The Chao Phraya River Basin: water quality and anthropogenic influences

Nuanchan Singkran, Pitchaya Anantawong, Naree Intharawichian and Karika Kunta

ABSTRACT

Land use influences and trends in water quality parameters were determined for the Chao Phraya River, Thailand. Dissolved oxygen (DO), biochemical oxygen demand (BOD), and nitrate-nitrogen (NO_3-N) showed significant trends ($R^2 \geq 0.5$) across the year, while total phosphorus (TP) and faecal coliform bacteria (FCB) showed significant trends only in the wet season. DO increased, but BOD, NO_3-N, and TP decreased, from the lower section (river kilometres (rkm) 7–58 from the river mouth) through the middle section (rkm 58–143) to the upper section (rkm 143–379) of the river. Lead and mercury showed weak/no trends ($R^2 < 0.5$). Based on the river section, major land use groups were a combination of urban and built-up areas (43%) and aquaculture (21%) in the lower river basin, paddy fields (56%) and urban and built-up areas (21%) in the middle river basin, and paddy fields (44%) and other agricultural areas (34%) in the upper river basin. Most water quality and land use attributes had significantly positive or negative correlations (at $P \leq 0.05$) among each other. The river was in crisis because of high FCB concentrations. Serious measures are suggested to manage FCB and relevant human activities in the river basin.

Key words | basin management, land use, Thailand, water quality

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INTRODUCTION

The Chao Phraya River Basin covers most or parts of 19 provinces in central Thailand (Figure 1) and serves about 13 million inhabitants (DOPA 2018). The rapid expansion of population settlements, economic growth, and land use activities has affected the river basin's environment (Muttamara & Sales 1994; Liu *et al.* 2015; Xu *et al.* 2016). In particular, the water quality in the Chao Phraya River often does not comply with its water classes assigned by the Pollution Control Department (PCD 1994). A large amount of untreated wastewater from domestic, industrial, aquaculture, and agricultural activities contributed to water quality deterioration in the river (PCD 2008).

Although strategic measures have been implemented, the water quality in the river has not been significantly rehabilitated (PCD 2008), especially in the downstream section, where crowded provinces, such as Bangkok and Samut Prakan, are located (Figure 1). The vast urbanization and extreme human activities along the lower part of the Chao Phraya River have discharged a large amount of wastewater into this river section. These sometimes caused eutrophication and have brought about a

