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Effects of Rainfall Variability and Extremes on Stream Water Quality in the Haean Basin, South Korea

Park, Ji-Hyung (1) ; Lee, Hyun-Ju (2); Shope, Christopher L. (3)

(1) Kangwon National University, Department of Forest Environment Protection, Chuncheon 200-701, Republic of Korea, jihyungpark@kangwon.ac.kr (corresponding author)
(2) Kangwon National University, Department of Forest Environment Protection, Chuncheon 200-701, Republic of Korea, suni211@hanmail.net
(3) University of Bayreuth, Department of Hydrology, D-95440 Bayreuth, Germany, chris.shope@uni-bayreuth.de

Abstract: Increasing rainfall variability and extremes as a consequence of global climate change have been emerging as a major challenge for sound management of freshwater resources in steep mountainous watersheds in East Asia. To evaluate potential risks to stream water quality posed by rainfall variability and extremes, we investigated seasonal and storm-induced short-term changes of stream water quality in a mountainous mixed land-use watershed (the Haean Basin) in northern South Korea. We routinely monitored 10 stream locations every 2 – 4 weeks, combined with in-stream storm sampling at a headwater forest stream and a watershed outlet receiving agricultural runoff. Routine sampling results showed distinct spatial patterns for stream water quality, including increasing concentrations of TSS and dissolved nutrients toward downstream reaches of agricultural streams. TSS concentrations and UVA_{254} (as a measure of aromatic dissolved organic matter) intensities were generally higher during the summer monsoon period in all stream locations, while relatively high nutrient concentrations were observed in agricultural steams, particularly during extended drought periods. TSS concentrations in both the forest stream and watershed outlet rapidly increased upon initiation of storm events and reached unusually high levels during peak flow periods, suggesting that low-frequency routine stream sampling can not adequately capture rapid responses of suspended sediment export to storms. The results highlight the importance of extreme rainfall events for soil erosion and its impacts on stream water quality in steep mountainous watersheds. High dry-period nutrient concentrations in agricultural steams suggest that rapid expansion of agricultural lands in the Haean Basin over the recent decades can result in elevated risks of stream eutrophication during extended drought periods as well as the increased vulnerability of soil erosion on steep cultivated slopes.

Keywords: *climate change, extreme events, Haean Basin, mountainous watersheds, soil erosion, water quality*

1. Introduction

Although mountains occupy one fifth of the world terrestrial surface, half of the human population depends in various ways on mountain resources (Körner et al., 2005). Mountain areas supply much more discharge than could be expected from the land area they cover, with the proportion of discharge from a river basin contributed by mountains up to over 90% (Viviroli et al., 2003). Although mountainous watersheds play a crucial role in providing clean drinking water for people living both within and downstream of the mountain range, watershed management is particularly challenging in the mountain area of East Asia, due to intense rainfalls characteristic of the monsoon climate and recurring deterioration of downstream water quality associated with soil erosion and landslides in steep mountain slopes (Sidle et al., 2006; Park et al., 2010). Land use change on steep mountainous terrain, such as deforestation and agricultural expansion, has been linked to elevated flood risks and deteriorating steam water quality (Bradshaw et al., 2007; Eisenbies et al., 2007).

Intensifying monsoon rainfalls, as a potential consequence of climate change, can have significant impacts on the material transport and surface water quality in mountainous watersheds in East Asia (Park et al., 2010). Recent studies have shown the importance of extreme hydrologic events such as Typhoons in the flow of suspended sediments and nutrients in mountainous watersheds in East Asia (Zhang et al., 2007; Goldsmith et al., 2008; Tsai et al., 2009). Suspended sediment is a major water quality problem in headwater streams, degrading drinking water quality and habit quality for aquatic organisms (Binkley and Brown, 1993; Bilota and Brazier, 2008) and transporting nutrients (Ide et al., 2008) and toxic metals (Jo and Park, 2010). Changes in the amount and spatiotemporal distribution of precipitation can also influences stream water quality by affecting biogeochemical processes that regulate nutrient production and hydrologic export (Murdoch et al., 2000; Campbell et al., 2009; Park et al., 2010). Little is know about seasonality and short-term changes in water quality during monsoon rainfall events in mountainous watersheds in northern South Korea.

