Analysis of variation and relation of climate, hydrology and water quality in the lower Mekong River

Pham Thi Minh Hanh, Nguyen Viet Anh, Dang The Ba, Suthipong Sthiannopkao and Kyoung-Woong Kim

ABSTRACT

In order to determine the influence of climate and hydrology on water quality of the lower Mekong River, the long term monitoring data (from 1985 to 2004) of climatic, hydrological and water quality variables were analyzed. In general, water quality was 'good' or 'very good' for most of the investigated water quality parameters including DO, pH, conductivity, nitrate, phosphate and total phosphorus. All climatic and hydrological elements as well as most of the water quality parameters varied seasonally. Throughout the 18-year period, only evaporation, water level and TSS showed a significant pertinent trend. ARIMA models results reveal that among climatic and hydrological paremeters, water quality could be effectively predicted from the data of discharge flow and precipitation. The results showed good R^2 ($\geq$0.7) estimation between predicted and observed values for TSS, alkalinity and conductivity which are the chemically and biologically conservative parameters. For other water quality parameters such as Ca^{2+}, Mg^{2+}, Si, Cl^{-}, NO_3^{-}, and SO_4^{2-}, the predicting results by ARIMA model were reliable in shorter period than the above three mentioned variables.

Key words | ARIMA, climate, hydrology, lower mekong river, water quality

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INTRODUCTION

The Mekong River is the longest river in Southeast Asia, and the 10th largest river in the world by discharge (Dai & Trenberth 2002). Over 55 million people live in the lower Mekong Basin (LMB), in which about 75% earn their livelihood from agriculture in combination with other activities such as fishery, livestock, and forestry. This explains why river water is the most important natural resource within the area. Established since 1950s, the Mekong River Committee (MRC) has first paid attention to water quantity by collecting hydro-climatic data since 1960s (Jacobs 1996). Later in mid 1980s, water quality has also been monitored (monitoring of the Cambodian stretch of the Mekong only began in 1993) (MRC 2007). Using the available data from MRC, this study assessed the seasonal variation of water quality in the mainstream of the lower Mekong River and the long-term trend of climate, hydrology and water quality parameters. To take further steps from preliminary research of the relationship between climatic,

doi: 10.2166/wst.2010.449

hydrological elements and water quality in the lower Mekong River conducted by Lunchakorn *et al.* (2008), this study focused on the prediction of water quality from the climatic and hydrological data by applying the Autoregressive Integrated Moving Average models (ARIMA).

METHODS

Study area and data collection

The lower Mekong river of about 2,390 km length, runs through Thailand, Laos, Cambodia and Vietnam. The lower Mekong basin covers 76% (604,200 km^2) of the total Mekong river catchment area and contributes 80 to 85% of the water to the Mekong river (MRC 2005). The study area has tropical climate with two distinct seasons. The wet season (from mid-May to late-October) has higher average air temperature than that of a dry season (the rest of the year) and occupies 85% of annual precipitation (Jacobs 1996; MRC 2005). According to Mekong River Commission's land cover dataset 1997, forest is the dominant land use in the Laos and Cambodia part of the lower Mekong basin while agriculture is the dominant land use in the Thailand and Vietnam part. Agriculture is the single most important economic activity in the Lower Mekong Basin (MRC 2003). Data used in this study were obtained from 8 main stream sampling sites of the Mekong River Commission monitoring program (Figure 1). Hydrological (discharge and mean water level) and climatic (evaporation and precipitation) elements were daily measured while water quality parameters were managed as monthly values for all the sampling sites (Table 1). Chiang Saen is located in the most upstream part of the lower Mekong river, followed by Luang Prabang, Vientiane, Khong Chiam, Kratie, Kampong Cham, Tan Chau and My Tho where this river discharges into the South China Sea.

