

Assessment of spatio-temporal variations in water quality of Bandon Bay, Thailand

Chumkiew S., Jaroensutasinee K., & Jaroensutasinee M.*

Centre of Excellence for Ecoinformatics, School of Science, Walailak University,
222 Thaiburi, Thasala, Nakhon Si Thammarat, 80161, Thailand

Received 27 November 2013; revised 25 February 2014

Multivariate statistical techniques were used to analyse a ten-year water quality dataset. Monthly water samples were collected from 15 river mouths during 2002-2011 and analysed for spatio-temporal variation. The results indicated that water quality at Bandon Bay varied spatially and temporally during the past ten years. Four pollution factors were identified: (1) nutrient, (2) organic matter, (3) salinity and buffering and (4) erosion factors. Discriminant analysis on spatial variables identified only four parameters - i.e. water depth, alkalinity, salinity, and temperature - to discriminate between 15 river mouths. Salinity was the only parameter that discriminated between seasons.

[Keywords: Water quality, Spatial variations, Seasonal variations, Multivariate statistical techniques, Discriminant analysis]

Introduction

Estuary water quality has been subject to the consequences of a full range of anthropogenic activities, e.g. urban, industrial, and agricultural activities, and natural processes, e.g. precipitation, erosion and weathering¹⁻⁶. Estuary waters are highly vulnerable to pollution due to their easy accessibility to the disposal of wastewaters. Pollution load and its concentration are seasonal and largely affected by precipitation, surface runoff, interflow, and groundwater flow^{3,7,8,9}. Information on water quality is important for the implementation of sustainable water-use management strategies^{10,11,12}. Assessing spatio-temporal variation of water quality at river estuary is important for characterising the physical features of aquatic environments^{8,13,14}. Seasonal changes in natural processes such as temperature, precipitation, and hydrological condition, influence water quality in such a way that it presents different characteristics in different seasons^{7,13}.

Bandon Bay, a well-developed mangrove forest, formerly served as a nursery ground and feeding area for juvenile shellfish of great economic importance^{15,16}. Regardless of its long association with a full range of human activities and huge environmental problems, Bandon Bay serves as an excellent area for shellfish aquaculture of high commercial value. During 1994 local people converted available wasteland,

mangrove forests, and agricultural land around the coastal area into large-scale shrimp farms^{16,17}. Agricultural plantations in the area give rise to a common practice of nitrogenous fertiliser usage. With no wastewater and sewage treatment plant available, several villages and towns with a population of nearly 1,100,000 directly discharge untreated wastewater into Bandon Bay. Excessive cutting of the mangrove forest, over-development of aquaculture, discharge of wastewater containing degradable organic, nutrients and pathogen organisms from domestic effluents, and agricultural runoff have resulted in a decrease in water quality and growing sedimentation problems in the bay¹⁸.

Long-term systematic and well-planned water quality monitoring programs are a good approach to improving the knowledge of estuary physiology and hydrochemistry. However, water quality monitoring is difficult due to the complexity associated with analysing the large number of available data and interpreting them^{19,20}. Statistical analysis can help to assess the underlying forcing mechanisms. Application of different multivariate statistical techniques, such as cluster analysis (CA), factor analysis (FA), and discriminate analysis (DA) has been used widely in recent years for analysing environmental data. Multivariate statistical techniques help in the interpretation of complex data matrices to better understand the water quality and ecological status

of the systems under study, and the identification of possible factors that influence water systems. They provide a valuable tool for management of water resources, as well as rapid solution to pollution problems^{4,7,21,22,23}. This study attempts to describe the spatio-temporal variability in estuary water quality, and identify the main pollution factors and sources affecting water quality.

Materials and Methods

Bandon Bay is among the most productive coastal areas in southern Thailand (Fig. 1). It is located in Surat Thani province, southern Thailand (Latitude 9° 7'–9° 25' N and Longitude 99° 9'–99° 39' E) covering an area of 1215 km².¹⁷ Bandon Bay is a small open bay with a coastal area of gradual slope and shallow water. A large mudflat extends along the coast to about 2 km from shore contributing to the high sediment rate within the bay²⁴. The inner Bandon Bay from Chaiya District to Donsak District covers an area of 480 km² with 80 km of coastline with an average depth of 2.9 m.

The climate is characterised by constant high temperature and rainfall. During the period 1983–2012, the average annual rainfall is 1,530.95 mm ranging from 1,025.1 to 2,414.80 mm. The average rainfall in wet and dry seasons is 1,809 mm and 252 mm respectively. Rainfall is highest

in November and January is the driest month of the year. The average annual temperature is 26.45 °C with the warmest month in April and the coolest month in December. Bandon Bay is exposed to monsoon weather with northeast winds from November to April, and southwest winds from May to October. In the lower part of the tidal ranges are muddy soils whereas acid sulphate soil is found in the upper part. The major surface freshwater discharge into Bandon Bay is from the Tapi-Phum Duang River watershed with approximately 13,737 million m³ in annual runoff²⁵.

The Tapi River and its 18 channels are the main sources of freshwater, nutrients, organic matter, and sediment, and act as driving flow water courses that vary over the hydrological year with high rainfall concentrations in the rainy months and deficit during dry periods²⁶. Land use in Bandon Bay consists of mangrove forest, tropical forest, urban area, agricultural area and aquacultural area^{16,17}. Mangrove forests of Bandon Bay play an important economic role as food and energy sources. Local people depend on the mangrove areas for charcoal, timber, catching fishes, shrimps and crabs. Aquaculture, especially shrimp farming, is a traditional practice for local people and has expanded rapidly on a commercial

