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Water-use accounts in CPWF basins:

6. Simple water-use accounting of the Mekong Basin.

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1 Abstract

This paper applies the principles of water-use accounts, developed in the first of the series, to the Mekong River basin in Southeast Asia. The Mekong Basin covers six countries, the River rises in China, but there are substantial downstream tributaries from Thailand, Laos, Cambodia, and Vietnam, and from a small area in Myanmar. A unique feature is the reverse flow from the Mekong to the Tonle Sap via the Tonle Sap River at the height of the wet season flow and its ebb as the river levels fall.

Net runoff is about 37% of total precipitation. Forest and woodland cover 43% of the basin and use about 33% of the precipitation. Grassland covers much of the upper part of the Basin, consuming about 6% of the precipitation. Irrigated agriculture covers just 6% of the Basin and uses about 6% of the water (excluding runoff).

Climate change, using an assumed change in rainfall distribution, shows that with the expected shorter and more intense rainy season, and longer and more intense dry season, both floods and seasonal water shortages may be exacerbated.

Keywords: Water use accounts, Mekong basin, top-down modeling, basin water use.

2 Introduction

The Challenge Program on Water and Food aims to catalyze increases in agricultural water productivity at local, system, catchment, sub-basin and basin scales as a means to poverty reduction and improving food security, health and environmental security. It does this in several priority basins: the Indo-Gangetic Basin, the basins of the Karkheh, Limpopo, Mekong, Nile, São Francisco, Volta, and Yellow River and a collection of small basins in the Andes.

A useful output for each basin, and a key element of the understanding of basin function, is an overview water use account. Water use accounts produced in the same way for each basin would have the further benefit of making easier the development of syntheses of understandings from all the basins.

Here, we describe a draft water use account for the Mekong Basin, developed as an Excel spreadsheet. Water use accounting is used at national (ABS 2004; Lenzen 2004) and basin (Molden 1997; Molden et al. 2001) scales to:

- Assess the consequences of economic growth;
- Assess the contribution of economic sectors to environmental problems;
- Assess the implications of environmental policy measures (such as regulation, charges, and incentives);
- Identify the status of water resources and the consequences of management actions; and
- Identify the scope for savings and improvements in productivity.

One limitation of the existing accounting methods is that they are static, providing only a snapshot for a single year or an average year. Furthermore, they do not link water movement to use. In contrast to the static national and basin water use accounts referred to above, our accounts are dynamic, with a monthly time step, and thus account for seasonal and annual variability. They can also examine dynamic effects such as climate change, land use change, changes to dam operation, etc. Because the accounts are assembled in Excel, they are quick and easy to develop, modify and run. We have already applied this accounting method to several major river basins including the Murray-Darling, Karkheh and the Limpopo (Kirby et al. 2006a; Kirby et al. 2006b).

There are several other models of the Mekong Basin. The SWAT / IQQM / ISIS suite (Podger et al. 2004) was developed for policy and management support in the Mekong River Commission. A MIKE11 model was developed to study flooding of the lower floodplains only (Fujii et al. 2003; Morishita et al. 2004). A SLURP model, (Kite 2001) provides a basin-wide model based on a GIS framework. The RAM model (Johnston et al. 2003) is a hydrology – economics model that relies on the SWAT / IQQM / ISIS suite for many of its hydrology inputs. The economic - hydrology model of Ringler (2001) deals only with average conditions and does not deal with runoff inflows. Thus, these models leave a need for a simple water-accounting method that links hydrologic and water use dynamics in a versatile format and facilitates relatively rapid, integrated investigations on the basin-scale.

It must be emphasized that the best possible hydrologic modeling of the Mekong basin is already available in the SWAT / IQQM / ISIS suite (Podger et al, 2004). The model developed here is not a substitute, and is not designed to do the same job. As well as providing the best modeling, during the development of the SWAT / IQQM / ISIS suite flow records were analyzed extensively and consistent sets of corrected flow records were developed that satisfy mass balance, etc. The analysis and model developed here relies heavily on the SWAT / IQQM / ISIS suite development and output. Indeed, the model described here is calibrated against SWAT / IQQM / ISIS flow output.

3 Basic hydrology and model structure

3.1 Basic hydrology

The hydrology of the Mekong Basin is described in greater detail in MRC (2005). Here we give a brief summary. The Mekong Basin covers about 790,000 km^2, and is drained by the 4200 km long River Mekong. The basin is mostly long and thin, particularly in the upper, Chinese part, and the Mekong is fed mostly by many short tributaries draining small catchments (Figure 1 and Table 1). The largest catchments are the Mun-Chi (about 107,000 km^2), the Se San (73,000 km^2) and the Tonle Sap (87,000 km^2).

Note: the area of the Mekong Basin is often given as 795,000 km^2, though the exact area depends on what is classified as inside the basin in the area around the delta. Different maps show different areas around the delta. The area of 788,173 km^2 given in the table is the area used in the water use account spreadsheets.

Table 1. Catchments in the Mekong Basin with their areas.

Catchment	Location	Area, km^2
Mekong	Upper Mekong	90,771
Mekong	Chiang Saen	102,936
Moung Nouy	Moung Nouy	26,044
Mekong	Luang prabang	56,801
Mekong	Vientiane	28,349
Nam Ngum	Tha Ngon	17,695
Mekong	Nakhon Phanom	53,085
Mekong	Mukdahan	21,081
Se Bang Hieng	Ban Keng Done	18,050
Chi	Yasothon	45,368
Mun	Ubon Ratchathani	61,812
Mekong	Pakse	29,224
Se San	Se San	73,232
Mekong	Kratie	31,103
Mekong	Tonle Sap	87,192
Mekong	Phnom Penh	7,901
Mekong	Border	20,167
Mekong	Delta	17,362
Total		788,173

The source of the Mekong is fed by snowmelt, though precipitation is much less than throughout the Lower Mekong (Figure 2). The Lower Mekong is fed by runoff, characterized by a pronounced wet and dry season. The peak flow from the Upper Mekong more or less coincides with the peak inflows from runoff into the Lower Mekong. Furthermore, the wet season affects the whole of Lower Mekong more or less simultaneously (Figure 2). The rainfall is greater in the eastern, mountainous regions of Laos, from which the major portion of the runoff and flow is generated. The rainfall in NE Thailand is less, and the potential evapotranspiration somewhat greater than the rest of the basin, and this area contributes the smallest portion of the runoff and flow.

