Environment International 36 (2010) 212–225

Contents lists available at ScienceDirect

Environment International

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

Review article

Potential effects of climate change and variability on watershed biogeochemical processes and water quality in Northeast Asia

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ARTICLE INFO

Article history:
Received 20 May 2009
Accepted 26 October 2009
Available online 18 November 2009

Keywords:
Acidic deposition
Climate change
Climate variability
Northeast Asia
Water quality
Watershed biogeochemistry

ABSTRACT

An overview is provided of the potential effects of climate change on the watershed biogeochemical processes and surface water quality in mountainous watersheds of Northeast (NE) Asia that provide drinking water supplies for large populations. We address major 'local' issues with the case studies conducted at three watersheds along a latitudinal gradient going from northern Japan through the central Korean Peninsula and ending in southern China. Winter snow regimes and ground snowpack dynamics play a crucial role in many ecological and biogeochemical processes in the mountainous watersheds across northern Japan. A warmer winter with less snowfall, as has been projected for northern Japan, will alter the accumulation and melting of snowpacks and affect hydro-biogeochemical processes linking soil processes to surface water quality. Soils on steep hillslopes and rich in base cations have been shown to have distinct patterns in buffering acidic inputs during snowmelt. Alteration of soil microbial processes in response to more frequent freeze–thaw cycles under thinner snowpacks may increase nutrient leaching to stream waters. The amount and intensity of summer monsoon rainfalls have been increasing in Korea over recent decades. More frequent extreme rainfall events have resulted in large watershed export of sediments and nutrients from agricultural lands on steep hillslopes converted from forests. Surface water siltation caused by terrestrial export of sediments from these steep hillslopes is emerging as a new challenge for water quality management due to detrimental effects on water quality. Climatic predictions in upcoming decades for southern China include lower precipitation with large year-to-year variations. The results from a four-year intensive study at a forested watershed in Chongquing province showed that acidity and the concentrations of sulfate and nitrate in soil and surface waters were generally lower in the years with lower precipitation, suggesting year-to-year variations in precipitation as a key factor in modulating the effects of acid deposition on soil and surface water quality of this region. Results from these case studies suggest that spatially variable patterns of snow or summer precipitation associated with regional climate change across NE Asia will have significant impacts on watershed biogeochemical processes and surface water quality, in interactions with local topography, land use change, or acid deposition.

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0160-4120/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envint.2009.10.008

1. Introduction

Climatic warming can lead to disturbances in the global water cycle due to feedbacks between rising temperatures and hydrologic processes, with changing patterns of precipitation and runoff and more frequent occurrence of extreme weather events as major consequences (Milly et al., 2005; Zhang et al., 2007a). Climate-induced disturbances in the global water cycle represent an emerging challenge for sound management of water resources, given the existing high demands from population growth and water pollution (Kundzewicz et al., 2007). Freshwater resources in NE Asia are especially vulnerable to climate change, due to the variability associated with the East Asian monsoon and increasing water demand from population and economic growth. Extreme hydrologic events have been observed in the recent decades and projected to increase in the future (Manton et al., 2001; Min et al., 2006; Cruz et al., 2007). Despite growing concerns over potential adverse effects of climate change and variability on water resources in NE Asia, there have been few efforts to assess the environmental impacts of changing climate on the freshwater resources in NE Asia.

Climate change and increased variability, including extreme events such as floods and droughts, have been suggested to have significant impacts on water quality around the world (Murdoch et al., 2000; Worrall et al., 2003; Senhorst and Zwolsman, 2005; Kundzewicz et al., 2007). Climate change can impact human health and aquatic ecosystems through water quality deterioration caused by higher water temperatures, increased precipitation intensity, and longer periods of low flow (Kundzewicz et al., 2007). The linkages of climate change in affecting water resources and agriculture have been identified to be especially critical for NE Asia (Cruz et al., 2007). Unprecedented water quality deterioration and water facility failures due to recent extreme weather events across East Asia have clearly illustrated how climate change poses a major threat to both the quantity and quality of freshwater resources (e.g., Kim and Jung, 2007). These threats to water quantity and quality could result in enormous societal and economic costs.

