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# Nutrient Balance Assessment in the Mekong Basin: Nitrogen and Phosphorus Dynamics in a Catchment Scale

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ABSTRACT *Tropical regions are typically rather poorly covered by nutrient enrichment information, despite their soaring population, urbanization, industrialization, and intensifying agriculture. We provide an overview of nutrient fluxes and their temporal and spatial patterns in the Mekong River for 1985–2005. Total inorganic nitrogen fluxes increased significantly, while phosphorus fluxes increased less steeply. The majority of fluxes originated from agricultural and from forest and shrubland areas. Although the Mekong is not yet facing severe water quality problems, the concurrent rapid development can be expected to accelerate nutrient enrichment. There is thus an urgent need to improve water quality monitoring and pollution control measures, and to give water quality issues more weight at the policy level.*

## Introduction

Global riverine nitrogen and phosphorus inputs into the oceans have tripled during the second half of the 20th century due to human impact (Jennerjahn *et al.*, 2004). Numerous studies exist on catchment-level changes that influence nutrient cycling and lead to nutrient enrichment, changes in algal and fish ecology, deterioration of water for drinking and recreational purposes, and other consequences (e.g. Meybeck & Helmer, 1992; IOC, 1994; Kristensen & Hansen, 1994; Bootsma & Hecky, 1999; Smith *et al.*, 2003; Jennerjahn *et al.*, 2004; LWA, 2005). The critical nutrient levels at which eutrophication occurs, however, vary from one aquatic environment to another (see e.g. Di & Cameron, 2002). Regarding, among others, algal growth, there are significant differences between tropical and temperate regions (WHO, 1999).

Tropical aquatic environments are known to support a broad variety of ecosystems and biodiversity (Dudgeon, 2000). Nevertheless, there is generally little quantitative information on various processes, structures, and functions of tropical river systems (LWA, 2005; Sidle *et al.*, 2006). Meybeck (1982), already over a quarter of century ago, concluded that nutrient mass balances of watersheds in the tropics are much less studied than those in the temperate regions. This bias is still today more than obvious.

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The Mekong is Southeast Asia's largest international river and one of the planet's greatest river systems. It has a drainage area of 795,000 $km^2$ and a length of 4,800 km (MRC, 2005) (Figure 1). Regarding water quality, the Mekong is not as well studied as other large tropical rivers, yet its nutrient concentrations are reported to be relatively low compared to some other tropical rivers (Voss *et al.*, 2006). Water quality and nutrient balances in general are generally reported to indicate only small or modest human influence (e.g. Booty, 2001; White, 2002; Snidvongs & Teng, 2006; Campbell, 2007; MRC, 2007, 2010).

In the Mekong, problems (e.g. algal blooms related to eutrophication) are most often considered to be local, seasonal, and moderate in impact (Booty, 2001; Snidvongs & Teng, 2006). However, during the past two decades, increasing amounts of wastewater and agricultural high-nutrient-content leaching water have entered the river through its tributaries (Snidvongs & Teng, 2006). Booty (2001) found that the nutrients generated from urban centres such as Vientiane and Phnom Penh have a potential to cause concern in the future. Fedra *et al.* (1991) found that tributaries in north-east Thailand showed signs of eutrophication, and such signs continue to exist (Snidvongs & Teng, 2006). Kummu *et al.* (2006), Lamberts (2006), and Lamberts & Koponen (2008) pointed out that scientific information on eutrophication and related production biology of Tonle Sap Lake remains elusive, and Varis & Keskinen (2006) emphasized the high uncertainties and risks in drawing any conclusions on the threats to its eutrophication. Campbell (2007, p. 12), after analyzing the Mekong River Commission's (MRC's) water quality monitoring results, concluded, however, that water quality is not a "serious issue in the lower Mekong either now or in the immediate future". MRC (2010) represents a sharply contrasting view, reporting significantly growing trends in concentrations of total phosphorus and ammonium in the Mekong mainstream, and a decreasing trend in dissolved oxygen. An alert was given for certain nutrient enrichment hotspots located at the delta and around major urban centres, plus on the possible negative water quality impact of the intensive dam construction in the basin (MRC, 2010, pp. 60–68).

The most challenging water quality issue in the Mekong River is probably in the delta in Vietnam. According to Fedra *et al.* (1991), the mainstreams of the delta were already too contaminated to be used as drinking water in the early 1990s. The MRC (2003, 2010) has reported phosphorus levels in the delta that approach those typical for eutrophic waters and excessive algal blooms. Eutrophication occurs annually (Snidvongs & Teng, 2006), and nutrient concentrations are increasing (Campbell, 2007). White (2002) suggested an increasing trend in nutrient levels in the Mekong and Bassac Rivers in the lower parts of the basin. Campbell (2007) maintained that the water quality in the delta is poor, the phosphorus concentrations corresponding to those of a eutrophic temperate stream according to the classification by Dodds *et al.* (1998).

Altogether, Booty (2001, p. 24) concluded, "there appears to be little research data on the key nutrient processes taking place in the Mekong River system". According to Hawkins & Suthep (2005), there is a lack of information on nutrient limitations and their magnitude in the Lower Mekong Basin (LMB; see division between LMB and Upper Mekong Basin in Figure 1). Hart *et al.* concluded (2001, p. 30) that sufficient water quality data exist to conduct only a "preliminary assessment of the potential for eutrophic conditions to exist", underlining that important chlorophyll *a* concentration data are lacking for the entire LMB. The nutrient data availability has been improving considerably ever since, as manifested by MRC (2010), yet biological data as well as chlorophyll *a* trends await improvement.

**Figure 1.** Map of the Mekong basin and water quality (WQ) measurement stations used in this study (modified from Johnston & Kummu, 2012).

Economic activities and land use changes have, however, increased rapidly within the Mekong River Basin (MRB) during the past decades (see e.g. White, 2002; MRC, 2003, 2005, 2010; Iida *et al.*, 2004; Lu & Siew, 2006; Hart & Pollino, 2007; Keskinen *et al.*, Forthcoming). Further, the Mekong is at the moment under extremely rapid economic development, which includes various water-resources-related projects, such as hydropower projects and irrigation schemes (see e.g. Keskinen, 2006, 2008; Sokhem & Sunada, 2006, 2008; King *et al.*, 2007; Varis *et al.*, 2008). In terms of population growth, it is estimated that the population of the Mekong River basin will increase from 72 million (the estimate for the year 2000) to over 100 million by 2050 (Varis *et al.*, 2012). Increasing human population densities have usually been found to cause increased stream nutrient amounts within a catchment (Peierls *et al.*, 1991). According to Bootsma & Hecky (1999), land use within a catchment area is connected to water characteristics and quality. Yoshimura *et al.* (2009) indeed predict an increase of 13–25% in nutrient levels in the Mekong mainstream by the 2020s.

This paper has two goals. The first is to assess the status of nitrogen and phosphorus dynamics in the Mekong on the basis of available data. Different features of the nutrient dynamics, such as fluxes, seasonal variations, and trends, are calculated and analyzed. This information provides a needed overview on the current levels of nutrients in the Mekong mainstream, as most existing studies only tackle local water quality (e.g. Iida *et al.*, 2011; Irvine *et al.*, 2011) or future predictions (Campbell, 2007; Yoshimura *et al.*, 2009), and thus information on the overall picture, observed trends as well as connecting nutrient fluxes to land use, is limited. The second goal is to find a method that could be used to estimate and describe the nutrient dynamics in terms of leaching and fluxes of the LMB, for which geoinformatic system data exists. Such a method could describe how the nutrient fluxes are distributed geographically and by land cover type over the LMB.