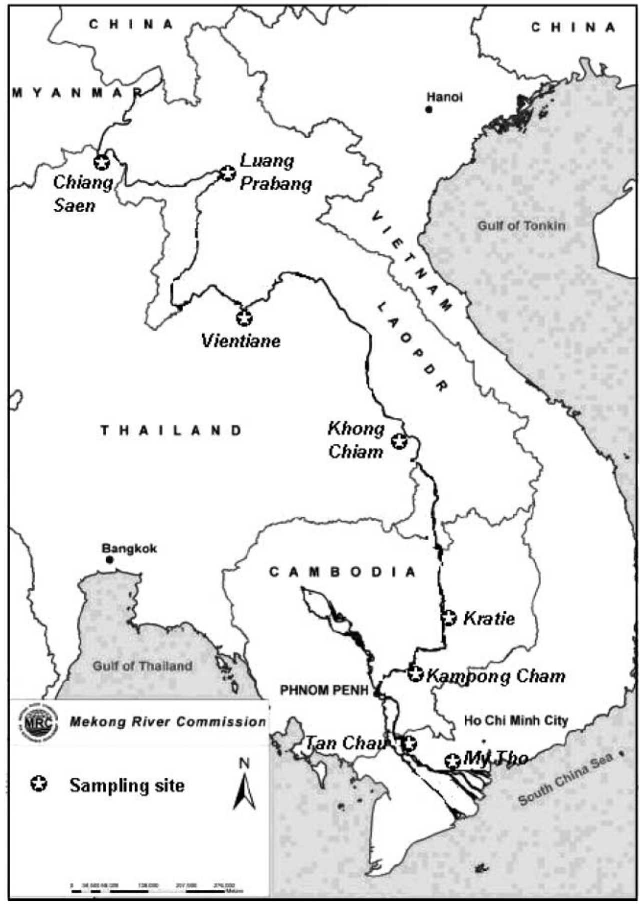

Figure 1 | Study area and sampling sites in the lower Mekong River.

Statistical analysis

The surface water quality, climatic and hydrological data were analysed using descriptive statistics (range, mean, standard deviation). Surface water quality was then compared with the referenced standard levels (SEQ-Eau 1999) and the major elements concentrations in Asia and Global river water (Berner & Berner 1996; Schlesinger 1997). At first, the normality distribution of data sets was checked by the Shapiro-Wilk test ($P > 0.05$) to determine the suitability of using these data for regression analyses (Interlandi & Crockett 2003). The trends of climatic, hydrological and surface water quality parameters over the study period were then analyzed by the linear regression model in which time (year) is set as an independent variable and monitored parameters set as time dependent variables.

In this study, the prediction of water quality from the climatic and hydrological data series was conducted by applying the ARIMA model. ARIMA model developed by Box & Jenkins (1976) is one of the most popular models used for time series forecasting analysis (Ho *et al.* 2002). The model is denoted as ARIMA $(p,d,q) \times (P,D,Q)_S$ for both non-seasonal and seasonal components. The equation of

Table 1 | Sampling points, sampling period and measured parameters

Sampling point	Sampling period	Measured parameters
Chiang Saen (Thailand)	1985–2003	Precipitation, evaporation, air temperature, mean water level, discharge flow, water quality (TSS, pH, DO, conductivity, alkalinity, NO_3^-, PO_4^{3-}, total phosphorus, COD, Ca, Mg, Na, K, Cl, SO_4^{2-}, Fe, Si)
Khong Chiam (Thailand)	1985–2003	
Vientiane (Laos)	1985–2004	
Luang Prabang (Laos)	1985–2004	
Kampong Cham (Cambodia)	1993–2002	Precipitation, mean water level, water quality
Kratie (Cambodia)	1996–2002	
Tan Chau (Vietnam)	2001–2004	Precipitation, mean water level, discharge flow, water quality
My Tho (Vietnam)	2001–2004	

the ARIMA model may be written as following:

$$\phi_p(B)\Phi_P(B_S)\nabla^d\nabla_S^D z_t = \theta_q(B)\Theta_Q(B_S)a_t \quad (1)$$

