Spatial and Temporal Variability in Water Quality, Sediment, and Benthic Macroinvertebrates in the Mae Klong River, Thailand

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ABSTRACT

Diversity and abundance of macrobenthic fauna have been extensively used to determine the quality of the aquatic environment. The Mae Klong River consists of several types of habitats which are important for human uses. The water quality of the river has deteriorated due to wastewater discharged from human activities. Although there have been many efforts to improve water quality in the past, problems still remain. This study used benthic macroinvertebrates as key indicators of water quality and sediment in the Mae Klong River and its tributaries. Spatio-temporal variability in water quality, sediment, and benthic macroinvertebrates in the Mae Klong River was investigated across 21 stations between April 2016 and March 2017, at an interval of three times per season (hot, rainy, and cold). Principal component analysis revealed that water quality variables in the cold season were clearly different from those in the hot and rainy seasons. Total organic matter, sulfide, and median grain size in the sediment were not different, whereas concentrations of copper, lead, cadmium, and zinc in the rainy and cold seasons were different from those in the hot season. Three phyla, 26 orders, 58 families, and 118 species of benthic macroinvertebrates were found. Species and their distributions were not different among the three seasons, but varied by location (upper, middle and lower parts of the river). The conditions of the upper Mae Klong River are satisfactory, but the lower Mae Klong River is contaminated with pollution. The main factors affecting the community structure, composition, and distribution of benthic macroinvertebrates in the Mae Klong River include conductivity, total organic matter, and sulfide. This present study also demonstrates that benthic macroinvertebrate taxa, including the families Ephemeridae, Baetidae, Caenidae (Ephemeroptera), Libellulidae (Odonata) and class Polychaeta (*Perinereis*) are useful for assessment of the health of Mae Klong River.

Keywords: Aquatic benthos, Mae Klong River, Sediment, Water quality

INTRODUCTION

Monitoring water quality using biological indicators as an inexpensive alternative to physical and chemical methods (Norris and Norris, 1995; Bendati *et al*., 1998) is a technique based on the ecological principle that a given organism can grow well in the right environment, but that whenever the environment changes, the diversity of life in that water source will change accordingly (Hauer and Hill, 1996; Resh *et al*., 1996). Benthic macroinvertebrates are invertebrates that crawl and feed on the bottom of lakes and rivers (Pennak, 1953), and include shrimp, crabs, mollusks, and aquatic insects. The species and abundance of these animals play a significant role in energy transfer,

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which is an important element of the food chain and the circulation of minerals in the ecosystem (Cummins, 1978). Diversity and distribution of benthic macroinvertebrates are used as biological data to evaluate water quality in different countries, including USA, Australia, New Zealand, China, and Korea (Dudgeon, 1999, Kullasoot *et al*., 2017; Liu *et al*., 2017; Rosenberg and Resh, 1993). Their popularity as biological indicators is due to their long life span and widespread distribution, as well as the fact that they rarely move out of their preferred habitat. These characteristics also force these organisms to deal with pollution in their habitat directly, and different species have different levels of pollution tolerance. They are also easy to find with the naked eye. In developed countries, most people have basic knowledge of the taxonomy and distribution of benthic macroinvertebrates (Dudgeon, 1999). In Thailand, several previous studies employed macrobenthic taxa as bioindicators for ecological monitoring in freshwater bodies (Boonsoong *et al*., 2009; Rattanachan *et al*., 2016; Chartchumni *et al*., 2017).

The Mae Klong River is one of five main rivers flowing into the Upper Gulf of Thailand that are highly important to the economy and population in the central region. The Mae Klong River is used for many kinds of human activities, such as dams, irrigation, transportation, community areas, industry, aquaculture, fruit orchards, and agriculture (Thongdonphum *et al*., 2011). These activities have dramatically affected the environmental quality of the Mae Klong River, particularly through impacts of wastewater from community, industrial and agricultural sources (Pollution Control Department, 2016). Accordingly, a long-term action plan for restoration and management to improve the water quality and biological status of the Mae Klong River has become necessary.

A few studies have evaluated the environmental status of the Mae Klong River based on macrobenthic assemblages. Kullasoot *et al*. (2017) employed macrobenthic taxa as bioindicators to monitor the water quality of upper Mae Klong River, and their results indicated a relationship between anthropogenic impact and species richness. However, their study mainly focused on the upper part of Mae Klong River (Kanchanaburi and Ratchaburi provinces); the Mae Klong River as a whole, and its tributaries are still poorly documented.

This study aims to provide basic knowledge of the diversity and distribution of benthic macroinvertebrates in the Mae Klong River including all tributaries in Kanchanaburi, Ratchaburi, and Samut Songkhram provinces, with reference to environmental factors, including water and sediment parameters as well as heavy metals. We also examine the relationships between benthic macroinvertebrate assemblages and season and environmental variables. This fundamental understanding and baseline information can be applied to the development of strategies for sustainable management and conservation of the Mae Klong River ecosystem.

MATERIALS AND METHODS

Study area

The Mae Klong River is located in the central region of Thailand and flows through Kanchanaburi, Ratchaburi, and Samut Songkhram provinces. In this study, 21 sampling stations were allocated among three main sections of the river. The upper Mae Klong stations comprised the Kwae Yai River (KY1), the Kwae Noi River (KN2), the Mae Klong River (MK3, Kwae Yai and Kwae Noi rivers merged), and sites upstream of the Mae Klong dam (MK4 to MK7). Most human activities near these stations consisted of tourism and housing for local communities. The middle Mae Klong stations (MK8 to MK16) were in areas where the main activity was agriculture. The lower Mae Klong stations (MK17 to MK21) were in areas primarily occupied by industrial plants (Figure 1).

Sample collection and processing

Samples were collected in three periods: hot (April–June 2016), rainy (August–October 2016), and cold (December 2016–February 2017) seasons. Benthic macroinvertebrate samples were collected using a 15×15 cm Ekman grab (3 replicates at random locations within each station) and sieved through a 500-µm standard sieve. The samples were preserved in 70% ethanol, sorted, and identified to the lowest possible taxonomic level in the laboratory.