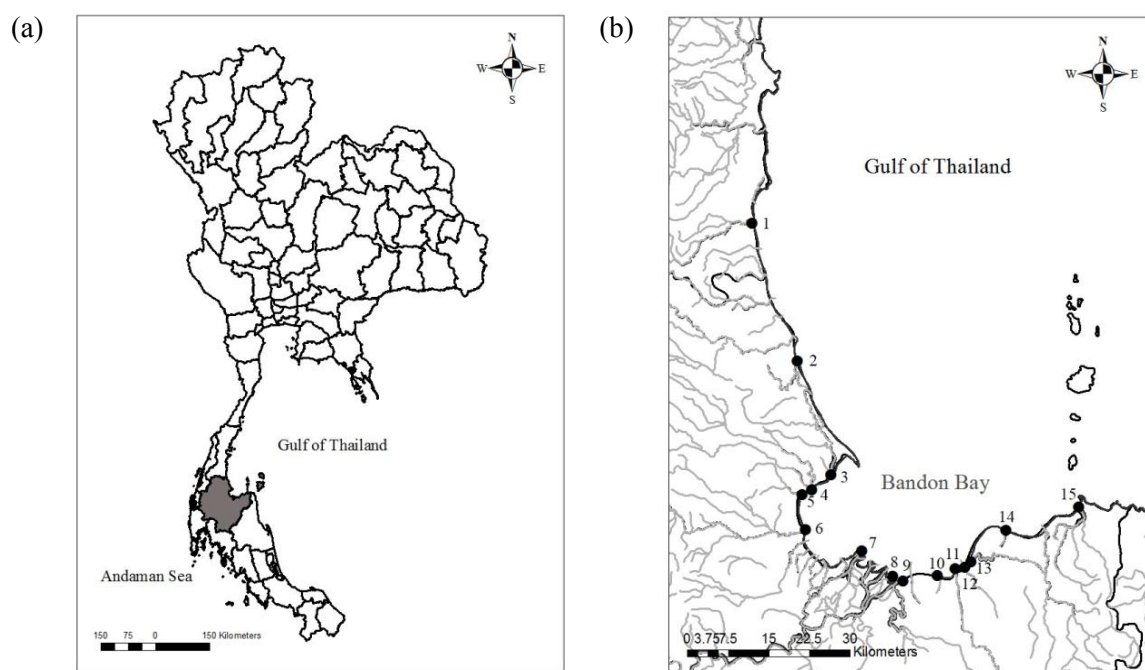


Fig. 1—(a) Bandon Bay, Thailand and (b) 15 river mouths: (1) Thakrajai, (2) Thamuang, (3) Pumreing, (4) Huawao, (5) Thapoon, (6) Thachang, (7) Liled, (8) Tapi, (9) Thathongmai, (10) Changoe, (11) Kradae, (12) Ram, (13) Thathong, (14) Nui, and (15) Donsak River mouths.

scale to meet increased national and international demands. Excessive cutting of the mangrove forest with massive development of shrimp aquaculture has led to decreasing water quality and increasing sedimentation¹⁸.

Monthly water samples were collected from 15 river mouths at Bandon Bay over a ten-year period (2002-2011). The 15 river mouths were (1) Thakrajai, (2) Thamuang, (3) Pumreing, (4) Huawao, (5) Thapoon, (6) Thachang, (7) Liled, (8) Tapi, (9) Thathongmai, (10) Changoe, (11) Kradae, (12) Ram, (13) Thathong, (14) Nui, and (15) Donsak river mouths (Fig. 1). The physiochemical parameters, consisting of water depth, water temperature, transparency, salinity, pH, dissolved oxygen, biochemical oxygen demand (BOD₅), alkalinity, total suspended solids (TSS), ammonium (NH₄-N), nitrite (NO₂), nitrate (NO₃), and orthophosphate (PO₄), were collected over a ten-year period. These data were obtained from the Surat Thani Coastal Fisheries Research and Development Centre (SCFRDC), Department of Fisheries. Sampling, preservation, and transportation of the water samples to the laboratory were analysed according to standard methods²⁷. Depth, temperature, transparency, salinity, pH, and DO were investigated in the field. Water samples were then fixed, and BOD₅, alkalinity, TSS, NH₄-N, NO₂, NO₃, and PO₄ were measured in the laboratory using APHA protocols²⁷. Based on Thai Meteorological Department reports, seasons of Bandon Bay area were grouped into wet (June-January) and dry (February-May) seasons.

Box whisker plots were used to describe water quality parameters. *T*-tests were performed to test the differences of water quality parameters between wet (June-January) and dry (February-May) seasons. FA was performed to identify pollution factors affecting water quality^{14,28}. Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests were conducted to examine the suitability of the data for FA. Data were standardised by the z-scale transformation to ensure normal distributions for FA^{14,29}. DA was used to determine the variables, which discriminate between temporal parameters (wet and dry seasons) and spatial parameters (15 river mouths). Discriminant functions reported in this study correspond to the treatment of raw data (without standardisation). The sites and the seasons were dependent variables, while water quality parameters constituted the independent

variables. The best discriminate function (DF) for each situation was selected, considering the goodness of the classification matrix and the number of parameters needed to reach such a matrix^{8,30}.

Results and Discussion

Spatial and temporal variation of water quality

Wet season had lower water temperature, transparency, salinity, pH, alkalinity, and higher BOD₅, NH₄-N, NO₂, NO₃ and PO₄ than dry season (Table 1). Water depth, DO, and TSS did not differ between wet and dry seasons (Table 1). Box-whisker plots demonstrate the temporal and spatial variation within the 13 variables and 15 river mouths (Fig. 2a-z). Seasonal variations in precipitation and surface runoff have a strong effect on the river discharge. The results of the monitoring show a seasonal fluctuation in salinity indicating the influx of freshwater causing low salinity during the wet season. Extreme fluctuations in salinity have implications for shrimp and shellfish aquaculture in Bandon Bay area.

Presence of highest concentration of nutrients - i.e. NH₄-N, NO₂, NO₃, and PO₄, Fig. 2s-z - in November (wet season) might originate from overland runoff from agricultural fields where nitrogenous fertilisers are used, intensive shrimp aquaculture along the river and anthropogenic activities surrounding the river mouths without waste water treatment plants^{31,32}. NH₄-N pollutants could originate from the decomposition of proteins and urea occurring in municipal wastewater discharges³³. About 80% of the total watershed area is classified as high soil erosion and landslide risk areas causing fast-diminishing top soils and fertilisers during the monsoonal runoff in November³⁴.