The primary objective of this study was to better understand effects of rainfall variability and extremes on stream water quality in mountainous watersheds in eastern monsoon Asia. We investigated seasonality and storm responses of suspended sediment and dissolved nutrients by conducting routine biweekly stream sampling combined with intensive storm sampling at various sampling locations in the Haean Basin in northern South Korea.

2. Methods

2.1. Study Site

The study site (Haean Basin) is a bowl-shaped mountainous watershed at the northern extreme of South Korea (38°15´–38°20´ N; 128°05´–128°10´ E; 400 m–1,304 m asl), 1–2 km south of the demilitarized zone (DMZ) between South and North Korea (Figure 1; for more details refer to Jo and Park, 2010). The bedrock in Haean Basin consists of highly weathered biotite granite at the basin bottom, surrounded by metamorphic rocks forming mountain ridges (Kwon et al., 1990). Mixed deciduous forests along the mountain ridges and steep slopes comprise 58% of the whole basin area (60 km^2). These forests have been reestablished naturally after recurrent forest fires in the two decades following the Korean War in 1950-1953. Dominant tree species include *Quercus mongolica* Fisch. ex Ledeb. and *Fraxinus rhynchophylla* Hance. Rapid agricultural expansion in the steep terrain combined with highly erodible soils developed from saprolites across the basin bottom has transformed the basin into a major source of suspended sediments in the North Han River, which supplies drinking water to tens of millions of people living in metropolitan areas.

2.2. Sampling and Laboratory Analysis

For the first 1-year monitoring period from May 2008 to April 2009, routine biweekly stream sampling was conducted in 10 sampling locations, including six locations along two tributaries to the Mandae Stream that flows through the Basin to the Inbuk River, two locations along the main-stem of the Mandae Stream, and two locations along the Inbuk River up- and downstream of the confluence with the Mandae Stream (Figure 1). For the second monitoring year, routine sampling was conducted at 2-4 week intervals in six locations (MD1, MD4, MD5, MD7, IB1 and IB2). Six intensive storm event samplings were conducted in a headwater forest stream (MD1) and in an outlet location of the Mandae Stream (MD4) during two summer monsoon periods in 2008 and 2009. For routine water sampling, grab water samples were collected below the stream surface at the center of the flow with a 1-L Teflon bottle. During stream sampling, in situ water quality parameters including water temperature, pH, electrical conductivity, and dissolved oxygen were measured. For storm event sampling, water samples were taken every 2 h using two autosamplers (6712 Portable Sampler, ISCO).

Micrometeorological data were collected at the forested watershed, including precipitation, air temperature, and soil temperature and volumetric water content at 30 cm depth. No discharge measurements were made within the watershed during the study period. Discharge from the forested watershed during the study period was estimated using a hydrologic model (HBV-Lite).