## Data and Methods

### *Water Quality Data and Analysis*

Water quality data was analyzed to obtain information on the Mekong's nutrient fluxes. The entire basin's export rates of nitrogen and phosphorus (kg/ha/y) were estimated. Monitoring data series from 1985 to 2005 were provided by the MRC. The MRC has monitored the water quality of the LMB since 1985 at a total of 98 water quality sampling stations (MRC, 2003). The analyzed elements include nitrate plus nitrite ($NO_{32}$), ammonium ($NH_4$), total nitrogen (TIN), orthophosphate ($PO_4$), and total phosphorus (TOTP) at five mainstream sites and two delta sites. For the two delta sites we had data only for limited number of years; thus, those stations were not used in the trend analysis.

Four different analyses were carried out:

- The average monthly flux and concentration of nutrients were calculated for the monitoring sites with data records of 15–20 years in order to find out which months carry the largest nutrient amounts.
- The correlation between flooding and riverine nutrient transportation was analyzed to see whether larger water amounts always transport larger nutrient amounts or if the process is more complex.
- Trend analyses were conducted for nutrient delivery peak months (July–September) for the years 1985–2005 by using a Mann-Kendal test (Mann, 1945;

Kendall, 1975) and Sen's (1968) slope estimate. The analyses were done with the MAKESENS spreadsheet template (Salmi *et al.*, 2002).

- The average annual TIN and TOTP fluxes transported by the Mekong River at five mainstream sites and at two delta sites were calculated (see station locations in Figure 1). The results give an indication of the river's average annual nutrient load into the ocean as well as average nutrient export rates (nutrient · kg/ha/y) at the included sites.

### *Methods: Catchment Scale Nutrient Flux Modelling*

The modelling part includes an experimental assessment of the LMB's nutrient fluxes. We aimed to identify an appropriate catchment-scale model in order to estimate nutrient fluxes of the LMB on the catchment scale. Nutrient assessment methods provide information on where nutrients enter the river and can thus be used to assess nutrient policies and their effectiveness (EEA, 2005). TIN and TOTP were included. Due to limited data availability, the modelling of nutrient fluxes was only applied to the LMB, and not to the entire Mekong River basin.

Booty (2001) recommended that the nutrient loadings into the Mekong River system be determined for later mass balance modelling of the river. Current data and knowledge do not enable more than one-dimensional nutrient studies; a simple empirical model is suggested to be used first (Booty, 2001). Sidle *et al.* (2006) underlined that it is important to develop an appropriate approach for modelling catchment processes in tropical Asia, where data are scarce. For basin-wide assessments, simple methods are more suitable, according to Vassiljev & Stålnacke (2005).

After a review of 40 different models (Liljeström, 2007), the WinCMSS approach (Atech Group, 2000) was chosen to model the nutrient fluxes of the LMB. The method was found straightforward, robust, and relatively flexible, not requiring large amounts of detailed data. WinCMSS estimates the diffuse nutrient emissions, which is suitable for the LMB, where industry and population are scarce. The model uses a consistent technique for the whole basin and relatively quickly gives indicative estimations for the basin's nutrient dynamics. The method is linear and allows calculations to be conducted in spreadsheets (e.g. Microsoft Excel). WinCMSS does not generate new water quality or other data, but only manipulates existing information. The disadvantages include that the method is not able to estimate nutrient retention, that is the movement or transformation of nutrients across the landscape or through the river system (e.g. sedimentation, assimilation, and denitrification).

The WinCMSS method estimates annual diffuse nutrient exports on the basis of nutrient export coefficients and on spatial land-cover data. In this study, the method's estimations were further improved by adding a modifying factor that considers the different LMB sub-areas' annual runoff rates. The results are given in tonnes per year (t/y) and as average generation rates (kg/ha/y). We used land cover data prepared from MRC (2001) and runoff data from MRC (2005). Table 1 shows the land cover types and their respective areas within the LMB.

A nutrient export coefficient expresses the nutrient amount that is generated from a land cover type per unit area and unit time (Novotny, 2003). According to the Atech Group (2000), studies have shown that nutrient leaching from different land cover types are often similar to each other, even when located in different geographical regions. A literature review did not identify estimates or empirical research results on LMB nutrient export rates.

**Table 1.** The areas of the land cover categories and their percentages of the total area of the LMB (MRC, 2001), presented together with the corresponding N and P export coefficients used in the assessment.

| Land cover category | Area (1,000 ha) | Area (% of total) | N export (kg/ha/y) | P export (kg/ha/y) |
|---|---|---|---|---|
| Agricultural area | 25,241 | 40.41 | 3.5–24.7 | 0.4–3.1 |
| Forest | 23,264 | 37.24 | 1.0–7.3 | 0.04–0.29 |
| Woods and shrubland | 11,006 | 17.62 | 1.5–10.8 | 0.09–0.62 |
| Water | 1,013 | 1.62 | * | * |
| Other/clouds | 997 | 1.60 | 6.36 | 0.42 |
| Inundated forest | 383 | 0.61 | 1.0–7.3 | 0.04–0.29 |
| Rocks/barren land | 236 | 0.38 | * | * |
| Wetland | 217 | 0.35 | * | * |
| Urban | 68 | 0.11 | 6.9 | 2.4 |
| Mangrove | 34 | 0.06 | 0 | 0 |
| **Total** | **62,465** | **100.00** | | |

* The nutrient export from water surfaces, rocks/barren land and wetlands is estimated on the basis of rainfall nutrient content. The N and P rainfall contents that are used are 0.77 mg/L and 0.04 mg/L, respectively.

Export coefficients developed in other regions, tropical and temperate, were therefore used. For the largest land cover type (agricultural land) a new local export coefficient was developed based on monitoring data of the Korat Plateau, which is a vast agricultural area (for details, see Liljeström, 2007, pp. 53–57). The nutrient export coefficients used in this study are presented in Table 1. The export rates of the agricultural, woods and shrubland, and forest areas varied according to runoff depth. The nutrient export from the areas marked as "other/clouds" was estimated as a weighted average of the export coefficients describing the nutrient export rates of the three largest land cover types, that is agricultural area, forest, and woods and shrubland (for details see Liljeström, 2007, pp. 69–72).

## Results

### *Water Quality Analysis*

The monthly pattern of the annual nutrient flux was rather similar at all five mainstream sites and followed the same pattern as the distribution at Chiang Saen and Nakhon Phanom (Figure 2). The three peak months were July, August and September, followed by October and then June, for both TIN and TOTP. The three peak months accounted for 52–63% of the annual TIN flux and for 59–68% of the annual TOTP flux, depending on the site.

The comparison of the nutrient flux history with the flood history of the selected five mainstream sites was done for the years 1985–2004. The results at the Nakhon Phanom site are presented in Table 2. High flood years only roughly coincided with the high nutrient flux years. At Nakhon Phanom the greatest flooding of the studied period occurred in 1994, which corresponds to the 8th largest annual TIN load and the 5th largest annual TOTP load. Nutrient loads at Nakhon Phanom were greater than the loads of 1994 even in years when the total flow volume was reported as below the average level. This indicates that the largest water quantities do not always transport the largest nutrient fluxes and that large amounts of nutrients are occasionally transported by relatively small water quantities.