In which, $\phi_p(B)$, $\Phi_P(B_S)$, $\theta_q(B)$ and $\Theta_Q(B_S)$ are polynominals of order p,P,q and Q respectively, and have the form:

$$\phi_p(B) = (1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_p B^p) \quad (2)$$

$$\Phi_P(B_S) = \left(1 - \Phi_1 B_S - \Phi_2 B_S^2 - \cdots - \Phi_P B_S^P\right) \quad (3)$$

$$\theta_p(B) = (1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q) \quad (4)$$

$$\Theta_P(B_S) = \left(1 - \Theta_1 B_S - \Theta_2 B_S^2 - \cdots - \Theta_Q B_S^Q\right) \quad (5)$$

where: B is a backshift (or lag) operator, p is the order of non-seasonal autoregression, d specifies the number of regular differencing, q is the order of non-seasonal moving average, P is the order of seasonal autoregression, D is the number of seasonal differencing, Q is the order of seasonal moving average, z_t is time series, a_t is a random parameter, S denotes the length of season.

The time series model development consists of three stages: identification, estimation and diagnostic check. The Ljung-Box statistic provides an indication of whether the model is correctly specified ($p > 0.05$) (SPSS Inc 2005). In addition, the necessity of minimum of 50 observations (Wei 1990) for building a reasonable ARIMA model was satisfied. All of these statistical tests are provided in SPSS 14.0 version for window.

RESULTS AND DISCUSSION

The overall patterns of water quality

Table 2 summarizes the concentrations of water quality parameters determined during the entire study period (from 1985 to 2004). The results reveal that in general, water quality at the mainstream stations of the lower Mekong River was 'good' or 'very good' for DO (standard values of $\geq 6\,mg\,l^{-1}$ and $\geq 8\,mg\,l^{-1}$, respectively), pH (6.0–8.5 and 6.5–8.2), conductivity ($\leq$3,000 us/cm and $\leq$2,500 us/cm), nitrate ($\leq 10\,mg\,l^{-1}$ and $\leq 2\,mg\,l^{-1}$), phosphate ($\leq 0.5\,mg\,l^{-1}$ and $\leq 0.1\,mg\,l^{-1}$) and total phosphorus ($\leq 0.2\,mg\,l^{-1}$ and $\leq 0.05\,mg\,l^{-1}$). Measured values of these parameters fell within the referenced standard level for "good" or "very good" surface water quality with some exceptions. Out of 1,156 measured values of pH, there were 34 values (2.94%) higher than 8.5; 3.8% of DO measurements were lower than the level of $6\,mg\,l^{-1}$ and 2.15% of total phosphorus measurements were higher than $0.2\,mg\,l^{-1}$. Higher TSS concentrations were observed in the upstream stations between Chiang Saen and Khong Chiam at an average of $310.31\,mg\,l^{-1}$. At the downstream of Khong Chiam, the average concentration of TSS dropped to $105.75\,mg\,l^{-1}$. The highest concentrations of Na^+, Cl^- and conductivity were observed in My Tho the most downstream station which is 64 km from the river mouth ($292.28\,mg\,l^{-1}$, $499.10\,mg\,l^{-1}$ and 1,873 μs/cm, respectively) in comparison with the maximum measured values of the same parameters in Chiang Saen-the most upstream station ($20.88\,mg\,l^{-1}$, $24.15\,mg\,l^{-1}$ and 366 μs/cm, respectively). This is because of the effect

Table 2 | Seasonal variation of climate, hydrology and water quality in the lower Mekong River, 1985–2004