Before collecting the benthic macroinvertebrate samples, a water sample was taken with a Rutter water sampler at a depth of 1 meter above the sediment. The pH, water temperature, depth, transparency, salinity, and

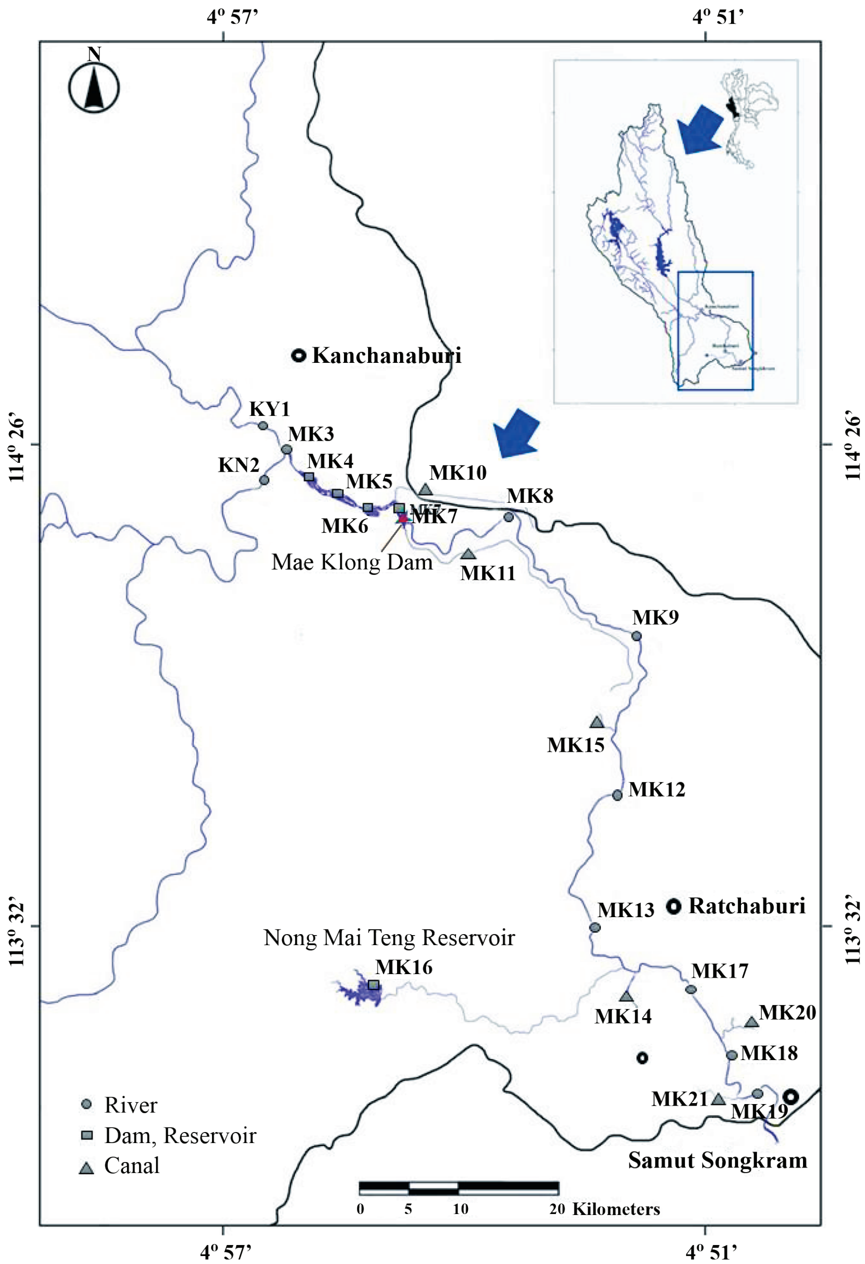

Figure 1. Location of sampling stations in the Mae Klong River and its tributaries.

electrical conductivity of the samples were analyzed in situ by using a pHmeter (YSI, pH100A), thermometer, depth meter, secchi disk and salinity and electrical conductivity meter (YSI, EC 300), respectively. Total alkalinity ($mg{\cdot}L^{-1}$), total hardness ($mg{\cdot}L^{-1}$), total suspended solids (TSS) ($mg{\cdot}L^{-1}$), dissolved oxygen (DO) ($mg{\cdot}L^{-1}$), biochemical oxygen demand (BOD) ($mg{\cdot}L^{-1}$), nitrate-nitrogen ($mg{\cdot}L^{-1}$), nitrite-nitrogen ($mg{\cdot}L^{-1}$), ammonia-nitrogen ($mg{\cdot}L^{-1}$) and orthophosphorus ($mg{\cdot}L^{-1}$) were analyzed in the laboratory according to standard methods (APHA, 2017). Sediment samples were collected with an Ekman grab to measure total water content (%), total organic matter (TOM) ($mg{\cdot}kg^{-1}$ dry weight), sulfide ($mg{\cdot}kg^{-1}$ dry weight), grain size (µm), zinc ($mg{\cdot}kg^{-1}$ dry weight), cadmium ($mg{\cdot}kg^{-1}$ dry weight), lead ($mg{\cdot}kg^{-1}$ dry weight) and copper ($mg{\cdot}kg^{-1}$ dry weigt) in the laboratory, using standard procedures for soil analysis (Soil Science Society of America, 2001).

Data analysis

The spatial and temporal differences in environmental variables, sediment quality, and abundance of benthic macroinvertebrates were analyzed via principal component analysis (PCA). The adequacy of data for PCA was confirmed with the Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests. A $p\text{-value}<0.05$ was considered to be significant. The vectors of the water quality and sediment quality variables were displayed in the PCA ordination to highlight relationships between variables, axes, and samples. The relationship between species distribution, water quality, and sediment quality was investigated using canonical correspondence analysis (CCA). The CCA process also involved down-weighting of rare species. A forward selection procedure was performed on the set of environmental variables. A Monte Carlo simulation using 999 unrestricted permutations ($p<0.05$) was performed to test for the significance of the correlations between environmental factors and species distributions. Only the significant variables were included in the model (Ter Braak and Verdonschot, 1995). All statistical analyses were performed using PC-ORD software version 7.01 (McCune and Mefford, 2011).