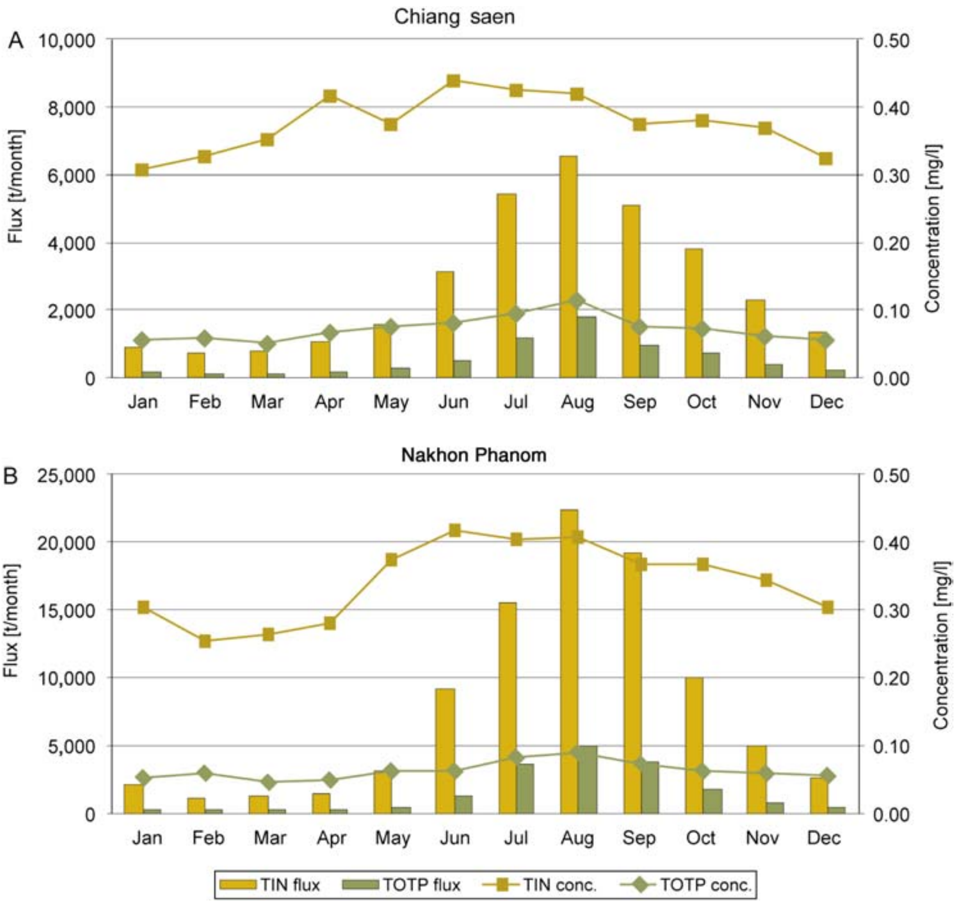

**Figure 2.** Average monthly nutrient fluxes and nutrient concentrations during 1985–2005 at (a) Chiang Saen and (b) Nakhon Phanom (see station locations in Figure 1).

Trend analysis of peak-month (July–September) nutrient fluxes was conducted for five mainstream sites. The results for Chiang Saen and Nakhon Phanom are illustrated in Figure 3, while results of trend and slope analyses are summarized in Table 3. For all sites, the trend of the TIN flux was positive and showed an increase towards the end of the study period. The coefficient of determination ($R^2$) values of the regression lines vary between 0.09 and 0.53. The trend was statistically very significant ($p < 0.01$) for all sites except Chiang Saen ($p < 0.1$) (Table 3). The TOTP flux trends were also positive and the $R^2$ values ranged from 0.01 to 0.48 (Table 3). The trend was significant, however, only at two sites (Chiang Saen and Nakhon Phanom). The TOTP flux series were thus not as uniform or as steep as the TIN flux series.

Part of these increased nutrient loads can be explained by a growing trend in discharges: in all stations but Chiang Saen the discharge had an increasing trend (appendix, Table A3). The discharge trends were not, however, statistically significant, except in Nakhon Phanom (appendix, Table A3). The average annual nutrient concentration trends were, nevertheless, alone statistically significant at the same stations as the flood season fluxes (appendix,

**Table 2.** June–November TIN (total inorganic nitrogen) and TOTP (total phosphorus) flux at Nakhon Phanom, in descending order and with corresponding flood recurrence intervals. A blank cell means that the flood condition of the year was below normal level, according to MRC (2005, p. 38).

| Year | TIN flux [t] | Flood recurrence interval | Year | TOTP flux [t] | Flood recurrence interval |
|---|---|---|---|---|---|
| 2001 | 144,851 | 5–10 | 2002 | 55,527 | 5–10 |
| 2000 | 144,678 | 5–10 | 2004 | 41,207 | |
| 2004 | 110,247 | | 1995 | 22,153 | 10–20 |
| 1999 | 106,214 | 2–5 | 2000 | 19,278 | 5–10 |
| 1995 | 103,107 | 10–20 | 1994 | 18,908 | >20 |
| 1996 | 90,179 | 2–5 | 2001 | 15,051 | 5–10 |
| 1990 | 89,044 | | 1990 | 14,680 | |
| 1994 | 78,844 | >20 | 1993 | 14,474 | |
| 1985 | 69,235 | | 1999 | 14,051 | 2–5 |
| 1993 | 66,218 | | 1989 | 13,972 | |
| 1986 | 54,365 | | 1991 | 12,457 | |
| 1991 | 53,373 | | 1997 | 11,068 | 2–5 |
| 1998 | 51,311 | | 1988 | 8,578 | |
| 1988 | 44,759 | | 1998 | 8,137 | |
| 1989 | 39,618 | | 1992 | 6,888 | |
| 1987 | 33,390 | | 1986 | 5,330 | |
| 1992 | 31,156 | | 1985 | 5,275 | |
| 1997 | data incomplete | 2–5 | 1987 | 4,537 | |
| 2002 | data incomplete | 5–10 | 1996 | data incomplete | 2–5 |
| 2003 | data incomplete | | 2003 | data incomplete | |

Tables A1 and A2). Interestingly, for the TIN values, the maximum concentrations had a stronger positive trend than the average concentrations in most of the stations (appendix, Table A1), while for the TOTP this was not the case (appendix, Table A2).

The calculated average annual nutrient fluxes at five mainstream sites and two delta sites can be seen in Table 4. The nutrient fluxes increased in the downstream direction, except after Chiang Saen and Nakhon Phanom. The sum of the fluxes at the two delta sites, My Thuan and Can Tho, indicates the total annual nutrient export from the Mekong River basin. The My Thuan site is located in the Mekong mainstream and the Can Tho site in the Bassac River. The estimated total annual nitrogen flux was 288,231 t/y and the total annual phosphorus flux 55,475 t/y. Table 4 also shows the average annual nutrient yield (kg/ha/y) delivered from the watersheds of the mainstream sites, and the nutrient export rate of the entire Mekong River basin into the South China Sea.

### *Catchment Scale Nutrient Model*

The results of the modelling of generated diffuse nutrient export within the LMB in WinCMSS are presented in Figure 4. The TIN emissions (Figure 4a) were largest in sub-basins that lie close to the mainstream and where annual runoff is largest, as well as in the delta. The average nitrogen emissions are very large (> 12 kg/ha/y) only in a few sub-basins, with most sub-basins belonging to the lowest emission ranges. The majority of the sub-basins (74 of 104) belong to the two lowest nitrogen emission ranges (0–4 and 4–8 kg/ha/y).

