Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse

Rapid development in the upper reaches of the Mekong River, in the form of construction of large hydropower dams and reservoirs, large irrigation schemes, and rapid urban development, is putting water resources under stress. Recent studies have concluded that these developments will lead to flow alterations in the Mekong River. These flow alterations would threaten the sensitive ecosystems downstream, particularly Tonle Sap River, Tonle Sap Lake, its floodplain, and its gallery forest and protected areas, by changing the flood-pulse system of the lake. This article estimates the changes in parameters of the Tonle Sap flood pulse due to the aforementioned flow alterations. The impacts on the flooded area and loss of gallery forest and protected areas were analyzed using geographic information system–based methods. Relatively small rises in the dry-season lake water level would permanently inundate disproportionately large areas of floodplain, rendering it inaccessible to floodplain vegetation and eroding the productivity basis of the ecosystem. It is highly important to maintain the natural hydrological pattern of the Mekong River, particularly the dry-season water levels, to preserve Tonle Sap Lake’s ecosystem productivity.

INTRODUCTION

During the last decades, the human impact on water resources has increased remarkably, and it will continue to increase, although probably not as rapidly as it has in the twentieth century (1). The standing stock of natural river water has increased sevenfold due to 8400 km$^3$ of water stored in reservoirs behind dams (1). The water renewal time (3) of the world’s rivers has increased dramatically, from 20 to 100 d, as a consequence of dam and reservoir consumption (4). According to Skole et al. (5), land-cover change may be the most significant agent of change in hydrology, climate, and global biogeochemical cycles. Furthermore, climate change may play a very important role in those changes in the future (e.g., 6, 7).

Wetlands, including floodplains, are important parts of rivers and other freshwater ecosystems. On a global scale, wetlands cover between 2.0–5.3 million km$^2$ (8) and 12.8 million km$^2$ (9), corresponding to ~3%–9% of the land surface. The degradation and loss of wetlands occur more rapidly than that of other ecosystems (9, 10). Maintenance of the hydrological regime of a wetland and its natural variability is necessary to sustain the ecological characteristics of the wetland, including its biodiversity (9). According to the Millennium Ecosystem Assessment (9), dams play a major role in fragmenting and modifying aquatic habitats by altering the flow of matter and energy. Existing, large-scale utilization of the Mekong’s resources is limited compared to almost all large river basins in the world. The present flow regime in the main stem of the Mekong is essentially natural (11); although, in many parts of the basin, water resources are used intensively at a small-scale, local level. However, the Mekong Basin is under rapid development. The construction of large-scale hydropower dams and reservoirs in the basin began on the tributaries in the 1970s in Lao People’s Democratic Republic (PDR) and Thailand, and in the main stem a decade ago in China. Numerous additional dams are envisaged in China, Lao PDR, Cambodia, and Vietnam (12–16). Population growth and economic development have led to rapid land-cover changes, mainly deforestation, in many parts of the basin (17). Development in the river and the basin will alter the flows and floods in the basin. This is also the conclusion of the cumulative impact assessments (CIAs) that have been made (17–19). The impact of climate change on the hydrology has not been included in the CIAs, but it is considered to have an important impact on the Mekong and Tonle Sap hydrology, especially during the latter part of the 21st century (20).

Each CIA report (17–19) made for the Mekong Basin, mainly for hydropower impact assessment, concludes that dry-season water levels would rise and wet-season water levels would be lower than at present. The flow alterations would be more significant close to the dam and gradually decrease with distance in the lower Mekong Basin. The flow alterations in the Mekong main stem would directly impact the flood pulse of Tonle Sap Lake. This is because around 60% of the Tonle Sap flood water originates from the Mekong, and the water level in the lake is controlled by the water level in the Mekong main stem (21).

Flood pulses in rivers and lakes can be described by a number of characteristics that are important from an ecosystem productivity point of view. The list of flood-pulse parameters used in this analysis is based on Welcomme and Halls (22) and was adapted to Tonle Sap Lake by Lamberts (23). The list is as follows: flow duration, amplitude, flood volume, timing, rapidity of the water-level change, continuity, and smoothness.

