Science of the Total Environment 485–486 (2014) 653–665

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam

Gert-Jan Wilbers [a,*], Mathias Becker [b], La Thi Nga [a], Zita Sebesvari [a], Fabrice G. Renaud [a]

[a] United Nations University, Institute for Environment and Human Security, Platz der Vereinten Nationen 1, Bonn D-53113, Germany
[b] University of Bonn, Institute of Crop Sciences and Resource Conservation, Karlrobert-Kreiten-Strasse 13, Bonn D-53115, Germany

HIGHLIGHTS

- Usage of water in lower order canals of the Mekong Delta may lead to health concerns.
- Seasonality does not have major effects on water quality in lower order canals.
- A principal component analysis was used to identify contamination sources.
- Water quality was spatially visualized to identify hot-spot areas of pollution.

ARTICLE INFO

Article history:
Received 16 December 2013
Received in revised form 12 March 2014
Accepted 13 March 2014
Available online 18 April 2014

Editor: Eddy Y. Zeng

Keywords:
Drinking water
E. coli
Heavy metals
Land-use
Principal component analysis
Water quality

ABSTRACT

Surface water pollution in the Vietnamese Mekong Delta (MD) could threaten human, animal and ecosystem health given the fact that this water source is intensively used for drinking, irrigation and domestic services. We therefore determined the levels of pollution by organic pollutants, salts, metals and microbial indicators by (bi)monthly monitoring of canals between November 2011 and July 2012 at 32 sampling locations, representing fresh and saline/brackish environments. The results were compared with national water quality guidelines, between the studied regions and with water quality data from main waterways. Key factors explaining the observed levels of pollution in surface water were identified through principal component analysis (PCA). Temporal variations due to tidal regime and seasonality were also assessed. Based on regression models, the spatial variability of five water quality parameters was visualized using GIS based maps. Results indicate that pH (max. 8.6), turbidity (max. 461 FTU), maximum concentrations of ammonium (14.7 mg L^{-1}), arsenic (44.1 μg L^{-1}), barium (157.5 μg L^{-1}), chromium (84.7 μg L^{-1}), mercury (45.5 μg L^{-1}), manganese (1659.7 μg L^{-1}), aluminum (14.5 mg L^{-1}), iron (17.0 mg L^{-1}) and the number of *Escherichia coli* (87,000 CFU 100 mL^{-1}) and total coliforms (2,500,000 CFU 100 mL^{-1}) in canals exceed the thresholds set by Vietnamese quality guidelines for drinking and domestic purposes. The PCA showed that i) urbanization; ii) metal leaching from soils; iii) aquaculture; and iv) tidal regime explain 85% of the variance of surface water quality attributes. Significant differences in water quality were found due to daily tidal regime and as a result of seasonality. Surface water quality maps for dissolved oxygen, ammonium, ortho-phosphate, manganese and total coliforms were developed to highlight hot-spot areas of pollution. The results of this study can assist policy makers in developing water management strategies and drinking water companies in selecting optimum water extraction locations.

1. Introduction

In the Mekong Delta (MD), Vietnam and in other coastal regions of Southeast Asia, people rely on surface water not only for the irrigation of crops, aquaculture and the transportation of goods, but also for daily domestic uses including for drinking. Poor water quality and inadequate pre-treatment of surface water before use can lead to serious health risks and may be a contributing factor to the high mortality rate of 8.5% of all deaths due to diarrhea in Southeast Asia (WHO, 2013). It is widely known that the quality of surface water in the region is threatened by a variety of pollutants from both natural and anthropogenic sources. The surface water quality in the MD is therefore regularly monitored not only by the provincial authorities (DONRE) and by the Mekong River Commission (MRC), but also by a number of time-bound projects, covering diverse pollutants (Sebesvari et al., 2012). The results of these studies show for example that pesticide residues in the aquatic environment can lead to a chronic exposure of humans and aquatic organisms (Toan et al., 2013). Due to the low topographical elevation of the MD, saline water intrusion is another water quality