RESULTS AND DISCUSSION

Water quality variables

There were differences in water quality in the Mae Klong River among the three seasons and the 21 stations. PCA analysis revealed that the water variables in the cold season were clearly different from those in the hot and rainy seasons. The parameters pH, alkalinity, transparency, and nitrate-nitrogen were all higher in the hot and rainy seasons. Furthermore, water turbidity was reduced and siltation increased during the cold season due to lower water flow. Organic materials disintegrate and release nutrients, causing high nitrate levels and accelerating phytoplankton growth, thus causing the water to become light green (Sosnovsky *et al*., 2010). As a result of CO_2 consumption by phytoplankton for photosynthesis, particularly in the afternoon, pH and alkalinity tended to be higher in the cold season than in the hot and rainy seasons. However, these parameters did not exceed the surface-water quality standard (Pollution Control Department, 1992) Thailand. Among the water quality variables, discharge was strongly correlated with Axis 3 and it increased during periods of stable water level in the Mae Klong River in the hot season (Figure 2). Slight variations were found in water temperature (average, 30.07±1.57 °C), depth (3.58±2.61 cm), transparency (48.76±27.86 cm), pH (7.62±0.35), salinity (0.31±0.85 psu.), conductivity (417.06±449.26 $\mu s{\cdot}cm^{-1}$), TSS (28.73 ±20.25 $mg{\cdot}L^{-1}$), alkalinity (140.54±48.66 $mg{\cdot}L^{-1}$), hardness (178.23±68.14 $mg{\cdot}L^{-1}$), DO (5.61±1.30 $mg{\cdot}L^{-1}$), BOD (1.79±0.94 $mg{\cdot}L^{-1}$), nitrate-nitrogen (1.3813±0.37 $mg{\cdot}L^{-1}$), nitrite-nitrogen (0.0250± 0.01 $mg{\cdot}L^{-1}$), ammonia-nitrogen (0.0194±0.13 $mg{\cdot}L^{-1}$) and orthophosphate (0.0081±0.00 $mg{\cdot}L^{-1}$) (Table 1).

The water quality in each station was mostly suitable for aquatic organisms (Elfritzson *et al*., 2020). Most parameters did not exceed the surface-water quality standards of Thailand or the appropriate water quality criteria for aquatic life (Pollution Control Department, 1992). The water temperature varied between 23–32 °C and pH between 7.24–8.56. For most stations, DO was

Table 1. Mean value (±SD) of water quality parameters at sites on the Mae Klong River during April 2016–March 2017.

Station code	Water Temp. (°C)	Depth (m)	Transparency (cm)	pH	Salinity (psu)	Conductivity (µs·cm^{-1})	TSS (mg·L^{-1})	Alkalinity (mg·L^{-1})	Hardness (mg·L^{-1})	DO (mg·L^{-1})	BOD (mg·L^{-1})	NO_3-N (mg·L^{-1})	NO_2-N (mg·L^{-1})	NH_4^+-N (mg·L^{-1})	PO_4^{3-} (mg·L^{-1})
KY1	28.76±2.09	3.99±1.48	60.39±37.23	7.60±0.25	0.09±0.02	240.56±8.57	17.22±20.62	144.00±38.17	133.11±14.79	6.03±0.47	1.38±0.19	0.6148±0.20	0.0173±0.01	0.0353±0.00	0.0081±0.00
KN2	29.50±1.56	3.89±1.49	44.17±23.23	7.46±0.29	0.09±0.02	192.74±44.33	29.40±24.12	116.00±42.81	106.00±3.71	5.79±0.13	1.12±0.60	1.1238±0.60	0.0170±0.01	0.0366±0.00	0.0081±0.00
MK3	29.12±1.79	3.42±2.00	57.22±36.91	7.62±0.37	0.09±0.02	224.47±16.61	17.02±15.59	136.67±43.89	120.22±15.24	5.42±0.53	1.56±0.88	0.7712±0.32	0.0125±0.00	0.0353±0.00	0.0080±0.00
MK4	29.31±1.76	4.45±1.34	57.06±35.73	7.50±0.39	0.09±0.02	219.63±23.83	21.72±15.28	125.56±32.01	116.78±10.24	5.56±0.50	1.12±0.51	1.1334±0.52	0.0150±0.00	0.0350±0.00	0.0080±0.00
MK5	29.71±1.85	5.07±3.18	54.22±32.90	7.61±0.33	0.09±0.02	213.89±33.02	21.29±14.70	133.33±47.96	114.22±9.18	5.72±0.19	1.77±0.55	1.3027±0.70	0.0158±0.01	0.0333±0.00	0.0081±0.00
MK6	29.85±1.87	5.82±3.57	52.28±30.48	7.54±0.41	0.09±0.02	219.66±23.38	22.40±15.83	122.22±35.35	114.33±9.33	5.09±0.74	1.39±0.23	1.2845±0.69	0.0145±0.00	0.0335±0.00	0.0081±0.00
MK7	29.71±1.76	6.80±5.06	49.78±30.96	7.57±0.52	0.09±0.02	214.30±28.70	25.78±15.43	121.44±36.29	114.89±9.34	5.83±0.37	2.17±1.01	1.3457±0.68	0.0170±0.00	0.0334±0.00	0.0080±0.00
MK8	30.11±1.63	2.32±0.77	50.56±27.10	7.69±0.39	0.10±0.00	218.13±30.57	17.71±16.00	127.33±40.71	113.56±9.00	6.78±0.91	1.27±0.18	1.5660±0.46	0.0168±0.00	0.0324±0.00	0.0081±0.00
MK9	29.98±1.73	1.68±0.81	52.33±31.70	7.24±0.38	0.10±0.00	203.14±74.98	21.53±11.45	128.00±44.17	114.67±9.68	6.28±0.13	1.62±0.36	1.5019±0.69	0.0167±0.00	0.0368±0.00	0.0081±0.00
MK10	30.18±1.59	1.24±0.83	34.56±18.59	7.51±0.11	0.10±0.00	248.33±14.48	23.13±11.15	131.17±53.30	114.00±10.58	8.34±1.98	2.51±1.79	1.1162±0.87	0.0146±0.00	0.0340±0.00	0.0081±0.00
MK11	30.68±1.73	1.50±0.49	54.44±34.17	7.71±0.38	0.10±0.00	270.62±32.12	23.62±20.04	139.33±48.31	123.78±14.02	5.90±1.13	2.73±0.53	1.4930±0.83	0.0206±0.01	0.0367±0.00	0.0081±0.00
MK12	30.48±1.30	1.45±0.98	47.50±27.04	7.61±0.39	0.11±0.02	273.43±37.48	20.51±14.70	133.56±42.58	126.44±15.45	5.47±1.13	1.89±0.87	1.7515±0.91	0.0188±0.01	0.0351±0.00	0.0081±0.00
MK13	30.79±1.90	1.60±0.70	43.72±26.25	7.65±0.35	0.12±0.02	302.36±46.58	47.56±47.94	138.22±52.20	131.56±14.79	5.27±1.80	1.64±0.48	1.8824±0.94	0.0383±0.02	0.0423±0.01	0.0081±0.00
MK14	31.19±1.57	9.78±24.34	40.28±24.24	7.63±0.36	0.17±0.06	323.97±59.10	25.22±13.07	142.67±52.84	140.00±13.32	5.99±0.80	2.20±0.83	1.4437±0.93	0.0227±0.01	0.0390±0.01	0.0081±0.00
MK15	30.03±1.70	1.18±0.43	37.00±7.55	7.56±0.20	0.23±0.18	475.99±343.15	36.09±30.63	214.22±95.48	167.22±34.41	3.57±1.73	3.42±1.97	1.2603±0.85	0.0858±0.09	0.1092±0.06	0.0086±0.00
MK16	31.08±2.19	1.68±1.00	49.17±19.09	8.56±0.62	0.10±0.00	265.23±29.46	7.93±1.23	137.11±29.77	111.33±7.42	7.43±1.80	3.17±1.24	0.8104±0.85	0.0133±0.00	0.0416±0.00	0.0081±0.00
MK17	30.57±1.90	2.42±0.50	59.22±34.26	7.70±0.34	0.20±0.00	412.64±55.22	32.22±27.12	141.56±46.29	152.22±8.88	5.28±1.25	1.34±0.79	1.4221±0.58	0.0311±0.03	0.0349±0.01	0.0082±0.00
MK18	30.40±1.71	2.76±1.02	44.44±28.00	7.69±0.33	0.27±0.12	528.84±246.46	39.87±20.65	143.67±49.08	164.67±29.07	5.06±1.46	0.91±0.50	1.9675±0.85	0.0301±0.02	0.0380±0.00	0.0082±0.00
MK19	30.53±1.97	10.24±3.59	62.56±44.82	7.43±0.20	2.83±3.88	1476.85±1581.46	46.00±18.03	157.22±59.01	959.78±1020.27	4.34±0.08	0.96±0.59	1.5094±1.47	0.0337±0.02	0.0419±0.00	0.0082±0.00
MK20	30.13±1.63	3.40±0.69	38.39±19.46	7.59±0.24	0.81±0.55	957.58±527.37	41.53±13.39	159.22±47.99	273.33±121.54	4.18±1.03	1.04±0.33	1.9856±1.12	0.0356±0.03	0.0519±0.02	0.0082±0.00
MK21	29.33±1.04	0.59±0.21	34.67±15.38	7.61±0.25	0.63±0.08	1275.93±311.51	65.60±58.22	158.78±38.67	230.67±52.67	4.48±0.40	2.41±0.64	1.7222±1.07	0.0383±0.03	0.0546±0.02	0.0082±0.00