Lamberts (24) presented a detailed description of the Tonle Sap flood-pulse parameters susceptible to anthropogenic flow alterations in the Mekong River and discussed the possible impacts of these alterations on ecosystem productivity. This paper aims to assess the impacts of the flow alteration on the flood characteristics, gallery forest, and protected areas in Tonle Sap Lake. The paper consists of three parts: i) statistical analysis of the present Tonle Sap flood characteristics, ii) assessment of the flow alteration impacts on flood characteristics, based on the recent CIA studies, and iii) spatial analysis of the flow alteration impacts on the flooded area, gallery forest, and protective areas.

TONLE SAP LAKE

Tonle Sap Lake (Fig. 1) is an integral part of the Mekong River, and it is the largest freshwater lake in Southeast Asia. The Mekong River is among the largest rivers in the world and is ranked as the 10th largest by volume, with an annual discharge of 475 km$^3$ (10). The importance of the lake is unquestioned for Cambodia and the lower Mekong Basin (25–29). Over one million people depend on the natural resources of the lake. The value of Tonle Sap Lake has also been recognized internationally, and the lake has three Biosphere Reserve core areas under the United Nations Educational, Scientific and Cultural Organization (UNESCO) Programme on Man and the Biosphere (30) and one Ramsar site under the Ramsar Convention (31).
Water Balance

Water-balance calculations for Tonle Sap Lake have shown that most of the inflow into the lake (57%) originates from the Mekong main stem, either by discharge through the Tonle Sap River (52%) or by overland flooding (5%) (21). Tributaries to Tonle Sap Lake contribute about 30%, and precipitation directly into the lake contributes some 13% of inflow. The average annual inflow is 79.0 km$^3$, ranging between 44.1 km$^3$ in 1998 and 106.5 km$^3$ in 2000. Around 88% of the receding lake water returns to the Mekong River through the Tonle Sap River (87%) and overland flooding (1%), while 12% evaporates from the lake. The average annual outflow is 78.6 km$^3$, ranging from 43.5 km$^3$ in 1998 to 104.8 km$^3$ in 2000. The flow in the Mekong River is the principal factor determining the flood pulse of Tonle Sap Lake (21).

Flood Pulse and Floodplain Gallery Forest

According to Junk (32), ecosystems that experience fluctuations between terrestrial and aquatic conditions are called pulsing ecosystems and can be described in terms of the flood-pulse concept. Junk’s flood pulse concept (32) has been widely accepted as describing the highly productive floodplain environments and the ecology of pulsing systems. Tonle Sap Lake and floodplain ecosystem is well described by the flood-pulse concept, where the annual monsoon floods of the Mekong River are a key driver of its productivity (23).

The floodplain vegetation is one of the most important elements of the Tonle Sap ecosystem (23, 28). Among it, the tall gallery forest stripe in the immediate vicinity of the permanent lake shore (illustrated in Fig. 1) covers only a small part of the floodplain, but it constitutes an important physical barrier between the open lake and the floodplain, creating favorable conditions for effective sedimentation within the forested zone (33). In addition to the permanent lake edge and the river banks, isolated stands of trees are scattered throughout the floodplain. The total area of the gallery forest of Tonle Sap Lake’s floodplain is around 198 km$^2$, calculated from the land-use map created by Japan International Cooperation Agency (JICA) in 1999 (34). McDonald et al. (35, 36) provide more information about the gallery forest and other floodplain vegetation.

DATA AND METHODS

Data for Analysis of the Present Flood-Pulse Characteristics

Reliable water-level data from Tonle Sap Lake are available only for the years 1997–2006 due to the unstable history of Cambodia. Water-level data exist also for the period 1923–1965 (26), but these data were not used in this analysis because the aim was to analyze the current flood-pulse characteristics with comparable data. The data were used for statistical analysis of the present flood-pulse parameters. Daily water-level data are available from the Kampong Luong station, located on the edge of the permanent lake (station location in Fig. 1). The water-level data in this article are always expressed as elevation above mean sea level (amsl) in Hatien, Vietnam.