The major freshwater discharge into Bandon Bay is from the Tapi-Phum Duang River watershed²⁵. This watershed accounts for approximately 13,737 out of 17,847 million m³ in annual runoff (around 77% of total annual runoff). Present study show that the Liled and Tapi River mouths (site 7, 8), where the Phum Duang and Tapi Rivers reach the Gulf of Thailand, had the lowest overall mean values for seven of the 13 water quality parameters (i.e. temperature, salinity, alkalinity, TSS, NH₄-N, and PO₄) (Fig. 2a-z). Nui and Donsak River mouths (site 14, 15) are the river mouths furthest from the mouth of

Table 1—Mean $\pm$ SD of water qualities at Bandon Bay during wet and dry seasons. * $P < 0.05$, ** $P < 0.001$

Variables	Wet season	Dry season	<i>t</i> -test
Water Depth (m)	1.75 $\pm$ 1.13	1.69 $\pm$ 1.11	$t_{1186} = -0.85$
Temperature ($^{\circ}\text{C}$)	29.05 $\pm$ 2.12	29.71 $\pm$ 1.83	$t_{1216} = 5.23^{**}$
Transparency (cm)	32.43 $\pm$ 17.63	40.88 $\pm$ 19.87	$t_{1180} = 7.37^{**}$
Salinity (ppt)	10.87 $\pm$ 9.23	17.55 $\pm$ 10.51	$t_{1291} = 11.60^{**}$
pH	7.47 $\pm$ 0.58	7.66 $\pm$ 0.43	$t_{1366} = 6.04^{**}$
DO (mg/l)	4.59 $\pm$ 1.03	4.66 $\pm$ 1.14	$t_{1276} = 1.05$
BOD ₅ (mg/l)	1.80 $\pm$ 1.43	1.62 $\pm$ 1.33	$t_{1186} = -2.03^{*}$
Alkalinity (mg/l)	84.31 $\pm$ 36.27	93.58 $\pm$ 30.70	$t_{1395} = 4.70^{**}$
TSS (mg/l)	43.76 $\pm$ 38.70	46.22 $\pm$ 35.96	$t_{1146} = 1.14$
NH ₄ -N (mgN/l)	0.18 $\pm$ 0.33	0.11 $\pm$ 0.23	$t_{1396} = -3.65^{**}$
NO ₂ (mgN/l)	0.04 $\pm$ 0.10	0.02 $\pm$ 0.06	$t_{1395} = -4.52^{**}$
NO ₃ (mgN/l)	0.12 $\pm$ 0.13	0.06 $\pm$ 0.07	$t_{1396} = -8.79^{**}$
PO ₄ (mgP/l)	0.05 $\pm$ 0.09	0.03 $\pm$ 0.05	$t_{1394} = -5.18^{**}$

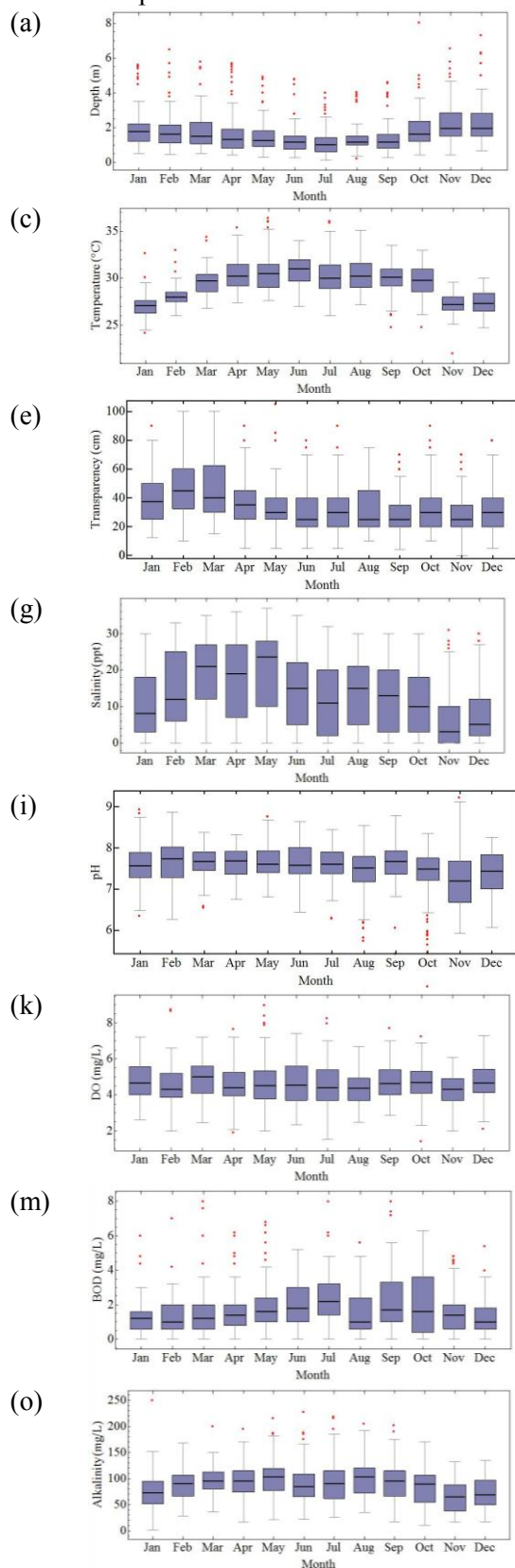
the Tapi-Pumduang River had the highest overall mean values for nine out of 13 water quality parameters (i.e. temperature, salinity, pH, BOD₅, alkalinity, TSS, NH₄-N, NO₂, and PO₄) (Fig. 2a-z).

Low transparency values were recorded at the Nui River mouth (site 14) as a result of its exposure to intensive shrimp aquaculture along the river (Fig. 2e-f). Nutrient, suspended solids, and organic wastes produced by intensive shrimp pond culture consist of solid matter (mainly uneaten feed, faeces and phytoplankton) and dissolved metabolic (mainly urea, NH₄-N and NO₂). The discharge of untreated effluent rich in nutrients and organic matter together with chemotherapeutants seriously upsets the ecological balance. Prolonged use of a shrimp pond can lead to an incremental build-up of sludge at the pond's bottom from waste products and excrement. The sludge can be removed mechanically by flushing it directly into the river causing increased sedimentation when it settles. This practice leads to siltation of river mouths and possibly an alteration in the structure of the benthic community.