The estimated annual TOTP emissions (Figure 4b) were large (> 2 kg/ha/y) or medium-sized (1–2 kg/ha/y) only in a few sub-basins. The largest phosphorus emissions were

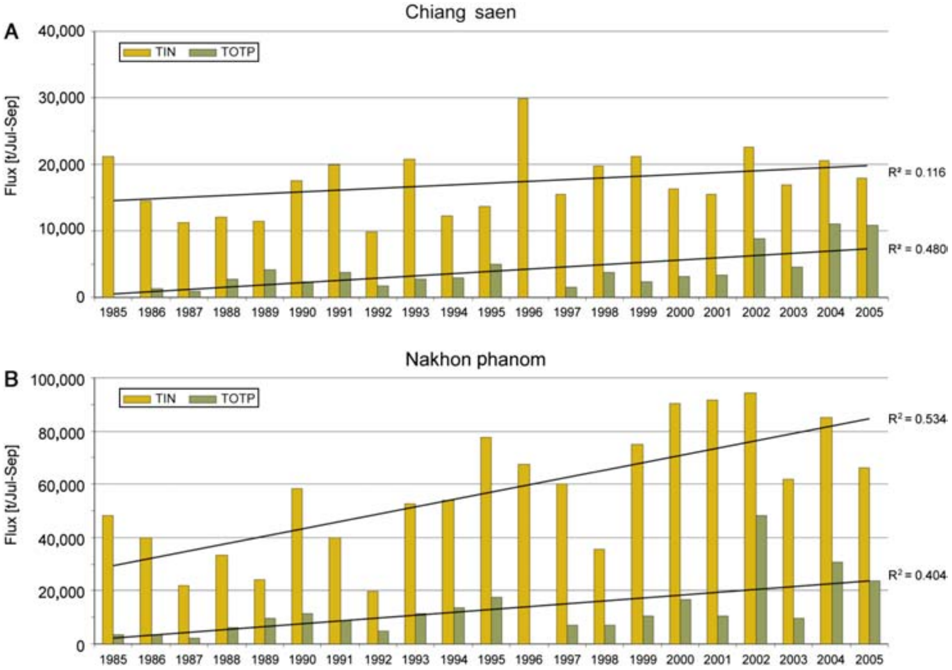

**Figure 3.** TIN (total inorganic nitrogen) and TOTP (total phosphorus) fluxes during peak months (July–September) during the years 1985–2005, at A: Chiang Saen, and B: Nakhon, displayed with regression lines and $R^2$ values. See station locations in Figure 1 and trend analysis results in Table 3.

generated from small or medium-sized sub-basins downstream of Vientiane, downstream of Pakse, and from the large delta sub-basin. Around half of the sub-basins (56 of 104) belonged to the lowest phosphorus emission range (0–0.5 kg/ha/y) (Figure 4b).

The results obtained with the WinCMSS model were mainly larger than the results based on monitored data (Table 5). All obtained TIN fluxes were larger than the monitored

**Table 3.** Regression analysis, Mann-Kendall trend test and Sen's slope analysis results for peak months (July–September) TIN (total inorganic nitrogen) and TOTP (total phosphorus) fluxes.

| | TIN | | | | TOTP | | | |
|---|---|---|---|---|---|---|---|---|
| Monitoring site | $R^2$ | *Z* | *Signif.* | *Q* | $R^2$ | *Z* | *Signif.* | *Q* |
| Chiang Saen | 0.116 | 1.72 | + | 318 | 0.480 | 3.08 | ** | 223 |
| Luang Prabang | 0.439 | 3.08 | ** | 1011 | 0.010 | 0.55 | | 27 |
| Vientiane | 0.462 | 2.89 | ** | 1116 | 0.070 | 0.81 | | 55 |
| Nakhon Phanom | 0.534 | 3.41 | *** | 2705 | 0.404 | 3.28 | ** | 854 |
| Pakse | 0.310 | 2.82 | ** | 1617 | 0.046 | 0.68 | | 118 |

*Notes:* Coefficient of determination $R^2$ represents the goodness of fit of a linear regression to the trend. *Z* indicates the direction of the trend: positive *Z* upward, negative *Z* downward. *Signif.* is the statistical significance of the trend, while *Q* indicates the slope estimate based on Sen's slope analysis. See also Tables A1, A2, and A3 in the appendix.
*** trend at $\alpha = 0.001$ level of significance; ** trend at $\alpha = 0.01$ level of significance; + trend at $\alpha = 0.1$ level of significance

**Table 4.** Average annual TIN (total inorganic nitrogen) and TOTP (total phosphorus) fluxes at selected monitoring sites and an estimate of the Mekong River's average annual nutrient delivery from catchment to ocean.

| Monitoring site | Catchment area ($km^2$) | TIN (t/yr) | TIN yield (kg/ha/yr) | TOTP (t/yr) | TOTP yield (kg/ha/yr) |
|---|---|---|---|---|---|
| Chiang Saen | 189,000 | 59,170 | 3.13 | 7,496 | 0.40 |
| Luang Prabang | 268,000 | 50,436 | 1.88 | 6,086 | 0.23 |
| Vientiane | 299,000 | 64,090 | 2.14 | 9,673 | 0.32 |
| Nakhon Phanom | 373,000 | 169,829 | 4.55 | 21,157 | 0.57 |
| Pakse | 545,000 | 109,084 | 2.00 | 17,329 | 0.32 |
| My Thuan | – | 151,489 | – | 26,604 | – |
| Can Tho | – | 136,742 | – | 28,870 | – |
| **Mekong River**[1] | 760,000 | 288,231 | 3.63 | 55,475 | 0.70 |

[1] Sum of fluxes at My Thuan (Mekong River) and Can Tho (Bassac River).

*Note:* For My Thuan and Can Tho, only data for 2003–2005 was used.

ones (Table 5). The modelled TOTP flux output was larger than the results based on monitored data except for at Nakhon Phanom and in the delta. However, the obtained TOTP fluxes were of a reasonable order of magnitude, except in the delta, where the assessed flux was lower than the monitored average flux (Table 5).

The distribution of the nutrient fluxes over the different land cover categories is presented in Figure 5. For both nitrogen and phosphorus, the agricultural areas of the LMB accounted for the majority of the nutrient flux from catchment into river system. Forest and

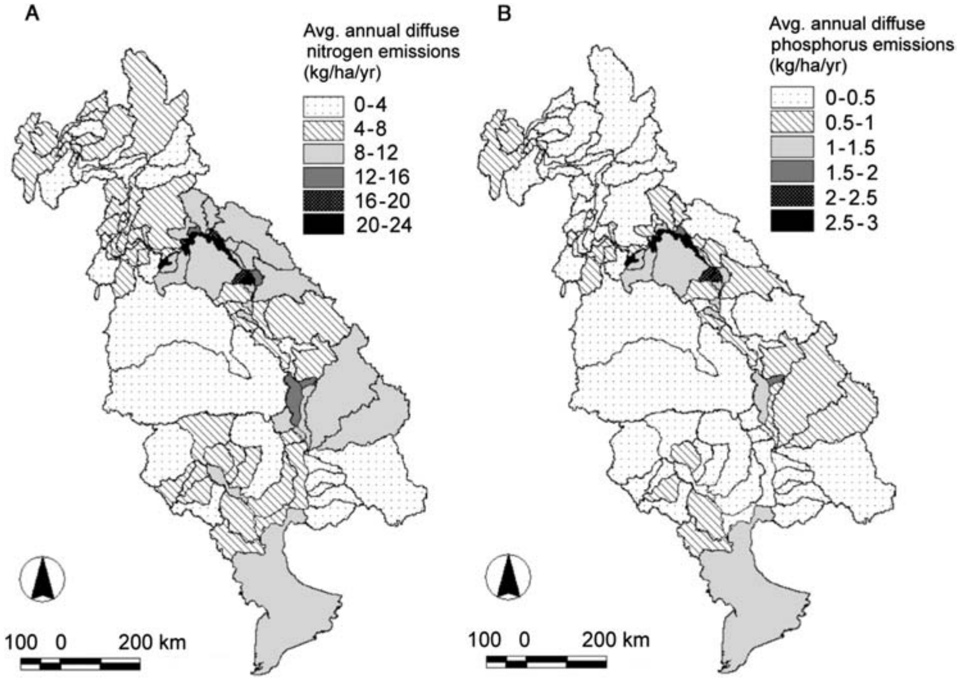

**Figure 4.** Average annual diffuse emissions from the Lower Mekong Basin. A: Average annual total nitrogen diffuse emissions. B: Average annual total phosphorus diffuse emissions.