greater than 3 mg·L^{-1}, and BOD, nitrate-nitrogen, and ammonia-nitrogen concentrations were lower than 4, 5, and 0.5 mg·L^{-1}, respectively, which are favorable levels for freshwater aquatic resources (Pollution Control Department, 1992). Conductivity and salinity exhibited the greatest variation in stations MK19, MK20, and MK21; changes in limnological characteristics from saltwater intrusion during high tide would be expected to affect species diversity and distribution of benthic macroinvertebrates (Moi *et al*., 2020). The cycle of rising and falling tides is reflected in a direct association with floodplain utilization by migratory benthic macroinvertebrates (Resh *et al*., 1996). In addition, the lower section of the Mae Klong River (MK19, MK20, and MK21) mixes with the sea, especially during the hot season, resulting in higher salinity and higher conductivity. This poses a significant risk to aquatic organisms in that area (Hintz *et al*., 2017; Jones *et al*., 2017; Schuler and Relyea, 2018b); meanwhile, changes in the freshwater ecosystem may facilitate the spread of some more tolerant species (Coldsnow and Relyea, 2018).

Sediment variables

PCA analysis of sediment variables in the Mae Klong River showed that total organic matter, sulfide, and median grain size were not different among seasons, while the levels of copper, lead, cadmium, and zinc in the rainy and cold seasons were different from those in the hot season (Figure 3). Among the sediment variables, discharge strongly correlated with Axis 1 and increased in periods of constant sediment level in the rainy and cold seasons (Figure 3). Slight variations in sediment variables were found in water content (average, 45.71±13.63 %), total organic matter (78.82±28.99 mg·kg^{-1} dry weight), sulfide (0.04±0.08 mg·kg^{-1} dry weight), median grain size (271.52±252.36 µm), copper (16.78±11.18 mg·kg^{-1} dry weight), lead (32.27±16.93 mg·kg^{-1} dry weight.), zinc (46.33±28.63 mg·kg^{-1} dry weight), and cadmium (0.11±0.20 mg·kg^{-1} dry weight) (Table 2). The samples from above the Mae Klong dam (MK4, MK5, MK6 and MK7) and from the lower Mae Klong River (MK17, MK18, MK19 and MK21) reflect

