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Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River-Tonle Sap system identified using continuous monitoring

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ABSTRACT
Continuous monitoring of turbidity, dissolved oxygen (DO), conductivity, temperature, and fluorescence was done at five locations on the Tonle Sap Lake and the Mekong–Bassac Rivers near Phnom Penh, Cambodia, between 2004 and 2010 using autonomous datasondes. Seasonal, daily, and spatial trends were clearly identified in the data and were related to the annual monsoon rainy season–dry season cycle, system metabolism, system hydraulics, and in some cases, localized phenomena such as waste discharges. The datasondes were particularly useful to track the oxygenation of anoxic black water areas in the flooded forest fringe of the Tonle Sap that occurred during the rainy season freshwater pulse. A strongly developed vertical variation of turbidity, DO, and conductivity in the flooded forest fringe may be related to a combination of factors, including dissolved material release from bed sediment and a floating organic-rich particulate layer near the bottom of the lake. Grab samples for total suspended solids (TSS) were collected at the Preak Leap (PL) site (Mekong River) in 2009 and 2010. An excellent relationship was established between daily mean turbidity and TSS concentration for the PL site, with $r^2 = 0.95$. Autoregressive, integrated, moving average models adequately forecast water level and water quality data one month ahead.

Keywords: Tonle Sap; Mekong–Bassac Rivers; flood pulse system; dissolved oxygen; turbidity; continuous monitoring; ARIMA models

1 Introduction

The Mekong River (including the Tonle Sap Lake) is one of the major rivers of the world, flowing through parts of six countries, China, Laos, Myanmar, Thailand, Cambodia, and Vietnam. The river conjures strong imagery in both Southeast Asian and Western countries because of its cultural and historical significance, yet Osborne (2000) maintains that compared with other major rivers such as the Nile and Amazon, relatively little is known about the Mekong River. There are a number of underlying reasons for Osborne’s assertion, including the unsettled political situations that have affected the Mekong countries for more than 60 years; the economic challenges that, in some ways, are linked to the politics of the region, and the complex and diverse natural and social systems within the basin (Kaosa-ard and Dore 2003, Sarkkula et al. 2007, Lamberts 2008, Leepreecha et al. 2008). Over the past decade, however, countries of the Mekong Basin have seen increasing populations, expansion of industry, and exploitation of natural resources (e.g. Jones 2010, Trinh Thi 2010), and this development will place greater pressure on the water resources of the Mekong River system in a number of ways. In particular, several countries have begun or planned
hydropower projects on the mainstem of the Mekong River and major tributaries (e.g. Greacen and Palett 2007, Stone 2011). China has plans for a cascading series of eight hydropower reservoirs on the upper Mekong, four of which have been completed (Stone 2011). Installed capacity for all eight projects is estimated at 15,650 MW (Dore et al. 2007). The water resources and ecosystems of the lower Mekong countries, especially Cambodia and Vietnam, also are highly vulnerable to potential impacts from climate change due to factors including low coastal elevations and extensive reliance on agriculture and fishing for livelihoods (Chaudhry and Ruyschaert 2007, Va et al., 2010).

Over the past 20 years, Integrated Water Resources Management (IWRM) has evolved into an important philosophy that increasingly has been used by water agencies throughout the world to guide programme practices (Irvine et al. 2010). The Mekong River Commission (MRC) recently embraced the IWRM approach for the lower Mekong Basin (http://www.mrcmekong.org/download/programmes/bdp/IWRM-based-Basin-Dev-Strategy-1st-Incomplete-Con-Draft6Oct09.pdf). UNESCO (2009) identified nine conditions as being essential for the successful implementation of IWRM and these included ‘good knowledge of natural resources present in the basin’ and ‘comprehensive monitoring’ (i.e. good management plans must be based on sound data). The MRC oversees the collection and maintains the most readily available and extensive water quantity and quality data set for the basin. The MRC water quality database represents monthly sample results for 99 sites across the basin (46 of which are in the Mekong Delta in Vietnam) beginning in 1985 (1992 in Cambodia; Campbell 2007). There are nine mainstem sites located upstream of Phnom Penh and no sites within China. Analytes are restricted to conventional parameters such as total suspended solids (TSS), nutrients, cations, dissolved oxygen (DO), conductivity, temperature, and pH. While these data provide an indication of broad-scale water quality conditions, the MRC (2007) noted that they are not sufficient to comprehensively assess the impacts (real or anticipated) of present and proposed issues of land use. Data collected at monthly time steps limit accurate assessment of seasonal dynamics within the system and are unable to assess diurnal variation related to metabolic processes. Walling (2008) reviewed the TSS data from the MRC and other sources and concluded that the limited available data had a number of deficiencies that increased uncertainty in long-term trend analysis. The MRC (2007) also noted that: (i) there was no systematic or substantial scientific study of the nutrient dynamics of the Tonle Sap Lake system and therefore it was not known with certainty if the lake was N or P limited and whether nutrient loadings from the surrounding land are transported through the wetlands into this shallow lake, or if these loads are consumed within the wetlands; (ii) there was little data on metals or organic contaminants through the system (although this was addressed in a preliminary way by the MRC (2007) report); and (iii) there was little data on point source discharges or the impact of urbanization on water quality. Some of these issues are starting to be addressed (e.g. Eloheimo et al. 2002, Ministry of Water Resources and Meteorology (MoWRAM) 2009, Murphy et al. 2009, Visoth et al. 2010) but much more work is needed.