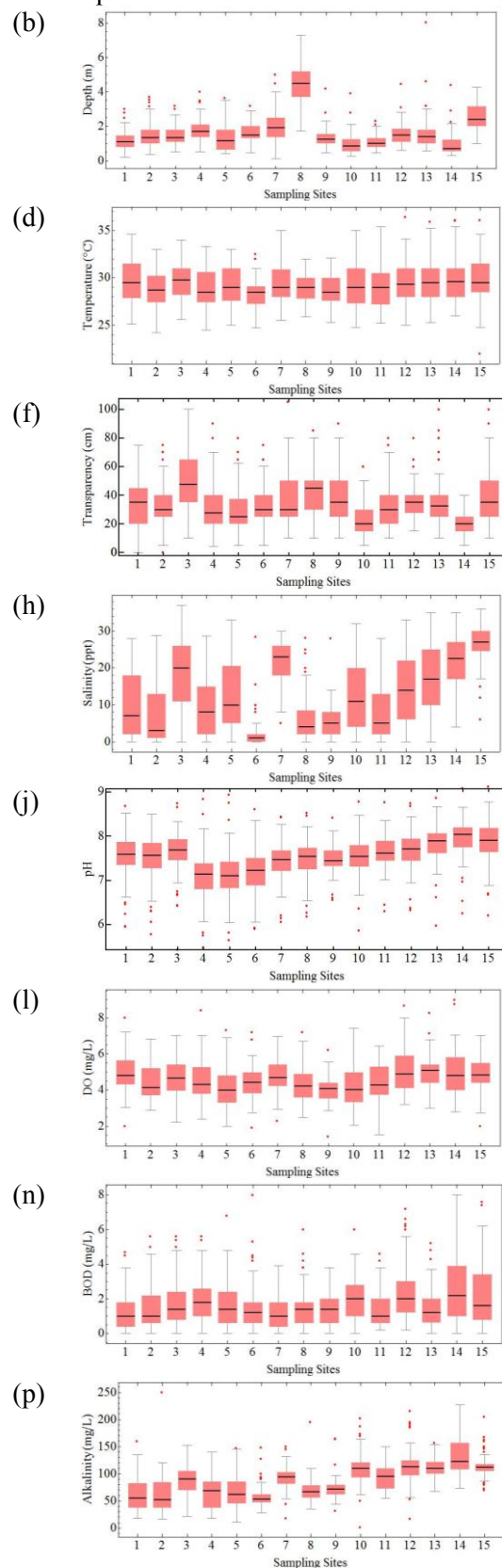
Our results showed that there were high concentrations of nutrients - i.e. NH₄-N, NO₂, NO₃, and PO₄ - at the Ram, Thathong and Nui River mouths (site 12-14) (Fig. 2s-z). The high concentrations of nutrients in these rivers could be due to several reasons. Firstly, untreated

wastewater from industries, e.g. fish processing, freezer and rubber factories, is dumped into the river. Fish processing is an important industry in the area with several dried fish, shrimp and squid factories, and canning plants²⁴. Secondly, effluents rich in nutrients and organic matter from intensive shrimp aquacultures along the rivers are released directly into the rivers untreated. Shrimp aquaculture area in Bandon Bay area increased from 2,200 ha in 1984 to 4,100 ha in 2013³⁵ mostly by clear-cutting of mangrove forests. There were 3,000 out of 4,100 ha of shrimp aquaculture area located along these three rivers. Thirdly, other water pollution sources that might increase nutrients in these rivers are watershed sediment, agricultural runoff and untreated wastewater from domestic sources²⁵. These nutrient loadings may provide essential nutrients for the huge production of phytoplankton supporting filtering shellfish, e.g. oyster (*Crassostrea lugubris*, *C. belcheri*, and *Saccostrea commercialis*), blood cockle (*Anadara granosa*), green mussel (*Perna viridis*), short-necked clam (*Paphia undulate*), mudcrab (*Scylla serrata*) and white shrimp (*Penaeus merguensis*) in the Bandon bay³⁶. However, Gannarong et al. (2000) reported that tremendous wastewater discharge from households and shrimp farms have caused reduction of shellfish production and deterioration of water quality in shellfish culturing grounds.