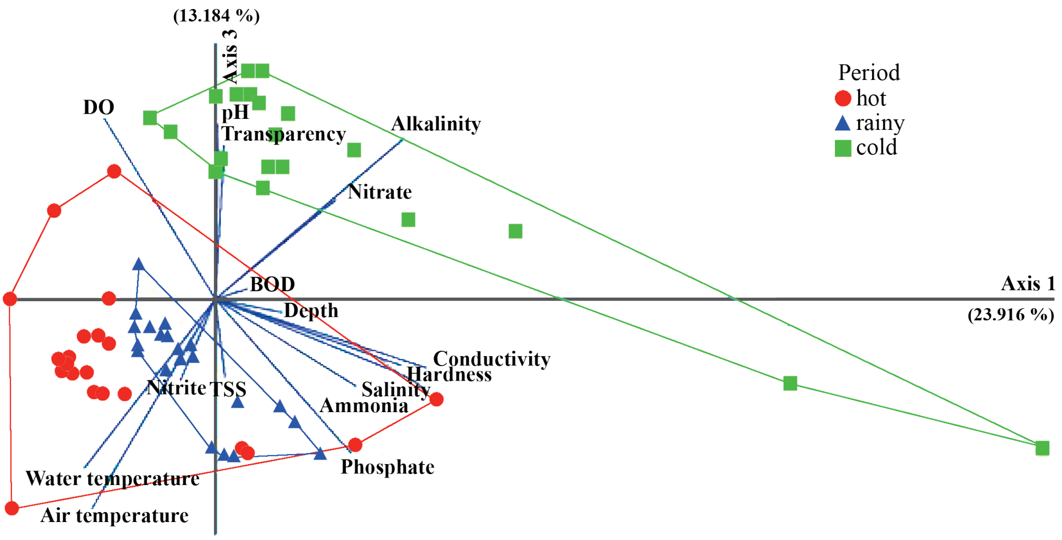

Figure 2. Biplot of sample coordinates on the first two axes of PCA with distance-based biplot scores, including all water quality variables from 21 sites on the Mae Klong River, collected during three seasons (63 total samples).

Table 2. Mean value (±SD) of sediment parameters at sites on the Mae Klong River during April 2016–March 2017.

Station code	Water content (%)	TOM (mg·kg^{-1} dry weight)	Sulfide (mg·kg^{-1} dry weight)	Median grain size (µm)	Zinc (mg·kg^{-1} dry weight)	Cadmium (mg·kg^{-1} dry weight)	Lead (mg·kg^{-1} dry weight)	Copper (mg·kg^{-1} dry weight)
KY1	40.55±16.34	49.01±35.39	0.0417±0.04	467.40±186.98	13.09±11.65	0.00±0.00	25.48±22.11	9.42±13.29
KN2	43.50±7.06	63.32±14.46	0.0017±0.01	193.11±146.96	48.58±14.79	0.20±0.35	32.34±17.89	16.78±8.82
MK3	22.78±7.75	17.97±18.12	0.0755±0.07	752.03±150.05	nd	nd	nd	nd
MK4	45.74±8.98	74.04±4.09	0.0057±0.01	77.09±14.71	40.13±25.61	nd	32.29±19.36	21.29±16.57
MK5	51.44±2.74	88.36±3.36	0.0040±0.01	90.78±10.24	nd	nd	nd	nd
MK6	56.59±7.43	97.88±14.88	0.0104±0.01	84.11±14.94	64.95±33.73	0.11±0.19	43.65±25.52	21.79±15.07
MK7	55.73±6.79	102.09±9.57	0.0375±0.03	82.21±20.52	nd	nd	nd	nd
MK8	43.94±2.77	85.55±10.24	0.0338±0.03	340.37±337.71	43.90±27.83	0.18±0.31	30.47±22.07	12.52±11.58
MK9	47.87±13.85	74.19±8.39	0.0243±0.02	219.18±74.22	nd	nd	nd	nd
MK10	26.09±12.70	50.67±2.53	0.0531±0.05	491.69±323.21	nd	nd	nd	nd
MK11	28.71±4.70	41.39±7.66	0.0073±0.01	456.61±306.61	26.31±7.83	0.16±0.27	18.64±12.58	6.86±4.54
MK12	42.76±16.91	69.61±15.70	0.0352±0.03	218.25±103.43	nd	nd	nd	nd
MK13	47.15±8.37	72.88±17.63	0.0523±0.05	205.16±93.40	45.35±25.87	nd	30.96±19.87	15.69±10.80
MK14	38.58±13.26	83.03±37.99	0.0221±0.02	471.61±373.21	nd	nd	nd	nd
MK15	38.72±8.98	72.82±5.02	0.0651±0.06	62.15±3.83	nd	nd	nd	nd
MK16	40.43±7.84	60.73±20.19	0.0110±0.01	648.51±215.93	nd	nd	nd	nd
MK17	53.77±12.09	107.14±8.53	0.0216±0.02	62.51±21.45	nd	nd	nd	nd
MK18	66.19±9.93	102.75±1.28	0.0415±0.04	78.11±32.36	nd	nd	nd	nd
MK19	59.42±14.75	100.96±16.61	0.0462±0.04	58.40±9.04	69.64±43.18	0.31±0.32	34.72±24.31	22.46±16.91
MK20	53.66±10.61	135.54±29.71	0.0875±0.08	591.96±38.26	nd	nd	nd	nd
MK21	56.26±11.66	103.14±16.61	0.3216±0.32	50.59±1.61	65.06±30.74	0.39±0.34	41.93±24.88	24.19±16.28

Note : nd = not detectable

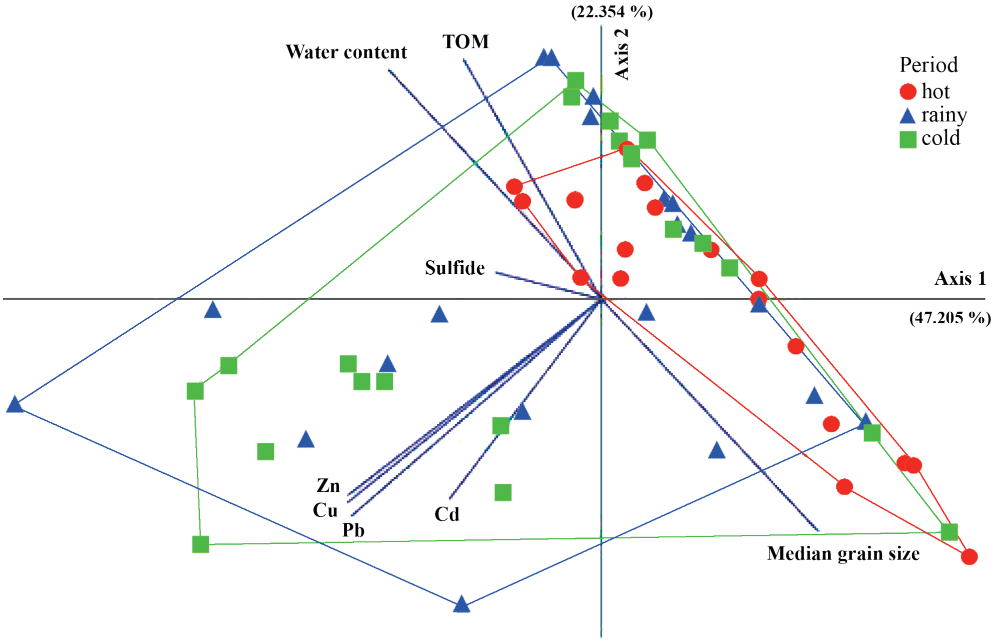

Figure 3. Biplot of sample coordinates on the first two axes of PCA with distance-based biplot scores, including all sediment variables from 21 sites on the Mae Klong River, collected during three seasons (63 samples).