Given one of the greatest challenges for natural resource planning in the region is a distinct lack of reliable physical and biological data, the objective of this study was to identify temporal and spatial trends in turbidity, DO, conductivity, temperature, and fluorescence using high-resolution measurements for the Tonle Sap Lake and Mekong, Bassac, and Tonle Sap Rivers in the vicinity of Phnom Penh, Cambodia. This is the first of a series of papers associated with a larger project led by the University of Washington that is seeking to examine regional-scale landscape dynamics in river basins in Southeast Asia relative to their connectivity to the South China Sea, with an emphasis on the Mekong River. The basic premise of the larger project is that the understanding of regional scale processes requires the higher resolution now possible with satellite data, process-based models, and autonomous field measurements. By focusing on how transient forcing of the atmosphere combines with land use change at multiple space and time scales to mobilize water and carbon to the sea, we are examining the critical and poorly understood interfaces between the atmosphere, land surface and sea function. Data described in this paper will serve as the basis for improved understanding of the lower Mekong River ecosystem. Oxygen conditions in July and August, for example, are important for fish eggs, larvae, and juveniles entering the Tonle Sap Lake at that time (Koponen et al. 2005). Campbell et al. (2006) noted that Anabantoidei suborder fishes make a froth nest where the eggs are deposited in surface waters having higher oxygen levels. Yet, relatively little high-resolution, autonomous field data on DO exist to assess spatial and temporal patterns and their relation to organism life cycles. The basic ecosystem parameters described in this paper can be used to calibrate conceptual, deterministic models capable of exploring the potential impacts of climate change, dam construction, and land use conversion on primary and higher order productivity (Koponen et al. 2005, Costa-Cabral et al. 2008). This study benefited from collaborative support early on with the WUP-FIN (Water Utilization Programme – Finland) programme, a complementary project to the MRC that was funded through Finland’s Ministry of Foreign Affairs. The objective of the first phase of the WUP-FIN programme was to understand physical, chemical, and biological processes in the Tonle Sap Lake and to assist in the maintenance of sustainable conditions of the lake.

2 Sample area, data collection methods, and applied time-series analysis

2.1 Sample area

Monitoring of turbidity, DO, conductivity, temperature, and fluorescence was conducted at five different locations on the Tonle Sap–Mekong–Bassac system (Cambodia) between 2004 and
2010 using a combination of Hydrolab and YSI datasondes. The sample site locations are shown in Figure 1(a) and (b).

One of the reasons for focusing the monitoring on the Tonle Sap–Bassac–Mekong intersection (locally known as the Chaktomuk Junction) is the interesting and complex hydraulic situation as seen in the satellite image (Figure 1(b)). In addition, we were interested to see if the impact of Phnom Penh waste discharges could be detected at the Bassac (Chbar Ampov) site. Finally, the Tonle Sap represents a complex ‘pulsing system’ ecology as the result of the high flows in the rainy season and low flows during the dry season. These ecological conditions have helped to support the largest inland freshwater fishery in Asia. Flood pulsing also is an important factor governing species diversity and distribution for rivers in other tropical and temperate areas (Junk et al. 1989, Benke et al. 2000, Petry et al. 2003).

High flow down the Mekong River during the rainy season (May/June–October) is sourced from glacier and snowmelt at the headwaters in the Himalayas, as well as rainfall runoff, with September having the highest monthly mean flow (36,700 m$^3$ s$^{-1}$ at Kratie; MRC 2005). Between late May and late September, it is not hydraulically possible for all flow to reach the South China Sea via the Mekong and Bassac Rivers, so excess flow goes up the Tonle Sap River to fill the lake. During the dry season, as flow on the Mekong River declines, water reverses direction, draining from the Tonle Sap Lake, down the Tonle Sap River, to the Bassac/Mekong system. Because of this ‘pulsing’ characteristic, the surface area of the Tonle Sap Lake varies from about 2500 km$^2$ during the dry season to about 15,000 km$^2$ in the rainy season. Water depth increases from around 1 m in the dry season to approximately 7–9 m in the rainy season (Fujii et al. 2003, Koponen et al. 2005).

Lamberts (2008) noted that the flood pulsing appears to be the main force determining the relatively high productivity of the system and that organisms have adapted their life cycle to the pulsing. The flooding of the forest fringe around the lake during the rainy season introduces large amounts of organic and inorganic matter (and associated nutrients) to the water so that the floodplain vegetation acts as a ‘nutrient pump’ promoting

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**Figure 1** (a) Cambodia, showing the Siem Reap and Pursat sample sites on the Tonle Sap Lake, the Preak Kdam water level gauge site, and Phnom Penh and the Chaktomuk Junction to the southeast. (b) Sample sites at the junction of the Mekong, Tonle Sap, and Bassac Rivers (Chaktomuk Junction).
aquatic productivity. Lamberts (2008) also noted that anoxic conditions in the sediment–water interface may release nutrients into the water column. The monitoring at the Pursat sites specifically was designed to explore the dynamics of the flood pulse in the flooded forest fringe, while the monitoring at the other sites was meant to provide an overall view of system dynamics.

2.2 Data collection methods

The monitoring conditions for each site are summarized in Table 1. We migrated from Hydrolab datasondes used earlier in the project to YSI datasondes primarily because the plug and play option with the YSIs reduced down time and maintenance costs, an important consideration when deploying in a remote, developing country. The datasondes at the sites near Phnom Penh (Preak Leap, Chbar Ampov, Russey Keo) were cleaned and data were downloaded once a week. The DO sensor was calibrated using the 100% air saturation method at this time. DO sensor membranes and electrolyte were replaced approximately every 6 weeks. This maintenance schedule is consistent with studies done in the past for US EPA-approved projects (e.g. Irvine et al. 2005). Maintenance and downloading at the sites
on the Tonle Sap Lake was done every 2 weeks because of their remoteness. The datasondes at the PL and Chbar Ampov sites were fixed to floating houses, at Siem Reap the installation was on a floating restaurant, and at Russey Keo the units were attached at a floating dock. Monitoring depth at these sites ranged between 0.5 and 2.0 m below the surface. At the Pursat sites (Figure 1(a)) on the Tonle Sap Lake, the Hydrolabs were held in place using a pole with a weighted bottom stand constructed of a tyre rim filled with cement. The Hydrolab 1 m up from the bottom of the lake was fixed to the stand inside a PVC tube that had holes drilled in it to facilitate water movement. The Hydrolab unit 1.4 m below the surface was attached to the weighted pole with a chain and was floated using empty plastic water containers.

Grab samples (500 ml volume, approximately 0.3 m below the surface) of water for TSS analysis were collected at the PL site on the same days that data were downloaded from the YSI 6920, between 9 July 2009 and 26 March 2010. The samples were filtered using 0.45 μm membrane filters at the Resource Development International – Cambodia water quality laboratory in Ken Svay. The filters were pre-weighed to the nearest tenth of a milligram and 200 ml of the sample was filtered. The sediment and filters were oven-dried at 102°C for 2 h, cooled in a desiccator, and weighed to the nearest tenth of a milligram.