Climate change, including extremes, can affect water quality, not only by directly changing the characteristics of the water, but also by influencing land surface processes that regulate the production, release, and transport of natural materials and anthropogenic contaminants to ground and surface waters (Murdoch et al., 2000; Williams et al., 2008; Campbell et al., 2009). Many hydroclimatic factors play important roles in land-water transport of chemicals affecting water quality, including water and air temperature, precipitation amount and intensity, and droughts. Water temperature changes can directly influence temperature-dependent water quality parameters including dissolved oxygen, redox potentials, pH, lake stratification and mixing, and microbial activity.

Changes in temperature and precipitation, along with irregular, extreme hydrologic events, can lead to changes in land surface geomorphic (e.g., hillslope failures) or hydro-biogeochemical processes (e.g., stormflow effects on contaminant mobilization) as well as deterioration in water quality. For example, warming affects numerous land surface processes involved in chemical transport and water quality deterioration, such as warming-induced increases in soil N transformation leading to changes in streamwater nitrate concentrations (Murdoch et al., 1998) or hydrologic flushing of soil nitrate or DOC triggered by winter temperature fluctuations (Park et al., 2003, 2005). Recent studies have emphasized the importance of landscape features of NE Asia, especially steep mountainous terrain, as a key watershed characteristic exacerbating the effects of monsoon rainfalls or snowmelts on watershed processes (Tao, 1998; Kim et al., 2000; Ogawa et al., 2006; Park et al., 2007). Considering the importance of forested headwater watersheds in supplying potable water, proactive management of climate risks to the water resources requires a more thorough understanding of hydrological and biogeochemical responses of these steep, upland watersheds.

Topography exerts a primary control on biogeochemical processes within a climatic zone (Yoo et al., 2006). Stream chemistry patterns in NE Asia have often shown spatial differences attributable to chemical and topographic features of individual watersheds. For example, Ogawa et al. (2006) investigated that the relationship between the basin topography and stream chemistry for a series of nested watersheds in northern Japan. Those catchments with steeper hillslopes and relatively narrow basins were sources of nitrate, whereas riparian areas with gentle slopes and wider basins retained nitrate. The topographic index (a measure of potential wetness; Mitchell, 2001) as well as vegetation patterns (Xu and Shibata, 2007) were good predictors of nitrate and DOC concentrations in stream waters. In vulnerable areas with steep slopes the frequency and magnitude of soil erosion and landslides increase in response to elevated precipitation intensities (Kundzewicz et al., 2007). Although there have been substantial research efforts to obtain a better understanding of landslides and soil erosion, little attention has been paid to climate-related trends in affecting soil erosion and landslides. Biogeochemical and hydrologic processes associated with soil erosion also affect the transport of carbon (C) and other elements in mountainous terrain (Berhe et al., 2007). The importance of the steep terrain is illustrated by the greater dominance of particulate organic C (POC) compared to dissolved organic C (DOC) for total C transport in this region (Degens et al., 1991; Kim et al., 2000). Extreme events such as typhoons play a major role in the transport of sediments and nutrients from steep hillslopes to surface waters (Zhang et al., 2007b; Goldsmith et al., 2008).

To provide an overview of the potential effects of climate change and variability on the biogeochemical processes and surface water quality in mountainous watersheds of NE Asia, we reviewed recent trends and future predictions of climate change effects on watersheds in NE Asia. Major local issues were addressed in the context of regional climate change by comparing results from watersheds along a latitudinal gradient from northern Japan through the central Korean Peninsula to southern China. We evaluated these results in the context of the spatially variable patterns of watershed biogeochemical responses to concomitant changes in climate, land use, and atmospheric deposition, which represent the three primary environmental factors affecting water resources around the world (Williams et al., 2008). We focused particularly on the projected changes of precipitation regimes in three NE Asian countries (Japan, Korea, and China) and the resultant effects on biogeochemical processes and water quality.

2. Climate change and variability in NE Asia

As in other parts of Asia, unambiguous warming trends have been observed across NE Asia over recent decades, with more pronounced warming seasonally in winter and spatially in northern latitudes (Cruz et al., 2007). Precipitation trends have shown large inter-seasonal, inter-annual, and spatial variability across NE Asia (Cruz et al., 2007; Choi et al., 2009). For example, annual precipitation has increased by 85.5 mm per decade over the last 35 years (1973–2007) in South Korea (Choi et al., 2008), while declining or no trends in precipitation amounts have been observed in some regions of China and Japan (Cruz et al., 2007; Choi et al., 2009). The frequency and intensity of extreme weather events, particularly heavy rainfalls during the summer monsoon, have increased in some parts of NE Asia, although spatial variation makes it difficult to draw general conclusions on trends across the entire region (Easterling et al., 2000; Manton et al., 2001; Jung et al., 2002; Cruz et al., 2007). As with the increasing frequency and intensity of tropical storms originating in the Pacific (Wu et al., 2005; Cruz et al., 2007), the increasing frequency of extreme precipitation events has been attributed to global warming (Jung et al., 2002).