Season	Precipitaion (mm)	Mean water level (mm)	Discharge flow (m^3/s)	Air temp (°C)	Evaporation (mm)
Dry	0.36 (0.0 ÷ 12.14)	2.55 (−0.02 ÷ 14.10)	1,782.5 (74.6 ÷ 13,478.5)	24.1 (17.7 ÷ 33.4)	4.41 (0 ÷ 8.29)*
Rainy	7.01 (0.0 ÷ 27.19)*	6.59 (−0.17 ÷ 21.6)*	5,927.8 (974 ÷ 31,946.7)*	27.9 (23.8 ÷ 31.8)*	4.15 (0 ÷ 7.04)
	pH	**DO ($mg\,l^{-1}$)**	**Alkalinity ($mg\,l^{-1}$) as $CaCO_3$**	**Conductivity (μs/cm)**	**Total phosphorus ($mg\,l^{-1}$)**
Dry	7.87 (6.14 ÷ 9.04)*	7.96 (2.3 ÷ 13.85)*	88.57 (11.51 ÷ 127.1)*	233 (104 ÷ 1,873)*	0.035 (0.002 ÷ 0.776)
Rainy	7.76 (6.01 ÷ 8.96)	7.20 (1.03 ÷ 13.38)	72.56 (16.01 ÷ 115.09)	189 (61 ÷ 1,246)	0.055 (0.003 ÷ 0.91)*
	TSS ($mg\,l^{-1}$)	**COD ($mg\,l^{-1}$)**	**PO_4^{3-} ($mg\,l^{-1}$)**	**NO_3^- ($mg\,l^{-1}$)**	**SO_4^{2-} ($mg\,l^{-1}$)**
Dry	56 (1 ÷ 2,040)	1.0 (0.05 ÷ 11.31)	0.017 (0.001 ÷ 0.11)	0.191 (0.001 ÷ 1.0)	17.45 (0.19 ÷ 75.55)*
Rainy	245 (1.6 ÷ 5,716)*	1.7 (0.02 ÷ 11.09)*	0.023 (0.001 ÷ 0.23)*	0.26 (0.001 ÷ 0.79)*	13.92 (0.34 ÷ 53.23)
	Ca^{2+} ($mg\,l^{-1}$)	**Mg^{2+} ($mg\,l^{-1}$)**	**Na^+ ($mg\,l^{-1}$)**	**K^+ ($mg\,l^{-1}$)**	**Total Fe ($mg\,l^{-1}$)**
Dry	28.52 (4.9 ÷ 49.58)*	6.0 (0.62 ÷ 38.64)*	8.72 (0.87 ÷ 292.28)*	1.56 (0.078 ÷ 19.46)	0.112 (0.002 ÷ 3.904)
Rainy	23.71 (3.18 ÷ 58.0)	4.8 (0.04 ÷ 27.23)	5.80 (0.74 ÷ 178.92)	1.56 (0.156 ÷ 15.6)	0.102 (0.004 ÷ 6.146)
	Cl^- ($mg\,l^{-1}$)	**Si ($mg\,l^{-1}$)**			
Dry	7.65 (0.21 ÷ 499.1)*	6.0 (0.38 ÷ 14.0)*			
Rainy	5.18 (0.21 ÷ 289.1)	4.9 (0.48 ÷ 12.4)			

*Concentration is significantly higher when compared to another season, $p < 0.001$.
Note: Median (min, max) values.

from the intrusion of saline water from the South China sea (Öjendal & Torell 1997). In comparison with average concentrations of major elements in river water of Asia and Global (Berner & Berner 1996; Schlesinger 1997), mean values of K^+ and NO_3^- were smaller than that of both Asia and Global; SO_4^{2-} and Ca^{2+} values were much higher than both referenced values; Mg^{2+} and Cl^- values were similar to that of Asia but higher than the Global level; SiO_2-Si value was similar to that of Asia but smaller than the Global level; Na^+ value was smaller than the Asia level but higher than the Global level; finally total Fe level was much higher than the Asia level but similar to the Global level.

Seasonal variations of climate, hydrology and water quality

The seasonal differences (significant $p < 0.05$) were verified by nonparametric tests, the Mann Whitney *U*-test, since the normality assumption of the data set was violated (Ott 1988; Morgan *et al.* 2007). The results clearly show that climate, hydrology and water quality were significantly seasonal dependent (Table 2). Although evaporation depends on both air temperature and humidity, higher evaporation level was observed during the dry season than that in the wet season. Figure 2 presents the variation pattern of discharge and some selected water quality parameters in the lower Mekong River during 1985–2004. Discharge increased throughout the rainy season and had the highest peak in August or September and the lowest one in April. Higher water level in the wet season was followed by increasing discharge.