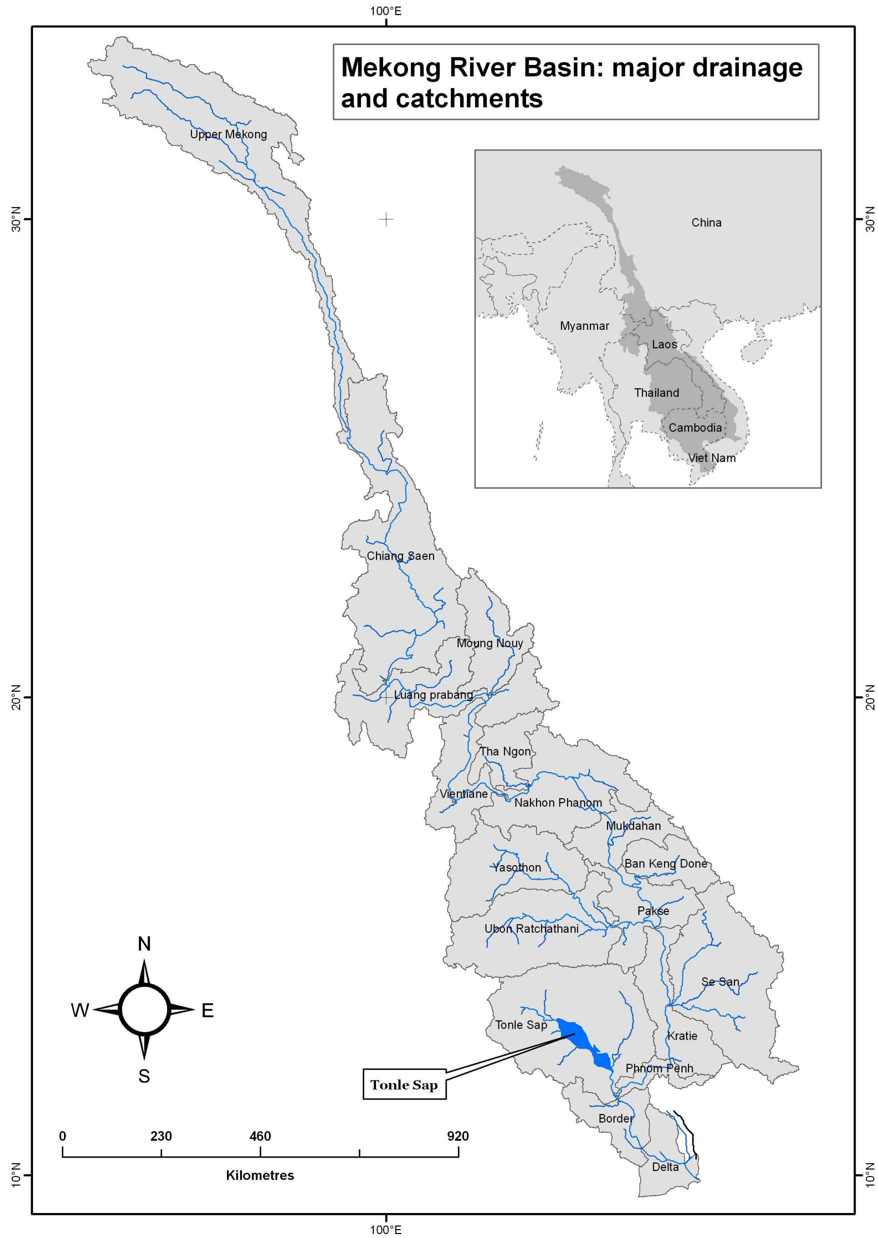

Figure 1. The Mekong Basin, with the catchments used in the water-use account.

3.2 Simple water account structure

The simple water account has two parts:

- A hydrological account of the water flowing into the basin (primarily rain), flows and storages within the basin, and water flowing out of basin (primarily as evapotranspiration and discharge to the sea); and
- A further partitioning of the evapotranspiration into the proportion of evapotranspiration accounted for by each vegetation type or land use, including evapotranspiration from wetlands and evaporation from open water.

The account is a top-down model (Sivapalan et al. 2003), based on simple lumped partitioning of rainfall into evapotranspiration and runoff. This is done at the catchment level, with the separation into different vegetation types within catchments not spatially explicit. Runoff flows into the tributaries and into the Mekong, with discharge downstream calculated by simple water balance. During high flows, some of the flow is stored in the channels, and some in lakes and wetlands from which much water is lost to evaporation.

The simple hydrological account is based on a monthly time step, this being considered adequate for our purpose. The model is described in detail in a companion report “Basin water use accounting concepts and modeling” (Kirby et al. 2009). Here we describe only that part of the model which differs from the general set of equations in Kirby et al. (2009).

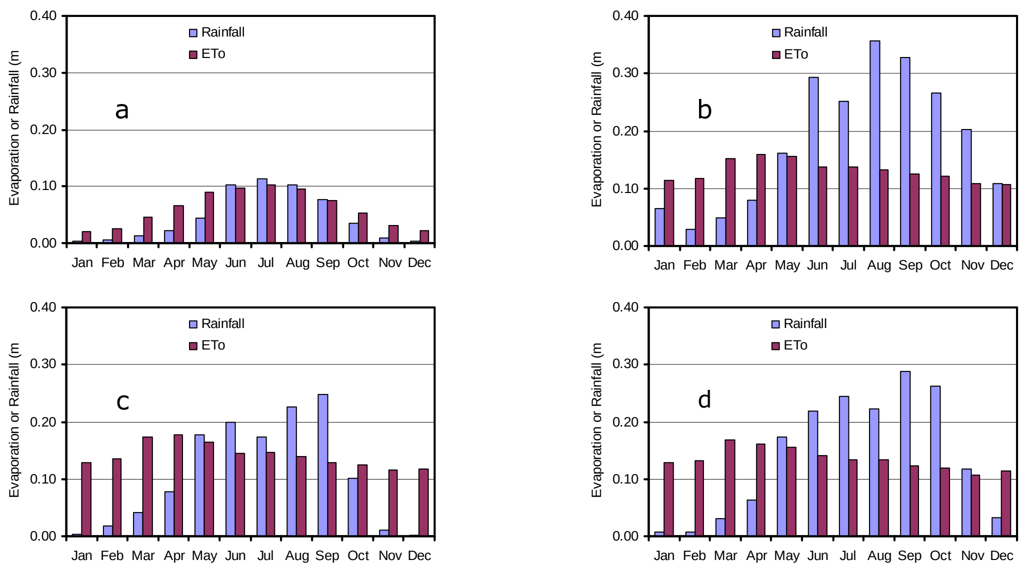

Figure 2. Monthly average rain and potential evapotranspiration in the Mekong Basin. a). Upper Mekong; b). Se Bang Hieng in central Laos; c). Chi in NE Thailand; d). Lower Mekong around Phnom Penh.

In addition to the spatial variability of precipitation, there is considerable year-to-year variability (Figure 3).