Cumulative Impact Assessment Studies

Due to the considerable variety and ambiguity of different development plans, the prediction of cumulative impacts of ongoing and planned development is extremely challenging. For example, existing cumulative impacts assessment (CIA) studies focusing on flow changes have applied different approaches, and used different values, and therefore provide different estimates of the potential changes in flow. Three different CIA studies were analyzed and used for flow-alteration predictions in this article:

i) CIA 1: The Mekong River Commission (MRC) has compiled a basinwide CIA under the Integrated Basin Flow Management (IBFM) project by using Decision Support Framework (DSF) modeling tools (19).

ii) CIA 2: The Asian Development Bank (ADB) conducted a basinwide CIA within the Nam Thuon 2 environmental impact assessment study (18).

iii) CIA 3: Adamson (17) compiled analyses of the downstream hydrological impact of the Chinese cascade of dams.

The results of the aforementioned CIAs were used to analyze the flow alteration due to upstream development and its impacts on the Tonle Sap flood pulse. A summary of the CIA studies is presented in Table 1, and each CIA and its background are briefly summarized here.
Table 1. Summary of the flow alteration according to the CIA studies.

<table>
<thead>
<tr>
<th>CIA 1</th>
<th>CIA 2</th>
<th>CIA 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic assumptions and methods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased storage in the Mekong Basin</td>
<td>49.5 km$^3$</td>
<td>54.9 km$^3$</td>
</tr>
<tr>
<td>Increased irrigation</td>
<td>+53%</td>
<td>—</td>
</tr>
<tr>
<td>Other development activities taken into account</td>
<td>Increased domestic and industrial use of water, and basin diversions Hydrological and hydrodynamic model</td>
<td>—</td>
</tr>
<tr>
<td>Flow alteration impacts on Tonle Sap water levels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet-season water level</td>
<td>−0.36 m</td>
<td>−0.54 m</td>
</tr>
<tr>
<td>Dry-season water level</td>
<td>+0.15 m</td>
<td>+0.60 m</td>
</tr>
</tbody>
</table>

* Only reservoirs planned to be constructed in China are considered.

CIA 1: Mekong River Commission

The Mekong River Commission compiled the CIA as part of its Integrated Basin Flow Management project by using Decision Support Framework modeling tools (19). Altogether, six scenarios, including the baseline, were developed. The scenarios represent the possible development alternatives occurring by 2020. Here, the High Development Scenario has been selected for the analysis so as to be as comparable with the other CIAs as possible, especially with the ADB (18) CIA. In summary, this scenario predicts that the overall character of the hydrograph is maintained. However, the low flows are systematically higher than the historically observed values, and the dry-season water level will rise 0.15 m in Tonle Sap Lake. High flows are reduced in frequency, and the flood peak of the lake will be reduced by 0.36 m (19).

CIA 2: Asian Development Bank

The ADB conducted a basinwide CIA within the Nam Thuon 2 environmental impact assessment study (18). Two different scenarios were constructed: 5 y and 20 y scenarios. Here, the results from the 20 y scenario were used for further analysis. This scenario was selected so that the time span would be roughly equivalent to the MRC scenario. In the 20 y scenario, the ADB assessment (18) predicts that the average annual maximum level of Tonle Sap Lake will be lowered in average by 0.54 m and the dry season water levels increased by about 0.60 m.

CIA 3: Adamson

Adamson (17) compiled an analysis of the downstream hydrological impact of the planned Chinese cascade of dams. However, Adamson (17) did not consider other basin development in the analysis. Two different scenarios were analyzed for selected sites on the main stem, one with 10% and the other with 20% regulation of the dams. A 20% regulation in China would result, according to Adamson (17), in a 50% increase in average discharge in Kratie (location in Fig. 1) in March. By this point, the potential impacts on the wet-season hydrology of the main stem are modest (17). The Danish Hydraulic Institute (37) analyzed the impact of flow changes in Kratie on the Tonle Sap water level by using the results presented by Adamson (17). The 20% regulation was predicted to increase the dry-season water level in Tonle Sap Lake by 0.3 m (37).

Spatial Data

We used the available land-use, bathymetric, and elevation data, as well as other related spatial data sets, for geographic information systems (GIS) analysis to assess the impacts of flow alteration on the flooded area, including the gallery forest and protected areas in the floodplain.