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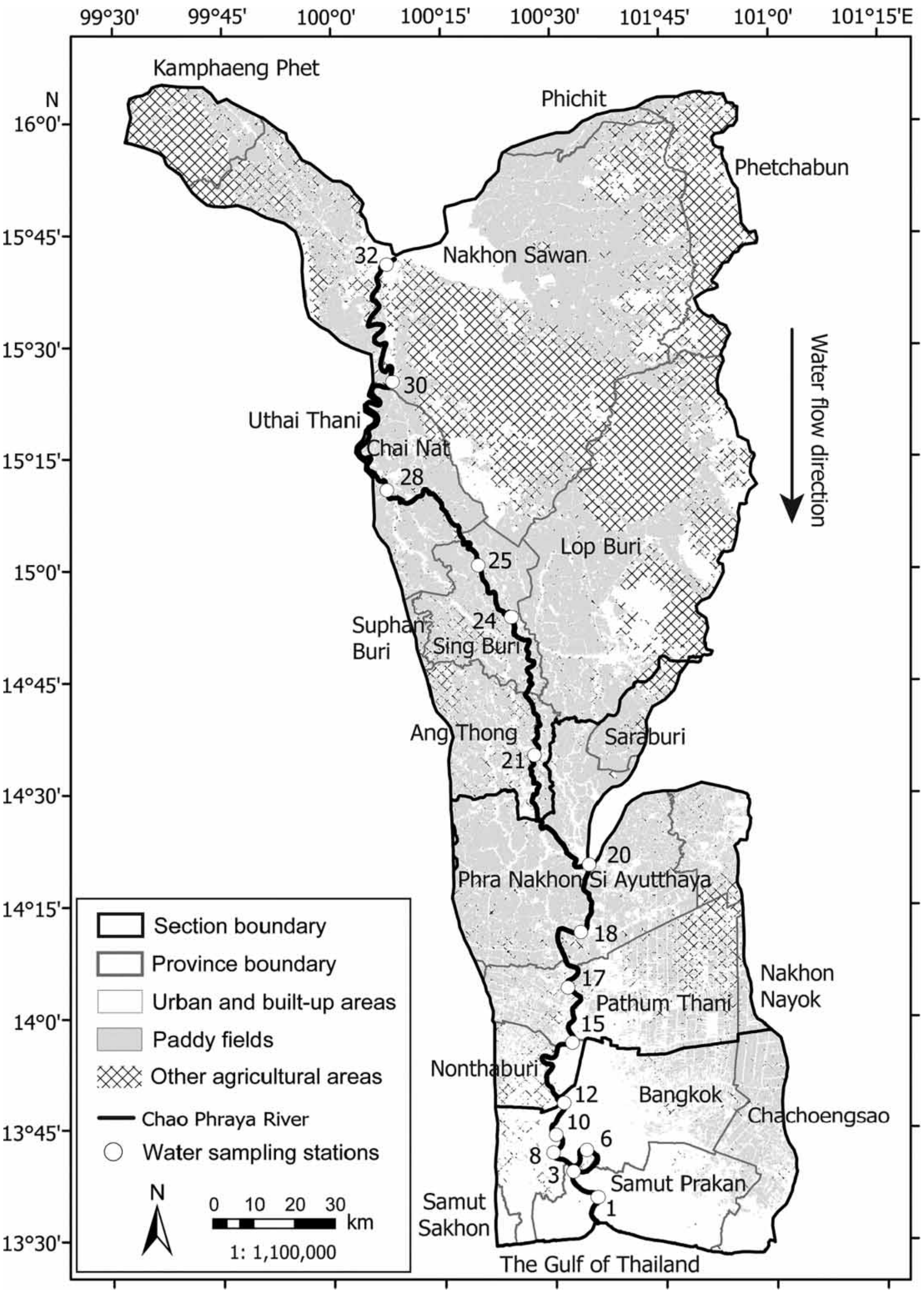

Figure 1 | The Chao Phraya River Basin (Department of Water Resources, unpublished data) showing water sampling stations in the lower (1–12), middle (15–20), and upper (21–32) sections of the Chao Phraya River (PCD, unpublished data) and major land use groups in the river basin (LDD, unpublished data).

deficit of dissolved oxygen (DO) in the lower Chao Phraya River (Muttamara & Sales 1994). More studies are needed to explore patterns of water quality in relation to anthropogenic influences as a result of wastewater and nutrient loads discharged from land use activities (Liu *et al.* 2015).

The objectives of this study were thus to (1) determine spatial and temporal trends of important water quality parameters along the Chao Phraya River and (2) analyse influences of land use activities on water quality in the river.

MATERIALS AND METHODS

Study area and data collections

The Chao Phraya River Basin (located between 13°28′N, 99°33′E and 16°6′N, 101° 5′E) covers a 21,604 km^2 area and has a major river, namely the Chao Phraya, that runs through it before emptying into the Gulf of Thailand (Figure 1). The water discharges into the river were 12–500 million m^3/month in the wet season (May–November) and 0.6–11 million m^3/month in the dry season (December–April) (Royal Irrigation Department, unpublished data). The PCD (1994) divided the river into three sections (Figure 1) for the purpose of water quality management. The lower section covers the PCD's water sampling stations 1–12 (located between river kilometres (rkm) 7–58 from the river mouth). The middle section covers stations 15–20 (rkm 58–143). The upper section covers stations 21–32 (rkm 143–379). Water classes 4 (poor), 3 (fair), and 2 (good) are assigned to the lower, middle, and upper river sections, respectively (PCD 1994). The PCD has sampled water 2–3 times a season each year at each of the 16 stations since 1990. The water samples were collected using the stratified random sampling method, preserved, and sent for laboratory analysis following *Standard Methods for the Examination of Water and Wastewater* (APHA *et al.* 2005).

