monthly and B) seasonal scale. Hoanh et al. (2010) also considered irrigation scenarios in their analyses while all other studies only considered impacts of hydropower development. Lauri et al. refers to this study.

165 **S2.3 Combined climate change and hydropower development impacts**

The combined climate change and hydropower development impacts on the Mekong's flows have to our knowledge been assessed at Chiang Saen and Kratie so far only by Hoanh *et al.* (2010) and Mekong River Commission (2010b). Again, both the estimates of Hoanh *et al.* (2010) and Mekong River Commission (2010b) also incorporate irrigation, and therefore the results at Kratie are not fully comparable with our results. The comparison between Hoanh *et al.* (2010) and our study shows that both studies agree relatively well with the combined impacts on flows at Chiang Saen on a seasonal scale (Fig. S6A and S6B). Both assessments suggest that June-November flows will decrease by 6-18% and that December-May flows will increase by 52-76%. The annual changes vary from a decrease of 4% to an increase of 12%.

175 The estimates on flow changes at Kratie are somewhat different, but both assessments agree that the December-May flows will increase significantly and annual flows will slightly increase (Fig. S6C and S6D). More accurate comparison of results at Kratie would require closer examination on the irrigation scenarios used by Hoanh *et al.* (2010).



180 *Figure S6. Comparison of combined climate change and reservoir development impact on flow estimates: A) Chiang Saen, A-scenario B) Chiang Saen, B-scenario, C) Kratie, A-scenario and D) Kratie, B-scenario. Our assessment is based on GCM ECHAM5 and the assessment of Hoanh et al. (2010) is based on GCM ECHAM4. The estimate of Hoanh et al. (2010) includes the impact of irrigation, which we do not consider in our assessment. Lauri et al. refers to this study.*

Mekong River Commission (2010b) estimates that, compared to the baseline situation, the cumulative impact of development scenario for 2060 (including considerable increases in hydropower, irrigation and water supply) and climate change (scenario B2) will increase remarkably the dry season flows (in March) throughout the basin: up to 105% in Vientiane and 69% in Kratie, The average peak daily flow during the wet season is estimated to decrease in Vientiane by 14%, but increase by 5% in Kratie. Mekong River Commission (2010b) also assessed the climate change's impact to the flow from the Mekong River to the Tonle Sap system (the key fisheries production system in the basin, see e.g. Keskinen, 2006; Mekong River Commission, 2010a). Its estimates indicate that the cumulative impacts of water development and climate change will decrease the average flow volume entering Tonle Sap by around 8% and the average date of flow reversal move almost three weeks earlier, when compared to the baseline situation.

200 **References**

- ADB: Cumulative impact analysis and Nam Theun 2 contributions, Final report. Prepared by NORPLAN and EcoLao for Asian Development Bank. 143 pp, 2004.
- Eastham, J., Mpelasoka, F., Mainuddin, M., Ticehurst, C., Dyce, P., Hodgson, G., Ali, R., and Kirby, M.: Mekong River Basin Water Resources Assessment: Impacts of Climate Change, 205 CSIRO: Water for a Healthy Country National Research Flagship, 2008.
<http://www.clw.csiro.au/publications/waterforahealthycountry/2008/wfhc-MekongWaterResourcesAssessment.pdf> Accessed February 2012
- Hoanh, C., Jirayoot, K., Lacombe, G., Srinetr, V.: Impacts of climate change and development on the Mekong flow regime, First assessment – 2009, MRC Technical Paper No. 210 29 Mekong River Commission, Vientiane, Lao PDR, 2010.
<http://www.mrcmekong.org/assets/Publications/technical/tech-No29-impact-of-climate-change.pdf> Accessed January 2012
- Keskinen, M.: The Lake with Floating Villages: A socio-economic analysis of the Tonle Sap Lake, International Journal of Water Resources Development, 22, 463-480, 2006.
- 215 Kingston, D. G., Thompson, J. R., and Kite, G.: Uncertainty in climate change projections of discharge for the Mekong River Basin, Hydrology and Earth System Sciences, 15, 1459-1471, 2011.
- Mekong River Commission: State of the Basin Report 2010, Mekong River Commission, Vientiane, Lao PDR, 2010.
- 220 Räsänen, T., Kummu, M., Koponen, J., and Lauri, H.: Downstream hydrological impacts of hydropower development in the Upper Mekong Basin, Water Resources Management, submitted.
- 225 Västilä, K., Kummu, M., Sangmanee, C., and Chinvanno, S.: Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains, Journal of Water and Climate Change, 1, 67-86, 2010.