Daily mean water-level data for the Preak Kdam site (Figure 1(a)) were made available through the WUP-FIN programme for the period January 1997 through December 2009. Information about the Preak Kdam site can be accessed at http://fw.mrcmekong.org/stations/pre.htm.

2.3 Applied time-series analysis

Time-series analysis using autoregressive, integrated, moving average (ARIMA) approaches have been used to examine runoff and river discharge (Rao et al. 1982, Kurunc et al. 2005, Yurekli et al. 2005), water levels in lakes (Irvine and Eberhardt 1992, Sheng and Chen 2011), sediment erosion and yield (Caroni et al. 1984, Irvine and Drake 1987, Hanh et al. 2010), and water quality (Ahmed et al. 2001, Lehmann and Rode 2001, Faruk 2010, Hanh et al. 2010). ARIMA models are capable of reproducing the main statistical characteristics of a hydrologic or environmental time series. The models therefore provide information about system dynamics and can be used to forecast a time series into the future.

Much has been written about the theory and applications of ARIMA modelling (e.g. Nelson 1973, Box and Jenkins 1976, Pankratz 1983, Vandaele 1983), so only a brief review is provided here for background. Autoregressive (AR) models basically estimate values for the dependent variable, Zt, as a regression function of previous values, Zt−1, Zt−2, . . . , Zt−p. An AR model of order 1 (i.e. an AR(1) model) can be expressed as:

\[ Z_t = \Phi_1 Z_{t-1} + \alpha_t \]  

(1)

where \( Z_t \) and \( Z_{t-1} \) are the deviations from the mean of the time series, \( \Phi_1 \) is the first-order AR coefficient describing the effect of a unit change in \( Z_{t-1} \) on \( Z_t \), and \( \alpha_t \) represent random shock errors or white noise. Values for \( \alpha_t \) are assumed normally and independently distributed with mean 0 and constant variance. Model stationarity requires that the variance of \( Z_t \) be non-negative and finite (Vandaele 1983) and for these conditions to be met, \(|\theta_1|\) must be less than 1. Higher order AR models are possible, much like a multiple regression, and in this case, the absolute value of each AR coefficient should be less than 1.

Moving average (MA) models incorporate past random fluctuations to represent the time series and an MA model of order 1 (i.e. an MA(1) model) can be expressed as:

\[ Z_t = \alpha_t - \theta_1 \alpha_{t-1} \]  

(2)

where \( \theta_1 \) is the MA coefficient to be estimated and the random shocks (\( \alpha_t \)) are assumed normally and independently distributed with mean 0 and constant variance. The model structure requires the condition of invertibility to be met and \(|\theta_1|\) therefore must be less than 1. Values greater than 1 indicate that observations further in the past have a greater influence on \( Z_t \) than more recent observations which is unlikely in hydrologic time series. Higher order MA models are possible, and like the AR model coefficients, the absolute value of each MA coefficient should be less than 1.

The statistical structure of a time series should be represented by a parsimonious model, and in some cases, parsimony can be achieved using a mixed (ARMA) model rather than a pure AR or MA model. As such, it would be more parsimonious to represent a time series with an ARMA(1 1) model than an AR(3) model because fewer model parameters need to be estimated. It is possible to mix models because these models theoretically can be rewritten as pure AR or MA models of infinite order (Vandaele 1983). Furthermore, a hydrologic time series is the result of several interactive processes that may have both a seasonal and a random fluctuation component. The mixed model structure can provide additional flexibility in describing the result of the interaction between the processes (Salas et al. 1980).

Hydrologic time series frequently exhibit a regular seasonal pattern that can be removed by standardizing the data for the seasonal mean and standard deviation and then re-trending the forecasts using the inverse of the de-seasonalizing transformation. Alternatively, an ARIMA model can be developed simultaneously for both the antecedent and seasonal component and is known as a multiplicative, seasonal model with the general form:

\[ (p \ d \ q) \times (P \ D \ Q) \]  

(3)

where \( p \) is the non-seasonal AR order, \( P \) the seasonal AR order, \( q \) the non-seasonal MA order, \( Q \) the seasonal MA order, \( d \) the non-seasonal differencing order, \( D \) the seasonal differencing order, and \( s \) the seasonal span (e.g. = 12 for an annual trend in monthly data). Differencing is done as a de-trending step to
Table 1  Sample sites and monitoring methods, 2004–2010.

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
<th>Parameters measured</th>
<th>Time step for measurements (min)</th>
<th>Monitoring period</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL, Mekong River</td>
<td>Hydrolab 4a</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>15</td>
<td>16 August 2004–20 August 2006</td>
</tr>
<tr>
<td>PL, Mekong River</td>
<td>YSI 6920</td>
<td>Turbidity, DO, conductivity, temperature&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30</td>
<td>17 September 2007–30 April 2010</td>
</tr>
<tr>
<td>Chbar Ampov, Bassac River</td>
<td>Hydrolab 4a</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>15</td>
<td>18 November 2004–18 August 2006</td>
</tr>
<tr>
<td>Chbar Ampov, Bassac River</td>
<td>YSI 6600 or 6920</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>30</td>
<td>1 September 2007–22 February 2009&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Russey Keo, Tonle Sap River</td>
<td>Hydrolab 4a</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>15</td>
<td>16 August 2004–19 August 2006</td>
</tr>
<tr>
<td>Pursat, Site 1, Tonle Sap Lake</td>
<td>Hydrolab 4a</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>30</td>
<td>1 August 2005–9 September 2005&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pursat, Site 2, Tonle Sap Lake</td>
<td>YSI 6920</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>30</td>
<td>9 September 2005–22 January 2006&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Siem Reap, Tonle Sap Lake</td>
<td>YSI 6920</td>
<td>Turbidity, DO, conductivity, temperature</td>
<td>30</td>
<td>1 September 2007–31 March 2009</td>
</tr>
</tbody>
</table>

<sup>a</sup>A second YSI 6920 was installed at this site between 3 July 2009 and 27 November 2009 to provide redundant measures of DO, conductivity, and temperature; and in place of turbidity, fluorescence was measured.