**Table 5.** Average annual TIN (total inorganic nitrogen) and TOTP (total phosphorus) fluxes at five mainstream sites and in the delta, as estimated by the catchment-scale modelling and observed in monitoring data.

| | TIN (t/year) | | TOTP (t/year) | |
|---|---|---|---|---|
| Monitoring site | Modelled | Observed[1] | Modelled | Observed[1] |
| Chiang Saen | [59,170][2] | 59,170 | [7,496][2] | 7,496 |
| Luang Prabang | 93,105 | 50,436 | 10,256 | 6,086 |
| Vientiane | 107,143 | 64,090 | 11,475 | 9,673 |
| Nakhon Phanom | 171,339 | 169,829 | 17,111 | 21,157 |
| Pakse | 243,207 | 109,084 | 24,534 | 17,329 |
| **Mekong** | **404,685** | **288,231** | **38,392** | **55,475** |

[1] Sum of fluxes at My Thuan (Mekong River) and Can Tho (Bassac River).
[2] Only monitored data available because site is located in the uppermost part of the LMB.

woods-and-shrubland were the second and third most important generators of nutrient flux. The fourth most important contribution to the total nutrient flux was the rainfall nutrient content that enters the system directly through the water surfaces. All other land cover categories accounted for less then 1% of the total nutrient flux, except that the undefined "other/clouds" areas contributed 1.8% (N) and 1.3% (P) of the total flux. The three most important nutrient contributor land cover categories accounted for 92.8% of the TIN flux, and for 95.1% of the TOTP flux.

## Discussion

We assessed the nutrient dynamics in the LMB. Although several reports exist on water quality and nutrients in the Mekong, they dominantly represent the general level only, without connecting nutrient concentration analyses analytically to land cover, nutrient leaching, nutrient retention, or runoff data (e.g. Booty, 2001; White, 2002; MRC, 2003, 2010; Campbell, 2007). Further, the existing analyses are mostly based on nutrient concentration data only and the effects of land use changes on nutrient balances have not

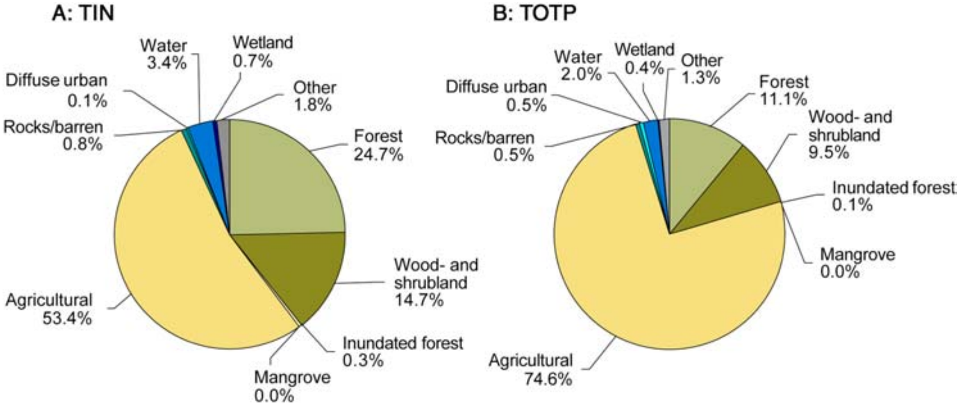

**Figure 5.** Nutrient fluxes from LMB catchments into the river network, percentage breakdown per land cover category. A: Total nitrogen (TIN) flux; B: Total phosphorus (TOTP) flux. *Note:* point pollution is not included in the estimation.

been analyzed systematically in any of the found reports. Our comprehensive analysis on nutrients in the LMB thus provides valuable baseline information on the nutrient flux trends over the past two decades and analysis on land use impact on these fluxes.

Generally, nutrient balances are reported to indicate a fairly good status for the Mekong's water quality. There are, however, many reports on increasing nutrient leaching (e.g. Snidvongs & Teng, 2006), and the delta especially has been seen as an area of concern because of increased nutrient concentrations (e.g. Campbell, 2007). Many classify the eutrophication problems as local and seasonal. Some reports on water quality and nutrient dynamics (e.g. Campbell, 2007) do not express concern about LMB nutrient levels, or directly suggest that nutrient issues are not of concern. However, MRC (2010) reports statistically significant growing trends in total phosphorus and ammonium concentrations, in line with our findings. They also report a decreasing trend in dissolved oxygen concentration. MRC (2010) expresses clear worries about this development.

Some specific consequences of eutrophication, such as fish deaths, algal blooms, and increased water hyacinth growth, could be especially serious for people in the LMB because many of the basin's inhabitants have a very close relationship to surrounding waters. Literature indicates (Wilson *et al.*, 2005) that if, for example, nitrogen concentrations increase to levels of 1 mg/L, there is a risk that water hyacinth growth in the LMB would reach maximum capacity during the hottest months of the year (when temperatures are around 30°C). Based on the observed data, the maximum nitrogen concentrations during our study periods were 0.5–0.8 mg/L in the Mekong mainstream, while in the delta area the concentration has already at various times exceeded the critical level of 1 mg/L. Water hyacinth growth risk zones should thus be identified and nutrient pollution prevention actions started in these possible risk zones. We equally support the concerns expressed by Snidvongs & Teng (2006) on the mounting risk for algal blooms in the Mekong River.

There seems to be consensus on the region's increasing land cover changes and accelerating economic activities (e.g. White, 2002; MRC, 2003; Keskinen, 2006, 2008; Sokhem & Sunada, 2006, 2008; Hart & Pollino, 2007; King *et al.*, 2007; Varis *et al.*, 2008). Little concern, however, exists in the Mekong regarding the possibility of future negative changes in the river's nutrient balances, although much literature clearly states that population growth and catchment level changes influence a river system's water quality (e.g. Meybeck & Helmer, 1992; IOC, 1994; Kristensen & Hansen, 1994; Bootsma & Hecky, 1999; Smith *et al.*, 2003; Jennerjahn *et al.*, 2004; LWA, 2005). This concern is, however, increasing (MRC, 2010).

Yoshimura *et al.* (2009) predict an increase of 13–25% in nutrient levels in the Mekong mainstream by the 2020s. If this kind of trend continues with a warmer future climate, as predicted by climate change studies (e.g. Västilä *et al.*, 2010), measures to better manage the nutrients in the river system should be developed in the near future to prevent eutrophication. On the other hand, the plans to build various large reservoirs to the Mekong mainstream and tributaries might actually trap a large part of the nutrients, particularly those bounded to suspended sediments (Kummu & Varis, 2007; Kummu *et al.*, 2010). Yet, the MRC (2010) maintains that the dams may critically change the nutrient flushing conditions, and thus lead to increasing eutrophication.

### *Data and Research on Eutrophication*

Experimental research on nutrient leaching does exist to some extent, for example at local universities and local research institutes. Research material or results are, however, hardly publicly available. Data on plot-scale nutrient leaching have not been published or are not easily available. Only one literature estimate of nutrient delivery rates of the Mekong River on the catchment scale was found: White (2002). Data availability in the region is not large enough for a more detailed study.

Despite years of continuous improvements, the MRC's monitoring programme still has room for improvement. Nutrient concentration monitoring is too scarce and should be more frequent, especially during the transition from wet season to dry season and vice versa, when discharge varies highly in time and quantity. Nutrient monitoring on and around Tonle Sap Lake is scarce. Monitoring should be increased to start identifying the lake's nutrient dynamics, which are believed to be complex and variable. Further, most parts of the Mekong River basin, for example most tributaries, seem to fall outside the scope of nutrient concentration analyses and investigations, as indicated by a sparse monitoring network. We welcome MRC's recent (2010) activity in this regard, and the agreement of LMB countries that they will "make every effort to maintain acceptable/good water quality", as a part of the MRC's *Procedures for Water Quality* (MRC, 2011). Besides increasing temporal and spatial coverage of the conventional monitoring parameters, we wait particularly for the availability of biomonitoring data and studies in production biology (MRC, 2010) in order to better understand the current level and threats of eutrophication in the Mekong River and its tributaries. Apart from eutrophication-related aspects, other aspects of water quality such as heavy metals and micropollutants call for further studies and improved data collection.