* Corresponding author. Tel.: +49 6 428 06 433.
E-mail addresses: Gertjan.wilbers@yahoo.com, Wilbers@ehs.unu.edu (G.-J. Wilbers).

http://dx.doi.org/10.1016/j.scitotenv.2014.03.049
0048-9697/

concern especially affecting rice production in coastal areas (Kotera et al., 2008). An assessment of microbial indicators of fecal pollution revealed high loads of *Escherichia coli* (10^2–10^7 CFU 100 mL^{-1}) and total coliforms (10^3–10^7 CFU 100 mL^{-1}) in many surface waters (Isobe et al., 2004). However, the concentrations of various heavy metals, including cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb), investigated in main waterways and coastal zones, were low compared to other catchment areas in the world (Cenci and Martin, 2004). The MRC also investigated water quality of the Mekong River in Laos, Thailand, Cambodia and Vietnam, and concluded that for most observation points, water quality was moderate to good with respect to nutrients and metals. However, salinity and especially acidity levels were found to be problematic within the delta (MRC, 2008).

In the MD, most investigations on surface water quality focus on acid sulfate soils (ASS), covering 40% of the total agricultural surface area (Guong and Hoa, 2012). The strong acidity in these soils increases the mobility of toxic elements, potentially affecting crop production, aquatic organisms and drinking water sources (Ljung et al., 2009). In the Plain of Reeds of the MD, pH values of 3.5 were associated with elevated concentrations of aluminum (Al) and iron (Fe) in the early wet season (Tin and Wilander, 1995; Husson et al., 2000). The observed Al concentrations of >100 mg L^{-1} exceeded the toxicity levels for fish and plant roots (Minh et al., 1997). Besides Al and Fe, other metals like Cd, Cu, Ni, Mn and Zn are present in higher concentrations in surface water than in areas with alluvial soils (Hoa et al., 2007).

Another important source of water contamination is aquaculture, leading to high levels of (bio)chemical oxygen demand (COD, BOD) and nutrients in water as a result of the applied fish food (Anh et al., 2010). Shrimp farming is a main activity in the coastal areas (e.g. in Soc Trang and Ca Mau provinces) leading to low concentrations of dissolved oxygen, while suspended solid concentrations are consistently high (Johnston et al., 2002). Furthermore, the effects of urbanization on surface water contamination are well recognized. Two independent studies in Ohio, USA showed clear correlations between electrical conductivity and concentrations of nutrients with urban land-uses (Wang and Yin, 1997; Tong and Chen, 2002). Similar findings were reported from urbanized areas in China (Wang et al., 2007), and a study conducted in Shanghai revealed that 94% of the variability in water quality was explained by industrial/domestic urban land uses (Ren et al., 2003). There are no comparable studies in the MD except for one report by Quyen et al. (1995) who concluded that both urbanization and industrialization are becoming serious threats to water quality.

Besides these anthropogenic and soil type-related sources of pollutants, climatic and seasonal effects are also found to influence water quality. Thus in the lower Mekong River, hydrological and climatological factors (precipitation, flow discharge, mean water level and air temperature) were strongly correlated with COD and dissolved oxygen concentrations in surface water (Prathumratana et al., 2008). Studies in Florida (USA), Spain and northern China revealed seasonal differences in water quality parameters (Ouyang et al., 2006; Vega et al., 1998; Chen et al., 2005). Similar studies in the MD are limited to a study by Stärz (2012) who investigated surface water quality in two districts of Can Tho province.