The observed data of seven water quality parameters at the 16 stations of the PCD (unpublished data) over a 28-year period (1990–2017) were used in this study, including DO, biochemical oxygen demand (BOD), nitrate-nitrogen (NO_3-N), total phosphorus (TP), lead (Pb), mercury (Hg), and faecal coliform bacteria (FCB). The National Environment Board (1994) specified that water class 4 should contain $\geq$2 mg/L DO and $\leq$4 mg/L BOD; water class 3 should contain $\geq$4 mg/L DO and $\leq$2 mg/L BOD, and water class 2 should contain $\geq$6 mg/L DO and $\leq$1.5 mg/L BOD. The concentrations of NO_3-N, Pb, and Hg in these water classes should be $\leq$5, $\leq$0.05, and $\leq$0.002 mg/L, respectively. FCB should be $\leq$1,000 MPN/100 mL in water class 2 and $\leq$4,000 MPN/100 mL in water classes 3 and 4. Land use data for the river basin in 2016 of the Land Development Department (LDD, unpublished data) were considered. They were obtained from the Theos and Landsat 8 satellite images and field observations of the LDD and were mapped with a scale of 1:50,000 for producing the relevant shapefiles.

Data analyses

Linear mixed models in the SPSS program were used to analyse each water quality parameter across the three river sections, between the two seasons, and by the interactions between the river sections and seasons. The total observed values (n) over the 28-year period of each parameter for statistical testing in the wet season were 362, 235, and 350 for the lower, middle, and upper sections, respectively. In the dry season, they were 284, 186, and 270 for the lower, middle, and upper sections, respectively. The population sizes varied because of different numbers of sampling stations among river sections and different frequencies of water sampling between seasons (i.e. twice and three times in the dry and wet seasons, respectively). The ArcGIS program was used to categorize land use areas across the river basin into eight groups, including urban and built-up areas, industrial areas, paddy fields, other agricultural areas, aquaculture, forestry areas, miscellaneous areas, and water bodies. Kendall correlation analysis was used to determine correlations among water quality parameters and land use groups in each season.

RESULTS AND DISCUSSION

Trends of water quality and anthropogenic influences

DO, BOD, and NO_3-N showed significant trends ($R^2 \geq 0.5$) along the Chao Phraya River in each season, while TP and FCB showed significant trends only in the wet season. DO increased, but BOD, NO_3-N, and TP decreased, from the lower section through the middle section to the upper section of the river. Pb and Hg showed weak/no trends in each season (Figure 2). Each water quality parameter, except Hg, was significantly different among the three river sections ($P \leq 0.05$), but most of them were not significantly different between the two seasons and by the interactions between the river sections and seasons (Table 1). Except DO and FCB, mean concentrations of all