Among the observed climate trends in NE Asia, changing rainfall patterns during the summer monsoon and changes in winter climate regimes (the latter especially in northern latitudes) have important implications for watershed biogeochemical processes and hence surface water quality. For this region the majority of annual runoff is concentrated around the summer monsoon period in the south and spring snowmelt in the north (Kim et al. 2000; Shibata et al. 2002). In Korea, changing rainfall patterns during summer monsoons (called “Changma”) have been recently observed, with fewer rainfall days but increased intensity (Chung et al., 2004). Long-term changes in East Asian monsoons have been linked to changes in the Northern Hemisphere summer insolation (incoming solar radiation) on orbital time scales ranging from thousands of years to tens of millennia (Wang et al., 2008). However, the sensitivity of monsoons to climate changes might result in a stronger monsoon with large increase in monsoon precipitation (Overpeck and Cole, 2008). Although little is yet known about the response of winter monsoon to climatic warming, a recent climate simulation over the southern half of the Korean Peninsula predicted declines in winter snow depth in response to the increase of minimum temperature and large increases in winter precipitation (Im et al., 2008).

In the following three chapters we will review recent trends and future predictions for climate change-induced changes in surface water quality. Climate patterns observed for the selected areas represent distinct changes in rainfall regimes across Northeast Asia. Although annual precipitation is similar, seasonal distribution of precipitation, along with winter snow regimes, is distinctively different across the areas (Table 1; Fig. 1). Common to all three areas is the importance of the forested headwater watersheds as the source of drinking water for large populated areas downstream. While major soil types are different (Table 1), steep terrain is a typical landscape feature in all areas.

3. Potential changes in winter monsoon in northern latitudes and implications for watershed processes and water quality in Hokkaido, Japan

3.1. Importance of snow regimes for watershed hydro-biogeochemical processes in northern cool-temperate forest ecosystems

In northern cool-temperate regions, winter climate is characterized as being cold and snow-dominated, with large seasonal fluctuations in temperature, precipitation (rainfall and snowfall) and stream discharge. The accumulation and melting of snowpacks in winter influence the movement of water and the transport of various solutes from soils to surface waters. Long-term measurements of snowpack in Hokkaido showed a slightly decreasing trend over the recent decades (Fig. 2), although most recently the maxima snow depths have averaged ~2 m, providing substantial insulation of the forest floor from low above-ground temperatures. The long-term trend of decreasing snow depth is likely a result of the combined effects of changes in increased falling snow density, higher proportion of rain events in the winter, and increasing air temperature affecting snow thermal melting. Recent declines in snowpack depth observed in Hokkaido (Fig. 2) are consistent with other reports showing similar patterns, particularly from the north western side of the Japanese archipelago (Ishizaka, 2004; Suzuki, 2006). Using a 20 km-mesh atmospheric general circulation model (AGCM), Hosaka et al. (2005) predicted decreasing snowfall in Hokkaido Island. Changes in snowpack moisture and/or timing of snowmelt will affect the hydrological processes during the snowmelt period.

The importance of snowmelt in affecting surface water biogeochemistry has been emphasized especially from studies in North America (Williams and Melack, 1991; Murdoch and Stoddard, 1992; Hornberger et al., 1994; Campbell et al., 1995; Creed et al., 1996; Stottlemyer, 2001; Campbell et al., 2005, 2007). These studies have suggested that flushing of solutes from snowpack and surface soil and dilution by snowmelt water and groundwater are major driving factors in affecting the concentration and fluxes of major solutes, particularly nitrate and DOC. By comparison, there have been few studies that have focused on stream chemistry associated with snowmelt processes in NE Asia (Sakamoto et al., 1999; Aga et al., 2001; Ozawa et al., 2001; Shibata et al., 2002). Some of these studies, however, have quantified snowmelt-induced flushing of carbon, nitrogen and acids during the snowmelt period. For instance, Sakamoto et al. (1999) estimated that DOC export during the snowmelt period comprised 65 % of the annual DOC export from a small headwater forested watershed in Hokkaido.