The following GIS data were used for the spatial analysis:

- The digital bathymetry model (DBM) for Tonle Sap Lake, Tonle Sap River, and their floodplains is based on the combined data sets of the Certeza survey (38) of the Tonle Sap floodplain and the Mekong River Commission Hydrographic Atlas for the lake proper and Tonle Sap River (39).
- Land-use data around Tonle Sap, from which we use only the gallery forest layer, were compiled by JICA (34).
- Protected areas—the location of Tonle Sap Biosphere Reserve and Ramsar site—are based on the Mekong River Commission spatial databases (40).
- Tonle Sap catchment boundaries, Tonle Sap tributaries, Mekong main stem, and the Lower Mekong Basin inundated areas are based on the Mekong River Commission spatial databases (40).
- Country boundaries are based on the Mekong River Commission spatial databases (40).

Method Used for Analyzing the Present Flood-Pulse Characteristics

Water-level data from the Kampong Luong station were used to calculate the present flood-pulse characteristics. First, the lake area (km$^2$) and lake volume (km$^3$) were expressed as functions of water level (m) above the mean sea level (amsl), based on the DBM of the lake (21). Next, the maximum and minimum water levels and related flooded areas and volumes were calculated from the available water-level data.

In this paper, flooding is considered to occur during the period when water level is higher than 1 m above the average 30 d minimum water level of 1.44 m amsl, i.e., when the water level is above 2.44 m amsl. The start, end, peak, and duration of the flood were analyzed for each water year in which data were available. The water year starts on 1 May and ends on 30 April to coincide with the flood timing.

The rate of water-level change was calculated based on daily water-level changes. The average for each month was then calculated.

Method Used for Assessment of Flow-Alteration Impacts on Flood-Pulse Characteristics

The flow-alteration data from each CIA were first documented and analyzed. The changes in the hydrograph due to flow alteration for the selected scenarios were then analyzed and used to calculate the new water levels for the “average” water year in Tonle Sap Lake. For the average year, the daily average water
levels were used. Finally, the flood-pulse parameters (methods presented in previous section) were analyzed and compared to the measured water levels. However, due to the lack of time variability, it was not possible to analyze all of the parameters for each CIA.

Method Used for Assessment of Flow-Alteration Impacts on Flooded Area, Gallery Forest, and Protective Areas

Using the GIS data listed previously and ESRI’s ArcGIS 9.2 software and its extensions, an assessment of the impacts caused by flow alteration on the flooded area—gallery forest and protected areas—was achieved. The inundated areas were first analyzed for each water level by using the DBM constructed for Tonle Sap Lake and its floodplain. This resulted in polygons of inundated areas. The inundated areas were then mapped, and their extent was calculated using the polygons. Thereafter, the areas of gallery forest inundated due to the increased dry-season water level were mapped. The same was done with the location of the protected areas.

RESULTS

Current Flood-Pulse Characteristics

According to the statistical flood analysis, the timing of the flood peak is very regular in Tonle Sap Lake. However, the start and end dates of the flood (41) vary significantly, depending on the timing of the flood on the main stem Mekong and local rainfall in the Tonle Sap tributaries. The bottom of the lake is at an altitude of 0.6–0.7 m amsl. Thus, during low water, the lake water depth is around 0.8 m.

On average, the flood starts on the 22nd of June, has its peak on the 7th of October, and ends on the 5th of March (Table 2). The average flood duration is 258 d, or 71% of the year. During the analysis period, it varied from 205 d (1998) to 299 d (2000). The start of the flood varied from 27 May (2000) to 15 June (1998), and the end date varied from 04 February (1998) to 10 April (2004), 49 d and 65 d, respectively. The peak of the flood occurred more consistently around early October, varying from 28 September to 17 October, i.e., within 20 d. Figure 2A illustrates the timing of the flood, including start date, peak date, and end date.

The water level varied from the lowest (daily minimum) value of 1.32 m amsl to the peak flood of 9.14 m amsl. At the same time, the flooded area varied from 2215 km$^2$ to 13 258 km$^2$, and the volume varied from 1.6 km$^3$ to 59.7 km$^3$. All this information is summarized in Table 2.