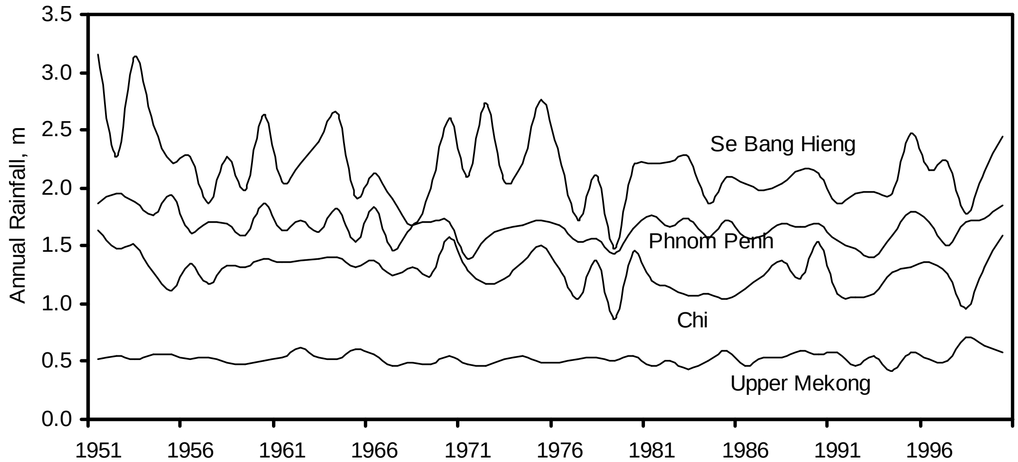

Figure 3. Annual rainfall 1951-2000.

3.3 Units:

Rain, evapotranspiration and potential evapotranspiration are given in mm.

River flows and storages, and lake storage, are given in mcm (million cubic meters). 1 mcm is equivalent to one metre over one square kilometer. 1000 mcm = 1 bcm (billion cubic meters) = 1000 m over 1 km^2 = 1 km^3.

4 Data sources

The datasets used in this water use account were taken from several sources. Some were readily available on the internet; others were obtained from the authors of reports and papers about the Mekong.

4.1 Rainfall

The rainfall and other climate data were taken from the Climate Research Unit at the University of East Anglia (specifically, a dataset called CRU_TS_2.10). They cover the globe at 0.5° (about 50 km) resolution, at daily intervals for 1901 to 2002. The dataset was constructed by interpolating from observations. For recent decades, many observations were available and the data show fine structure. For earlier decades, few observations were available and the data were mostly modeled and lack fine structure. We sampled the rainfall and other climate surfaces for each catchment within the basin, to calculate catchment area-means of rainfall and potential evapotranspiration for each month. The method is described in more detail in Kirby et al. (2009).

4.2 Flows

Reach flows were taken from a dataset called ds552.1, available on the internet (http://dss.ucar.edu/catalogs/free.html) (Dai and Trenberth 2003). The dataset also gives contributing drainage areas for each flow gauge. Flow records were not available for all the catchments, particularly those downstream of Pakse. For downstream catchments, the flow results used in the RAM (Johnston et al. 2003) were used here. For some catchments, no flow records or estimates were available: these included the Upper Mekong (the upper part of the Lancang in China, the lower part of the Lancang being gauged at Chiang Saen), the Se San, and the delta region. For these catchments, runoff and flows were calculated such that calculated flow matched the next measured flow downstream.

Land use was taken from the 1992-3 AVHRR dataset (IWMI 2006). For the current water account, land use was considered static throughout the period assessed.

5 Components and results in detail

5.1 Stream flow

The consequence of the rainfall is that the Mekong has a very pronounced seasonal variation in flow, with the high season flow being 15 – 30 times the low season flow. Furthermore, the high season flow occurs along the whole length of the Mekong at more or less the same time, with only a short lag between upstream and downstream, as shown in Figure 4.

5.1.1 Upper Mekong

The flow at Chiang Saen shows the pronounced seasonal pattern, with some base flow (Figure 5).

5.1.2 Chiang Saen to Kratie

The middle reaches of the Mekong preserve the flow pattern established at Chiang Saen, with the volumes growing greater as tributaries add to the flow (Figure 6 to Figure 8). Despite being only about one sixth the area of the drier Mun-Chi (Figure 7) the wetter Nam Ngum supplies nearly as much water to the Mekong (Figure 6).

5.1.3 Tonle Sap dynamics

When the Mekong is at the peak flow, its level is above that of the Tonle Sap River which drains the Tonle Sap (Great Lake). Hence water is pushed up the Tonle Sap River and is stored in the lake. This reverse flow reverts to normal flow when the Mekong flow recedes, and the Tonle Sap River then drains the stored water plus additional water from runoff within the Tonle Sap catchment. The storage of water within the lake is of great importance to local fisheries and livelihoods.

Flow in the Tonle Sap River, Q_{TS}, and consequently storage in the Lake, depends on the difference in height between the Tonle Sap River and the Mekong. It is also assumed that the flow capacity of the Tonle Sap River increases with increasing height. Thus:

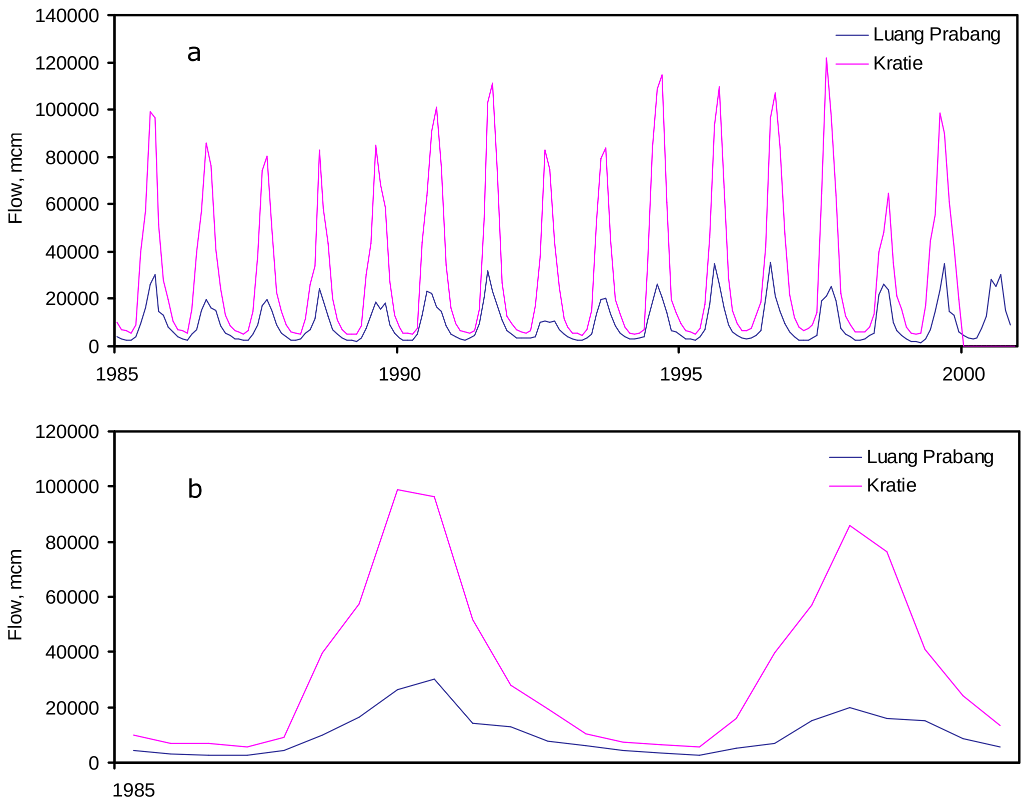

Figure 4. Monthly flow volumes for 1985-1999 for Luang Prabang and Kratie. a). 1985-2000; b). detail 1985-1986.