The seasonal variation of water quality is mainly because of discharge flow. Precipitation which then related to water runoff was also taken into account. The group of water quality parameters including alkalinity, conductivity and major ions (SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, Cl^- and Si) had the inverse relationship between their concentrations and discharge flow (Figure 2(A)). Lower concentrations of these parameters were observed in August or September during the peak of discharge, meanwhile their higher values were monitored in April. Statistical test also identifies the significant seasonal variation ($p < 0.001$) of this group of parameters (Table 2). The mean monthly discharge of the lower Mekong River from 1960 to 2004 shows that the wet season occupied about 80% of the annual discharge (MRC 2005). Therefore the dilution effect can be interpreted as a main

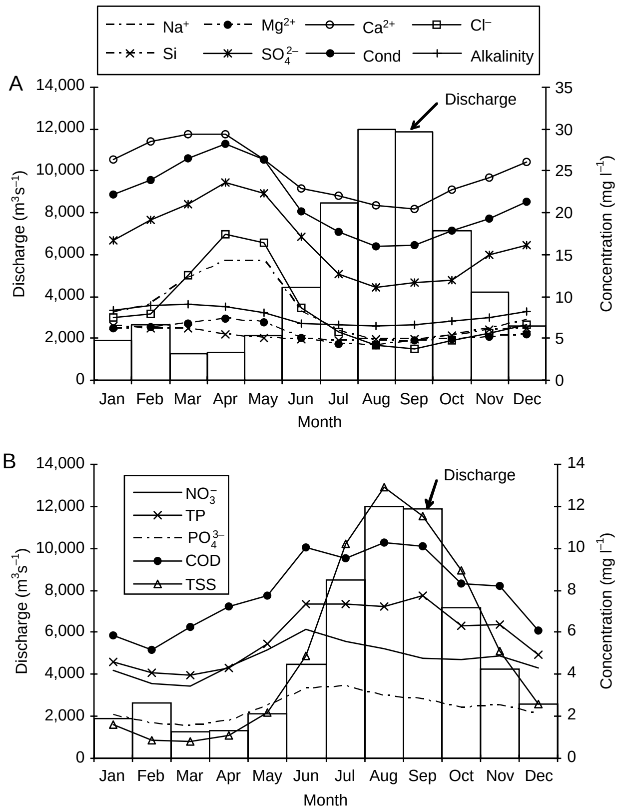

Figure 2 | (A) Monthly mean of discharge and water quality parameter concentrations, lower Mekong River, 1985–2004; conductivity (μs/cm × 0.1), alkalinity (as mg l^{-1} $CaCO_3 \times 0.1$). (B) Concentration of NO_3^- was multiplied by 20, TP and PO_4^{3-} by 100, COD by 5 and TSS by 0.02.

reason for these trends. In addition, saline water intrusion from the South China sea in the dry season is a main reason for increasing Na^+ and Cl^- concentrations during the dry season. On the contrary, TSS, COD and nutrients parameters (nitrate, phosphate and total phosphorus) had positive relationship between their concentrations and discharge flow (Figure 2(B)). Strong water flux during the wet season which might lead to river bank erosion and sediment resuspension might cause the seasonal TSS variation. Agriculture is the single most important economic activity in the Lower Mekong Basin (MRC 2003). Water runoff during a wet season from intensive rice farms might be a reason for the increasing concentrations of COD and nutrients. Higher concentration of DO during a dry season might be the result of lower average temperature in this season. Slight seasonal difference in pH was observed. There were insignificant seasonal variations for K^+ and total Fe.

Long term trends of climate, hydrology and water quality

The study on the long-term trend requires appropriate monitoring data. The 18 year monitoring data of Laos and Thailand are plenty for this study. However, the limited and incomprehensive monitoring data of Cambodia (10 years for Kampong Cham and 7 years for Kratie) and Vietnam (4 years for each station of Tan Chau and My Tho) cannot be used for this analysis.