Figure 2B illustrates the rate of water-level change, which is plotted along with the average water level over one flood cycle starting in May. The rapidity of the water-level change was greatest during July, around 8 cm d$^{-1}$. During the receding flood, the most rapid water level change occurred during December, around −6 cm d$^{-1}$.

Flow-Alteration Impacts on Flood-Pulse Characteristics

The general results for each CIA, a comparison of the flood-pulse parameters calculated from the observed values (daily average value for the entire study period), and parameters based on the CIA scenario results are presented in Table 3. The flood duration would be reduced by 14 d, while the floodplain area, total flood volume, and amplitude would be reduced by 7%–16%.

The predicted average annual hydrograph, based on the monthly average water levels under present situation and CIA 2, is presented in Figure 3. The figure shows a clear drop in the flood peak and increase of the low water levels in the most extreme estimation of flow-alteration impacts on the water levels of Tonle Sap, i.e., the amplitude of the flooding would decrease. According to Lamberts (24), the water depth in the floodplain determines the volume of the euphotic zone in which aquatic photosynthesis can occur. Thus, smaller flooding amplitude would decrease the ecosystem productivity.

Flow-Alteration Impacts on Flooded Area

The dry-season water-level rise in Tonle Sap Lake due to upstream development on the Mekong River has been summarized in Table 3. The results of the spatial analysis illustrate how the increased dry-season water level would impact

<table>
<thead>
<tr>
<th>Year</th>
<th>Min WL (m)</th>
<th>Area (km$^2$)</th>
<th>Volume (km$^3$)</th>
<th>Max WL (m)</th>
<th>Area (km$^2$)</th>
<th>Volume (km$^3$)</th>
<th>Amplitude (m)</th>
<th>Start date</th>
<th>Peak date</th>
<th>End date</th>
<th>Duration (d)</th>
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<tbody>
<tr>
<td>1997</td>
<td>1.40</td>
<td>2307</td>
<td>1.7</td>
<td>9.33</td>
<td>13 542</td>
<td>61.5</td>
<td>7.9</td>
<td>07/07</td>
<td>08/10</td>
<td>13/02</td>
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<td>1998</td>
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<td>1.4</td>
<td>6.86</td>
<td>9637</td>
<td>33.0</td>
<td>5.6</td>
<td>15/07</td>
<td>12/10</td>
<td>04/02</td>
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<td>1999</td>
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<td>1.6</td>
<td>8.97</td>
<td>12 950</td>
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<td>7.6</td>
<td>28/05</td>
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<tr>
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<td>1.48</td>
<td>2402</td>
<td>1.8</td>
<td>10.36</td>
<td>15 278</td>
<td>76.1</td>
<td>8.9</td>
<td>27/05</td>
<td>28/09</td>
<td>21/03</td>
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<tr>
<td>2001</td>
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<td>2331</td>
<td>1.7</td>
<td>9.89</td>
<td>14 478</td>
<td>68.2</td>
<td>8.5</td>
<td>14/06</td>
<td>05/10</td>
<td>15/03</td>
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</tr>
<tr>
<td>2002</td>
<td>1.19</td>
<td>2061</td>
<td>1.3</td>
<td>10.10</td>
<td>14 834</td>
<td>72.2</td>
<td>8.9</td>
<td>20/06</td>
<td>06/10</td>
<td>16/03</td>
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<tr>
<td>2003</td>
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<td>2155</td>
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<td>8.26</td>
<td>11 805</td>
<td>48.1</td>
<td>7.0</td>
<td>03/07</td>
<td>08/10</td>
<td>08/02</td>
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<tr>
<td>2004</td>
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<td>1.4</td>
<td>9.20</td>
<td>13 327</td>
<td>59.8</td>
<td>8.0</td>
<td>21/06</td>
<td>04/10</td>
<td>10/04</td>
<td>294</td>
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<tr>
<td>2005</td>
<td>1.26</td>
<td>2143</td>
<td>1.5</td>
<td>9.29</td>
<td>13 475</td>
<td>61.0</td>
<td>8.0</td>
<td>09/07</td>
<td>11/10</td>
<td>28/02</td>
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<tr>
<td>Avg</td>
<td>1.32</td>
<td>2212</td>
<td>1.6</td>
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<td>02/03</td>
<td>258</td>
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</table>
the permanently inundated area (Fig. 4). The average 30 d minimum water level during the analysis period of 1997–2006 was 1.44 m amsl, and this was used as a reference level for the dry-season water level. The lake area corresponding to a water level of 1.44 m amsl is 2300 km$^2$. Rises of 0.15 m, 0.3 m, and 0.6 m, representing each analyzed CIA, would result in a permanent lake area of 2700 km$^2$, 3000 km$^2$, and 3200 km$^2$, respectively. Thus, the permanent lake area would increase between 400 and 1000 km$^2$ (17%–40%).