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where $c6$ and $c7$ are parameters, and

H_{TS} and H_M are the heights of the Tonle Sap River and the Mekong.

The terms in brackets account for the flow dependence on height difference, whereas the ***Error! Objects cannot be created from editing field codes.*** term accounts for the increasing flow capacity of the Tonle Sap River with increasing height. The $c7$ parameter accounts for the fact that the absolute heights in the two rivers are not calculated. Rather, relative heights are calculated from the volume of water stored in the Tonle Sap Lake, S_l and the flow in the Mekong as:

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Where $c8$ and $c9$ are parameters.

Note that the height of the Mekong, H_M, is calculated from the flow at Kratie, Q_{MK}. When $(H_M + c7) > H_{TS}$, Q_{TS} is negative, indicating flow reversal.

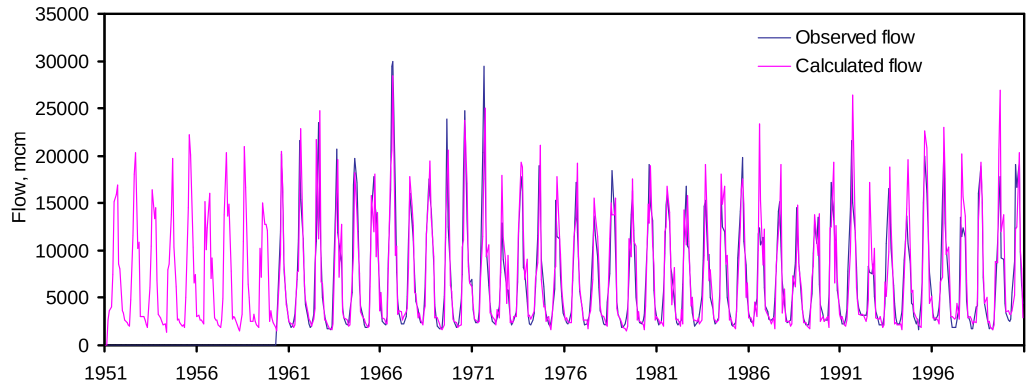

Figure 5. Flow from the upper Mekong at Chiang Saen for 1951 to 2000.

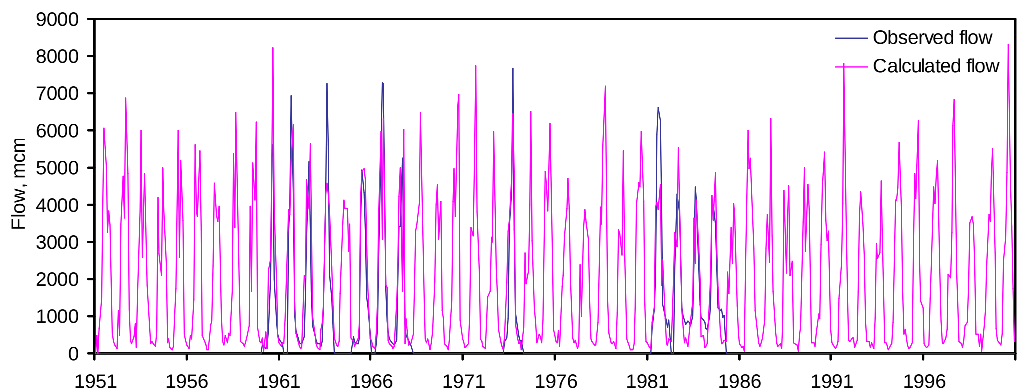

Figure 6. Flow from the Nam Ngum at Tha Ngon for 1951 to 2000.

Lake storage, S_l, is given by the storage at the previous time step, plus runoff from the Tonle Sap catchment, minus losses (evaporation, etc), minus flow in the Tonle Sap River.

$$S_l^t = S_l^{t-\Delta t} + Ro - L - Q_{TS} \quad (3)$$

This model was tested using observed Mekong flows at Kratie and SWAT/IQQM-modeled catchment runoff, and compared to observed flows in the Tonle Sap River (Figures 9 and 10).

The modeled flow in Figure 9 and Figure 10 uses the observed flows at Kratie as input. Using the modeled flows as input results in a somewhat poorer fit (Figure 11).

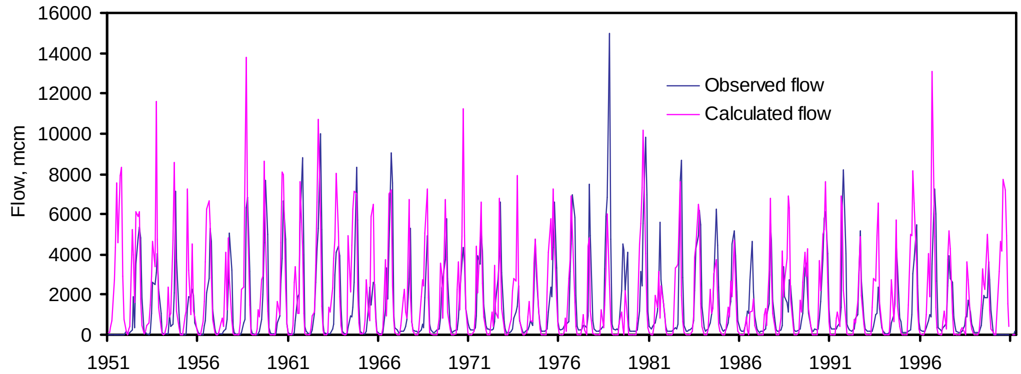

Figure 7. Flow from the Mun-Chi at Ubon Ratchthani for 1951 to 2000.

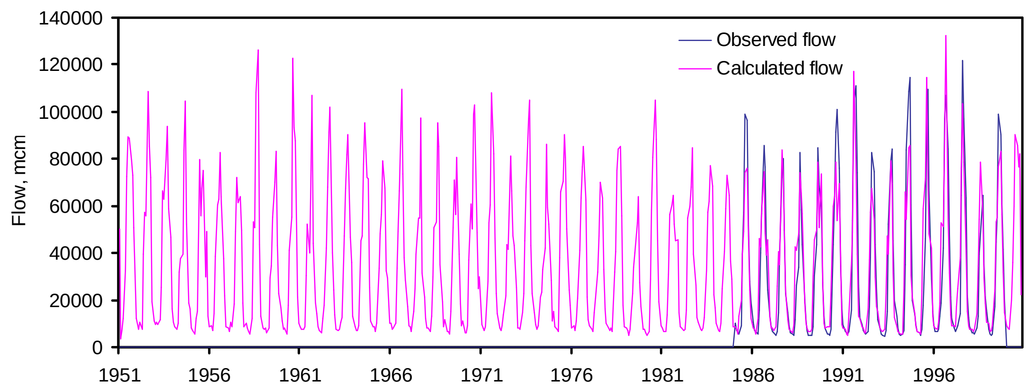

Figure 8. Flow in the Mekong at Kratie for 1951 to 2000.