<sup>b</sup>Fluorescence measurements were done using a YSI 6600 at this site between 3 July 2007 and 14 August 2007.

<sup>c</sup>Monitoring was done 1.4 m below the surface from 1 August 2005 to 27 August 2005 and 1 m up from the lake bottom (average of 5.5 m below the surface) from 27 August 2005 to 9 September 2005.

<sup>d</sup>Monitoring was done 1.4 m below the surface and 1 m up from the lake bottom (5–9 m below surface).
help produce stationarity in a non-stationary time series. Greater detail on the multiplicative, seasonal model form also is provided by Irvine and Eberhardt (1992) and Ahmed et al. (2001).

The general steps in ARIMA modelling are: (1) identify the model, (2) estimate the coefficients of the identified model, and (3) verify the model through diagnostic checks. Model identification was done using trend analysis with the Mann–Kendall test and an examination of the autocorrelation and partial autocorrelation plots for the time series (e.g. Nelson 1973, Box and Jenkins 1976, Pankratz 1983, Vandaele 1983). The coefficients of candidate models were estimated using the approximate maximum-likelihood approach. Verification of the model was done using a combination of the Akaike information criteria (AIC) and the Ljung–Box Q-statistic. In essence, the AIC considers residual variance, together with the number of model coefficients, and the preferred model is the one that yields the minimum AIC value. The Ljung–Box Q-statistic is used to determine if the residual autocorrelations from the model in question can be considered white noise (i.e. all deterministic information has been removed from the time series), based on a comparison with a \( \chi^2 \) distribution.

The data used for the ARIMA modelling were the monthly mean water levels at Preak Kdam (averaged from daily means) for 1997–2009 \((n = 156)\) and monthly mean temperature, DO, and conductivity at the PL site, 2004–2010 \((n = 53)\). There is some debate in the literature about the minimum number of observations needed for successful ARIMA analysis, although frequently a minimum of \( n = 50 \) is suggested (Yurekli and Kurunc 2005, Hyndman and Kostenko 2007). It was decided to use the entire record available for the water level to capture as many seasons as possible. There were some months of missing data for the PL site, although it met the minimum observation guideline of \( n = 50 \) and had the longest uninterrupted time series of the water quality sites. The ARIMA analyses were conducted using the XLSTAT add-in for Excel.

3 Results

3.1 Monthly mean water quality at PL and Chbar Ampov, 2004–2010

The PL (Mekong River) and Chbar Ampov (Bassac River) sites have the longest and most complete data records of the sites monitored and therefore were used to calculate monthly mean values of temperature, conductivity, DO, and turbidity, representing the period 2004–2010 (Figure 2(a)–(d)). The mean values shown in Figure 2(a)–(d) were calculated by averaging the monthly means from the period 2004–2010. The monthly mean temperatures at the two sites exhibit a similar temporal trend, with peak temperatures corresponding to the warmest months of February through April in Cambodia. A secondary peak appears in October. The Chbar Ampov site tends to be slightly warmer than the PL site as the Bassac River is smaller than the Mekong and also is impacted by discharges and urban infrastructure along the Phnom Penh waterfront (Figure 1(b)).

Conductivity at both sites starts to decrease with the onset of the rainy season and as flow down the Mekong River increases. In most years, conductivity increases at the PL site within a span...
of 1–2 weeks in mid-October, when the flow on the Mekong River begins to recede with the start of the dry season. The conductivity then stays relatively high at PL during the duration of the dry season. Conductivity at the Chbar Ampov site differs from the PL site in that values stay relatively low in November through February. These lower values during this 4-month period are related to the impact of outflow from the Tonle Sap Lake, which normally starts in mid- to late-September (MRC 2005). Conductivity on the Tonle Sap Lake tends to be lower than the Mekong River (see also Figure 3(b)).

The levels of DO generally are higher at the PL site, and this results from a combination of several factors: (i) flow is greater and more turbulent at the PL site, (ii) Chbar Ampov receives waste discharges and associated higher biochemical oxygen demand (BOD) levels from Phnom Penh, and (iii) Chbar Ampov is impacted directly by the drainage from the Tonle Sap Lake starting in mid- to late-September and DO levels associated with the lake may be lower (see also Figure 3(c)). Both the PL and Chbar Ampov sites exhibit relatively lower DO levels during the later dry season period of March and April.

Turbidity at both the PL and Chbar Ampov sites peak in August, in association with the increasing flows of the rainy season down the Mekong River, but 1 month earlier than the peak flows of September. The higher turbidity values at the Chbar Ampov site may be related to the smaller channel, local erosion of the unprotected banks, and discharges from the city of Phnom Penh.

Correlations between the water quality parameters at each of the PL and Chbar Ampov sites, as well as water level at Preak Kdam, are shown in Tables 2 and 3. In general, it was found that a log_{10} transformation of the data provided the strongest correlations.

The best ARIMA models for Preak Kdam water level and temperature, conductivity, and DO at PL are summarized in Table 4 and the 1-month ahead forecasts are shown in Figure 4. In the first step of model identification, the Mann–Kendall test showed there was no significant long-term trend in the data series for water level, but there was a significant seasonal (12 months) trend, and these results were also supported by the autocorrelation and partial autocorrelation plots (in consideration of space, the autocorrelation and partial autocorrelation plots for the different data series are not shown). The Mann–Kendall test, autocorrelation and partial autocorrelation plots also suggested that there were: (1) a small, but significant long-term (increasing level) trend and seasonal (12-month) trend for DO; (2) no significant long-term trend, but a significant seasonal trend for conductivity; and (3) interestingly, no significant long-term or seasonal trend for temperature. From competing possible models that were identified, the models summarized in Table 4 were those that minimized the AIC statistic, that met the invertibility condition, and for which the residuals could be considered white noise based on the Ljung–Box Q-test (α = 0.05).