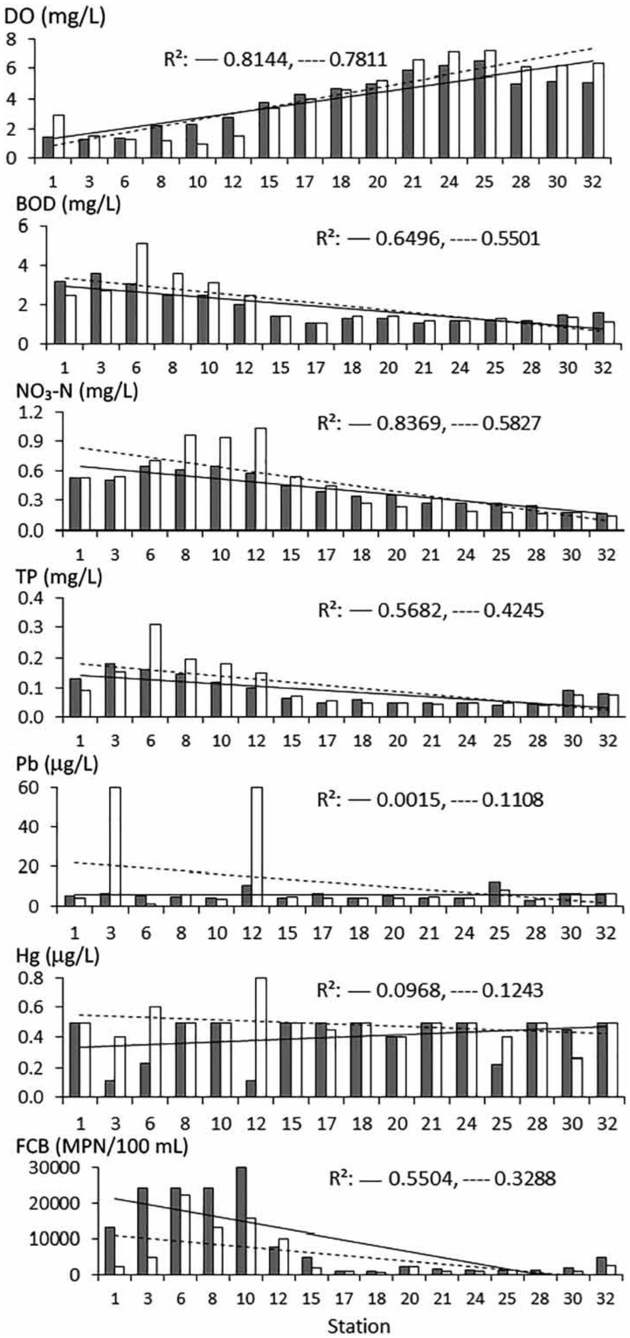

Figure 2 | Median values of each water quality parameter observed at each station along the Chao Phraya River (PCD, unpublished data) over a 28-year period (1990–2017) are shown by season (wet: grey bars, dry: white bars). Spatial trends with the associated R^2 values are shown for each parameter in the wet (May–November, thick line) and dry (December–April, dashed line) seasons.

Table 1 | Linear mixed model results for each water quality parameter observed along the Chao Phraya River over a 28-year period (1990–2017) among the three river sections (lower, middle, and upper), between the two seasons (wet and dry), and by the interactions between the river sections and seasons

	River section		Season		River section × season	
Parameter	F-value	*P*-value	F-value	*P*-value	F-value	*P*-value
DO	1,637.5	**0.00**	14.0	**0.00**	42.7	**0.00**
BOD	278.3	**0.00**	0.2	0.64	1.0	0.39
NO_3-N	39.8	**0.00**	0.4	0.55	0.1	0.87
TP	64.2	**0.00**	0.0	0.96	1.5	0.21
Pb	5.2	**0.01**	4.6	**0.03**	2.4	0.09
Hg	0.6	0.53	0.0	0.98	1.4	0.25
FCB	45.6	**0.00**	3.9	**0.05**	4.0	**0.02**

The significant differences of values ($P \leq 0.05$) are in bold.

water quality parameters conformed to their values specified for the water classes in each river sections, whereas the National Environment Board (1994) did not specify the concentrations of TP for all water classes. DO and FCB were therefore widely discussed.

In the wet season, mean DO concentration (5.5 mg/L) was slightly lower than that required for water class 2 (≥6 mg/L) in the upper river section. In the dry season, it (1.8 mg/L) was lower than that required for water class 4 (≥2 mg/L) in the lower river section. Mean FCB concentrations were highest in the lower river section (Table 2); and they were more than the limitations for water classes 2–4 assigned for the associated river sections.

Based on the river section, the largest land use groups were a combination of urban and built-up areas (43%) and aquaculture (21%) in the lower river basin, paddy fields (56%) and urban and built-up areas (21%) in the middle river basin, and paddy fields (44%) and other agricultural areas (34%) in the upper river basin (Appendix, available with the online version of this paper). Most water quality parameters and land use groups showed significantly positive or negative correlations (+/–Tau at $P \leq 0.05$) among each other. In both seasons, DO had significantly negative correlations with BOD, NO_3-N, TP, FCB, urban and built-up areas, industrial areas, aquaculture, and miscellaneous areas, while it had significantly positive correlation with other agricultural areas (Table 3). Discharge of wastewater from land use activities, such as urban and built-up areas, industrial areas, and aquaculture into the lower Chao

Table 2 | Mean concentration ± standard error (SE) for each water quality parameter by season and section of the Chao Phraya River over a 28-year period (1990–2017)

	Mean concentration ± SE of water quality parameter[b]						
River section[a]	**DO**	**BOD**	**NO_3-N**	**TP**	**Pb**	**Hg**	**FCB**
Wet season (May–November)							
Lower	2.0 ± 0.07	3.5 ± 0.09	1.4 ± 0.09	0.2 ± 0.01	8.7 ± 1.65	0.7 ± 0.74	54,281 ± 3,729
Middle	4.4 ± 0.08	1.5 ± 0.12	0.9 ± 0.11	0.1 ± 0.01	7.1 ± 1.51	0.8 ± 0.72	7,702 ± 4,680
Upper	5.5 ± 0.07	1.5 ± 0.10	0.6 ± 0.09	0.1 ± 0.01	7.3 ± 1.27	2.0 ± 0.57	11,805 ± 3,832
Dry season (December–April)							
Lower	1.8 ± 0.08	3.7 ± 0.11	1.4 ± 0.10	0.2 ± 0.01	15.8 ± 1.92	2.1 ± 0.93	33,726 ± 4,212
Middle	4.2 ± 0.09	1.6 ± 0.13	0.9 ± 0.12	0.1 ± 0.02	7.7 ± 1.74	0.5 ± 0.88	8,247 ± 5,131
Upper	6.6 ± 0.08	1.4 ± 0.11	0.5 ± 0.10	0.1 ± 0.01	8.0 ± 1.48	0.9 ± 0.71	10,757 ± 4,281