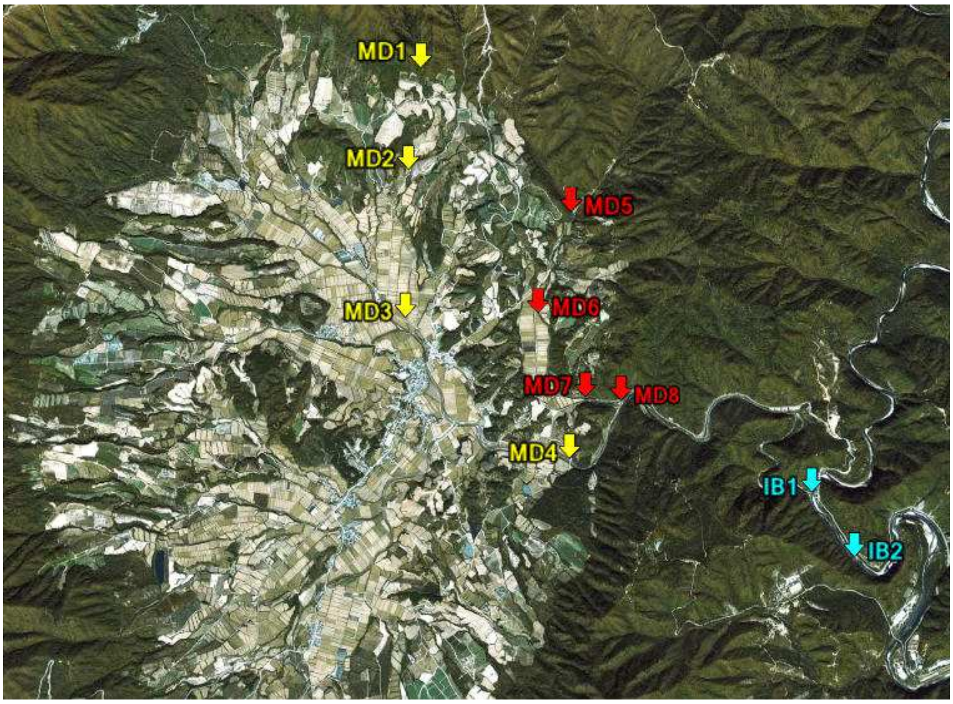

Figure 1. Sampling locations along two tributaries (MD1, MD2, MD3, MD5, MD6, and MD7) and the main stem of Mandae Stream (MD4 and MD8) and Inbuk River above (IB1) and below (IB2) the confluence marked on a Google Earth map

Stream samples were kept refrigerated at < 4°C and filtered within 24 hr after the sampling. A portion of the water sample (50–200 ml) was filtered through a pre-combusted glass fiber filter (GF/F, Whatman; nominal pore size of 0.7 m) after pre-filtering through a plastic sieve with 2-mm pores. TSS concentrations were measured gravimetrically as the difference in filter weight before and after filtering. Prior to filtering GF/F filters were combusted at 45°C to remove any organic materials in the filters and then weighed. After filtering of water samples, the filters were dried at 65°C and re-weighed for the calculation of TSS. Filtered water samples were analyzed for UV absorbance at 254 nm (UVA_{254}) by a UV/vis spectrophotometer (Libra S32PC, Biochrom), DOC with a TOC analyzer using high-temperature combustion of organic matter followed by thermal detection of CO_2 (TOC 5000a, Shimadzu), and dissolved ions including Cl^-, SO_4^{2-}, NO_3^-, and NH_4^+ using an ion chromatograph (DX-320, Dionex). As part of quality control, a laboratory blank (Mili-Q ultrapure water) and a standard solution were measured for every batch of ten samples. Replicate analysis was conducted for approximately 10% of the total samples. Contamination from sampling and filtering was checked with field blank samples (Mili-Q ultrapure water).

3. Results and Discussion

3.1. Spatiotemporal Variations in Stream Water Quality

Distinct spatial patterns were present for most measured water quality components (Table 1). Annual mean concentrations of suspended sediment and dissolved nutrients generally increased from headwater forest streams toward downstream reaches of two Mandae Stream tributaries, reflecting influence of turbid, high-nutrient runoff from agricultural fields. While EC and dissolved ion concentrations were highest in the watershed outlet (MD4) and became lower downstream in MD8, TSS concentrations were highest in MD7 near the mouth of the tributary stream draining an adjacent subcatchment. These results suggest that this second tributary contains more suspended sediment but smaller nutrients compared to the main-stem Mandae Stream. Concentrations of both TSS and all measured ions increased from the upstream (IB1) to downstream location (IB2) of the confluence of the Inbuk River and Mandae Stream, suggesting disproportionate influence of the small Mandae Stream on the water quality of the larger Inbuk River.

Table 1. Summary of measured water quality components in 10 stream locations for the 1-yr monitoring period from May 2008 to April 2009. Values are means followed by one standard deviation in parentheses (n = 22).