### 3.2 Monthly mean water quality at Siem Reap and PL, 2007–2009

Monitoring was conducted concurrently on the Tonle Sap Lake at Siem Reap and at the PL site between September 2007 and March 2009 and the monthly mean temperature, conductivity,
DO, and turbidity are shown in Figure 3(a)–(d). The PL data, 2007–2009, is a subset of the PL data, 2004–2010, discussed in the previous section. The monthly mean temperatures at the two sites exhibit a similar temporal trend, given their distance apart and the difference in the water body characteristics. The Siem Reap site tended to be warmer than the PL site because the water is shallower in this area and there also is much less water movement when compared with that in PL.

The peak in conductivity at Siem Reap in April 2008 occurred at the end of the dry season and just prior to the freshwater pulse from the Mekong River. The April peak may, in part, reflect resuspension of the bed material due to wind events when the lake is at its shallowest, as well as waste inputs from local floating villages on the lake. It is worth noting that the conductivity on the Tonle Sap is relatively low from October through March each year, and as noted above, this is a period during which water will drain from the Tonle Sap Lake and result in lower conductivity on the Bassac River (Figure 2(b)).

DO levels are lower on the Tonle Sap Lake at the Siem Reap site when compared with the Mekong River at PL (Figure 3(c)). This result is not surprising given the greater turbulence and flow rate on the Mekong River. In addition, organic decay associated with the flooded forest fringe (Lamberts 2008) and waste inputs from local floating villages would act to lower the DO levels.

Turbidity on the Tonle Sap Lake at the Siem Reap site is relatively low during the dry season and generally is lower than that observed for PL. The transport capacity of the flow would be greatly diminished as it enters the lake during the rainy season, resulting in some deposition. Deposition would continue as the dry season progresses. Some of the higher turbidity values at Siem Reap (e.g. April and May 2008) may be the result of inputs from local rivers and/or bed resuspension by wind.

**Table 2** Water quality and water level correlations for monthly mean data, PL.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Conductivity (mS/cm)</th>
<th>DO (mg/l)</th>
<th>Turbidity (NTU)</th>
<th>Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO (mg/l)</td>
<td>−0.440</td>
<td>−0.226</td>
<td>−0.505</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>0.075</td>
<td>−0.514</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water level (m)</td>
<td>−0.588</td>
<td>−0.836</td>
<td>0.421</td>
<td>0.221</td>
<td></td>
</tr>
</tbody>
</table>

Note: Bold values were significantly different from 0 ($\alpha = 0.05$).

*Water level data are for the Preak Kdam site.

**Table 3** Water quality and water level correlations for monthly mean data, Chbar Ampov.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Conductivity (mS/cm)</th>
<th>DO (mg/l)</th>
<th>Turbidity (NTU)</th>
<th>Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>0.639</td>
<td>1</td>
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<td></td>
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</tr>
<tr>
<td>DO (mg/l)</td>
<td>−0.220</td>
<td>0.272</td>
<td></td>
<td>−0.280</td>
<td>1</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>0.050</td>
<td>0.071</td>
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<td></td>
</tr>
<tr>
<td>Water level (m)</td>
<td>−0.599</td>
<td>−0.237</td>
<td>0.500</td>
<td>0.10</td>
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</tr>
</tbody>
</table>

Note: Bold values were significantly different from 0 ($\alpha = 0.05$).

*Water level data are for the Preak Kdam site.

**Table 4** Summary of ARIMA model structure and coefficient values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model structure</th>
<th>AR(1)</th>
<th>MA(1)</th>
<th>AR(1)s</th>
<th>AR(2)</th>
<th>MA(1)s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water level (m)</td>
<td>(1 0 1) × (0 1 1)12</td>
<td>0.785</td>
<td>0.168</td>
<td></td>
<td>−0.904</td>
<td></td>
</tr>
<tr>
<td>DO (mg/l)</td>
<td>(0 1 1) × (2 1 0)12</td>
<td>0.613</td>
<td>−0.513</td>
<td>−0.984</td>
<td>−0.936</td>
<td></td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>(1 0 0) × (1 1 0)12</td>
<td>0.672</td>
<td>0.998</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>(1 1 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Water level data are for Preak Kdam; water quality data are for PL.

$s$ is the seasonal (12 months) part of the model.

3.3 Freshwater pulse and vertical variability on the Tonle Sap Lake flooded forest fringe

At the Pursat site on the Tonle Sap Lake, Hydrolab Site #1 was operated between 1 August 2005 and 27 August 2005 with measurements made at a depth of 1.4 m below the surface and between 27 August 2005 and 9 September 2005 at a depth of
Figure 4  ARIMA model 1 month ahead forecasts for (a) water level at Preak Kdam, (b) DO at PL, (c) specific conductivity at PL, and (d) temperature at PL.
approximately 1 m up from the lake bed (or an average of 5.5 m below the surface). Site #1 was specifically located within an area of black water (so-called because high organic and humic acid content produces both a distinctive black colour and low oxygen level) that was expected to be inundated by a freshwater pulse. Monitoring was moved to Site #2 (approximately 4.5 km southwest) on 9 September 2005 and ended on 22 January 2006. The site was moved in an effort to continue tracking the expansion of the freshwater inflow. At Site #2, one Hydrolab was fixed on a stand, approximately 1 m up from the lake bed (5.0–9.0 m below the surface), while a second Hydrolab was attached to floats connected to the stand and took readings approximately 1.4 m below the surface.

A well-developed diurnal pattern for DO was observed at Hydrolab Site #1, superimposed by wind-induced mixing of oxygenated flood waters and oxygen-depleted black water fronts developed within the flooded forest fringe (Figure 5). This pattern is related to the daily cycle of aquatic organism photosynthesis during the day and respiration at night and represents system metabolism (Odum 1956, Chapra and Di Toro 1991, Ansa-Asare et al. 1999, Mulholland et al. 2005). The DO levels were low for much of the period between about 1 August 2005 and 11 August 2005, representing black water conditions (Figure 5). As the levels in the Tonle Sap rose, the flooded forest became inundated with oxygenated water, a process that occurred between about 11 August 2005 and 21 August 2005. Conductivity and turbidity (Figures 6 and 7) also showed an increasing trend during this time. Some of the noise in the data was due to storm events and wave action.