The early phase of snowmelt flushes solutes from the forest floor and mineral soil, contributing to episodic acidification and increased nutrient concentrations in surface waters (Baird et al., 1987; Laudon et al., 2000; Wellington and Driscoll, 2004; Piatek et al., 2005). In a forested watershed in Hokkaido the loss of nitrate was notably greater during snowmelt compared to other hydrological events associated with high precipitation inputs in the summer (Christopher et al., 2008b). Anthropogenic activities including acidic deposition and nutrient additions to surface waters have been shown to amplify acidic episodes and the eutrophication of surface waters in the northeastern US and Scandinavia (Baird et al., 1987; Laudon et al., 2000; Chen and Driscoll, 2005). Few studies in NE Asia, however, have evaluated the importance of hydrologic events in affecting acidification and eutrophication of surface waters. Different climatic, geologic and biological characteristics in Asian regions result in different chemical response patterns associated with snowmelt than those observed for North America and Europe (Ohte et al., 2001a,b).

In the Japanese archipelago, parent materials are often associated with volcanic activity. These substrates have relatively high weathering rates and high concentrations of base cations resulting in elevated concentrations of base cations in soils and drainage waters

Table 1
Site information of the three case studies in Japan, Korea, and China.

Site name	Country	Latitude	Longitude	Elevation (min–max; m)	Major soil type	Mean annual temperature (°C)	Annual precipitation (mm)	Lowest monthly precipitation (mm)	Highest monthly precipitation (mm)	Winter precipitation in snow (mm)
Uryu	Japan	44° 21′N	142° 15′ E	280–680	Dystric cambisols	2.5	1255	60 (Mar)	180 (Dec)	728 (Nov–Apr)
Soyang	Korea	37° 56′N	127° 49′E	180–1708	Cambisols	10.9	1267	20 (Jan)	319 (Jul)	67 (Dec–Feb)
Tieshanping	China	29°38′N	104°41′E	450–500	Haplic acrisols	18.2	1105	20 (Jan)	175 (Jul)	0

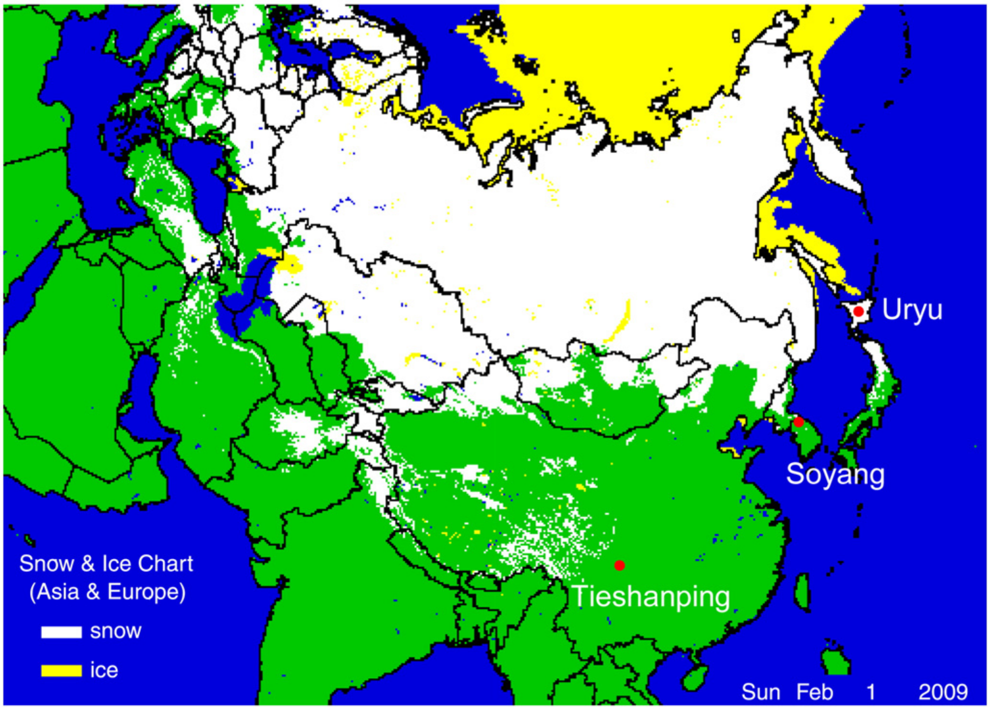

Fig. 1. The locations of three study sites marked on a NASA (NIC IMS) satellite image map showing the snow-covered area by February 1, 2009. (Source of the map: http://www.natice.noaa.gov/ims/).