[a]The three river sections divided by the PCD (1994).
[b]Concentrations of Pb and Hg were measured in μg/L, of FCB were measured using most probable number (MPN)/100 mL, and of the remaining parameters were measured in mg/L. The observed values for each parameter in the wet season were 362, 235, and 350 in the lower, middle, and upper sections, respectively. In the dry season, they were 284, 186, and 270 in the lower, middle, and upper sections, respectively.

Phraya River (Singkran 2017) mainly contributed to the lowest mean concentration of DO observed in this river section as reflected by their significantly negative correlations with DO.

FCB showed a strong trend only in the wet season and its concentrations were more than the specified amounts for the relevant water classes across the three river sections. This indicates that the river is contaminated with human or animal faecal materials (Singkran 2017). FCB had significantly positive correlations with BOD, NO_3-N, TP, urban and built-up areas, industrial areas, aquaculture, miscellaneous areas, and water bodies, but negative correlations with DO, paddy fields, and other agricultural areas. These correlation patterns were strongly detected in the wet season (Table 3) when surface runoffs into the Chao Phraya River were more than that in the dry season.

The highest concentrations of all water quality parameters (except DO) were detected in the lower river section, where various sources of wastewater containing these contaminants are densely located along the riverbanks, such as residential areas, municipalities, business centres, hotels, restaurants, etc. (Singkran 2017). Although faecal matter from certain agricultural activities, such as livestock and poultry, were another major source of FCB (Sullivan *et al.* 2007; Jayakody *et al.* 2014), these farms were located in higher elevated areas, far from the riparian zone, to avoid flooding. Thus, runoffs containing FCB from the farms into the river seemed to be low. That is, the farther the distance from the river, the greater the amount of residual pollutant degradation (Lv *et al.* 2015).

Paddy fields and other agricultural areas might have been non-point sources of FCB contamination (Ramos *et al.* 2006; Fumiko 2017) in the Chao Phraya River Basin in the old days when cattle labour and manure were employed for farming. However, nowadays, the traditional farming in the river basin has been replaced by intensive farming that relies on mechanical engines and chemical fertilizers for mass production. As a result, paddy fields and other agricultural areas are currently not a major source of FCB in the river basin. Their high negative correlation with FCB implied that the larger the agricultural areas observed, the smaller were the urban and built-up areas, which are major sources of FCB.

Critical management suggestions

There is no regulation to enforce residential area, small-scale farming, and aquaculture to treat their wastewater before discharging it into the environment. Unless effective management is undertaken to reduce the FCB concentrations in the Chao Phraya River Basin, this growing problem will tend to affect not only water quality, but also the public health of communities living along the river edges. High FCB concentrations in the river indicate disease-causing

Table 3 | Kendall correlation coefficients (Tau) among mean water quality parameters by station along the Chao Phraya River over a 28-year period (1990–2017) in the wet and dry (in brackets if the values are different) seasons, areas of eight land use groups observed in 2016 (L1 = urban and built-up areas, L2 = industrial areas, L3 = paddy fields, L4 = other agricultural areas, L5 = aquaculture, L6 = forestry areas, L7 = miscellaneous areas, and L8 = water bodies), and parameters from both sets