Temporal variation



Spatial variation



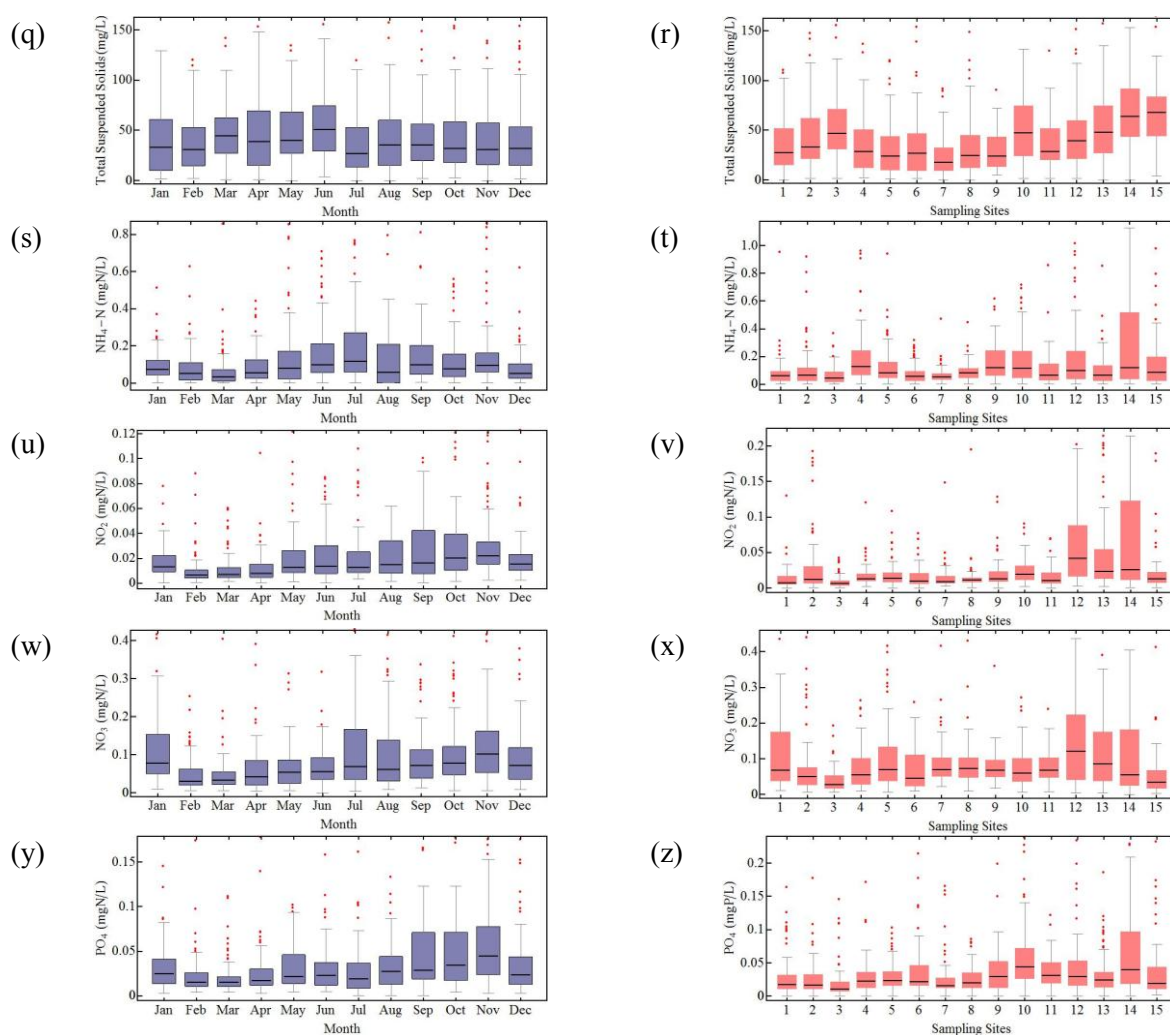


Fig. 2—Temporal and spatial variation of water qualities at 15 river mouths of Bandon Bay during 2002-2011. Blue and red colours represent month and river mouths. (a, b) depth (m), (c, d) temperature ($^{\circ}\text{C}$), (e, f) transparency (cm), (g, h) salinity (ppt), (i, j) pH, (k, l) DO (mg/l), (m, n) BOD₅ (mg/l), (o, p) Alkalinity (mg/l), (q, r) TSS (mg/l), (s, t) $\text{NH}_4\text{-N}$ (mgN/l), (u, v) NO_2 (mgN/l), (w, x) NO_3 (mgN/l), and (y, z) PO_4 (mgP/l). River mouths were (1) Thakrajai, (2) Thamuang, (3) Pumreing, (4) Huawao, (5) Thapoon, (6) Thachang, (7) Liled, (8) Tapi, (9) Thathongmai, (10) Changoe, (11) Kradae, (12) Ram, (13) Thathong, (14) Nui, and (15) Donsak River mouths.

Factor analysis of water quality

KMO and Bartlett's sphericity test were 0.72 and 2665 ($P < 0.001$), respectively. This suggests that FA would be effective in reducing dimensionality^{12,14}. Based on the correlation matrix of variables, the results of FA were expressed in Table 2. The first four rotated factors with eigenvalue greater than 1 were extracted, and they explained 60.35% of the total variance.

Factor 1, the nutrient factor, accounted for 18.06% of the total variance and was highly positively correlated with inorganic nutrients - i.e. NO_2 , NO_3 , $\text{NH}_4\text{-N}$ and PO_4 . The strong rainfall events occurring in November cause an increase in the freshwater discharges. Soil erosion runoff on river water during the wet season has a polluting effect, which results in higher values of NO_2 , NO_3 , $\text{NH}_4\text{-N}$ and PO_4 . Due to their

agricultural activities, farmers usually apply fertilisers - i.e. nitrogen, urea, ammonium nitrate, and phosphate - to their crops twice a year in May-June and September-October. Major crops in this area are rubber (48% of total area) and palm plantations (7% of total area). These results indicate that agricultural pollution from cultivated fields is collected in the rivers through the action of rain erosion on farmland^{37,38}. Furthermore, the process of intensive aquaculture causes a high concentration of inorganic nutrient variables in Bandon Bay³⁹.

Factor 2, the organic matter factor, accounted for 16.92% of total variance and consists of temperature, DO and BOD₅. DO and BOD₅ refer to the oxide-related processes. When organic matter in the river water is oxidised at the expense of oxygen, the BOD₅ concentrations increase with

Table 2—Factor loadings of the 13 variables on VARIMAX rotation of Bandon Bay

Variables	Factor			
	1	2	3	4
NO ₂ (mgN/l)	0.83	0.18	0.05	-0.01
NO ₃ (mgN/l)	0.72	0.08	-0.37	0.27
NH ₄ -N (mgN/l)	0.71	-0.09	0.17	-0.05
PO ₄ (mgP/l)	0.68	0.02	0.12	-0.13
Temperature (°C)	-0.01	0.71	0.16	-0.13
DO (mg/l)	0.01	0.69	-0.05	0.18
BOD ₅ (mg/l)	0.01	0.56	0.48	0.07
TSS (mg/l)	0.32	0.48	0.14	-0.23
Salinity (ppt)	0.12	-0.03	0.82	-0.07
Alkalinity (mg/l)	-0.07	0.49	0.68	0.08
pH	0.15	0.53	0.60	-0.06
Water Depth (cm)	0.03	-0.23	0.03	0.81
Transparency (cm)	-0.19	0.24	-0.05	0.72
Eigenvalue	3.26	2.27	1.27	1.05
Variance (%)	18.06	16.92	15.18	10.19
Cumulative (%)	18.06	34.98	50.16	60.35