(Nakagawa and Iwatsubo, 2000; Shibata et al., 2001). These high concentrations of base cations generally buffer surface waters with little evidence of increased acidification in response to elevated acid deposition. For example, a study of stream chemistry in a headwater forested watershed on Tertiary Andesite in the northern Japan (Shibata et al., 2002) showed relatively large fluctuations of stream discharge and ionic concentration but little change in pH (from ~7.0 to 7.7 during the snowmelt period; Fig. 3). These watershed responses to snowmelt reflect snowmelt dilution for a well-buffered watershed. During snowmelt the dominant solutes were bicarbonate and base cations that result in high acid neutralizing capacity against the mobilization of acids during snowmelt flushing. Small peaks of electrical conductivity during the early phase of snowmelt were related to the flushing of sea salts accumulated (Shibata et al., 2002). At the same site plot-scale investigations also showed that the snowmelt dominated annual solute exports (Ozawa et al., 2001).

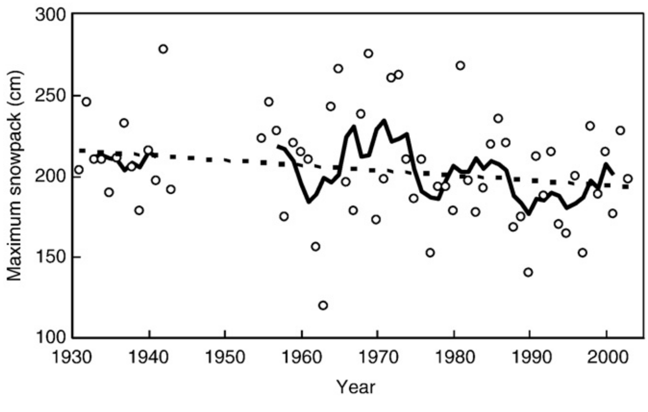

Fig. 2. Long-term changes in maximum snowpack depth in Hokkaido University's Uryu Experimental forest located in northern Japan (unpublished data except for the data from 1956 to 1989 published in the 1990 report of Hokkaido University Forests (1990)). Open circles represent annual data, while the line plot shows five-year means. Linear regression through the line plot indicates significant decreases in snowpack depth with year ($P<0.001$).

Nakagawa and Iwatsubo (2000) and Koshikawa et al. (2007) have reported that many Japanese streams have elevated base cation concentrations and circumneutral pH values. Relatively high weathering rates and differences in parent materials play an important role in affecting watershed responses to acidic deposition in NE Asia compared to Europe and North America (Ohte et al., 2001b).

3.2. Implications of winter climate change for watershed biogeochemical processes and water quality

Recent studies using chemical analyses and isotopic tracers have indicated that most of the nitrate in surface waters is derived from soil microbial nitrification with little nitrate derived directly from atmospheric deposition (Burns and Kendall, 2002; Campbell et al., 2002; Christopher et al., 2008a,b), corroborating the earlier findings using N input–output budgets (Rascher et al., 1987). Nitrate accumulated in surface soil is affected by soil temperature and moisture conditions. Recent studies have suggested that winter microbial processes beneath the snowpack are also a substantial contributor for solute leaching and gaseous emissions (Brooks et al., 1996; Monson et al., 2006).

Many climate change scenarios implicate that the regimes of temperature and precipitation in winter are changing in northern cool-temperate region (Likens, 2000; Stottlemyer and Toczydlowski, 2006). The change of snowfall and temperature will alter soil temperature, moisture and freeze–thaw regimes, which in turn have impacts on many hydro-biogeochemical processes affecting the production and transport of solutes in soils and stream waters (Mitchell et al., 1996; Park et al., 2005). With warmer winters, the timing and the magnitude of snowmelt will change, with net effects including a shift to shallower soil depths for snowmelt lateral flow increasing the flux of more mobile solutes, and a significant increase in solar inputs to forested soils (Chapin et al., 2005). Snow manipulation studies have found that soil freezing has strong impacts on belowground processes especially with respect to influences on fine root mortality and subsequent diminishment of nutrient uptake by trees (Groffman et al., 2001; Nielson et al., 2001; Fitzhugh et al.,