While many water quality studies have been conducted in the MD, most focused on either point sources or soil type effects or investigated the surface water quality in main waterways. The lower order canals are generally not included in monitoring programs. However, the total length of small man-made canals in the MD is more than 50,000 km (Truong, 2006), which is a factor of 10 higher than the entire length of the Mekong River. Both their hydrological regimes and their use by local population differ from the main waterways with a much more intensive use for various domestic purposes. It cannot a priori be assumed that the quality of these secondary canals is similar to that of the main waterways. It is therefore important to assess the water quality and its spatio-temporal variability in these lower order canals and to determine the potentially health-related risks associated with their use. To provide insight into the water quality status and the main sources of pollution in lower order canals, this study addressed the following objectives: 1) analyze the water quality in lower order canals in representative areas and compare the results with Vietnamese guidelines for drinking and domestic use; 2) compare water quality in lower order canals between inland and coastal regions and water quality attributes from main waterways; 3) identify the factors which explain the spatial variability in surface water quality in lower order canals; 4) assess the effects of tidal regime and seasonality on water quality; and 5) spatially visualize water quality of these waterways to identify hot-spot areas of pollution.

2. Materials and methods

2.1. Study area

The MD is located in the south of Vietnam. Measurement locations in the MD were selected in three provinces: Can Tho, Hau Giang, and Soc Trang provinces (Fig. 1, presented as KML file in the supplementary data).

The Mekong River originates in the Tibetan Plateau and flows via China, Myanmar, Lao PDR and Thailand to Cambodia where it enters the Tonle Sap Lake. At this location, the Mekong River splits in nine branches (Cuu Long — or nine dragons in Vietnam) and flows through the MD in an easterly direction to the South China Sea. The climate in this tropical region is influenced by the southwestern monsoon (MRC, 2005). The wet season is generally between May and October with a mean annual rainfall of 1660 mm (23 years of measurements — Delta Alliance, 2011). During the wet season, 35%–50% of the total surface area of the MD is flooded (MRC, 2005). Sea-water intrusion dominates the hydrology along coastal areas with water level fluctuations >3 m per day due to tidal regime. Further inland in the MD, the diurnal tidal movement results in water level fluctuations of 1.0 m to 1.5 m between low and high tides (DONRE, 2011). The MD is well-known for its large density of artificial canals which are connected to the Mekong distributaries. These canals are of three different orders: the primary canals are used for irrigation and water discharge from agricultural fields. They mostly have very low flow velocities roughly between 0 and 1 m^3/s and are dry during the dry season. The inlets and outlets of water in these waterways are often controlled by means of small gates. Secondary canals collect water from surrounding fields and primary canals and discharge into third order waterways (main canals, rivers). Secondary canals have a water flow of around 1–15 m^3/s although in coastal regions the water flow is significantly higher (up to 30 m^3/s) due to a strong influence from the tidal regime. Water flow in main rivers ranges between 400 and 6000 m^3/s with the highest flow in the wet season (SIWRR, 2013). Land-use is dominated by intensive agriculture while natural vegetation such as forests occupies less than 10% of the area (MRC, 2005). The dominant land-use system is irrigated rice, representing nearly 50% of the agricultural production. Other agricultural activities include fruit orchards, aquaculture, shrimp farming, livestock rearing and the cultivation of upland crops (maize, sweet potatoes, sugar cane, vegetables) (GSO, 2010). Various types and mixtures of fertilizers were used in 2011–2012 in the MD in order to maintain and increase agricultural production particularly for rice cultivation, fruit orchards and other (upland) crops and include: i) different mixtures of N–P_2O_5–K_2O; ii) urea (46% N); iii) DAP (di-ammonium phosphate; 16-48-0); iv) Lân Super ($Ca_3(H_2PO_4)_2$; 0-20-0); and v) Kali clorua (0-0-60). Farmers generally mix two or three of these fertilizers at application time. However, the type and location of agricultural activities are also strongly defined by soil types. Alluvial soils are mainly located near rivers and support diverse field crops; acid sulfate soils are mainly used for rice production; saline soils in coastal areas are mainly used for shrimp farming while degraded soils and sandy ridge soils along the eastern coastline are used mainly for upland crops and fruit orchards (Guong and Hoa, 2012). Main soil characteristics of the MD are mentioned in Supplementary material S1.1. Industrial activities