the accumulation of sediment by small grain size, which is responsible for the high water, total organic matter, sulfide, and heavy metal content. This demonstrates the contamination of the sediment by water discharged from communities and factories (Dudgeon, 2000; Schuler and Relyea, 2018a). Sediment found in upstream stations within the reservoir (MK4, MK5, MK6 and MK7) have small grain size, caused by slowly flowing or stagnant water. In the lower Mae Klong River (MK17, MK18, MK19 and MK21), soil sediment is also dominated by small grains due to the location close to the sea.

Most sediment parameters did not exceed Thailand's standards for sediment in surface water resources or the appropriate sediment criteria for the protection of benthic animals established by the Pollution Control Department (2018). The average levels of cadmium, copper, lead, and zinc did not exceed 0.16, 21.5, 36, and 80 $mg \cdot kg^{-1}$ dry weight, respectively, in any of the stations with the exception of the lower Mae Klong River (MK19 and MK21), where concentrations of cadmium, copper, and lead were higher than the standard that is appropriate for freshwater aquatic resources (Pollution Control Department, 2018).

Benthic macroinvertebrate composition and abundance

In this study, 57,965 benthic macroinvertebrates were collected from 21 stations along the Mae Klong River, representing three phyla, 26 orders, 58 families, and 118 species. Benthic macroinvertebrate samples were composed of 41.53 % insects (49 species), 29.66 % gastropods (35 species), 10.17 % bivalves (12 species), 5.91 % oligochaetes (7 species) 5.93 % polychaetes (4 species), 3.39 % malacostracans (6 species), 1.69 % crustaceans (2 species), 0.86 % maxillopods (1 species) and 0.86 % ostracods (1 species) (Figure 4).

Throughout the sites on the Mae Klong River, insects were the most noticeable and dominant group (Figure 5). The aquatic insect larvae in order Odonata were the most diverse (14 species), followed by Ephemeroptera (9 species) and Diptera (8 species). These insect groups show the highest diversity in South East Asia (Dudgeon, 1999). Meanwhile, the most abundant order was Ephemeroptera (61.15 % of total), followed by Diptera (15.57 %), Hemiptera (12.41 %), Odonata (10.75 %), Coleoptera (1.03 %), and Megaloptera (0.11 %). Consequently, benthic macroinvertebrates

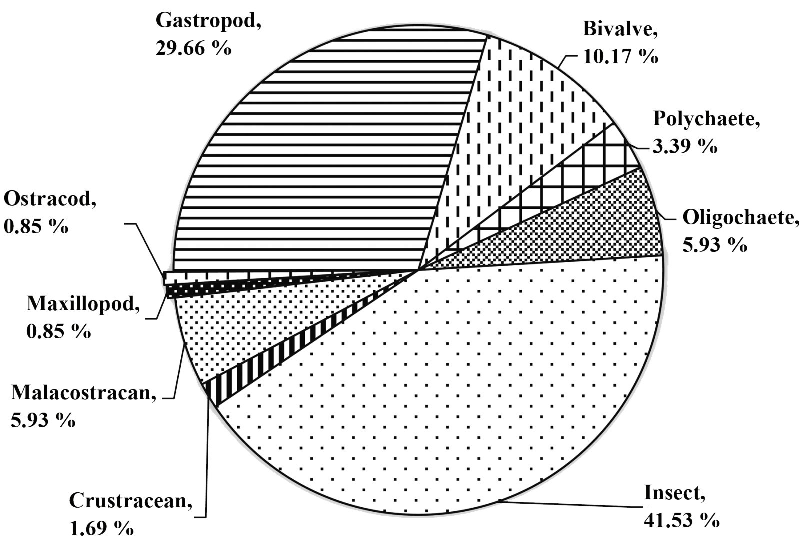

Figure 4. Composition of benthic macroinvertebrate samples from the Mae Klong River.

found in this study have a medium level of diversity because of the sampling locations (focused on the mainstem of the Mae Klong River) and the similarity of spatial features among sites (Vinson and Hawkins, 1998).

Spatial and temporal distribution of benthic macroinvertebrates

The assemblage of macroinvertebrates collected was relatively similar among seasons, and salinity was an important factor in the lower Mae Klong River. There are distinct differences with regard to benthic invertebrates in each area. The upstream Mae Klong River sites (MK4, MK5, MK6, MK7) are influenced by the dam, with its water retention and water control, and the sites most downstream (MK19, MK20, MK21) are influenced by sea water, resulting in reduced water velocity and the accumulation of organic substances in water and sediment. This causes some benthic macroinvertebrates, including *Cloeon* sp. and *Baetis* sp. (Ephemeroptera) and *Cordulia* sp. and *Libellula* sp. (Odonata) to be absent; meanwhile, the number of *Chironomus* sp. and *Thaumale* sp. (Diptera), *Branchiura* sp. and *Naidium* sp. (Oligochaeta), and *Perinereis* sp. (Polychaeta) was higher than at other sites. *Branchiura* sp., *Naidium* sp., and *Perinereis* sp. can adapt to the natural organic load, the accumulation of heavy metals, and the low oxygen content (Yen *et al*., 2020). As for the tributaries and the middle section of Mae Klong River, there is a sandy substrate, which is suitable for aquatic insects to be found in large groups (Resh *et al*., 1996). Changes in macroinvertebrate communities are associated with an increase in the amount of organic matter and with changes in other environmental factors (Spence and Hynes, 2011).