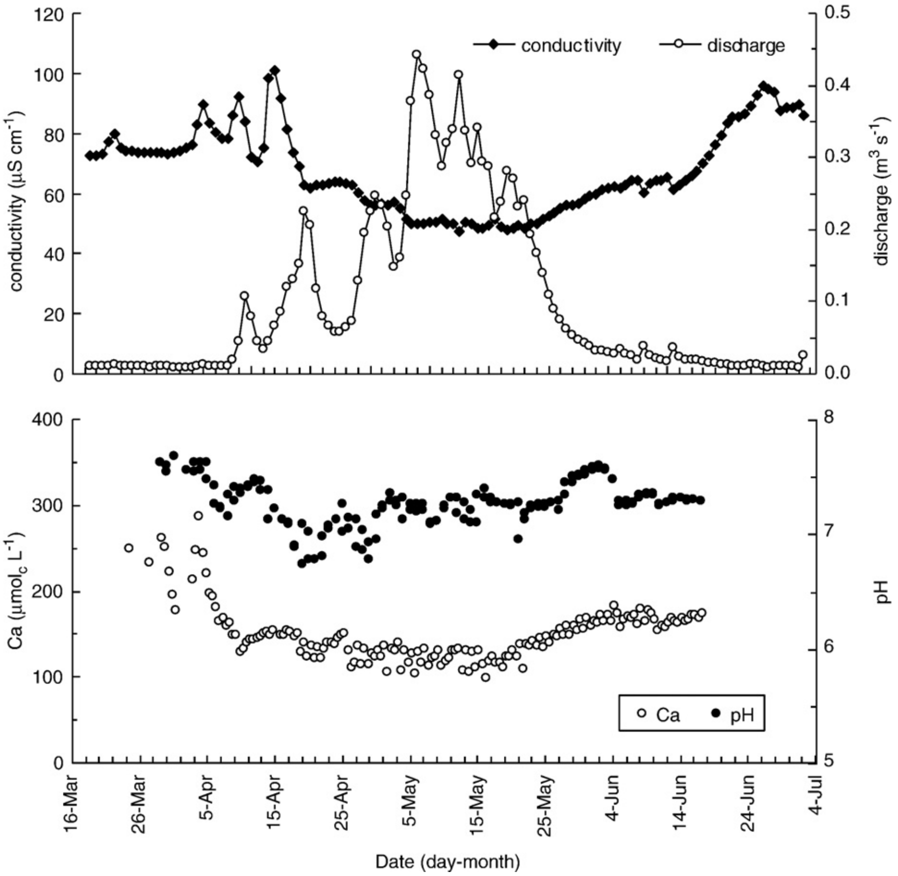

Fig. 3. Temporal change of stream discharge, electric conductivity (upper graph), pH and calcium concentrations (lower graph) in stream water during snowmelt period in 1997 (created and partly modified from Shibata et al., 2002), collected in the M-1 experimental watershed of Hokkaido University's Uryu Experimental forest located in northern Japan.

2001, 2003). Christopher et al. (2008b) conducted reciprocal transplants of surface soil for field incubation between northwestern (with dense snowpack and unfrozen soil) and eastern (with less snowpack and frozen soil) Hokkaido. The net nitrogen mineralization in surface soil transplanted from the unfrozen area with dense snowpack was enhanced by the freezing, suggesting that the freezing of soil increased the production and/or availability of labile organic nitrogen from microbial biomass and fine roots.

Long-term analyses of meteorological data have indicated that winter climate in NE Asia has changed towards warmer temperatures and less snowfall (Jhun and Lee, 2004; Hosaka et al., 2005; Ishizaka, 2004; Hirota et al., 2006; Suzuki, 2006). Less snowfall will decrease the heat insulation by snowpacks and can lead to lowered microbial activity under colder soil temperature, as shown by various freeze–thaw studies such as Campbell et al. (1971). Although lowered microbial activity under thinner snowpacks might be expected to lead to a slowed turnover of nitrogen and carbon in soil and hence a reduced nutrient leaching, experimental evidence from the manipulation studies conducted in Japan suggests that enhanced freeze–thaw cycles under thinner snowpacks result in higher leaching rates. Studies by Yanai et al. (2004) and Christopher et al. (2008b) have suggested that freeze–thaw cycles, particularly in early and late winter, increase the pools of nitrogen and carbon from microbial biomass and fine roots resulting in elevated nitrate and DOC mobilization during snowmelt.