Data from Hydrolab Site #2 illustrate the onset of the dry season and the expansion of the black water area, as the freshwater drained back down the Tonle Sap to the Mekong and Bassac Rivers (Figure 8). DO levels 1.4 m below the surface declined to near 0 mg/l by the end of October. Interestingly, the water 1 m up from the lake bed remained anoxic throughout the monitoring period while the upper water column had higher levels of DO.

Turbidity also exhibited vertical variation in the water column at Site #2 (Figure 9), for example, with the turbidity 1 m up from the lake bed averaging 230 Nephelometric Turbidity Units (NTU) between 14 October 2005 and 27 October 2005 and the turbidity 1.4 m below the surface averaging 32.3 NTU for the same period. The higher turbidity near the bed may be due to a layer of floating organic matter. Dr Michael Sampson, Director of Resource Development International – Cambodia (personal communication), observed this type of layer, which drastically reduced light penetration, in the small lakes (preaks) around Kean Svay when he was diving to install sediment peepers.

Finally, it is worth noting that vertical variation in conductivity at Hydrolab Site #2 was also observed, with higher conductivity near the bottom. The higher conductivity could have two sources: dissolved material release from bed sediment and the possibility of the floating organic-rich layer near the bottom noted by Dr Sampson.

3.4 Redundant measurements, fluorescence, turbidity, and TSS at PL

Two YSI 6920 datasondes were installed at PL for redundancy analysis and also to simultaneously measure turbidity and
fluorescence (chlorophyll a) between 3 July 2009 and 27 November 2009. Weekly mean values were calculated for each parameter measured by the two datasondes and the correlation (r) between the two units was 0.9995, 0.998, and 0.74 for conductivity, temperature, and DO, respectively. These results were acceptable in providing a level of quality assurance for the data.

The correlation (r) between fluorescence and turbidity was 0.71 and between DO and fluorescence was −0.59. Fluorescence is a surrogate measure for chlorophyll a. We did not directly measure chlorophyll a in the Mekong River but Irvine and Murphy (2009) found that the mean measured chlorophyll a level in a study on the Buffalo River, NY, was 3.3 μg/l and the level represented by a YSI fluorescence sensor was 3.5 μg/l. While strong relationships between fluorescence and chlorophyll a have been reported, strictly speaking fluorescence should be calibrated using site-specific chlorophyll a measurements (Wiltshire et al. 1998, Pinto et al. 2001) and this should be done in future studies. Weekly mean chlorophyll a levels (as represented by fluorescence) for the period 3 July 2009 to 27 November 2009 frequently were quite low, averaging 9 μg/l and ranging between 4.6 and 41.2 μg/l. The highest two levels of mean chlorophyll a (41.2 and 17.5 μg/l) occurred in successive weeks (ending 9 October 2009 and 16 October 2009). Between 3 July 2007 and 14 August 2007, separate fluorescence measurements at the Chbar Ampov site averaged 4.2 μg/l. By comparison, Irvine and Murphy (2009) used a guideline of 8 μg/l to identify eutrophic conditions in the temperate, mid-latitude, Buffalo River. Eloheimo et al. (2002) reported chlorophyll a levels for the Tonle Sap Lake averaged 4.5 μg/l with a range of 0.3–14.0 μg/l. Campbell et al. (2006) noted that there was limited chlorophyll a data for the Tonle Sap Lake, but showed average monthly values from Kampong Luang to be between approximately 7.5 and 10 μg/l in August, October, and December 2003. The data from Eloheimo et al. (2002) and Campbell et al. (2006) are consistent with our measurements.

A linear regression was done between the TSS samples (n = 34) and the daily mean turbidity on the sample day and the results are shown in Figure 10. The sampling time for the regression covered both the rainy and dry season. The slope of the regression was significantly different from 0 (α = 0.05; p = 1.86 × 10−22) and the r² was 0.95. The strength of the relationship certainly is at the higher end of those reported in the literature (Lewis 1996, Sun et al. 2001, Irvine et al. 2002, Pfannkuche and Schmidt 2003, Gould et al. 2010). The regression could be used to estimate TSS values for the PL site based on the continuous turbidity monitoring to construct a daily mean record for TSS. However, TSS–turbidity relationships may be both site- and time-specific, so that a relationship is normally unique for a particular catchment and within a particular period of time (Sun et al. 2001, Irvine et al. 2002). The relationship shown in Figure 10 therefore could not necessarily be used directly for other sites in the Mekong system.

4 Discussion

Routine monitoring of water quality in the Mekong River/Tonle Sap Lake system is overseen by the MRC and in collaboration with Mekong country line agencies. This routine monitoring is important, but has some limitations in that the samples are collected on a monthly basis. It is highly unlikely that monthly spot sampling will capture short-lived, extreme events such as night-time anoxia or temporary, point-source releases. From a biological perspective, such events have the potential to significantly impact local populations despite their short duration. Figures 5 and 8 illustrate this point well. The minimum DO level of 0.2 mg/l occurred at 04:00, for example, on 15 August 2005 (Figure 5), while the maximum value of 5.5 mg/l was observed at 18:30. A typical daytime spot sampling would miss this brief anoxia period where DO was well below lethal levels for some fish.

Extreme values determined on a particular sample day could bias results reported for that month and identification of regular system trends, distinct from extreme values, will be complicated. For example, the 30 min duration curves of DO at the Siem Reap site for the month of September 2008 and at the PL site for the month of November 2007 are shown in Figure 11. If a sample was collected once in September 2008, at Siem Reap and the measured DO was 1 mg/l, this value would considerably
underestimate the true monthly mean DO, as levels were >1 mg/1 83% of the time. The duration curve for the PL site, November 2007, is considerably flatter than the September 2008 curve for Siem Reap. As a result, the day that a single particular sample was collected during the month at the PL site (November 2007) would have less impact on how representative that value was for the month. The duration curve shapes varied at each site from month to month and also were different between sites. For locations that exhibit a pronounced diurnal pattern, the time of day that DO is measured would also influence monthly values that are based on single measurements. Using the 15 August 2005 (Figure 5) example from above, a single sample collected, say, between 10:00 and 11:00 would result in a ‘monthly’ estimate of 1.3 mg/l, whereas a single sample collected between 16:30 and 17:30 would result in a ‘monthly’ estimate of 4.4 mg/l.