Results from the liner regression reveal that most water quality parameters, climatic and hydrological data showed insignificant overall trend during the study period. Annual evaporation and water level exhibited slightly a positive direction trend (slope $= 0.033\,\text{mm}\,\text{yr}^{-1}, r^2 = 0.241, p = 0.038$ and slope $= 0.068\,\text{m}\,\text{yr}^{-1}$, $r^2 = 0.391$, $p = 0.005$, respectively). Meanwhile total suspended solid decreased significantly (slope $= -24.73\,\text{mg}\,\text{l}^{-1}\,\text{yr}^{-1}$, $r^2 = 0.725$, $p = 7.42 \times 10^{-6}$). The long-term increasing trend of evaporation might support the suggestion that Asia is becoming warmer and drier (Smit *et al.* 1988). There was significant increasing in water level with a small magnitude but without any significant change in discharge and precipitation. It is suggested that the climate change during the study period is not clear. The notable drop in TSS concentration can be explained by the effect from the construction of new dams in the upper-part of the basin (MRC 2007). As reported in the MRC technical report (MRC 2007), there are only a few sources that could potentially pollute the mainstream of the lower Mekong River. And still, there are no data suggesting that the agriculture or the limited industrial activity in Lower Mekong Basin are signifcant contributors of pollution to the mainstream of the river. This statement can be explained for insignificant trends of other water quality parameters.

Prediction of water quality from the climatic and hydrological data series

Statistical models are widely applied for water quality forecasting (Ahmad *et al.* 2001; Lehmann & Rode 2001; Kurunc *et al.* 2005; Georgakarakos *et al.* 2006). In this study the relationship between climatic and hydrological and water quality variables was revealed by applying

ARIMA model in which water quality was forecast based on climatic and hydrological variables. Among the four available climatic and hydrological parameters (discharge flow, water level, evaporation and precipitation) discharge flow and water level were strongly correlated ($r = 0.973$, $p < 0.01$). While discharge flow depends on water quantity only, water level however depends also on stream channel morphology. Therefore discharge, precipitation and evaporation parameters were chosen as predictors for water quality forecast. The first 15 years (1986–2000) monthly-based data of Laos and Thailand were used to obtain the best-fitted ARIMA models for each water quality parameter. The remaining 3-year (2001 to 2003) data were utilized for models verification and comparison.

ARIMA models fitted well to 9 water quality variables (Table 3). All the models had both nonseasonal and seasonal components. Nonseasonal component in the form (p, 0, q) showed the stationary of data series which is important for an ARIMA modeling. Most models had an autoregressive $(p) = 1$ specifying that the value of the series one time period (one month in this case) in the past could be used to predict the current value. Discharge was a single factor for predicting TSS, Cl^-, Ca^{2+} and Mg^{2+}; both factors, discharge and precipitation, were useful for predicting NO_3^-, SO_4^{2-}, Si, alkalinity and conductivity. Evaporation was not useful for predicting any water quality parameters. It is probably because evaporation (0–8.29 mm) does not have much effect on decreasing of a huge water volume in the mainstream Mekong. Out of 17 water quality parameters, pH, DO, COD, NH_4^+, PO_4^{3-}, TP, K^+ and total Fe were not able to be predicted by the above mentioned factors.

ARIMA model is considered as a useful tool for short term forecasting (Ahmad et al. 2001). Concerning all 9 water quality variables, a one year prediction gave a relatively good agreement between observed and predicted data, R^2 ranging from 0.60 to 0.91. The R^2 values were decreasing as a predicted period became longer, ranging from 0.41 to 0.86 for 2-year and 0.24 to 0.77 for the 3-year period. The results show that the statistical model was most useful for predicting TSS, alkalinity and conductivity. Figure 3 displays the curves of observed vs. predicted for 3-year monthly-based values of TSS (Figure 3(A)), alkalinity (Figure 3(B)) and conductivity (Figure 3(C)) with relatively good R^2 estimation ($R^2 = 0.70$, 0.70 and 0.77 respectively). The river is a dynamic system in which water quality variation is subjected to natural phenomena as well as anthropogenic activities. The complicated physical, chemical and biological processes (such as survival of bacteria, degradation of organic matters, nutrient cycling, adsorbed/desorbed metals etc.) are involved in such a variation. This explains why discharge and precipitation factors can be best used for prediction relatively biologically and/or chemically conservative water quality parameters such as TSS, alkalinity and conductivity.