Parameter	Site									
	MD1	MD2	MD3	MD4	MD5	MD6	MD7	MD8	IB1	IB2
pH	6.30	6.98	8.12	7.18	6.77	7.29	7.01	7.29	7.29	7.13
	(1.27)	(0.10)	(0.96)	(0.42)	(1.16)	(0.40)	(0.57)	(0.61)	(0.58)	(0.63)
EC	36.39	87.78	150.73	165.03	63.74	114.78	120.70	137.74	53.47	68.36
(uS cm^{-1})	(15.94)	(29.55)	(50.68)	(108.90)	(12.83)	(48.56)	(41.02)	(49.98)	(8.55)	(20.82)
DO	9.72	9.55	8.85	10.47	9.88	9.07	9.49	9.45	10.14	9.83
(mg l^{-1})	(2.34)	(1.34)	(1.53)	(5.82)	(1.76)	(2.90)	(1.48)	(1.36)	(1.88)	(2.13)
UVA	0.023	0.037	0.042	0.038	0.035	0.034	0.039	0.041	0.029	0.029
at 254nm	(0.009)	(0.022)	(0.019)	(0.015)	(0.016)	(0.017)	(0.025)	(0.022)	(0.020)	(0.016)
TSS	2.56	14.37	6.66	33.46	2.62	4.52	50.96	45.49	2.99	9.14
(mg l^{-1})	(2.69)	(36.91)	(6.49)	(45.38)	(1.70)	(5.86)	(128.60)	(86.93)	(5.11)	(10.62)
DOC	0.97			1.43	1.15				1.07	1.19
(mg l^{-1})	(0.28)			(0.47)	(0.33)				(0.41)	(0.49)
Cl^-	1.84	5.75	10.99	15.33	3.53	6.34	6.76	8.73	2.73	4.54
(mg l^{-1})	(0.41)	(2.71)	(6.00)	(22.68)	(1.38)	(3.55)	(2.92)	(6.13)	(0.76)	(3.18)
SO_4^{2-}	2.50	4.97	7.35	7.81	4.98	7.33	7.60	7.12	3.91	4.31
(mg l^{-1})	(0.52)	(1.70)	(6.09)	(3.08)	(1.58)	(2.70)	(3.09)	(3.56)	(0.80)	(1.27)
NO_3^--N	1.05	2.76	3.55	4.65	1.09	3.71	3.27	3.58	0.63	1.21
(mg l^{-1})	(0.39)	(1.03)	(1.16)	(1.69)	(0.31)	(2.16)	(1.14)	(1.46)	(0.29)	(0.63)
NH_4^+-N	0.03	0.05	0.08	0.12	0.04	0.08	0.05	0.08	0.03	0.05
(mg l^{-1})	(0.03)	(0.06)	(0.18)	(0.08)	(0.03)	(0.23)	(0.10)	(0.07)	(0.03)	(0.06)