### *Water Quality Analysis*

Our water quality analyses provided information on nutrient dynamics of the LMB. The nutrient fluxes of the mainstream were highest between July and September. The nutrient flux peak months of tributaries are June–October (Liljeström, 2007). It is suggested that mainstream nutrient dynamics differ from tributary nutrient dynamics. Further, the latter might vary significantly from one tributary to another. Nutrient research should thus be carried out both in the mainstream and tributaries. The results further indicate that nitrogen and phosphorus movements across the basin differ, as phosphorus movement is slightly more seasonal compared to nitrogen movement. All in all, information on nutrient movement seasonality can allow degradation prevention measurements to be more effectively focused.

We found that water quantity movement across the basin and river nutrient flux did not always correlate. The flood history analyses show that relatively large water quantities often, but not always, transport relatively large amounts of nutrients. Our analysis also revealed that flood conditions below normal level occasionally do transport very large nutrient quantities. Rain intensity, rain duration and frequency, and the arrival time of the monsoon are suggested to be factors that, in addition to water quantity, influence the movements of nutrients across the basin.

The trend analysis revealed an augmentation in the TIN fluxes during the last two decades. Changes in TOTP fluxes were less readable. This is somewhat in contrast with the results reported by MRC (2010), in which the total phosphorus and ammonium concentrations had grown significantly whereas total nitrogen concentration had not shown a significant growing trend. This may be due to the different study period in the analyses; MRC's study was for 2000–2008 whereas ours was for mainly 1985–2005. In fact, MRC

(2010, p. 62) indicates sharply growing total phosphorus concentrations since 2005, suggesting that our time window might not have captured the most recent developments sufficiently. When comparing with temperate rivers, the Mekong River nitrogen levels do not indicate eutrophication at the sampling sites analyzed in this study, but phosphorus levels do, locally and during some times of the year. On the basis of the water quality analysis of this study, it can be concluded that seasonality exists in the LMB river system's tropic state. Nitrogen is suggested to be the limiting nutrient in much of the LMB river system. This gives an alert for the sensitivity of the river to cyanobacteria blooms. However, it is likely that large seasonal and temporal variations exist in the basin's limiting nutrient.

### *Catchment Scale Nutrient Model*

Our catchment-scale assessment resulted in estimates of the diffuse nutrient emissions generated in the LMB. The WinCMSS assessment model was chosen after a review of approximately 40 methods, and turned out to be a straightforward, rough, and relatively suitable model for a large catchment, where data are sparse. The model was successful in delivering basic nutrient dynamics information, according to the study's aims. Our assessment thus showed that enough basic land cover and nutrient leaching data exist to perform rough catchment-scale analyses on nutrient fluxes of the LMB.

Our model results revealed that the agricultural areas account for the largest part of both nitrogen (53%) and phosphorus (75%) fluxes. The forest and woods-and-shrubland areas are the next most important nutrient contributors (Figure 5). The MRC, however, maintains (2010) that 40% of the nutrient load comes from agriculture—far less than our estimate (Figure 5).

Subsistence farming is still more common than commercial farming in large parts of the LMB (MRC, 2003, 2010). Although farming practices are mostly of traditional type, agricultural areas already account for the largest nutrient fluxes in the basin. Commercial farming and growing fertilizer use have recently become more common, and this trend will continue (MRC, 2003, 2010). As agricultural land is the largest land cover type of the basin, it is possible that intensification of farming practices, followed by increased nutrient leaching, could also increase the nutrient fluxes in the LMB. It is recommended to identify more precisely which agricultural practices, crop types, and fields generate the largest amounts of nutrients into the LMB water body.

The model resulted in considerably higher nitrogen and lower phosphorus fluxes than those calculated on the basis of observations (Table 5). Our model results (Table 5) can also be compared with those published by the MRC (2010) for the Mekong basin: 225,000 t of nitrogen and 37,000 t of phosphorus annually. Our modelled nitrogen estimation is high in comparison, while the MRC (2010) result for phosphorus matches well with our modelled result.

The modelled and observed nutrient fluxes are presented in Table 6 separately for the upper and middle LMB region (north of Nakhon Phanom) and the lower LMB region (south of Nakhon Phanom, i.e. the area from which the floodplains start along the mainstreams). The WinCMSS assessment succeeded much better in modelling the areas north of Nakhon Phanom than for the areas south of it (Table 6). This indicates that, understandably, the used method is unable to describe important floodplain nutrient processes and dynamics. The LMB floodplain nutrient dynamics should thus be studied separately with more-detailed models and approaches.

**Table 6.** Annual TIN (total inorganic nitrogen) and TOTP (total phosphorus) flux estimation results of the WinCMSS approach and the water quality analysis. The results are shown separately for the watersheds north and south of Nakhon Phanom (see location in Figure 1).

| | TIN (t/year) | | TOTP (t/year) | |
|---|---|---|---|---|
| Area | Modelled | Observed[1] | Modelled | Observed[1] |
| North of Nakhon Phanom | 171,339 | 169,829 | 17,111 | 21,157 |
| South of Nakhon Phanom | 233,346 | 118,402 | 21,281 | 34,318 |
| **Mekong** | **404,685** | **288,231** | **38,392** | **55,475** |

[1] Sum of fluxes at My Thuan (Mekong River) and Can Tho (Bassac River).

## Conclusions

Tropical riverine nutrient dynamics is a relatively little-studied subject, especially when compared with investigations done in the temperate zones. Our aim in this article was to assess the nutrient dynamics in the Mekong River and model the main sources of nutrients within the Lower Mekong basin. We found that the nutrient fluxes coincided approximately with the flood peak and are thus highest between July and September. The concentrations, however, peak at most of the stations at the beginning of the flood season (April–June). The analyses revealed that water flow quantities and riverine nutrient transportation do not always correlate. Relatively small water quantities do occasionally transport very large amounts of nutrients. The trend analysis indicated that total inorganic nitrogen (TIN) fluxes increased statistically significantly during the analyzed two decades (1985–2005) while total phosphorus (TOTP) fluxes also increased, but not as steeply as TIN fluxes.

The catchment-scale modelling generated information on the Lower Mekong Basin's nutrient export distribution by sub-basin and by land cover category. The assessment succeeded rather well in describing the TIN and TOTP fluxes along the entire mainstream north of Nakhon Phanom while results were less accurate for the stations downstream from there. The exceptional hydrology and water quality dynamics of the lower Mekong floodplains might partly explain the failure of the nutrient estimates. According to the modelling results, the majority of the LMB nitrogen flux originates from agricultural areas (53%) and forest and woods-and-shrubland areas (39%). For the phosphorus flux the figures are 75% and 21%, respectively.

The growing and urbanizing population, the accelerating land use changes and the increasing economic activities will most probably increasingly influence the aquatic ecosystems of the Mekong River. It is expected that fertilizer use will grow within the basin countries in the near future; commercial farming is already becoming more frequent. Thus, systematic basin-wide research on nutrients should be one of the top priorities in the basin. Particular attention should be paid to key tributaries and the Tonle Sap system, as well as to the relative and absolute contributions of point sources and diffuse sources. Protecting the basin from future negative consequences would require that information be developed and research expanded. There is a need to start to focus attention on why and when deterioration of the basin's water quality will occur and how it could be minimized. The opportunity to start nutrient investigations in time is good and thus too valuable to be missed. Enhanced public and scientific discussion about the level and sufficiency of knowledge is necessary.

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## References

Atech Group (2000) *Aggregated Nutrient Emissions to the Murray-Darling Basin* (Canberra: National Pollutant Inventory, Environment Australia).