Areas with gravel substrate are favorable habitats for many aquatic insects (Resh *et al*., 1996), which are therefore often found in large groups. In contrast, muddy sediment can hold more heavy metals, which are harmful for the respiratory system and metabolism of benthic macroinvertebrates (Spurgeon and Hopkin, 1999, Laskowski *et al*., 2010, Lister *et al*., 2011). The accumulation of sediment along the river bottom, contaminated water entering the river, increased nutrients, and soil erosion have resulted in changes of the habitats of aquatic organisms, which have, in turn, reduced biological diversity (Cooper, 1993). These conditions

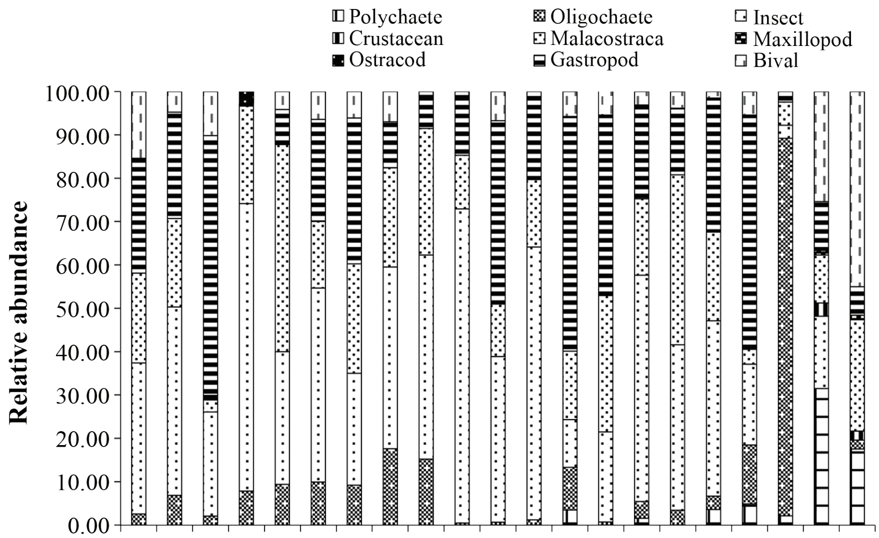

Figure 5. Relative abundance of macrofauna sampled at 21 stations on the Mae Klong River.

are consistent with the report of Lenat and Crowford (1994), who showed that the animal groups that are most sensitive to pollution (Ephemeroptera, Trichoptera, and Plecoptera) are low in diversity. Meanwhile, the groups with high pollution tolerance (Polychaete and Oligochaete) are found in higher numbers around the agriculture, city, and industrial factory areas.

At stations MK9, MK11, and MK16, high numbers of species were found: 41, 43, and 40 species, respectively. On the other hand, stations MK19 and MK21 held only 20 and 18 species, respectively. Density of benthic macroinvertebrates was highest at stations MK12 and MK19, each with 609 ind.·m^{-3}. Meanwhile, stations MK7 and MK21 had the lowest densities (104 and 138 ind.·m^{-3}, respectively). The benthic macroinvertebrates most common in the upper Mae Klong River (KY1, KN2, MK3, MK4, MK5, MK6, MK7) were Ephemeridae, Libellulidae, Dytistidae, and *Agriocnemis* sp. (Coenagrionidae). The benthic macroinvertebrates most common in the middle Mae Klong River (MK8, MK9, MK10, MK11, MK12, MK13, MK14, MK15, MK16) were Baetidae, Caenidae, Gerridae (*Gerris* sp.), and Notonectidae (*Anisops* sp.). The groups that dominated the lower Mae Klong River (MK17, MK18, MK19, MK20, MK21) were Oligochaeta (*Perinereis* sp.), Gastropoda (*Rehderiella* sp. and *Melanoides* sp.), and Bivalvia (*Corbicula* sp.) (Figure 6).

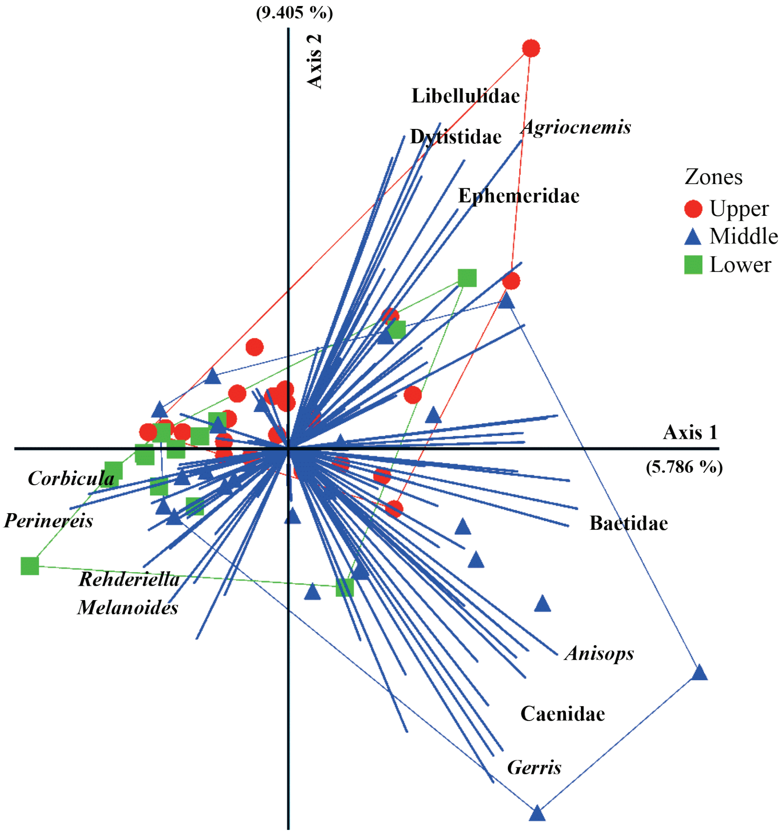

Figure 6. Biplot of sample coordinates on the first two axes of PCA with distance-based biplot scores, using benthic macroinvertebrate abundance from 21 sites on the Mae Klong River, collected during three seasons (63 samples).

Benthic macroinvertebrate abundance-environmental linkages

The relationship between water quality, sediment variables, and benthic macroinvertebrate abundance was analyzed via CCA. The resulting ordination plot shows that the water quality and sediment variables were strongly correlated with benthic macroinvertebrate abundance. The strong correlations of water quality and sediment variables with Axis 1 and Axis 3 were statistically significant ($p \leq 0.05$). Conductivity, total organic matter and sulfide was higher in the lower Mae Klong River (MK18, MK19, MK20, MK21) than upstream. Polychaeta (*Perinereis*) was strongly correlated with conductivity (Figure 7), sulfide, and total organic matter (TOM) (Figure 8). *Perinereis* dominated samples from the lower Mae Klong (67.90 ± 0.51 ind·m^{-3}).

