Journal of Hydrology 400 (2011) 323–332

Contents lists available at ScienceDirect

Journal of Hydrology

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

Implications of rainfall variability for seasonality and climate-induced risks concerning surface water quality in East Asia

Ji-Hyung Park [a,*], Edu Inam [b], Mohd Harun Abdullah [c], Dwi Agustiyani [d], Lei Duan [e], Thi Thuong Hoang [f], Kyoung-Woong Kim [f], Sang Don Kim [f], My Hoa Nguyen [g], Trai Pekthong [h], Vibol Sao [i], Antonius Sarjiya [d], Sianouvong Savathvong [j], Suthipong Sthiannopkao [b,1], J. Keith Syers [k], Wanpen Wirojanagud [l]

[a] *Dept. Forest Environ. Protection, Kangwon National University, Chuncheon 200-701, Republic of Korea*
[b] *IERC, Gwangju Institute of Sci. & Technol., Gwangju 500-712, Republic of Korea*
[c] *Water Research Unit, School of Sci. & Technol., Universiti Malaysia Sabah, Kota Kinabalu, Malaysia*
[d] *Center for Biology, Indonesian Institute of Sciences, Bogor, Indonesia*
[e] *Dept. Environ. Sci. & Eng., Tsinghua University, Beijing, China*
[f] *School of Environ. Sci. & Eng., Gwangju Institute of Sci. & Technol., Gwangju 500-712, Republic of Korea*
[g] *Dept. Soil Sci. & Land Management, Cantho University, Cantho, Viet Nam*
[h] *School of Sci., Mae Fah Luang University, Chiang Rai, Thailand*
[i] *Royal University of Agriculture, Phnom Penh, Cambodia*
[j] *Faculty of Agriculture & Forest Resources, Souphanouvong University, Luang Prabang, Lao Democratic People's Republic*
[k] *Faculty of Agriculture, Natural Resources and Environ., Naresuan University, Phitsanulok 65000, Thailand*
[l] *Dept. Environ. Eng., Khon Kaen University, Khon Kaen, Thailand*

ARTICLE INFO

Article history:
Received 19 January 2010
Received in revised form 3 December 2010
Accepted 25 January 2011
Available online 1 February 2011

This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Martin Beniston, Associate Editor

Keywords:
East Asia
Mekong River
Rainfall variability
Surface water quality
Suspended sediments
Trace metals

SUMMARY

Water resources in East Asia are considered particularly vulnerable to climate variability and extremes due to strong hydrologic variability inherent in the monsoon climate and rising water demand resulting from rapid economic growth. To obtain a better understanding of the current status and climate-induced risks concerning surface water quality in East Asia, seasonal and spatial variations in surface water quality were compared among 11 watersheds in eight countries during typical dry and wet periods from 2006 to 2008. While concentrations of dissolved ions tended to be higher during dry periods, concentrations of suspended sediments and dissolved organic matter were significantly higher during wet periods at most sampling locations. Metals with low solubility showed higher total concentrations during wet periods and had strong positive relationships with suspended sediment concentrations. Metals with high partitioning into the dissolved phase exhibited higher concentrations during dry periods at many sites. Seasonal and spatial patterns were distinct along the Lower Mekong River, including much higher monsoonal concentrations of sediment-associated metals and relatively high dry-season concentrations of dissolved As along upper reaches. The results suggest that rainfall variability is crucial in understanding seasonality and climate-induced risks concerning surface water quality in East Asia.

1. Introduction

Despite relatively high annual precipitation, freshwater resources in East Asia, including both Northeast and Southeast Asia, have recurrent problems of shortage and pollution due to strong seasonality in precipitation and rising water demand resulting from the rapid economic growth (Cruz et al., 2007). Seasonality in precipitation and runoff is primarily governed by monsoon rainfall regimes, which have different timing and duration across East Asia (Yihui and Chan, 2005). Recent analyses have suggested that climate change can influence rainfall patterns of Asian monsoon systems (Zhang et al., 2008). Although long-term precipitation trends show large inter-annual and spatial variability across East Asia, the frequency and intensity of extreme events, such as heavy rainfalls during the summer monsoon and droughts during the dry season, have increased in many parts of East Asia (Manton et al., 2001; Jung et al., 2002; Choi et al., 2009).

Increasing rainfall variability and extremes as a consequence of climate change can influence watershed biogeochemical processes and surface water quality through complex interactions between hydrology and biogeochemical processes, including the production, release, and transport of natural materials and anthropogenic pollutants (Murdoch et al., 2000; Delpla et al., 2009). For many parts of this region the majority of annual runoff is concentrated

---

[*] Corresponding author. Tel.: +82 33 250 8365, fax: +82 33 257 8361.
E-mail address: jihyungpark@kangwon.ac.kr (J.-H. Park).
[1] Current address: Department of Environmental and Occupational Health, National Cheng Kung University, Tainan, Taiwan.

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2011.01.050

during the summer monsoon period. Monsoon rains are thought to play a pivotal role in determining surface water quality through various hydro-biogeochemical processes such as hydrologic flushing of organic matter and rainfall dilution of ions (An and Jones, 2000; Kim et al., 2000; Park et al., 2010). Changing rainfall patterns during the summer monsoon, including changes in rainfall amount and the frequency of extreme rainfall events, can lead to changes in both terrestrial material export and in-stream physicochemical processes, affecting surface water quality (Park et al., 2010). Although there have been many reports on water quality deterioration following extreme events in other parts of the world (Mallin et al., 2002; Baborowski et al., 2004; Presley et al., 2006), water quality has rarely been associated with rainfall variability and extremes in East Asia. However, some recent studies of water quality changes during and following typhoons have illustrated the importance of extreme events in both hydrologic material transport and water quality in mountainous watersheds of East Asia (Zhang et al., 2007; Goldsmith et al., 2008; Tsai et al., 2009).