Bootsma, H. A. & Hecky, R. E. (1999) Nutrient cycling in Lake Malawi/Nyasa, in: H. A. Bootsma & R. E. Hecky (Eds) *Water Quality Report, Lake Malawi/Nyasa Biodiversity Conservation Project*, pp. 215–241 (Salima: Malawi Inland Fisheries Research Centre SADC/GEF project).

Booty, W. (2001) *Options for Modelling of Transboundary Water Quality, Final Report* (Vientiane: Mekong River Commission Secretariat, Environment Programme ME and WUP WG-1).

Campbell, I. (2007) Perceptions, data, and river management: lessons from the Mekong River, *Water Resources Research*, Vol. 43, W02407, DOI: 10.1029/2006WR005130.

Di, H. J. & Cameron, K. C. (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies, *Nutrient Cycling in Agroecosystems*, 64(3), pp. 237–256.

Dodds, W. K., Jones, J. R. & Welch, E. B. (1998) Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus, *Water Research*, 32(5), pp. 1455–1462.

Dudgeon, D. (2000) The ecology of tropical Asian rivers and streams in relation to biodiversity conservation, *Annual Review of Ecology, Evolution and Systematics*, 31, pp. 239–263.

EEA (2005) *Source Apportionment of Nitrogen and Phosphorus Inputs into the Aquatic Environment*, Report No. 7/2005 (Copenhagen: European Environment Agency).

Fedra, K., Winkelbauer, L. & Pantulu, V. R. (1991) *Expert Systems for Environmental Screening: an Application in the Lower Mekong Basin*, RR-91-19 (Laxenburg, Austria: International Institute for Applied Systems Analysis).

Hart, B. & Pollino, C. (2007) *Environmental Risk Assessment Training, Final Report* (Vientiane: Mekong River Commission).

Hart, B. T., Jones, M. J. & Pistone, G. (2001) *Transboundary Water Quality Issues in the Mekong River Basin*, Water Studies Centre, Monash University, Australia, in association with NSR Environmental Consultants, Australia (Vientiane: Mekong River Commission).

Hawkins, P. & Suthep, S. (2005) *Integrated Basin Flow Management Specialist Report, Water Quality* (Vientiane: Mekong River Commission, Water Utilisation Programme/Environment Programme).

Iida, T., Inkhamseng, S., Yoshida, K. & Tanji, H. (2011) Characterization of water quality variation in the Mekong River at Vientiane by frequent observations, *Hydrological Processes*, 25(23), pp. 3590–3601.

Iida, T. et al. (2004) Seasonal variations in nutrient loads in the Mekong River at Vientiane, Lao PDR, in: *Proceedings of the International Conference on Advances in Integrated Mekong River Management*, 25–27 October 2004, Vientiane, Lao PDR, pp. 195–200 (Japan: Research Group, MRC, JST).

IOC (1994) *IOC-SAREC Field Study Exercise on Nutrients in Tropical Marine Waters, 5–15 April 1994, Mombasa, Kenya*, Workshop Report No. 99 (Intergovernmental Oceanographic Commission, UNESCO).

Irvine, K. N., Richey, J. E., Holtgrieve, G. W., Sarkkula, J. & Sampson, M. (2011) Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River–Tonle Sap system identified using continuous monitoring, *International Journal of River Basin Management*, 9(2), pp. 151–168.

Jennerjahn, T. C., Ittekkot, V., Klöpper, S., Adi, S., Nugroho, S. P., Sudiana, N., Yusmal, A., Prihartanto & Gaye-Haake, B. (2004) Biogeochemistry of a tropical river affected by human activities in its catchment: Brantas River estuary and coastal waters of Madura Strait, Java, Indonesia, *Estuarine, Costal and Shelf Science*, 60(3), pp. 503–514.

Johnston, R. M. & Kummu, M. (2012) Water resource models in the Mekong basin: a review, *Water Resources Management*, 26(2), pp. 429–455.

Kendall, M. G. (1975) *Rank Correlation Methods*, 4th ed. (London: Charles Griffin).

Keskinen, M. (2006) The lake with the floating villages: socioeconomic analysis of the Tonle Sap Lake, *International Journal of Water Resources Development*, 22(3), pp. 463–480.

Keskinen, M. (2008) Water resources development and impact assessment in the Mekong basin: which way to go? *Ambio*, 37(3), pp. 193–198.

Keskinen, M., Kummu, M., Käkönen, M. & Varis, O. (Forthcoming) Mekong at the crossroads: next steps for impact assessment of large dams, *Ambio*.

King, P., Bird, J. & Haas, L. (2007) *The Current Status of Environmental Criteria for Hydropower Development in the Mekong Region: A Literature Compilation*, Consultants Report to ADB, MRCS and WWF (Vientiane, Lao PDR: Joint Initiative on Environmental Criteria for Hydropower in the Mekong Region).

Kristensen, P. & Hansen, H. O. (Eds) (1994) *European Rivers and Lakes: Assessment of their Environmental State*, EEA Environmental Monographs 1 (Copenhagen: European Environment Agency).

Kummu, M., Lu, X. X., Wang, J. J. & Varis, O. (2010) Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119(3–4), pp. 181–197.

Kummu, M., Sarkkula, J., Koponen, J. & Nikula, J. (2006) Ecosystem management of the Tonle Sap Lake: an integrated modelling approach, *International Journal of Water Resources Development*, 22(3), pp. 497–519.

Kummu, M. & Varis, O. (2007) Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85(2–3), pp. 275–293.

Lamberts, D. (2006) The Tonle Sap Lake as a productive ecosystem, *International Journal of Water Resources Development*, 22(3), pp. 481–496.

Lamberts, D. & Koponen, J. (2008) Flood pulse alterations and productivity of the Tonle Sap ecosystem: a model for impact assessment, *Ambio*, 37(3), pp. 178–184.

Liljeström, I. (2007) *Nitrogen and Phosphorus Dynamics in the Mekong Basin: Nutrient balance Assessment in a Catchment Scale*, Master's thesis, Water Resources Laboratory, Department of Civil and Environmental Engineering, Helsinki University of Technology, Finland.

Lu, X. X. & Siew, R. Y. (2006) Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams, *Hydrology and Earth System Sciences*, 10(2), pp. 181–195.

LWA (2005) *Australia's Tropical Rivers: Program Plan and Prospectus 2005–2010* (Canberra: Australian Government, Land & Water Australia).

Mann, H. B. (1945) Nonparametric test against trend, *Econometrica*, 13(3), pp. 245–259.

Meybeck, M. (1982) Carbon, nitrogen and phosphorus transported by world rivers, *American Journal of Science*, 282(4), pp. 401–450.

Meybeck, M. & Helmer, R. (1992) An introduction to water quality, in: D. Chapman (Ed.) *Water Quality Assessments: A Guide to Use of Biota, Sediments and Water in Environmental Monitoring*, 2nd Ed, Chapter 1 UNESCO/WHO/UNEP).

MRC (2001) *Metadata for MRC Secretariat GIS Core Datasets* (Phnom Penh: Mekong River Commission).

MRC (2003) *State of the Basin Report: 2003* (Phnom Penh: Mekong River Commission).

MRC (2005) *Overview of the Hydrology of the Mekong Basin* (Vientiane: Mekong River Commission).

MRC (2007) *Diagnostic Study of Water Quality in the Lower Mekong Basin*, MRC Technical Paper No. 15 (Vientiane: Mekong River Commission).

MRC (2010) *State of the Basin Report 2010* (Vientiane: Mekong River Commission).

MRC (2011) *Procedures for Water Quality* (Phnom Penh and Vientiane: Mekong River Commission).

Novotny, V. (2003) *Water Quality, Diffuse Pollution and Watershed Management*, 2nd ed (New Jersey: Wiley).

Peierls, B. L., Caraco, N. F., Pace, M. L. & Cole, J. J. (1991) Human influence on river nitrogen, *Nature*, 350(6317), pp. 386–387.