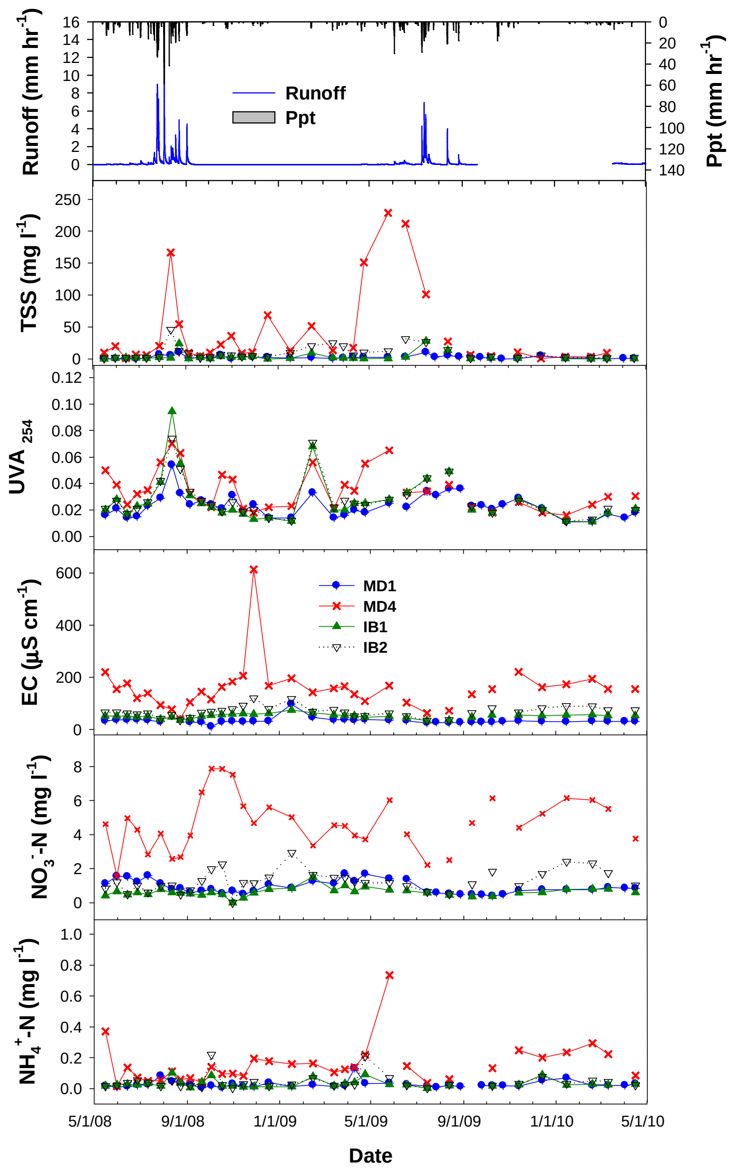

Figure 2. Temporal variations in runoff (mm hr^{-1}), precipitation (ppt; mm hr^{-1}), TSS (mg L^{-1}), UVA$_{254}$ (AU), EC (µS cm^{-1}), and concentrations of NO_3^--N and NH_4^+-N in four selected stream locations (MD1, MD4, IB1 and IB2) over the two-year monitoring period from May 2008 through April 2010

Stream water quality displayed strong seasonality as shown by temporal trends observed in four selected sampling locations (Figure 2). Both TSS concentrations and UVA$_{254}$ intensities (as a measure of dissolved organic matter) tended to be higher during the summer monsoon period, but the reversed trend was observed for electric conductivity and concentrations of all measured dissolved ions (Figure 2). This result suggests that frequent rainfalls during the summer monsoon period result in large export of suspended sediment and dissolved organic matter from upland soils, but dilute streamwater concentrations of dissolved ions.

Rainfall-induced increases in suspended sediment export were ascertained by the significant correlation between antecedent precipitation for 3 d before sampling and TSS concentrations in the forest stream (data not shown), but the relationship was weak in downstream locations reflecting human influences such as irrigation and sediment dredging. Monsoonal increases in streamwater suspended sediment have been ubiquitously observed in streams and rivers across East Asia (Park et al., 2011). Hydrologic flushing of organic matter from surface soils during storm events (Hornberger et al., 1994) might have contributed to increases in UVA_{254} intensity during the wet period.

Rainfall-induced dilution of dissolved ions is a well established phenomenon observed in a range of streams and rivers (e.g., Brown et al., 1999; van Vliet and Zwolsman, 2008; Tsai et al., 2009), although concentrations of nutrients derived from diffuse sources, such as NO_3^-, can increase as a result of rainfall flushing (van Vliet and Zwolsman, 2008). Relatively high concentrations of dissolved ions during dry periods posed a risk of water quality deterioration in the watershed outlet (MD4; Figure 2). As a consequence of rainfall-induced increases in TSS concentrations and higher nutrient concentrations during dry periods in the watershed outlet noticeable concentration increases occurred from the upstream (IB1) to downstream (IB2) location of the confluence of the Mandae Stream and Inbuk River (Figure 2).