This raises a major concern about the impact of climate change and hydropower (or multi-purposes) dams in China upstream of the Mekong River as well as throughout the lower Mekong basin on natural water resources in the lower Mekong River in both quality and quantity (White 2002).

Table 3 | Summary of statistical models fitted to water quality parameters of the lower Mekong River, Laos and Thailand, 1986–2000

Water quality variable	Statistical model ARIMA (p,d,q) × (P,D,Q)	Ljung-Box Q p value	Predictor Discharge	Precipitation
TSS	ARIMA (1,0,0) × (0,1,1)	0.3403	x	
Cl^-	ARIMA (1,0,1) × (0,1,1)	0.1511	x	
Ca^{2+}	ARIMA (1,0,1) × (0,1,1)	0.6602	x	
Mg^{2+}	ARIMA (1,0,0) × (0,1,1)	0.3916	x	
Si	ARIMA (1,0,0) × (1,1,0)	0.2757	x	x
Nitrate	ARIMA (2,0,0) × (0,1,1)	0.8049	x	x
Sulphate	ARIMA (1,0,0) × (0,1,1)	0.9908	x	x
Alkalinity	ARIMA (1,0,1) × (1,1,0)	0.7193	x	x
Conductivity	ARIMA (1,0,0) × (0,1,1)	0.9491	x	x