Watershed topographic features can play an important role in modulating the response of watershed biogeochemical processes to rainfall variability and extremes. Recent studies have emphasized the importance of steep mountainous terrain across Northeast Asia as a key watershed characteristic that can amplify the effects of monsoon rainfalls on watershed processes (Kim et al., 2000; Ogawa et al., 2006; Park et al., 2007). Turbid waters caused by sediments eroded from agricultural lands during extreme rainfall events illustrate the possibility of water quality deterioration as a consequence of the interaction between climate variability and rapid land use change on steep mountainous terrain (Goldsmith et al., 2008; Park et al., 2010). Given the importance of suspended sediments in determining the fate and bioavailability of nutrients and metals (Nagano et al., 2003; Cenci et al., 2006; Quinton and Catt, 2007), surface water siltation in response to extreme rainfall events can pose a serious threat to surface water quality.

The problem of surface water siltation is especially serious in the Lower Mekong River (LMR) Basin, associated with soil erosion from deforested steep hillslopes along Lao and Thai reaches of the Mekong River (Lu and Siew, 2006). For example, in an agricultural watershed in Thailand suspended sediment concentrations of up to 35 g l^{-1} were measured in an extreme rainfall event in June 2004, during which 218 mm fell in 6 h with a maximum intensity of 70 mm h^{-1} (Valentin et al., 2006). Although there is a growing interest in water quality monitoring in Southeast Asia, including river pollution with organic pollutants (Minh et al., 2007; Duong et al., 2010) and groundwater arsenic contamination (Pollizzotto et al., 2008; Winkel et al., 2008), little attention has been paid to climate effects on surface water quality.

Limited information on spatio-temporal variations in surface water quality does not allow an accurate prediction of water quality changes in response to changing patterns of monsoon rainfall regimes in East Asia. The primary objective of this study was to provide baseline information essential for the assessment of climate-induced risks to surface water quality by comparing spatio-temporal variations in surface water quality among 11 representative watersheds across East Asia from China through the LMR basin to Indonesia. A particular focus was placed on the interactions between suspended sediments and metals as an illustrative example of climate risks to surface water quality.

2. Materials and methods

2.1. Study site and sampling

Biannual water sampling was conducted in 11 watersheds in eight East Asian countries during two separate field campaigns (Fig. 1 and Table 1). The first biannual sampling was conducted in 2006 as a pilot study at five watersheds in four countries. A more extensive sampling campaign was conducted at nine watersheds in eight countries from July 2007 through May 2008 as part of a regional collaborative study.

Sampling locations were selected to cover major land use types, including unpolluted headwaters, and streams and rivers receiving agricultural or urban runoff. The Fenhe River (a major tributary of the Yellow River) in China and the Hwangryong and Soyang River in Korea were sampled along a distinct land-use gradient from the forested headwater through the agricultural part to the polluted downstream. In the LMR basin sampling locations were selected along the main-stem Mekong and its major tributary at each site. Because it was difficult to find forested headwaters along the monitored Mekong tributaries, water quality was compared for less polluted upstream versus more polluted downstream reaches. The Kiulu River in the northwestern Malaysian Borneo originates from a steep mountain area and flows through the sparsely populated rural area, with downstream reaches polluted by agricultural runoff and sewage from small towns near Kota Kinabalu. Sampling along the Ciliwung River in Indonesia was also conducted along a relatively distinct gradient of land use, covering headwater and agricultural reaches near Bogor and a polluted downstream reach near Jakarta.

In both campaigns water sampling was repeated during a dry and a wet period at the same 5–15 locations in each monitored watershed (Table 1). Most of the sampling locations in Ubon Ratchatani, Phnom Penh, and Kota Kinabalu were sampled for both sampling campaigns, to compare year-to-year variations in water quality. In Phnom Penh, some of the sampling locations along the Tonle Sap River were changed during the second campaign to encompass both up- and midstream locations.

For the comparison of seasonality in water quality, sampling timing was carefully selected to represent the typical dry or wet period of each country (Table 1). In six countries under the direct influence of the East Asian monsoon climate dry-season sampling was conducted between the mid March and late April, following at least one week without rain, while wet-season sampling was done around the peak of the monsoon. Antecedent precipitation for 1 month before sampling showed clear differences between the dry- and wet-season sampling, although the dry-season precipitation was unusually high in Luang Prabang and Phnom Penh in the 2007–2008 campaign (Table 1). Because Malaysia and Indonesia do not have such a distinct monsoon period as in other countries, a different strategy was used based on local weather conditions. In these countries tropical storms throughout the year, along with recent changes in rainfall regimes, resulted in relatively high 1-month antecedent precipitation before the dry-season sampling (Table 1).

Grab water samples were collected 10–20 cm below the stream surface at the center of flow, using a 1-l Teflon bottle. To avoid contamination from sample handling, newly purchased bottles of the same brand (HDPE bottles, Nalgene) were used after repeated rinsing with ultra-pure water (Milli-Q). During water sampling, in situ water quality parameters were measured, including water temperature, pH, and electrical conductivity. Immediately after water sampling, a portion of sample (50 ml) was filtered on-site using a syringe filter (25 mm Puradisc syringe filter, Whatman; nominal pore size of 0.45 μm) attached to a plastic-only syringe (50-ml PP/PE syringe, Norm-Jet), based on a simplified filtering method developed for trace metal analysis at remote sites (Shiller, 2003). To minimize potential contamination, only newly purchased filters and syringes were used after repeated rinsing with ultra-pure water. The filtered samples, together with unfiltered raw samples, were frozen prior to transport to the laboratory in Korea via express mail services for further chemical analyses.