At Phnom Penh, the Tonle Sap River joins the main stem of the Mekong. Flow at this point combines the influences of the floods in the reach from Kratie to Phnom Penh and the reversing flow of the Tonle Sap (Figure 12). The peak flows in the wet season are a little less than those at Kratie (Figure 8), because of the flow into the Tonle Sap. The draining of the Tonle Sap back to the Mekong in the dry season results in greater dry season flows.

Flows from Phnom Penh to the mouths of the Mekong in the delta in Vietnam are, in aggregate, similar to those at Phnom Penh, but are divided amongst several main channels.

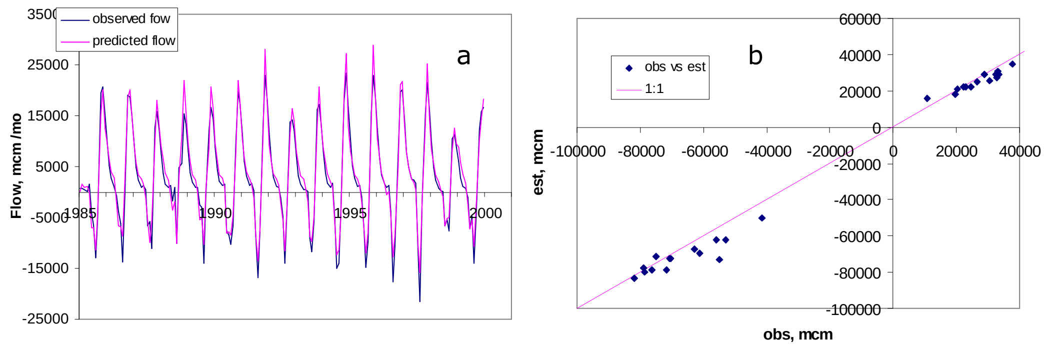

Figure 9. Comparison of observed and modeled flows in the Tonle Sap River, 1985 to 1999. a). hydrograph of the Tonle Sap River flows; b). observed and estimated total annual outflows and inflows into the Tonle Sap lake from the Tonle Sap River (i.e. the areas under the curves in Figure 9a).

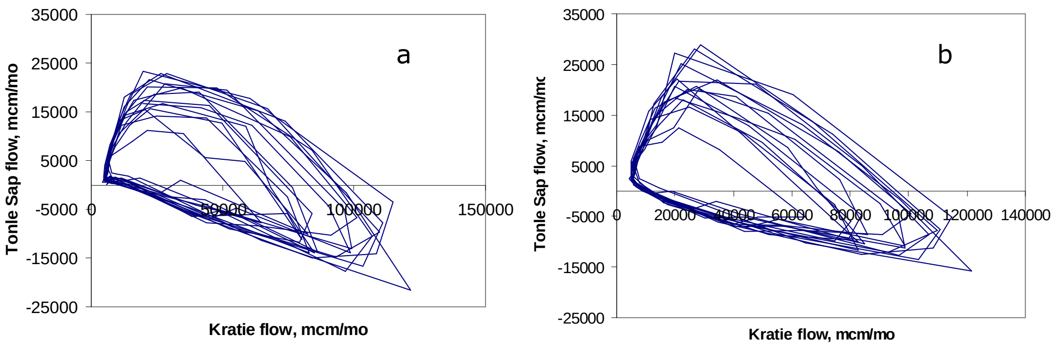

Figure 10. Hysteresis loop of Tonle Sap versus Mekong flows at Kratie. Comparison of the a). observed and b). predicted.

5.2 Water use

Figure 13 summarizes the major water uses in the basin. The mean annual input by precipitation to the Mekong basin totals about 1,200,000 mcm. Net runoff comprises the runoff remaining after all the water uses in the basin have been satisfied, and includes all other storage changes and losses. Net runoff from the basin is about 441,000 mcm or about 37% of the total precipitation input. Forest and woodland is the most extensive land use, covering 43% of the basin. Its water use is correspondingly high, with a mean annual water use of about 390,000 mcm, or 33% of the total precipitation, or about 52% of the water consumed by the various land uses (i.e., the latter figure excludes net runoff) (Figure 13).

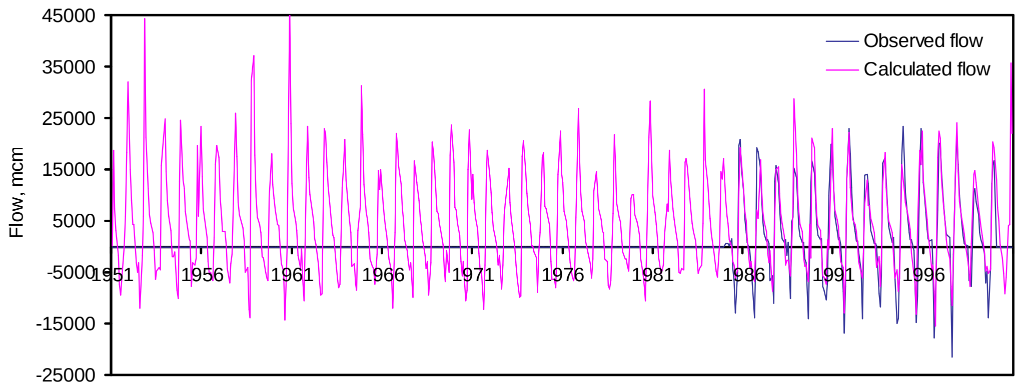

Figure 11. Flow in the Tonle Sap River for 1951 to 2000.

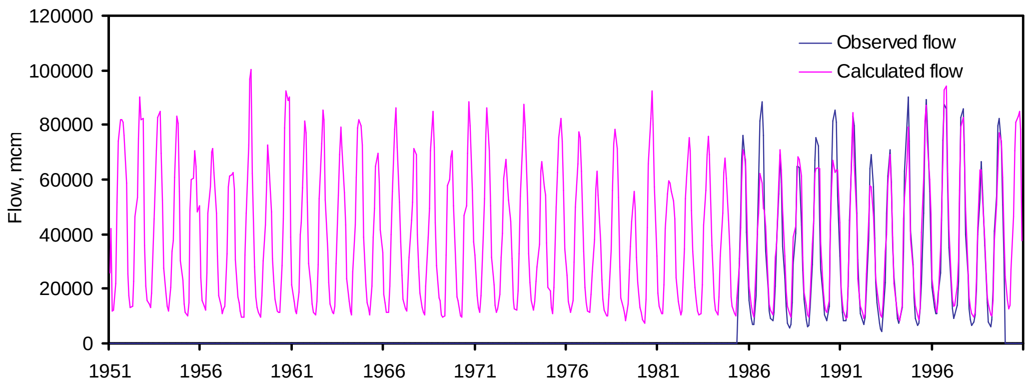

Figure 12. Flow in the Mekong at Phnom Penh for 1951 to 2000.