Bold values represent high loadings

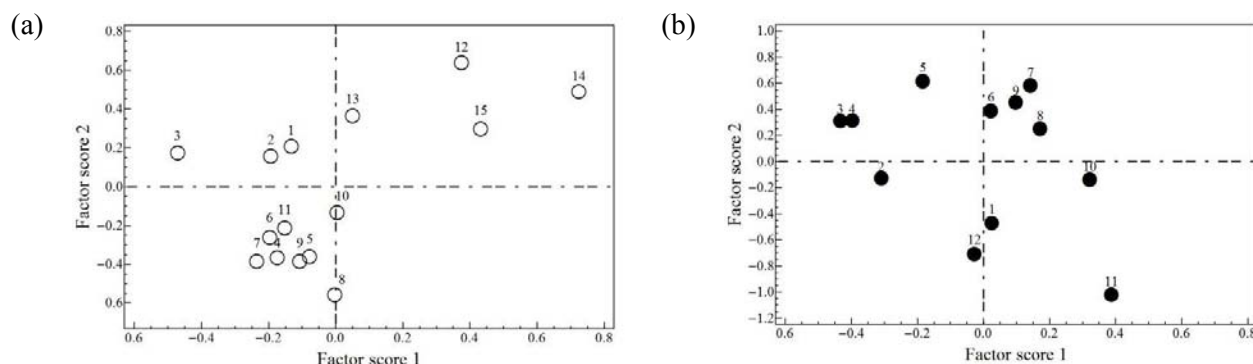


Fig. 3—Spatial and temporal variables of first two factor scores defined by the first two rotated factors. (a) spatial variables (O) with 15 river mouths: (1) Thakrajai, (2) Thamuang, (3) Pumreing, (4) Huawao, (5) Thapoon, (6) Thachang, (7) Liled, (8) Tapi, (9) Thathongmai, (10) Changoe, (11) Kradae, (12) Ram, (13) Thathong, (14) Nui, and (15) Donsak River mouths and (b) temporal variables (●) from January-December.

decreased DO⁴⁰. Warmer water tends to have high BOD₅ and low DO because of the increased decomposition of organic matter. Increased water temperature will speed up bacterial decomposition and result in higher BOD₅ levels. The highest BOD₅ value was recorded at the Nui River mouth (site 14) where water quality is influenced by local domestic waste and shrimp aquaculture. Moreover, warmer water is capable of holding less DO than colder water.

loadings on salinity, alkalinity and pH which accounted for 15.18% of the total variance. These variables represented the total soluble salt concentration and provided insight into chemical changes in relation to river recharge⁴¹. Alkalinity variability in the river mouth is controlled mainly by freshwater addition (precipitation) or removal (evaporation) which also acts to change salinity^{42,43}. The alkalinity concentration indicates the buffering capacity of water, where high

Factor 3, the salinity factor, had strong positive

Table 3—Classification functions for discriminant analysis of spatial and temporal variations of Bandon Bay

Variable	Spatial variation		Temporal variation
	Function 1	Function 2	Function 1
Water Depth (cm)	-0.60	0.82	-0.10
Temperature (°C)	-0.47	-0.07	0.18
Transparency (cm)	-0.23	-0.05	0.31
Salinity (ppt)	0.46	0.34	0.76
pH	0.11	0.40	0.15
DO (mg/l)	0.06	-0.17	-0.07
BOD ₅ (mg/l)	-0.02	-0.02	-0.26
Alkalinity (mg/l)	0.53	0.27	-0.05
TSS (mg/l)	0.07	0.04	-0.43
NH ₄ -N (mgN/l)	0.05	0.14	-0.07
NO ₂ (mgN/l)	-0.04	-0.07	-0.02
NO ₃ (mgN/l)	0.22	0.05	-0.30
PO ₄ (mgP/l)	0.14	0.16	-0.08
(Constant)	3.65	-8.43	3.65

Bold values represent high value

concentrations of alkaline can resist pH changes.

Factor 4, the erosion factor, accounted for 10.19% of the total variance and was strongly correlated with water depth and transparency. Higher river water depth and lower transparency can be explained by eluviation of soil washed off by intensive rainfall in the wet season^{14,44}.

The factor score of factor analysis can identify influences of each pollution type in the river system^{14,40,45,46} (Fig. 3). Higher factor scores represent greater influences of pollution types^{14,47}. For spatial influences (Fig. 3a), factor score 1 was significant to the condition of the Nui River mouth (site 14), reflecting the influences of agricultural activities and soil erosion along the river. Factor score 2 distinguished the Tapi and Ram River mouths (site 8 and 12) from the other sites, which were most likely polluted by domestic wastewater in the Ram River mouth and less polluted in the Tapi River mouth (greater discharge). For temporal influences (Fig. 3b), factor score 1 was significant to the less water discharge and increases in the total soluble salt concentration during March and April. This provides insight into chemical changes in relation to river recharge⁴¹. With regard to factor score 2, it shows that water quality is impacted by

monsoonal runoff in November (Fig. 3b). This implies that seasons affect water quality data at Bandon Bay.

Discriminant analysis of water quality

Spatial variations in water quality were evaluated using DA. DA was applied to raw data. Thirteen DFs were found: the first two functions had eigenvalues more than 1 and were statistically significant in Wilk's λ test ($P < 0.001$). The first two DFs explained 72% of total variance between 15 river mouths; the first DF accounted for 41.5%, and the second DF contained 30.5% of total spatial variance. Relative contribution of each parameter is given in Table 3. The first group had strong positive coefficient in alkalinity and salinity and negative coefficient in water depth and temperature. These parameters help to discriminate the 15 river mouths from each other. The second group had strong positive coefficient in only water depth. This indicates that water depth made a strong contribution to discriminate the 15 river mouths and accounted for most expected spatial variations in the river. The classification matrices showed 46.3% of cases are correctly classified to their respective groups. These results suggest that the different patterns of

spatial variation are due to the different kinds of weather processes along the river³.

Temporal variations in water quality were further evaluated through DA. Temporal DA was performed on raw data after dividing the whole data set into two seasonal groups (wet and dry seasons). Only one DF was found. Hundred percentage of the total variance between seasons was explained by one DF. Relative contribution of each parameter is shown in Table 3. Salinity contributed strong positive coefficient in discriminating wet and dry seasons, while other parameters made fewer contributions. The classification matrices showed that 69.4% of the cases are correctly classified to their respective groups. There were significant differences between wet and dry season, discriminated by the salinity parameter. The results suggest that agriculture, aquaculture, and other anthropogenic pollution, which are mainly discharges of wastewater into river, do not discriminate between seasons and are regular throughout the year³.