	Water quality parameters							**Land use groups**							
	DO	**BOD**	**NO_3-N**	**TP**	**Pb**	**Hg**	**FCB**	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**
DO	1														
BOD	−0.6**(−0.7**)	1													
NO_3-N	−0.4*(−0.8**)	0.4* (0.6**)	1												
TP	−0.6**	0.9** (0.7**)	0.3 (0.6**)	1											
Pb	−0.2 (−0.3)	0.2 (0.4*)	0.1 (0.5**)	0.1 (0.5**)	1										
Hg	0.2 (0.0)	−0.2 (0.1)	−0.4* (0.0)	−0.1 (0.1)	−0.2 (0.0)	1									
FCB	−0.4*	0.6** (0.5**)	0.5** (0.3)	0.6** (0.4*)	0.0 (0.2)	−0.2 (0.3)	1								
L1	−0.8**	0.6** (0.8**)	0.7** (0.8**)	0.6** (0.7**)	0.2 (0.5*)	−0.3 (0.1)	0.6** (0.4)	1							
L2	−0.8**	0.6** (0.8**)	0.7** (0.8**)	0.6** (0.7**)	0.2 (0.5*)	−0.3 (0.1)	0.6** (0.4)	1.0**	1						
L3	0.3	−0.6** (− 0.5*)	−0.4** (− 0.3)	−0.6**	−0.3 (− 0.6**)	0.3 (− 0.4)	−0.6**	−0.4	−0.4	1					
L4	0.8**	−0.6** (− 0.8**)	−0.7** (− 0.8**)	−0.6** (− 0.7**)	−0.2 (− 0.5*)	0.3 (− 0.1)	−0.6** (− 0.4)	−1.0**	−1.0**	0.4	1				
L5	−0.8**	0.6** (0.8**)	0.7** (0.8**)	0.6** (0.7**)	0.2 (0.5*)	−0.3 (0.1)	0.6** (0.4)	1.0**	1.0**	−0.4	−1.0**	1			
L6	0.3	−0.1 (− 0.3)	−0.3	−0.1 (− 0.2)	0.0	0.1 (0.2)	−0.1 (0.0)	−0.4	−0.4	−0.1	0.4	−0.4	1		
L7	−0.8**	0.6** (0.8**)	0.7** (0.8**)	0.6** (0.7**)	0.2 (0.5*)	−0.3 (0.1)	0.6** (0.4)	1.0*	1.0**	−0.4	−1.0**	1.0**	−0.4	1	
L8	−0.3	0.6** (0.5*)	0.4* (0.3)	0.6**	0.3 (0.6*)	−0.3 (0.4)	0.6**	0.4	0.4	−1.0**	−0.4	0.4	0.1	0.4	1

Significant Tau values at $P \leq 0.01$ and ≤ 0.05 are indicated by ** and *, respectively.

pathogens, such as *Escherichia coli* and *Salmonella* sp., which can increase human health risks of relevant diseases (DeLorenzo *et al.* 2012).

In the lower river basin, where urban and built-up areas dominated, the discharge of untreated domestic wastewater into water sources was apparently a major cause of FCB contamination in the lower Chao Phraya River. Similarly, in the middle river basin, although paddy fields were dominant, most of the urban and built-up areas (21%) were densely located along the river banks; and they were the major point source of wastewater discharged into this river section (PCD 2008). Sufficient onsite wastewater systems should be installed in all municipalities and crowded areas, and they should be maintained in good working order. Urban planning and building zoning should be considered for re-zoning, re-locating, or forbidding new development in the riparian zones that are currently crowded and generate large amounts of domestic wastewater.

In the upper river basin, while paddy fields and other agricultural areas were dominant, swine and poultry farms were also most observed among the three sections of the river basin. Faecal matter from all farm sizes should be managed using proper methods and onsite wastewater treatment systems. For pasturelands that are scattered in the middle and upper river basins, installation of vegetated buffers and the planting or the protection of vegetation nearby water sources are suggested to reduce FCB contamination in runoffs (Sullivan *et al.* 2007; Lewis *et al.* 2009).

CONCLUSIONS

Overall, the water quality in the Chao Phraya River was influenced by the dominant groups of land use in the river basin. The river will tend to have low DO concentrations at certain river sections and high FCB concentrations throughout the river gradient. Specific measures and action plans are need to increase DO in the upper river section in the wet season and in the lower river section in the dry season. FCB-related human activities, such as urban and built-up areas and swine and poultry farms, should be managed using both law enforcement and urban planning and zoning. It may be about time for wastewater polluters to pay for wastewater bills or for the installation of onsite wastewater treatment systems for their wastewater-related activities.

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REFERENCES

APHA, AWWA & WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association, American Water Works Association, and Water Environment Federation, Port City Press, Maryland, USA.