Salmi, T., Määttä, A., Ruoho-Airola, T. & Amnell, T. (2002) *Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates – the Excel Template Application MAKESENS*, Publications on Air Quality No. 31 (Helsinki: Finnish Meteorological Institute).

Sen, P. K. (1968) Estimates of the regression coefficient based on Kendall's tau, *Journal of the American Statistical Association*, 63(324), pp. 1379–1389.

Sidle, R. C., Tani, M. & Ziegler, A. D. (2006) Catchment processes in Southeast Asia: atmospheric, hydrologic, erosion, nutrient cycling, and management effects, *Forest Ecology and Management*, 224(1–2), pp. 1–4.

Smith, S. V., Swaney, D. P., Talaue-McManus, L., Bartley, J. D., Sandhei, P. T., McLaughlin, C. J., Dupra, V. C., Crossland, C. J., Buddemeier, R. W., Maxwell, B. A. & Wulff, F. (2003) Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean, *BioScience*, 53(3), pp. 235–245.

Snidvongs, A. & Teng, S. (2006) *Global International Waters Assessment: Mekong River*, GIWA Regional Assessment 55 (University of Kalmar, Sweden, on behalf of United Nations Environment Programme).

Sokhem, P. & Sunada, K. (2006) The governance of the Tonle Sap Lake, Cambodia: integration of local, national and international levels, *International Journal of Water Resources Development*, 22(3), pp. 399–416.

Sokhem, P. & Sunada, K. (2008) Population growth and natural-resources pressures in the Lower Mekong Basin, *Ambio*, 37(3), pp. 219–224.

Varis, O. & Keskinen, M. (2006) Policy analysis for the Tonle Sap Lake, Cambodia: a Bayesian network model approach, *International Journal of Water Resources Development*, 22(3), pp. 417–432.

Varis, O., Keskinen, M. & Kummu, M. (2008) Mekong at the crossroads, *Ambio*, 37(3), pp. 146–149.

Varis, O., Kummu, M. & Salmivaara, A. (2012) Ten major river basins in monsoon Asia-Pacific: an assessment of vulnerability, *Applied Geography*, 32(2), pp. 441–454.

Vassiljev, A. & Stålnacke, P. (2005) Statistical modelling of riverine nutrient sources and retention in the Lake Peipsi drainage basin, *Water Science & Technology*, 51(3–4), pp. 309–317.

Västilä, K., Kummu, M., Sangmanee, C. & Chinvanno, S. (2010) Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains, *Journal of Water and Climate Change*, 1(1), pp. 67–86.

Voss, M., Dombar, D., Loick, N. & Dippner, J. W. (2006) Riverine influence on nitrogen fixation in the upwelling region off Vietnam, South China Sea, *Geophysical Research Letters*, 33(7), L07604.

White, I. (2002) *Water Management in the Mekong Delta: Changes, Conflicts and Opportunities*, IHP-VI, Technical Documents in Hydrology, No. 61, International Hydrological Programme (Paris: UNESCO).

Wilson, J. R., Holst, N. & Rees, M. (2005) Determinants and patterns of population growth in water hyacinth, *Aquatic Botany*, 81(1), pp. 51–67.

WHO (1999) *Toxic Cyanobacteria in Water: A Guide to their Public Health Consequences, Monitoring and Management* (London: E & FN Spon, on behalf of WHO).

Yoshimura, C., Zhou, M. C., Kiem, A. S., Fukuami, K., Hapuarachchi, H. A. P., Ishidaira, H. & Takeuchi, K. (2009) 2020s scenario analysis of nutrient load in the Mekong River Basin using a distributed hydrological model, *Science of the total Environment*, 407(20), pp. 5356–5366.

## Appendix

**Table A1.** Mann-Kendall trend test and Sen's slope analysis results for annual average, maximum, and minimum total inorganic nitrogen (TIN) concentrations. *Z* indicates the direction of the trend: positive *Z* upward, negative *Z* downward. *Signif.* is the statistical significance of the trend, while *Q* indicates the slope estimate based on Sen's slope analysis.

| | TIN (avg) | | | TIN (max) | | | TIN (min) | | |
|---|---|---|---|---|---|---|---|---|---|
| Monitoring site | *Z* | *Signif.* | *Q* | *Z* | *Signif.* | *Q* | *Z* | *Signif.* | *Q* |
| Chiang Saen | 1.06 | | 0.002 | 2.20 | * | 0.008 | −1.99 | * | −0.003 |
| Luang Prabang | 2.51 | * | 0.006 | 2.42 | * | 0.009 | 1.81 | + | 0.004 |
| Vientiane | 2.26 | * | 0.009 | 2.45 | * | 0.016 | 1.78 | + | 0.005 |
| Nakhon Phanom | 2.02 | * | 0.006 | 1.66 | + | 0.008 | 1.60 | | 0.005 |
| Pakse | 2.02 | * | 0.005 | 2.45 | * | 0.008 | 0.91 | | 0.001 |

* trend at $\alpha = 0.05$ level of significance
\+ trend at $\alpha = 0.1$ level of significance

**Table A2.** Mann-Kendall trend test and Sen's slope analysis results for the annual average, maximum and minimum total phosphorus (TOTP) concentrations. *Z* indicates the direction of the trend: positive *Z* upward, negative *Z* downward. *Signif.* is the statistical significance of the trend, while *Q* indicates the slope estimate based on Sen's slope analysis.

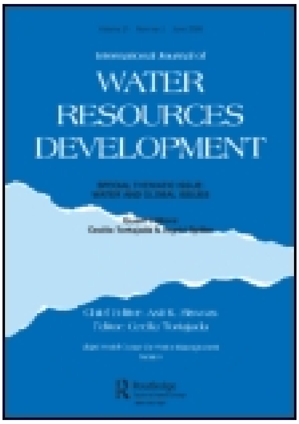
| | TOTP (avg) | | | TOTP (max) | | | TOTP (min) | | |
|---|---|---|---|---|---|---|---|---|---|
| Monitoring site | *Z* | *Signif.* | *Q* | *Z* | *Signif.* | *Q* | *Z* | *Signif.* | *Q* |
| Chiang Saen | 2.75 | ** | 0.003 | 3.11 | ** | 0.010 | 1.79 | + | 0.001 |
| Luang Prabang | − 0.69 | | 0.000 | 0.06 | | 0.000 | − 1.61 | | − 0.001 |
| Vientiane | − 0.57 | | 0.000 | − 0.33 | | − 0.001 | 0.00 | | 0.000 |
| Nakhon Phanom | 2.08 | * | 0.002 | 1.33 | | 0.003 | − 0.39 | | 0.000 |
| Pakse | − 0.57 | | 0.000 | 0.18 | | 0.000 | − 1.25 | | 0.000 |

** trend at $\alpha = 0.01$ level of significance
* trend at $\alpha = 0.05$ level of significance
+ trend at $\alpha = 0.1$ level of significance

**Table A3.** Mann-Kendall trend test and Sen's slope analysis results for the annual average discharge. *Z* indicates the direction of the trend: positive *Z* upward, negative *Z* downward. *Signif.* is the statistical significance of the trend, while *Q* indicates the slope estimate based on Sen's slope analysis.

| | Discharge | | |
|---|---|---|---|
| Monitoring site | *Z* | *Signif.* | *Q* |
| Chiang Saen | 0.00 | | − 0.08 |
| Luang Prabang | 0.27 | | 18.3 |
| Vientiane | 1.36 | | 40.1 |
| Nakhon Phanom | 2.63 | ** | 217.6 |
| Pakse | 0.75 | | 90.0 |

** trend at $\alpha = 0.01$ level of significance



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# Nutrient Balance Assessment in the Mekong Basin: Nitrogen and Phosphorus Dynamics in a Catchment Scale

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