3.2. Short-term Variations in Stream Water Quality during Storm Events

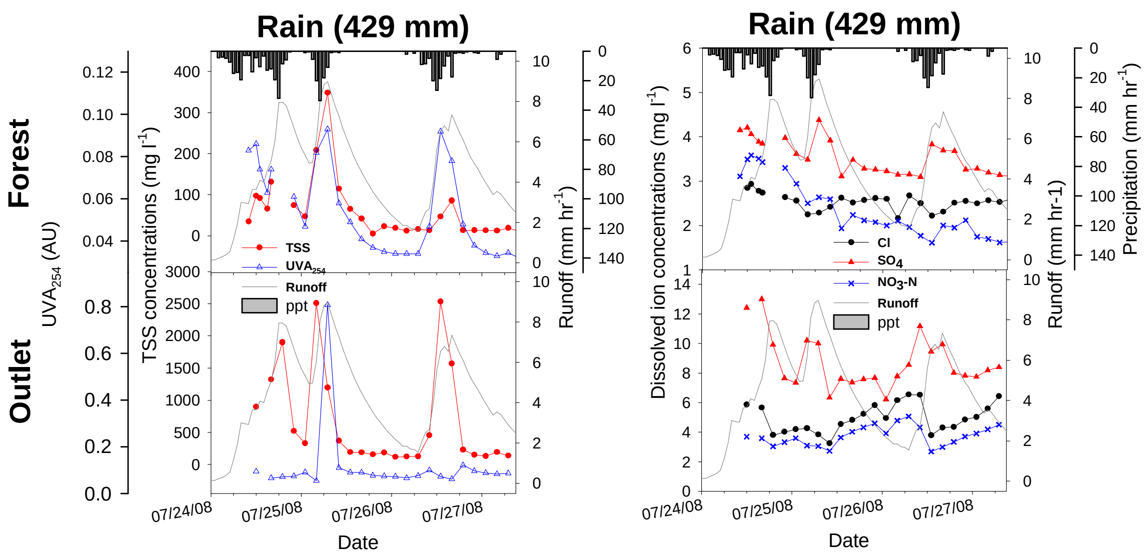

Figure 3. Short-term changes in runoff (mm hr^{-1}), precipitation (ppt; mm hr^{-1}), UVA_{254} (AU), and concentrations of TSS Cl^{-1}, SO_4^{2-}, and NO_3^--N (mg L^{-1}) in the forest stream (MD1) and watershed outlet (MD4) during two consecutive storm events in 2008

Storm-induced short-term changes in stream water quality were compared in the headwater forest stream (MD1) and watershed outlet (MD4) for six storm events in 2008 and 2009. Various storm responses were observed depending on water quality components, as illustrated by changes in dissolved ion concentrations observed during two consecutive storm events with a total precipitation of 429 mm. TSS concentrations and UVA intensities rapidly changed corresponding to changes in discharge during all monitored storm events (also illustrated in Figure 3), which is in agreement with the seasonal pattern observed by the routine stream sampling (Figure 2). Peak TSS concentrations during the extreme event (Figure 3) reached extraordinarily high levels in both forest stream and watershed outlet, particularly compared to the relatively low levels of TSS observed by the routine sampling. While rainfall-induced dilution of dissolved ion concentrations was observed during the summer monsoon periods by the routine sampling (Figure 2), short-term storm responses depended on storm characteristics and ions. During the extreme event depicted in Figure 2, for example, there were negative relationships between discharge and concentrations of Cl^- and NO_3^- as expected from rainfall-induced dilution, while SO_4^{2-} concentrations tended to increase with rising discharge in both forest stream and watershed outlet.

3.3. Summary and Implications

Routine stream sampling at 2- 4 week intervals in 10 stream locations showed distinct spatial patterns for stream water quality in the Haean Basin, including increasing concentrations of TSS and dissolved nutrients toward downstream reaches of agricultural streams. TSS concentrations and UVA_{254} intensities were generally higher during the summer monsoon period in all stream locations, while relatively high nutrient concentrations were observed in agricultural steams, particularly during extended drought periods. Rapid storm-induced increases in TSS concentrations resulted in extraordinarily high concentrations in both forest stream and watershed outlet during peak flow periods, suggesting that low-frequency routine stream sampling can not adequately capture rapid responses of suspended sediment export to storms, resulting in an underestimation of surface runoff and soil erosion. Siltation-related water quality problems occurred in the study area following extreme storm events over the recent years, including temporary malfunctioning of drinking water facilities by turbid waters (Park et al., 2010) and the export of soil-bound Pb (Jo and Park, 2010). The results of this study underline the importance of extreme rainfall events for soil erosion and its impacts on stream water quality in steep mountainous watersheds. High dry-period nutrient concentrations in agricultural steams suggest that rapid expansion of agricultural lands in the Haean Basin over the recent decades has resulted in elevated risks of stream eutrophication during extended drought periods.

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