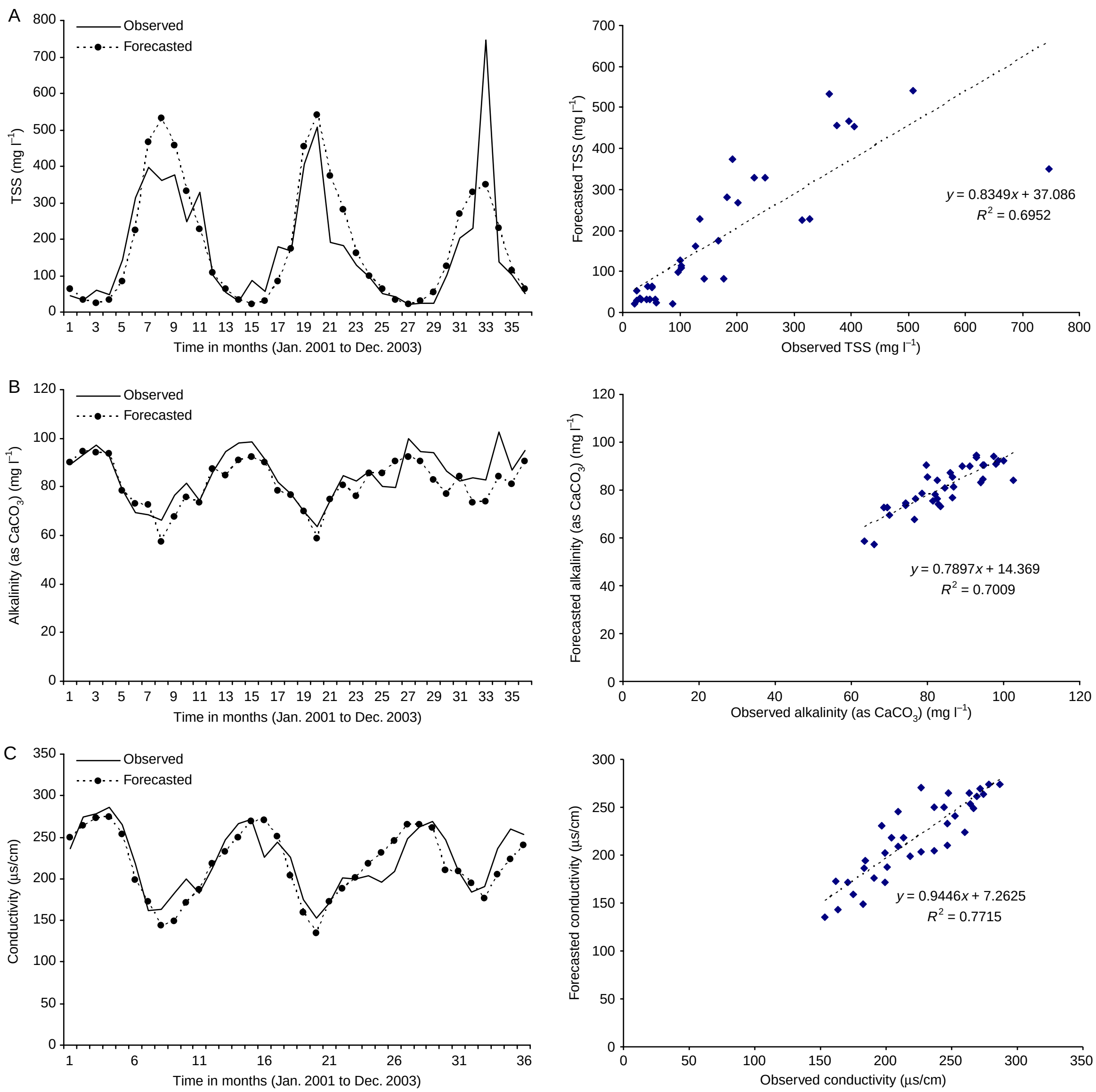

Figure 3 | Comparison of 3-year (2001–2003) observed data vs. ARIMA predicted values for TSS, alkalinity and conductivity concentrations in the lower Mekong River.

ARIMA models for 9 water quality variables therefore could help in predicting water quality based on the scenarios of changing in water quantity as well as climate change which can be reflected by discharge flow and precipitation variables.

CONCLUSIONS

It reveals that in general, the lower Mekong River still has good water quality. The entire monitored climate, hydrology and most water quality parameters were seasonally variable while only some showed a significant overall trend throughout the eighteen-year study period. Droughts may lead to the increasing in concentrations of alkalinity, conductivity and major ions (SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, Cl^- and Si) in a river. In addition, freshwater shortage and saline water intrusion from the South China Sea have become a serious issue in the Mekong Delta recently. Floods on the other hand will result in higher loading of TSS, COD and nutrients into the river water. The decreasing trend of sediment budget (i.e. TSS concentration) in the mainstream caused by damps trapping is a major concern because of its potential impacts on agricultural activities downstream. Consequently, flood and drought risks protection strategies are needed to reduce the impacts on water quality due to changes in regional precipitation, especially in extreme events. Furthermore, plans to address undesirable water quality impacts will require the integration of interventions across all sectors and institutions responsible for managing land and water resources. Finally, as an international river, co-operation between the downstream countries (Thailand, Laos, Cambodia and Vietnam) and the upstream countries (China and Myanmar) in land and water resource management is necessary to benefit all riparian countries and avoid conflicts caused by any countries.

There is no doubt of the power of numerical models on interpreting and predicting water quality. Statistical models are easier to apply and can also reduce the input data required for short term prediction. Discharge flow and precipitation were potentially useful as predictors of future water quality, especially for constituents, which are chemically and biologically conservative such as TSS, alkalinity and conductivity. For other water quality parameters in this study (Ca^{2+}, Mg^{2+}, Si, Cl^{-}, NO_3^{-}, and SO_4^{2-}), the predicting results were reliable in a shorter period than the above mentioned three water quality variables.

ACKNOWLEDGEMENTS

The authors would like to thank International Environmental Research Center (IERC), Gwangju Institute of Science and Technology (GIST), Korea for a financial support.

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