In the analyses of long-term and large-scale inventories of atmospheric deposition in Hokkaido, Noguchi et al. (2001, 2007) found that 31–50% of sulfate and 11–17% of nitrate were transported from China. They also reported that the fluxes and concentrations of non-sea salt (nss) sulfate and nitrate in wet deposition in the northernmost part of Hokkaido have recently increased from 9.2 (1991–1998) to 12.6 (1998–2003) mmol m^{-2} y^{-1} for nss sulfate and 7.8 (1991–1998) to 11.5 (1998–2003) mmol m^{-2} y^{-1} for nss nitrate, respectively. Long-term monitoring of precipitation and stream chemistry of Japanese watersheds, complemented with event samplings, will be essential for obtaining a mechanistic understanding of watershed hydro-biogeochemical responses to concurrent changes in atmospheric deposition and climate change (Ohte et al., 2001b; Nakahara et al., 2009).

4. Effects of summer monsoon rainfalls on watershed biogeochemical processes and water quality in Lake Soyang Watershed, Korea

4.1. Changing patterns of the summer monsoon and land use in Lake Soyang Watershed, Korea

Under a strong influence of the East Asian summer monsoon, over one half of the annual rainfall in Korea occurs from July through August (Choi et al., 2008). In Lake Soyang Watershed (LSW) summer precipitation from June through August averaged 786 mm over the last four decades (1968–2007), comprising 60.4% of average annual precipitation of 1303 mm (Korea Meteorological Organization, Chucheon station data). Usually several typhoons pass through Korea in the summer, accompanied by heavy rainfall often exceeding 100 mm day^{-1} (Yang, 2007). A few of these rainfall events can generate a substantial portion of the annual runoff. In contrast, base stream flow contributes a relatively small portion to the annual transport of water and nutrients. For moderate rain events (<30 mm daily rainfall) during the dry season, there is little increase in discharge.

Recent trends of precipitation and temperature in Korea have been linked to regional climate change (Chung et al., 2004). A recent analysis of precipitation data from 61 weather stations in Korea from 1973 to 2007 showed significant increases for two summer months, June and July (Choi et al., 2008; Fig. 4). This is consistent with longer-term patterns in summer precipitation identified for 14 weather stations in South Korea over the period of 1955–2007 (Choi et al., 2009). However, the total number of days with precipitation has remained similar, resulting in an increase of rain intensity. In the analysis conducted by Choi et al. (2008) annual precipitation of very wet days (above 95th percentile of rainy days) and extremely wet days (above 99th percentile) has significantly increased in Chucheon near LSW. Even though air temperature has increased with a potential increase in evapotranspiration, these higher precipitation inputs have resulted in greater surface runoff (Yang, 2007). Such increases can result in greater exports of both particulate and dissolved materials from the watershed.

The rate of agricultural production per unit area has been sustained at a high level in Korea due to the shortage of arable flat lands. The export of nutrients, especially phosphorus, from agricultural lands is higher than for other countries, with ~85% of phosphorus derived from fertilizer and animal manure (Kim et al., 2001). Discharge of phosphorus associated with sediments from agricultural areas is a major cause of eutrophication and deterioration of water quality in downstream reservoirs in Korea (Kim et al., 2001). Given the recent trend of increasing summer rain intensity and runoff, nutrient discharge from agricultural areas is likely to increase.

4.2. Watershed biogeochemical responses to summer monsoon rainfalls and implications for water quality in LSW

Lake Soyang, which is the deepest and largest reservoir in South Korea, is located in a sparsely populated mountainous region in the northernmost province of South Korea. The watershed has only a few small rural towns with 42,000 residents and few sources of industrial sewage. The watershed has an area of 2700 km^2, with ~90% of the watershed covered with forests and only 4.8% used for agriculture. Nevertheless, the agricultural fields export large amounts of nutrients due to the high rate of fertilizer application and pen-type livestock farming, causing eutrophication of the reservoir. The main inflowing tributary, the Soyang River, contributes 90% of the total water into Lake Soyang.