Conductivity shows a positive correlation with salinity and heavy metals (Praveena *et al*., 2008). These factors make it more difficult for aquatic organisms to spread (Hintz *et al*., 2017; Jones *et al*., 2017; Schuler and Relyea, 2018a). *Perinereis* was associated with high conductivity, high total organic matter, and high sulfide concentration, all of which are greater in the lower Mae Klong River (MK18, MK19, MK20, MK21). The salinity and conductivity level around a river mouth or river delta affect the type of wetlands and species of organisms that exist there (National Research Council, 1996). Excessive concentrations of sulfide and heavy metals are fatal to any organism, and these substances cause respiratory and metabolic difficulties for organisms living in the benthos (Spurgeon and Hopkin, 1999; Laskowski *et al*., 2010; Lister *et al*., 2011). Therefore, the abundance of *Perinereis* sp. in the lower Mae Klong River is possibly a result of its high pollution tolerance.

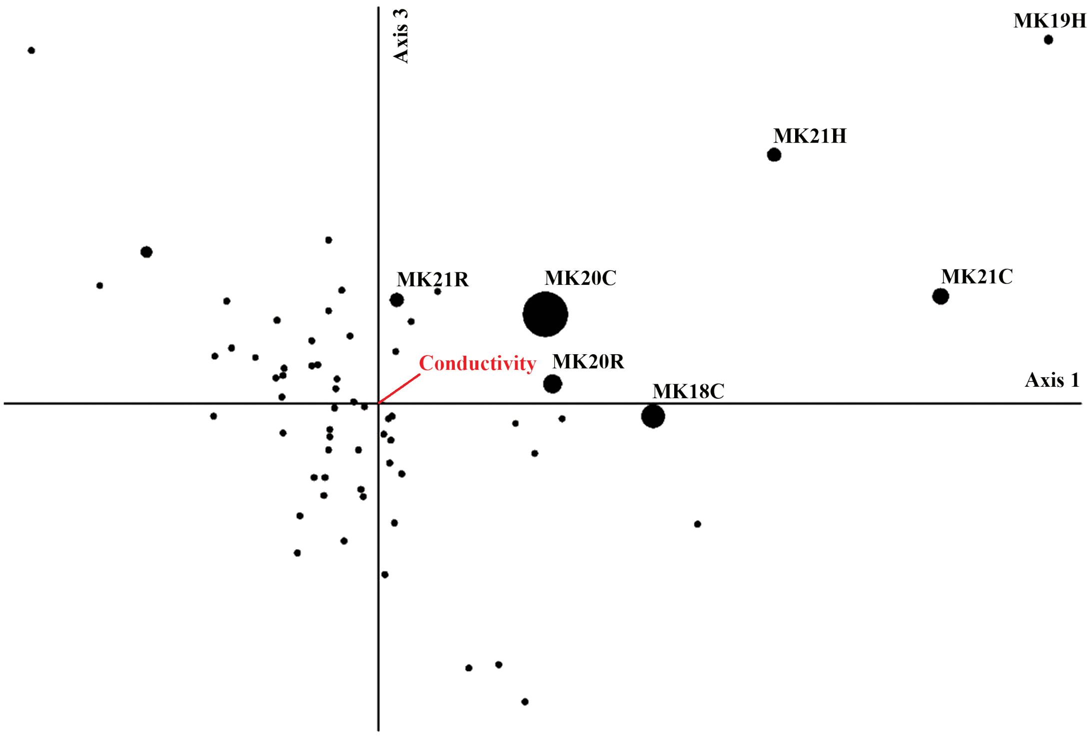

Figure 7. CCA ordination plot of samples by water quality variables and abundance of *Perinereis*.

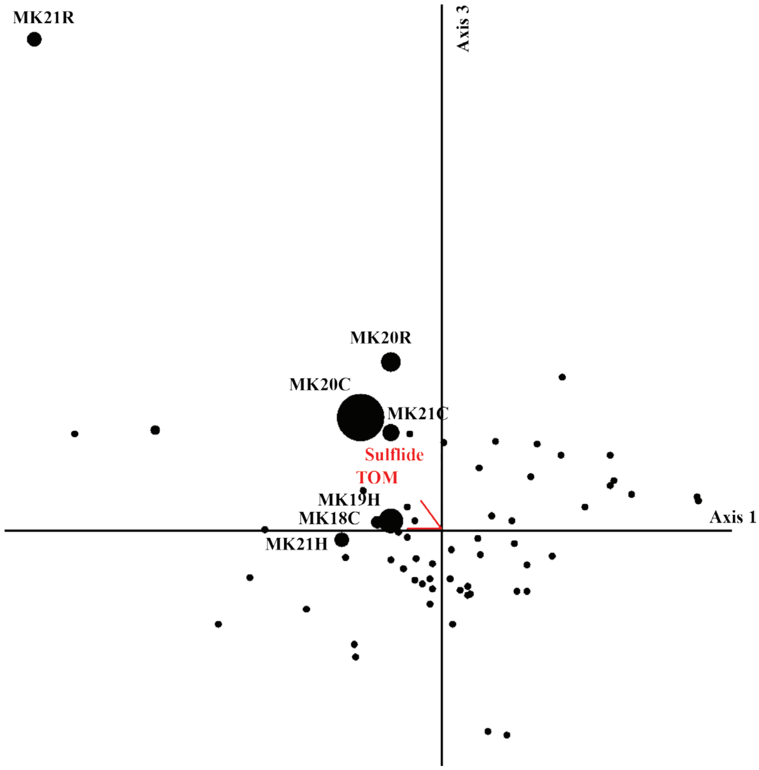

Figure 8. CCA ordination plot of samples by sediment variables and abundance of *Perinereis*.

CONCLUSION

Our study used the diversity and abundance of benthic macroinvertebrates and biotic indices to reflect the anthropogenic impacts existing in upstream and downstream locations within the Mae Klong River. The families Ephemeridae, Baetidae, Caenidae (Ephemeroptera), Libellulidae (Odonata) and class Polychaeta (*Perinereis*) are the most useful in indicating sediment conditions and water quality in the river, which ranges from polluted to clean.

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