DeLorenzo, M. E., Thompson, B., Cooper, E., Moore, J. & Fulton, M. H. 2012 A long-term monitoring study of chlorophyll, microbial contaminants, and pesticides in a coastal residential stormwater pond and its adjacent tidal creek. *Environmental Monitoring and Assessment* **184** (1), 343–359.

DOPA 2018 จำนวนประชากร (Number of population). http://stat.bora.dopa.go.th/new_stat/webPage/statByYear.php (accessed 27 April 2018).

Fumiko, O. 2017 *Agricultural Research Organization Research Report Rural Engineering Research Division No. 1: Use of Digested Slurry From Livestock Manure in Paddy Fields and its Environmental Effect in Southeast Asia*. National Agriculture and Food Research Organization, Japan.

Jayakody, P., Parajuli, P. B. & Brooks, J. P. 2014 Evaluating spatial and temporal variability of fecal coliform bacteria loads at the Pelahatchie watershed in Mississippi. *Human and Ecological Risk Assessment* **20** (4), 1023–1041.

Lewis, D. J., Atwill, E. R., Lennox, M. S., Pereira, M. D. G., Miller, W. A., Conrad, P. A. & Tate, K. W. 2009 Reducing microbial contamination in storm runoff from high use areas on California coastal dairies. *Water Science & Technology* **60** (7), 1731–1743.

Liu, R., Dong, G., Xu, F., Wang, X. & He, M. 2015 Spatial-temporal characteristics of phosphorus in nonpoint source pollution with grid-based export coefficient model and geographical information system. *Water Science & Technology* **71** (11), 1709–1717.

Lv, H., Xu, Y., Han, L. & Zhou, F. 2015 Scale-dependence effects of landscape on seasonal water quality in Xitiaoxi catchment of Taihu Basin, China. *Water Science & Technology* **71** (1), 59–66.

Muttamara, S. & Sales, C. L. 1994 Water quality management of the Chao Phraya River (a case study). *Environmental Technology* **15** (6), 501–516.

National Environment Board 1994 ประกาศคณะกรรมการสิ่งแวดล้อมแห่งชาติ ฉบับที่ ๘ (พ.ศ. ๒๕๓๗) ออกตามความในพระราชบัญญัติส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. ๒๕๓๕ เรื่อง กำหนดมาตรฐานคุณภาพน้ำในแหล่งน้ำผิวดิน (Notification of the National Environment Board, No. 8 (1994), issued under the Enhancement and Conservation of National Environmental Quality Act 1992 entitled the water quality standard setting for inland water). *Royal Thai Government Gazette* **111** (16 Ngor), 73–81.

PCD 1994 ประกาศกรมควบคุมมลพิษ เรื่อง กำหนดประเภทแหล่งน้ำในแม่น้ำเจ้าพระยา (Notification of the Pollution Control Department: Classification of surface water source in the Chao Phraya River). *Royal Thai Government Gazette* **111** (62 Ngor), 291–293.

PCD 2008 *โครงการประเมินศักยภาพการรองรับมลพิษของแม่น้ำเจ้าพระยา* (The Pollution Carrying Capacity Assessment Project for the Chao Phraya River). Report PCD.02/204. No. 1/3 Pollution Control Department, Ministry of Natural Resources and Environment, Bangkok, Thailand.

Ramos, M. C., Quinton, J. N. & Tyrrel, S. F. 2006 Effects of cattle manure on erosion rates and runoff water pollution by faecal coliforms. *Journal of Environmental Management* **78** (1), 97–101.

Singkran, N. 2017 Determining overall water quality related to anthropogenic influences across freshwater systems of Thailand. *International Journal of Water Resources Development* **33** (1), 132–151.

Sullivan, T. J., Moore, J. A., Thomas, D. R., Mallery, E., Snyder, K. U., Wustenberg, M., Wustenberg, J., Mackey, S. D. & Moore, D. L. 2007 Efficacy of vegetated buffers in preventing transport of fecal coliform bacteria from pasturelands. *Environmental Management* **40** (6), 958–965.

Xu, E., Zhang, H., Dong, G., Kang, L. & Zhen, X. 2016 Spatial variation of water quality in upper catchment of Miyun Reservoir. *Water Science & Technology: Water Supply* **16** (3), 817–827.

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