The analysis based on CIA studies also predicts that the peak water level would decrease and thus reduce the inundated area, i.e., size of the floodplain and of the lake. Thus, the area of the floodplain would decrease, depending on the CIA data used, between 7% and 16% (Fig. 5 and Table 3). This would have direct impact on the ecosystem productivity: the smaller the area that becomes flooded, the smaller the area between aquatic and terrestrial phases (the ATTZ) and the smaller the potential transfer of floodplain terrestrial organic matter and energy into the aquatic phase (24).

Flow-Alteration Impacts on Gallery Forest and Protected Areas

The predicted dry-season water-level rise of 0.15–0.60 m would mean permanent inundation of large areas of gallery forest stripes located in the vicinity of the lakeshore (illustrated in Fig. 6). This significant reduction, along with the 0.60 m dry-season water-level rise total extinction of the gallery forest stripe, could have a significant impact on the entire Tonle Sap ecosystem.

Two types of protected areas and in total four core sites are located within Tonle Sap Lake and its floodplains (locations in Fig. 1):

i) Tonle Sap Biosphere Reserve (TSBR): 3 core areas (established in 1997), and

ii) Ramsar site (established in 1999).

The impact of the dry-season water-level rise on the TSBR and Ramsar core sites is illustrated in Figure 6. Of the total area of 149 km$^2$ of the Ramsar core site, 6%, 31%, or 83% (CIA 1 vs. CIA 3 vs. CIA 2) would be inundated by an increase in dry-season water level. Rise in water level would inundate 13%, 23%, or 42% (CIA 1 vs. CIA 3 vs. CIA 2) of the TSBR core areas (total area of 423 km$^2$). Thus, the impacts of the dry-season water-level rise could be dramatic on these internationally recognized protected areas.

Discussion

The flood-pulse parameter analysis is based on water-level data from Tonle Sap Lake. The quality of these data has been checked, but still there is the possibility of some inaccuracy because only one measurement site has been used in a large lake. During periods of strong winds, the water level might...
differ significantly from one end of the lake to the other. However, this does not seem to be a major source of error since the wind velocities are normally relatively low, and strong wind events last only a few hours (42). The observed water levels show no evidence of any significant seiche oscillation, evidently due to the high friction caused by the floodplain vegetation. The flooded area analysis is based on the bathymetry data collected on 1960s by Certeza survey company (38). Even though the data used are rather old, their accuracy has been tested and reaffirmed during the MRC/WUP-FIN project (42), and it is generally agreed that it is the best data set available.

The flow alterations predicted by the CIAs have similar trends in each of the studies, but the magnitude of the predicted changes in the Tonle Sap hydrograph differs considerably between the scenarios. This is due to the different methods and assumptions used in each CIA. There are also many uncertainties in the CIAs, e.g., in the scenario definition, and assumptions involved in the modeling and analysis. Adamson (43) gives an overview of the hydrological models applied in the Mekong and reports the limited ability of the MRC's DSF model system, used in the CIA 1 (19), in some water-resource development simulations, such as for hydropower. Also, due to the different scenarios used in each CIA, the results cannot be directly compared with each other. Thus, since part of the analysis presented in this paper is based on the CIA studies, the results are subject to the possible inaccuracies in the source data.