Irrigated agriculture covers about 6% of the basin. The estimated mean annual water use by irrigated agriculture is about 46,000 mcm, or 4% of the rainfall and 6 % of the total water use (excluding net runoff). The majority of the irrigated water use is from crops irrigated from the surface water resources. Grassland covers 22% of the basin, almost all in the upper basin, and consumes about 72,000 mcm (10% excluding net runoff) of the water used.

The distribution of the different water uses across the basin is shown in Figure 14. The figure depicts the water uses in each catchment, and is the annual average water use in each category calculated from the individual monthly water uses. It does not, however, represent the water balance at the basin level: this is because, for example, the irrigation in the delta part of the basin uses the runoff water from upstream, and thus this water is double counted at the basin level. The net runoff from the whole basin is shown in Figure 13. The figure shows the different behaviour of the runoff-generating upper and eastern part of the basin, and the agriculture dominated middle-western parts of the basin in Thailand. Irrigation is a major water use in most parts of the basin.

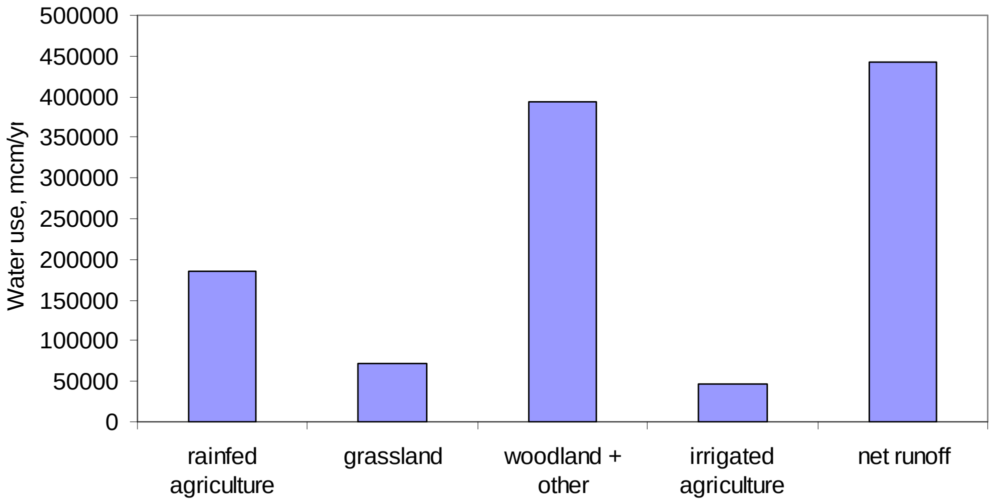

Figure 13. Summary of major water uses in the Mekong basin.

5.3 Catchment and basin hydrological characteristics

Selected hydrological characteristics will be useful for comparing the Mekong basin hydrological function and its vulnerability with those of other basins under study in the Challenge Program. Some of these hydrological characteristics are outlined briefly below.

Runoff characteristics for different basins may be compared by comparing their annual percentage runoff ratios (total basin runoff/total basin precipitation). The runoff ratio for the Mekong basin is 37 % (ie. mean annual net runoff is 37 % of mean annual precipitation). Similarly, differences in runoff characteristics for the different catchments in the basin can be seen by comparing their annual runoff ratios (Table 2).

The runoff ratios of the Nam Ngum at Tha Ngom and the Mekong at Nakhon Phanom are larger than might be expected, and may indicate a problem with the rainfall data, the flow data, or both.

The annual runoff increases with annual precipitation (Figure 15), but the data show considerable scatter. This may be a result of the data problems referred to above. The catchments with high rainfall but zero apparent net runoff are in the delta region. Here there is runoff, but it does not necessarily find its way to the Mekong.

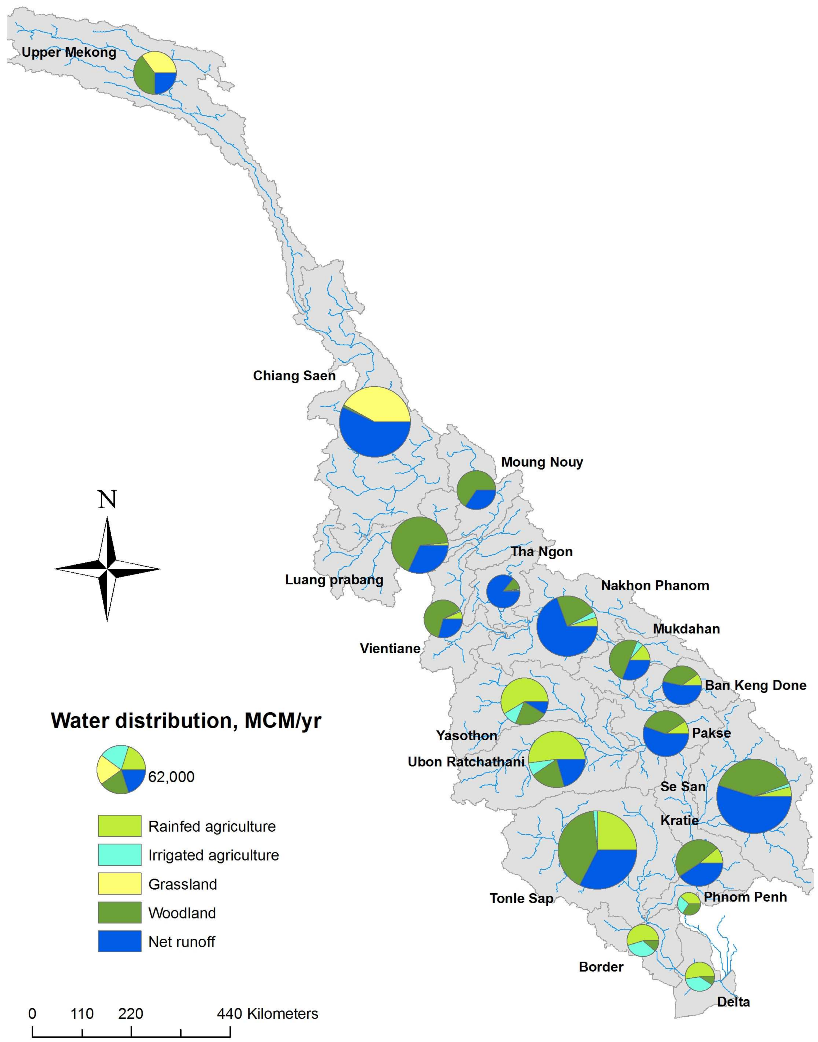

Figure 14. The spatial distribution of major water uses in catchments of the Mekong Basin. Woodland includes other minor land uses.