Major ecosystem events of 2–3 weeks duration might be entirely missed with a monthly sample framework. For example, turbidity averaged 113 NTU between 3 July 2009 and 12 July 2009 at the PL site on the Mekong River, while turbidity averaged 265 NTU between 13 July 2009 and 31 July 2009, a 134% increase. Turbidity averaged 765 NTU between 1 May 2008 and 19 May 2008 at the Siem Reap site on the Tonle Sap Lake, while turbidity averaged 243 NTU between 20 May 2008 and 31 May 2008, a 68% decrease. Continuous monitoring of basic water quality parameters can help to identify long-term, year-to-year, seasonal, and diurnal trends that will provide a better understanding of system dynamics, more accurate modelling, and better management decisions.

Water level (as measured at Preak Kdam) had a significant positive correlation with DO (PL and Chbar Ampov sites) and significant negative correlation with temperature (PL and Chbar Ampov sites) and conductivity (PL site only). The higher flows appear to dilute dissolved material, as reflected by lower conductivity, and this finding is consistent with Prathumratana et al. (2008) who analysed the monthly data from the MRC for the Kratie and Kampong Cham sites on the Cambodian section of the Mekong River. It is not surprising that DO is greatest during the higher flow months, as greater turbulence and freshwater runoff would serve to boost oxygen levels and dilute urban waste discharges (particularly at Chbar Ampov). Prathumratana et al. (2008) reported a significant positive correlation between suspended solids concentration and water level at the Kratie and Kampong Cham sites. Although there was a positive correlation between water level and turbidity shown in Tables 2 and 3, the relationships were not significant. The correlation between water level and turbidity for the PL site was greater than at the Chbar Ampov site, possibly because PL experiences a more well-defined, unidirectional flow, upstream of the Chaktomuk Junction and is not impacted by the dry season outflow from the Tonle Sap Lake, or the local waste discharges from Phnom Penh. These factors may also explain why the correlation between water level and conductivity was stronger for the PL site than the Chbar Ampov site.

Monthly mean water levels at Preak Kdam were adequately forecast at 1 month ahead time steps using an ARIMA model with the general form (1 0 1) × (0 1 1)12. The ARIMA model was able to represent the underlying statistical structure of the water levels, particularly the seasonal element. Irvine and Eberhardt (1992) found that monthly mean water levels for Lake Erie and Lake Ontario also could be represented by ARIMA models with the same general form. The seasonal MA(1)12 coefficient values for Preak Kdam, Lake Erie, and Lake Ontario were similar, being in the −0.904 to −0.9721 range, but there were differences in the non-seasonal coefficients, particular for the AR(1) elements which were negative for Lake Erie and Lake Ontario and positive for Preak Kdam. With a simple AR(1) model, a negative coefficient indicates that a positive change in level in the previous month would be balanced by a negative change in the current month. However, the situation is more complex with mixed ARIMA models and the differences in parameter signs would reflect differences in underlying processes that impact water level (rainfall, direct runoff, throughflow, evaporation, and storage terms). Rao et al. (1982) concluded that a (5 0 0) × (0 1 1)12 model was the best for two rivers in India. Such high-order non-seasonal AR components could not be supported for Preak Kdam. Kurunc et al. (2005) noted that the seasonal component for monthly flow of a river in Turkey had the form (0 1 1)12, although they did not provide information on the non-seasonal component. The
Conductivity and DO were adequately forecast 1 month ahead using mixed seasonal, multiplicative ARIMA models, but each had a different general form (Table 4). Ahmad et al. (2001) reported seven different appropriate forms of the seasonal, multiplicative model for conductivity, when applied to nine different water quality stations on the Ganges River. None of the models reported by Ahmad et al. (2001) had higher than a first-order operator. Temperature of the PL site did not exhibit a significant seasonal trend, but this in part may be due to a more complex, double peak structure, with the primary peak occurring in April–May and a secondary peak occurring in October. Zhang et al. (2007) also showed a double peak structure in monthly mean temperature for the Mekong River at the Chiang Saen (Thailand) site as did Campbell et al. (2006) for the Tonle Sap Lake at Kampong Luong. Campbell et al. (2006) attributed the decline in temperature between May and August to increased cloudiness and runoff during the rainy season. Temperature apparently then increased for a couple of months at the end of the rainy season but before the onset of the cold season in November. Temperature was adequately forecast at the PL site using a non-seasonal model approach, but the data structure should be investigated further, with a longer time series. Hanh et al. (2010) took a different approach to forecasting water temperature in the lower Mekong River, using ARIMA-based seasonal transfer functions to estimate water quality time series from river discharge. The seasonal transfer function models were successfully applied for 9 of 17 parameters (DO, pH, and chemical oxygen demand were among the parameters not well modelled with this approach).

Conductivity is a good indicator of seasonal change in flow characteristics and source water inputs. Towards the onset of the dry season (mid-October), conductivity tends to increase on the Mekong River and then starts to decline around June, with the beginning of the rainy season. Our study showed that conductivity on the Tonle Sap Lake (Siem Reap and Pursat sites) and Bassac River (Chbar Ampov site) tended to be lower than conductivity on the Mekong River during the dry season, but approached, and in some cases exceeded, the conductivity on the Mekong during the rainy season. MoWRAM (2009) averaged conductivity for 2005–2008 from four sites on the Mekong River (Stung Treng downstream to Chrouy Chanvar), three sites on the Bassac River (Takhmao to Koh Thom), and two sites on the Tonle Sap Lake (Phnom Krom and Kampong Loung). Generally, the monthly trends in conductivity were similar to those observed for our data, although the absolute values of conductivity were somewhat different because of MoWRAM’s averaging across several sites. MoWRAM (2009) also showed that conductivity was highest for the Mekong River sites while the Tonle Sap Lake had the lowest values and the Bassac River sites were intermediate between the Mekong River and Tonle Sap Lake. During July, August, and September, MoWRAM (2009) showed the conductivity for the three water bodies to be similar in value. Higher conductivity on the Mekong River may be related to greater ionic concentrations that are picked up as the river passes through the karst landscape of Laos (Campbell et al. 2006). The ionic strength in the Mekong River would be diluted during the rainy season. Interestingly, MoWRAM (2009) also showed a secondary peak in conductivity on the Bassac River for September, although not as high as that shown in Figure 2(b). The cause of this secondary peak is not clear. Irvine et al. (2006) showed that the conductivity at Chbar Ampov could exhibit a diurnal trend, particularly during the dry season, which was related to the discharge activities of Phnom Penh and the large Chbar Ampov market upstream of the site.