Various studies highlight the importance of future climate change impacts on precipitation through intensification of monsoon rains, which would lead to increased flooding in Southeast Asia (e.g., 44, 45), especially after 2030 (45), and particularly in the Mekong (20, 46). Thus, incorporating predicted climate change impacts into the basin development scenarios would change the outcomes of spatial modeling presented here (20). Cumulative assessment modeling is required where direct human development impact (reservoirs, irrigation, etc.) is modeled together with predicted climate change impacts on precipitation and temperature. However, the time spans of the events are different: the time span in climate change studies is normally several decades, while in the foreseen direct basin development, it is only 10–20 y. This should be
taken into account when comparing, or combining, the different impacts. A global analysis of the potential effect of climate change on river basins indicates that rivers impacted by dams or extensive development will require more management interventions to protect ecosystems and people than basins with free-flowing rivers (47).

The impacts of flow alterations on the analyzed flood-pulse parameters indicate a decline in every parameter in regard to ecosystem productivity. In this paper, the results have been presented separately for each parameter. It is possible that the combined impact of the parameters will result in severe impacts on the lake’s ecosystem. Work on quantification of the impacts of the predicted flood-pulse changes on the ecosystem productivity of Tonle Sap is ongoing. Lamberts (23, 24, 48) is focusing on the terrestrial and aquatic primary production of the floodplain. This is necessary to improve our understanding of the impacts of development and to make reliable estimates of the impact of flow alteration on the lake’s productivity and consequently fisheries, and further link those results with the socioeconomic livelihoods analysis (e.g., 27).

In this paper, the hydrological impacts of the large-scale water-resources development have been discussed and analyzed. However, the impact on water quality can be also significant, although not yet well studied. The impact of future hydropower construction on the basin sediment balance has been estimated to be considerable as well, impacting directly on the nutrients and ecosystem productivity (13). To understand better the possible impacts of development on the water quality and sediment, further basinwide research is urgently required to guide decisions for minimizing the impacts of flow alterations.

CONCLUSIONS

The recent cumulative impact assessment studies of the Mekong Basin are consistent, and they state that increased development activities, especially construction of hydropower dams and reservoirs, large irrigation schemes, and rapid urban development, will result in higher dry-season water levels and lower flood peaks. This paper aimed to assess the impacts of these predicted flow alterations on the flood characteristics, gallery forest, and protected areas of Tonle Sap Lake, by using the results of the CIA studies, hydrological data-series analysis, and spatial analysis.

The flow alterations in the Mekong River, due to development activities in the upstream countries, will cause negative effects for ecosystem productivity, and thus also for livelihoods of the inhabitants of Tonle Sap floodplain, who directly depend on the lake’s natural resources. Thus, it is extremely important for Tonle Sap, and other floodplains in the Lower Mekong Basin, to maintain the natural hydrological regime of the Mekong main stem. Changes in the dry-season water levels, estimated to increase the water level in Tonle Sap Lake by 0.15–0.60 m, would, in particular, be harmful to the present ecosystem of the lake.

Relatively small rises in the dry-season lake water level would permanently inundate disproportionately large areas of floodplain, rendering it inaccessible to floodplain vegetation and eroding the productivity basis of the ecosystem by reducing the inundated area and duration and amplitude of flooding. The lake extension would cause permanent submergence, in essence destruction, of considerable areas of the gallery forest stripe surrounding the lake in the floodplain. The reduction of gallery forest area would mean loss of livelihood sources for a significant number of people, due to both loss of gallery forests per se and the consequent negative effects on aquatic productivity (49). Large parts of internationally protected areas under Ramsar Convention and the Tonle Sap Biosphere Reserve Programme (under UNESCO) would also be lost by permanent submersion in the lake.

Hydropower dam regulation will probably be the main cause of flow alterations in the near foreseen future. Other important actors are land-cover changes and irrigation schemes. Climate change may play an equally important role from the latter part of the century on. Integrated, cross-boundary planning, involving both downstream and upstream countries, and cumulative impact assessment are urgently required to minimize the impacts of the flow alteration.

References and Notes


2. Water renewal time can be defined as follows: “ratio between its [this case river] total volume and the daily volume flux . . . [and] leaving it.” Based on (3).