6 Model utility

We demonstrate the utility of this simple spreadsheet model to aid in quick investigation and evaluation of aspects of Mekong basin dynamics. We give here two examples, the first tests the performance of alternative formulations, and the second explores climate change impacts in the basin.

Table 2. Annual percentage runoff ratios (net runoff/precipitation) for catchments in the Mekong basin.

Catchment	Location	Runoff ratio %
Mekong	Upper Mekong	25
Mekong	Chiang Saen	57
Moung Nouy	Moung Nouy	35
Mekong	Luang prabang	32
Mekong	Vientiane	29
Nam Ngum	Tha Ngon	86
Mekong	Nakhon Phanom	70
Mekong	Mukdahan	31
Se Bang Hieng	Ban Keng Done	53
Chi	Yasothon	9
Mun	Ubon Ratchathani	21
Mekong	Pakse	55
Se San	Se San	55
Mekong	Kratie	40
Mekong	Tonle Sap	32
Mekong	Phnom Penh	0
Mekong	Border	0
Mekong	Delta	0
Total		37

6.1 Testing alternative models – basing Tonle Sap flow on previous month's Mekong flow

Temporal discrimination in any model representation can have quite important impacts on model results. For the Mekong basin, we found this to be quite important, particularly in representing the dynamics of the Tonle Sap River flow and reversal of flow, where the flow in the Mekong (at Kratie, see discussion in section 5.1.2) is used in expressions to determine the magnitude and direction of flow in the Tonle Sap River. One other water accounting application, the Water Evaluation and Planning (WEAP) software, cannot determine model variables in a given time step using other model parameters also being evaluated in that time step. For such calculations, WEAP relies on the use of either values determined in the previous time step or expressions that estimate values for these needed parameters for the current time step.

To test the consequences of use of previous time step values to determine Tonle Sap river flow in a monthly time step construct, we make the simple substitution in the second of Equation (5) of using the previous month's Mekong flow

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The consequences of this change in the Tonle Sap River and in the Mekong downstream are shown in Figure 16. Comparing this figure with the corresponding figure for the "base case" (Figure 11) above reveals that the modeled flow into the Tonle Sap has both shifted by one month, and the annual flow in and out is less. The use of smaller time steps would diminish this problem, as would expressions that estimate current time step values of the needed parameters.

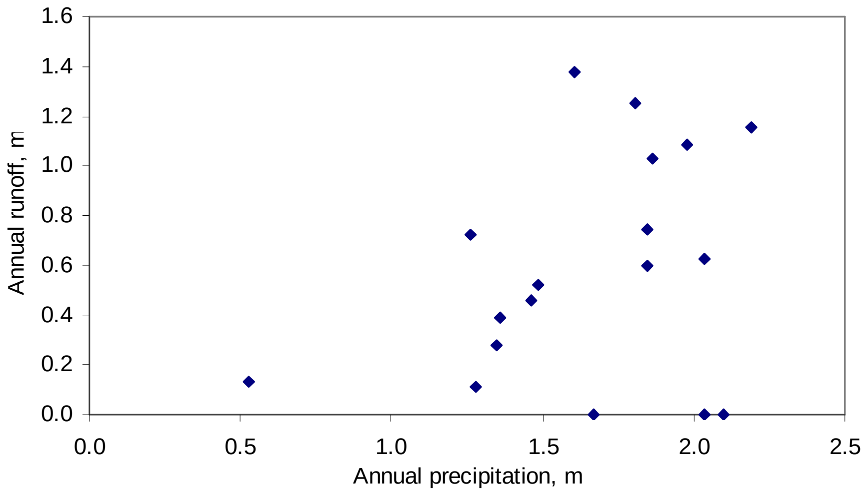

Figure 15. Runoff (annual averages 1951-2000) in the catchments in the Mekong basin.

6.2 Climate change

Some studies identify threats from climate change. The picture is neither clear nor uniform across the basin, but the studies suggest that in several regions the dry season may lengthen and intensify, and that the rainy season may shorten and intensify. Thus both seasonal water shortages and floods may be exacerbated, as may saltwater intrusion into the delta (Hoanh et al. 2003; Snidvongs et al. 2003; Chinvanno 2004). To demonstrate the sensitivity of flows to such changes in rainfall, the rainfall amount each month were adjusted with the following formula:

$$P_{cc,i} = P_o + f_s\left(P_{m,i} - P_o\right) \quad (4)$$

where $P_{cc,i}$ is the rainfall under climate change in month i,

$P_{m,i}$ is the historical (non-climate change) rainfall in that month,

f_s is a shift factor, taken as 1.3 for this demonstration, and

P_o is an offset value chosen such that the mean annual rainfall after the transform equals that before it.

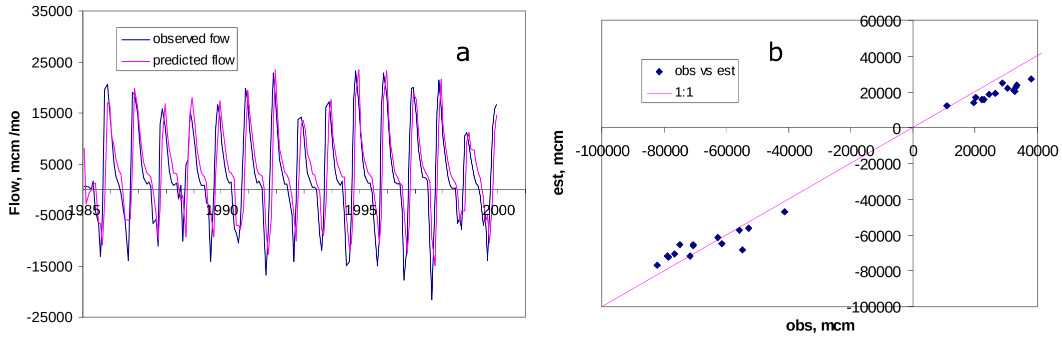

Figure 16. Comparison of measured and modeled flows of the Tonle Sap River, 1985 to 1999, with Tonle Sap flows based on previous month's Mekong flow. a). hydrograph of observed and predicted flow. b). observed and estimated total annual outflows and inflows into the Tonle Sap Lake from the Tonle Sap River (i.e. the areas under the curves in Figure 16a).

The transformed rainfall for the Se Bang Hieng in central Laos is seen in Figure 17. We emphasise that this is not a climate change prediction, but a simple demonstration of the use of the water use account spreadsheet and the sensitivity of the modeled flows to the change in rainfall.