Near surface DO levels were higher on the Mekong River at PL than at the monitoring sites on the Tonle Sap Lake (Pursat and Siem Reap), as there is much greater water movement, mixing, and gas exchange in the river. However, the dynamics of DO within the lake appear to be quite complex, both temporally and spatially. Sarkkula and Koponen (2003), using a 3D modelling approach, showed that surface DO levels in the Siem Reap area could be in the 0–4 mg/l range, consistent with the data for our Siem Reap site (Figure 3(c)). The model also showed that higher DO levels (in the 7 mg/l range) might be expected at the surface throughout the central, deeper water of the lake. Our monitoring at the Pursat sites clearly showed the diurnal pattern of DO in the flooded forest fringe related to the metabolic activity of the ecosystem, as well as the decreasing (horizontal) area of black water during the rainy season freshwater pulse and the increasing (horizontal) area of black water during the draining of the lake in the dry season (Figures 5–8). Although a diurnal cycle in DO levels was observed near the surface in the Tonle Sap Lake at Pursat, DO levels 1 m up from the lake bed remained constant and essentially anoxic. This finding is consistent with the model results from Sarkkula and Koponen (2003). This anoxic layer probably results from the large organic input related to the flooding of the forest and may be related to the high-anoxic layer also observed at this level.

Turbidity and conductivity in the flooded forest fringe of the Tonle Sap Lake (Pursat site) exhibited clear vertical variation. Turbidity 1.4 m below the surface was relatively low, in the range of 30–50 NTU, but 1 m up from the lake bed turbidity was in the 150–300 NTU range. This higher turbidity near the bed may be the result of floating organic matter that does not fully settle. Irvine et al. (2007) sampled water at both depths and performed non-destructive image analysis to assess sediment size. The sediment was quite fine in texture, with median
diameters ($d_{50}$) ranging between 2.86 and 3.24 $\mu$m, and the sediment was not highly flocculated. In comparison, a sample collected at the PL site had a $d_{50}$ of 3.52 $\mu$m, while Wolanski et al. (1998) reported mean suspended sediment diameter in the Mekong River Delta area (Vietnam) to be in the 4–7 $\mu$m range. The sediment was more flocculated in the Delta area, probably because of the saltwater influence.

There has been ongoing debate regarding the impact that dam construction for hydropower production may have on the lower Mekong River, Mekong Delta, and the Tonle Sap Lake. For example, proponents of the Chinese cascading dam system on the upper Mekong River (Lancang River) suggest that in addition to cheap hydropower, the dams will produce benefits, including flood control and improved irrigation and domestic water supply by increasing dry season flow (Zhou 2009). Furthermore, Zhou (2009) concluded that water from the Lancang River only accounts for 13.5% of the total flow to the ocean from the Mekong, so the impact of the dams decreases the further downstream one goes and that most sediment yield comes from northern Laos, not China, so impact on sediment delivery to the Mekong Delta would be minimal. Lu et al. (2008) analysed flow data for the period 1962–1991 (pre-Manwan dam construction on the Lancang) and 1992–2003 (post-Manwan dam construction). They concluded that the dam operation may be producing a slightly opposite result than expected, in that the flows seemed to be slightly lower in the dry season. Lamberts (2008) noted that although the total flow on an annual basis may not be impacted by the Lancang cascading system, in general water levels on the Tonle Sap could be less variable (higher in the dry season), which would result in areas of flooded forest that would not dry out, thereby impacting the ecology of the system. In contrast to Zhou (2009), Walling (2008) reported that the Lancang River contributes about 50% of the downstream sediment load of the Mekong River but concluded that as of 2002, the construction of dams on the Lancang River had little impact on the sediment load. Walling (2008) did not use the MRC-collected data in this analysis because samples in the MRC programme are collected monthly and near the surface, rather than being a depth-integrated collection. Walling (2008) noted that the sediment concentration increases with depth and sample collection near the surface would underestimate the sediment load. There is no doubt that sediment concentration will increase with river depth, although this relationship may be spatially variable (e.g. Wolanski et al. 1998) and it is interesting to note that Irvine et al. (2006) found turbidity and conductivity quite constant between the surface and a depth of 8 m (the full length of the communication cable) in Hydrolab profiling of the Chaktomuk Junction on 7 June 2004. Kurnmu and Varis (2007) used the MRC data and showed that a significant decrease in the TSS concentration occurred at the Chiang Saen (Thailand) sample station after the 1993 completion of the Manawan Dam on the Lancang, although impacts further downstream were more difficult to detect. Our monitoring started after the completion of the first two Lancang cascading dams, so we are unable to detect changes from pre-construction conditions, but continued monitoring would be helpful in detecting changes with future construction. The strong TSS–turbidity rating curve developed for the Mekong River in this study could be particularly helpful in these evaluations.

5 Conclusion

Seasonal, daily, and spatial trends in conventional water quality parameters were clearly identified in the Mekong–Tonle Sap system. These trends were related to the monsoonal rainy season–dry season annual cycle, system metabolism, hydraulics of the system, and in some cases, localized phenomena such as waste discharges. ARIMA models generally were successful in reproducing the statistical structure of these underlying trends and provided acceptable 1 month ahead forecasts. Strongly developed vertical variation of turbidity, DO, and conductivity was observed in the flooded forest fringe area of Pursat on the Tonle Sap Lake. An excellent relationship was established between daily mean turbidity and TSS concentration for the PL site on the Mekong River, with an $r^2$ of 0.95. Continuous monitoring of conventional water quality parameters appears to be a useful tool to help identify baseline system conditions in the Mekong–Tonle Sap system, against which impacts from development or climate change might be identified.

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