Conclusion

Monitoring estuary water quality generates multidimensional data that require statistics to analyse and interpret underlying information. Bandon Bay shows serious problems of pollution mainly due to inorganic nutrients - i.e. nitrogen, urea, ammonium nitrate, and phosphate - and organic matter - i.e. DO and BOD5. For spatial variations, the Thamuang and Nui River mouths were different from other river mouths in their amount of inorganic nutrients due to untreated domestic sewage discharge, intensive aquaculture, and/or agricultural runoff from soil erosion. For temporal variations, November differed from other months due to monsoonal runoff into the bay resulting in a decrease in salinity. Since salinity was the only factor that significantly differed between wet and dry seasons, this suggests that main discharges of wastewater into rivers by agriculture, aquaculture and other anthropogenic pollutions are not seasonal but rather regular throughout the year.

Acknowledgement

Authors thank Sherri Lynn Conklin and Thana na Nagara for comments on previous versions of this manuscript, the Surat Thani Coastal Fisheries Research and Development Centre for providing the water quality dataset, and their staff for kindly help. This work was supported in part by Higher Education Research Promotion, Office of the Higher Education Commission, National Research Universities, Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0307/2550), Centre of Excellence for Ecoinformatics, the Institute of Research and Development, Walailak University and NECTEC.

References

- 1 Jarvie, H.P., Whitton, B.A. & Neal, C., Nitrogen and phosphorus in east coast British rivers: Speciation, sources and biological significance, *Sci. Total Environ.*, 210-211(1998) 79-109.
- 2 Ravichandran, S., Hydrology influences on the water quality trends in Tamiraparani Basin, south India, *Environ. Monit. Assess.*, 87(2003) 293-309.
- 3 Najafpour, S.H., Alkarkhi, A.F.M., Kadir, M.O.A. & Najafpour, G.H.D., Evaluation of spatial and temporal variation in river water quality, *Int. J. Environ. Res.*, 2(4)(2008) 349-58.
- 4 Pejman, A.H., Nabi Bidhendi, G.R., Karbassi, A.R., Mehrdadi, N. & Bidhendi, M.E., Evaluation of spatial and seasonal variations in surface water quality using multivariate statistical techniques, *Int. J. Environ. Sci. Technol.*, 6(3)(2009) 467-76.
- 5 Zhao, J., Fu, G., Lei, K. & Li, Y.W., Multivariate analysis of surface water quality in the Three Gorges area of China and implications for water management, *J. Environ. Sci.*, 23(9)(2011) 1460-71.
- 6 Vieira, J., Fonseca, A., Vilar, V.J.P., Boaventura, R.A.R. & Botelho, C.M.S., Water quality in Lis River, Portugal, *Environ. Monit. Assess.*, 184(2012) 7125-40.
- 7 Vega, M., Pardo, R., Barrado, E. & Deban, L., Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis, *Water. Res.*, 32(12)(1998) 3581-92.
- 8 Singh, K.P., Malik, A., Mohan, D. & Sinha, S., Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India)-a case study, *Water. Res.*, 38(2004) 3980-92.
- 9 Monavari, S. & Guieysse, B., Development of water quality test kit based on substrate utilization and toxicity resistance in river microbial communities, *Int. J. Environ. Res.*, 1(2)(2007) 139-42.
- 10 Shrestha, S. & Kazama, F., Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan, *Environ. Modell. Softw.*, 22(4)(2007) 464-75.
- 11 Zhang, Q., Xu, Z., Shen, Z., Li, S. & Wang, S., The Han River watershed management initiative for the South-to-North water transfer project (Middle Route) of China, *Environ. Monit. Assess.*, 148(2009) 369-77.
- 12 Zhou, F., Huang, G.H., Guo, H.C., Zhang, W. & Hao, Z.J., Spatio-temporal patterns and source apportionment