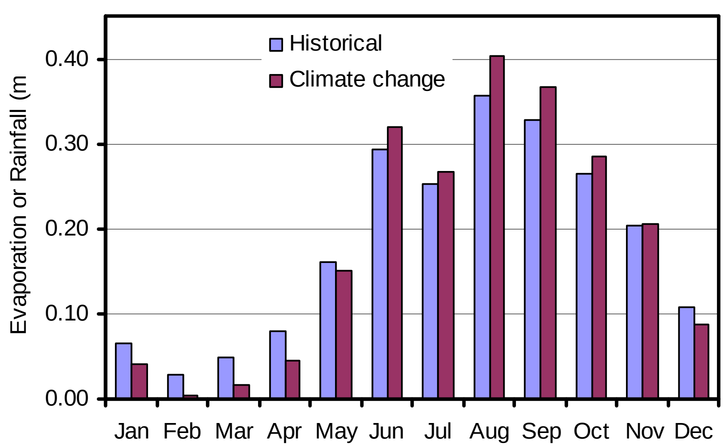

Figure 17. Historical and assumed climate change rainfall in Se Bang Hieng in central Laos.

With the changed rainfall, more water is modeled as flowing both out of (normal flow, positive values) and into (reversing flow, negative values) the Tonle Sap (Figure 18). The lake is predicted to expand more in the wet season with the greater reversing flow and greater local inflows, and to shrink to a smaller volume with the longer and drier dry season. Similarly, the peak wet season flow at Phnom Penh is predicted to be greater, and the dry season flow less, under the demonstration climate change scenario (Figure 19).

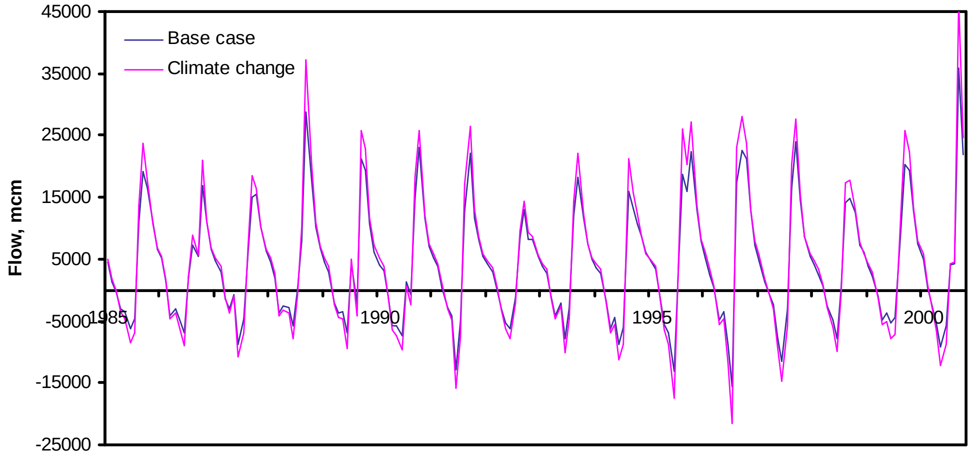

Figure 18. Flows in the Tonle Sap River with historical rainfall and a demonstration climate change rainfall.

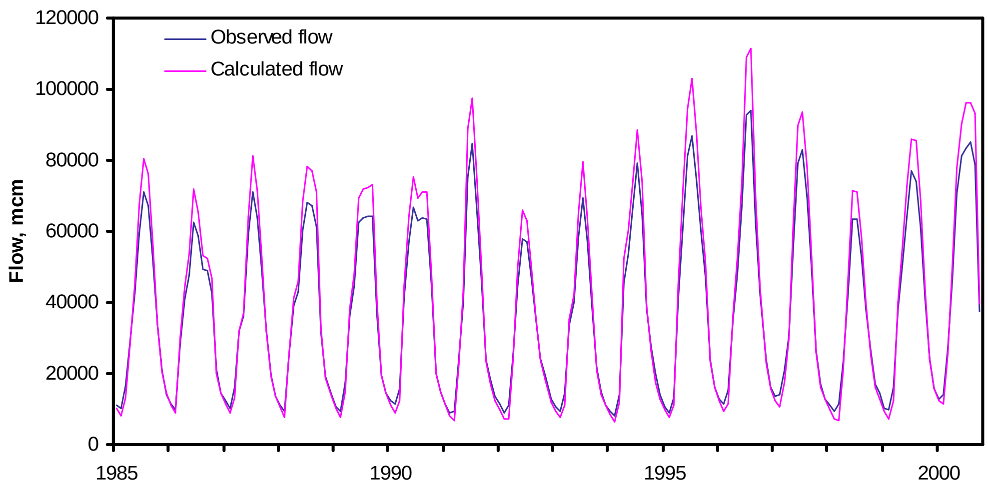

Figure 19. Flows in the in the Mekong at Phnom Penh with historical rainfall and a demonstration climate change rainfall.

With the changed rainfall, more water is modeled as flowing both out of (normal flow, positive values) and into (reversing flow, negative values) the Tonle Sap (Figure 18). The lake is predicted to expand more in the wet season with the greater reversing flow and greater local inflows, and to shrink to a smaller volume with the longer and drier dry season. Similarly, the peak wet season flow at Phnom Penh is predicted to be greater, and the dry season flow less, under the demonstration climate change scenario (Figure 19).

The floods in the Mekong destroy life and property on the one hand, while on the other they are vital to many ecosystems and to fish production and hence food resources. The anticipated changes to climate and hence flow are expected to affect agriculture and food production greatly, and exacerbate the problems of supplying the increase in food demand with growing populations (Hoanh et al. 2003; Snidvongs and Teng 2006).

7 Conclusions

A very simple spreadsheet model with few adjustable parameters has captured most of the runoff and river flow behavior in the lower Mekong Basin. Obvious features such as the flow reversal of the Tonle Sap are modeled reasonably well. Less obvious features such as flow lags and local storages are also simulated reasonably well. The flooding of the Cambodian floodplain resulting in overland flows to and from various reaches of the river is not simulated well at the moment. The flow records used here (drawn from a consistent set for convenience, even though they are inadequate for some purposes) do not permit better modeling, though other flow records are available.

The Mekong basin has considerable excess of rain over evapotranspiration, and about 37 % of the rain is ultimately discharged to the sea. Floods, particularly in the lower Mekong in Cambodia, are a major problem. Nevertheless, much of the drier part of the Mekong, particularly in NE Thailand, experiences seasonal water shortages during the dry season. Irrigation, primarily using water diverted from the rivers, is practiced throughout the lower basin, but is particularly important only in the delta region. A demonstration of the possible impacts of climate change using an assumed change in rainfall distribution, shows that with the expected shorter and more intense rainy season, and longer and more intense dry season, both floods and seasonal water shortages may be exacerbated.

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