- of coastal water pollution in eastern Hong Kong, *Water. Res.*, 41(2007) 3429-39.
- 13 Ouyang, Y., Nkedi-Kizza, P., Wu, Q.T., Shinde, D. & Huang, C.H., Assessment of seasonal variations in surface water quality, *Water. Res.*, 40(2006), 3800-10.
 - 14 Bu, H., Tan, X., Li, S. & Zhang, Q., Temporal and spatial variations of water quality in the Jinshui River of the South Qinling Mts., China, *Ecotox. Environ. Safe.*, 73(2010) 907-13.
 - 15 Wattayakorn, G., Aksornkoae, S., Tingsabadh, C., Sathirathai, S., Piumsomboom, A. & Praphavasit, N., *Economic evaluation and biogeochemical modelling of Bandon bay, Surat Thani, Thailand. Synthesis Report: Thailand Core Research Sit. SARCS/WOTRO/LOICZ PROJECT*, Bangkok, Thailand, 1999.
 - 16 Jarempornnipat, A., Pedersen, O., Jensen, K.R., Boromthananarat, S., Vongvisessomjai, S. & Choncheanchob, P., Sustainable management of shellfish resources in Bandon Bay, Gulf of Thailand, *J. Coast. Conservat.*, 9(2004) 135-46.
 - 17 Muttitanon, W. & Tripathi, N.K., Land use/land cover changes in the coastal zone of Ban Don Bay, Thailand using Landsat 5 TM data, *Int. J. Remote Sens.*, 26(11)(2005) 2311-23.
 - 18 Tookwinas, S. & Youngvanisset, K., Mollusk culture as a tool for sustainable integrated coastal zone management, Southern Thailand. *Phuket Mar. Biol. Cent. Spec. Publ.*, 18(1998) 177-80.
 - 19 Shin, P. K. S. & Fong, K.Y.S., Multiple discriminant analysis of marine sediment data, *Mar. Pollut. Bull.*, 39(1-2)(1999) 285-94.
 - 20 Saffran, K., *Canadian water quality guidelines for the protection of aquatic life, CCME water quality Index 1, 0. User's manual*, Excerpt from Publication No. 1299, ISBN 1-896997-34-1, 2001.
 - 21 Lee, J.Y., Cheon, J.Y., Lee, K.K., Lee, S.Y. & Lee, M.H., Statistical evaluation of geochemical parameter distribution in a ground water system contaminated with petroleum hydrocarbons, *J. Environ. Qual.*, 30(2001) 1548-63.
 - 22 Wunderlin, D.A., Diaz, M.P., Ame, M.V., Pesce, S.F., Hued, A.C. & Bistoni, M.A., Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality: A case study: Auquia river basin (Cordoba, Argentina), *Water. Res.*, 35(12)(2001) 2881-94.
 - 23 Reghunath, R., Murthy, T.R.S. & Raghavan, B.R., The utility of multivariate statistical techniques in hydrogeochemical studies: An example from Karnataka, India, *Water. Res.*, 36(10)(2002) 2437-42.
 - 24 Chuenpagdee, R., Knetsch, J.L. & Brown, T.C., Coastal management using public judgements, importance scales and predetermined schedule, *Coast. Manage.*, 29(2001) 253-70.
 - 25 Bunapong, S. Paw, J.N., The upper south: physical setting and land use. In: Paw, J.N., Bunapong, S., White, A.T. & Sadorra, M.S.M. (Eds.) *The coastal environmental profile of Ban Don Bay and Phangnga Bay, Thailand, ICLARM Technical Reports*, International Centre for Living Aquatic Resources Management, Manila, Philippines, 20(1988), pp. 1-9.
 - 26 Khaonuna, R., *Reproductive cycle of the large oyster Crassostrea belcheri (Sowerby) in Bandon Bay, Surat Thani*. Technical paper No.16/1994, Surat Thani Coastal Aquaculture Development Centre, Coastal Aquaculture Division, Department of Fisheries, Bangkok, Thailand, 1994.
 - 27 APHA., *Standard methods for the examination of water and wastewater*, 20th edition, APHA, AWWA, Washington D. C., 1999.
 - 28 He, M.C., Wang, Z.J. & Tang, H.X., Modeling the ecological impact of heavy metals on aquatic ecosystems: a framework for the development of an ecological model, *Sci. Total Environ.*, 266(2001) 291-8.
 - 29 Geoffrey, C.G., John, D.T., McCray, E. & Turner, A.K., Evaluation of graphical and multivariate statistical methods for classification of water chemistry data, *Hydrogeol. J.*, 10(2002) 455-74.
 - 30 Alberto, M.R., Farias, M.E. & Manca da Nadra, M.C., Effect of gallic acid and catechin on *Lactobacillus hilgardii* 5w growth and metabolism of organic compounds, *J. Agr. Food. Chem.*, 49(2001) 4359-63.
 - 31 Anon., *Coastal state of Surat Thani. Natural Resources and Environmental Management Division*, Office of Environmental Policy and Planning, Ministry of Science, Technology and Environment, Bangkok, Thailand, 1998.
 - 32 Gannarong, M., Phetnoi, C., Toudsin, P. & Jamnongphan, K., *Influence of high tide and low tide on bacterial counts and water qualities in oyster culture area, Bandon Bay, Surat Thani*. Technical paper No. 39/2000, Surat Thani Coastal Aquaculture Development Center, Coastal Aquaculture Division, Department of Fisheries, Bangkok, Thailand, 2000.
 - 33 Razmkhah, H., Abrishamchi, A. & Torkian, A., Evaluation of spatial and temporal variation in water quality by pattern recognition techniques: A case study on Jajrood River (Tehran, Iran), *J. Environ. Manage.*, 910(2010) 852-60.
 - 34 Vijarnsorn, P., Land capability. In: Paw, J.N., Bunapong, S., White, A.T. & Sadorra, M.S.M. (Eds.) *The Coastal Environmental Profile of Ban Don Bay and Phangnga Bay, Thailand, ICLARM Technical Reports*, International Centre for Living Aquatic Resources Management, Manila, Philippines, 20(1988), pp. 20-1.
 - 35 Surat Thani Provincial Fisheries Office, *Fisheries statistics 2013*. Surat Thani Province, 2013.
 - 36 Boonyubol, M., *Biology and life history of penaeid shrimp in Ban Don Bay, Surat Thani Province*. Technical Report No. 28. Upper Gulf of Thailand Marine Fisheries Development Centre, Department of Fisheries, Bangkok, Thailand, 1996.
 - 37 Jain, C.K., A hydro-chemical study of a mountainous watershed: the Ganga, India, *Water. Res.*, 36(2002) 1262-74.
 - 38 Absalon, D. & Matysik, M., Changes in water quality and runoff in the Upper Oder River Basin, *Geomorphology*, 92(2007) 106-18.
 - 39 Kaewnern, M. & Yakupitiyage, A., Shrimp and Mollusc Culture at the Bandon Bay in Thailand: A Situation Analysis, *Asian Fish. Sci.*, 21(2008) 35-54.
 - 40 Kannel, P.R., Lee, S. & Lee, Y.S., Assessment of spatial-temporal patterns of surface and ground water qualities and factors influencing management strategy of groundwater system in an urban river corridor of Nepal, *J. Environ. Manage.*, 86(2008) 595-604.
 - 41 Elbaz-Poulitchet, F., Favreau, G., Leduc, C. & Seidel, J.L. Major ion chemistry of groundwaters in the Continental Terminal water table of southwestern Niger (Africa), *Appl. Geochem.*, 17(2002) 1343-9.
 - 42 Brewer, P.G., Bradshaw, A.L. & Williams, R.T., Measurements of total carbon dioxide and alkalinity in

- the North Atlantic Ocean in 1981. In: Trabalka, J.R. & Reichle D.E. (Eds.) *The changing carbon cycle: A global analysis*, New York: Springer, (1986), pp. 348–70.
- 43 Millero, F.J., Lee, K. & Roche, M., Distribution of alkalinity in the surface waters of the major oceans, *Mar. Chem.*, 60(1998) 111-30.
- 44 Crosa, G., Froebrich, J., Nikolayenko, V. Stefani, F., Gallid, P. & Calamari, D., Spatial analysis of water quality of the Amu Darya River (Central Asia), *Water. Res.*, 42(2006) 3285-304.
- 45 Reisenhofer, E., Adami, G. & Barbieri, P., Using chemical and physical parameters to define the quality of karstic freshwaters (Timavo River, North-eastern Italy): a chemometric approach, *Water. Res.*, 32(1998) 1193-203.
- 46 Kowalkowski, T., Zbytniewski, R., Szpejna, J. & Buszewski, B., Application of chemometrics in river water classification, *Water. Res.*, 40(2006), 744–52.
- 47 Felipe-Sotelo, M., Andrade, J.M., Carlosena, A., & Tauler, R., Temporal characterisation of river waters in urban and semi-urban areas using physico-chemical parameters and chemo metric methods, *Anal. Chim. Acta.*, 583(2007) 128-37.