Although forests are the dominant land use type in LSW, there are two "hot spots" of agricultural pollution, with substantial impacts on the trophic state of Lake Soyang and downstream reservoirs. One of the hot spots is the watershed of the Mandae Stream, which flows into the Inbuk River, a major tributary of the Soyang River. The watershed of the Mandae Stream is a bowl-shaped basin in which intensive agriculture has dramatically transformed the otherwise heavily forested landscape into a basin with expanding arable lands and remaining forests along the mountain ridges. The area of the Mandae watershed is 61.8 km^2 and 16% of the watershed is cultivated area where mostly vegetables are grown. The second "hot spot" of nonpoint source pollution is the watershed of the Jawoon Stream where runoff waters from highland fields are very turbid due to high sediment loads derived from intensive tilling on the steep hillslopes (Jung et al., 2009).

Since 1990 the concentrations of nutrients and suspended solids have been monitored at a lake inlet into which the Soyang River flows. Over the monitoring period, the discharge rate of the Soyang River varied markedly from <10 to >4000 $m^3 s^{-1}$, with the large increases in water flow associated with summer rainfall events. The increase of particulate matter concentrations in rivers has often been linked to high flow rates (Hill, 1993; Kim et al., 1995; Creed et al., 1996; Campbell et al., 2000). In the Soyang River, the concentrations of both phosphorus and suspended sediments were usually higher during major summer rainfall events (Fig. 5), resulting in significant positive relationships between flow rates and either TP concentrations or turbidity ($r^2 = 0.20$ for TP and 0.22 for turbidity; both at $P<0.005$). Concentrations of dissolved phosphorus were also usually higher during monsoon rainfall events corresponding to the increase of flow rate in the Soyang River, although the proportion of dissolved phosphorus in total phosphorus is smaller in high flow periods (Kim and Kim, 2004).

During monsoon rainfall events increased turbidity in response to high discharge rates often concurred with increases in the concentration of total phosphorus (TP) from less than 10 to over than 1000 mg P m^{-3} (Fig. 5), with a strongly positive correlation between turbidity and TP concentrations as a consequence ($r = 0.85$, $P<0.005$). This strong correlation between turbidity and TP implies that phosphorus and suspended sediments might have the same source (i.e. agricultural fields) or transport routes. During the monsoon period increases in turbidity exceeding 1000 NTU (Nephelometric Turbidity Unit) have been more common over the recent years, reflecting the concurrent effects of more frequent heavy rainfalls and rapid expansion of intensive farming in erosion-susceptible areas.

The highest concentrations of TP and suspended solid (SS) in the Soyang River occur during the early phase of increasing discharge. Particulate phosphorus is the predominant form of transported phosphorus, although soluble reactive phosphorus concentrations

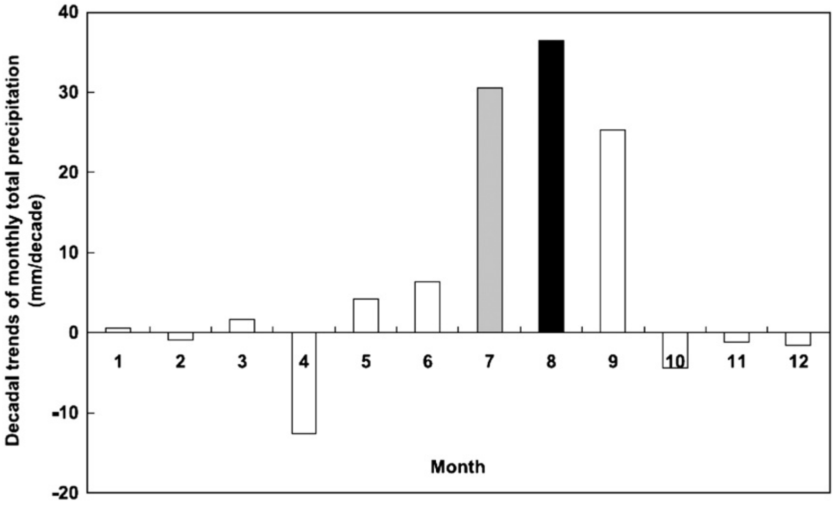

Fig. 4. Linear trends of monthly precipitation averaged across 61 weather stations in South Korea over the period of 1973–2007 (data presented in mm $decade^{-1}$). Gray and black bars indicate the linear trend at 90% and 95% significance level, respectively.
(Source: Choi et al., 2008).

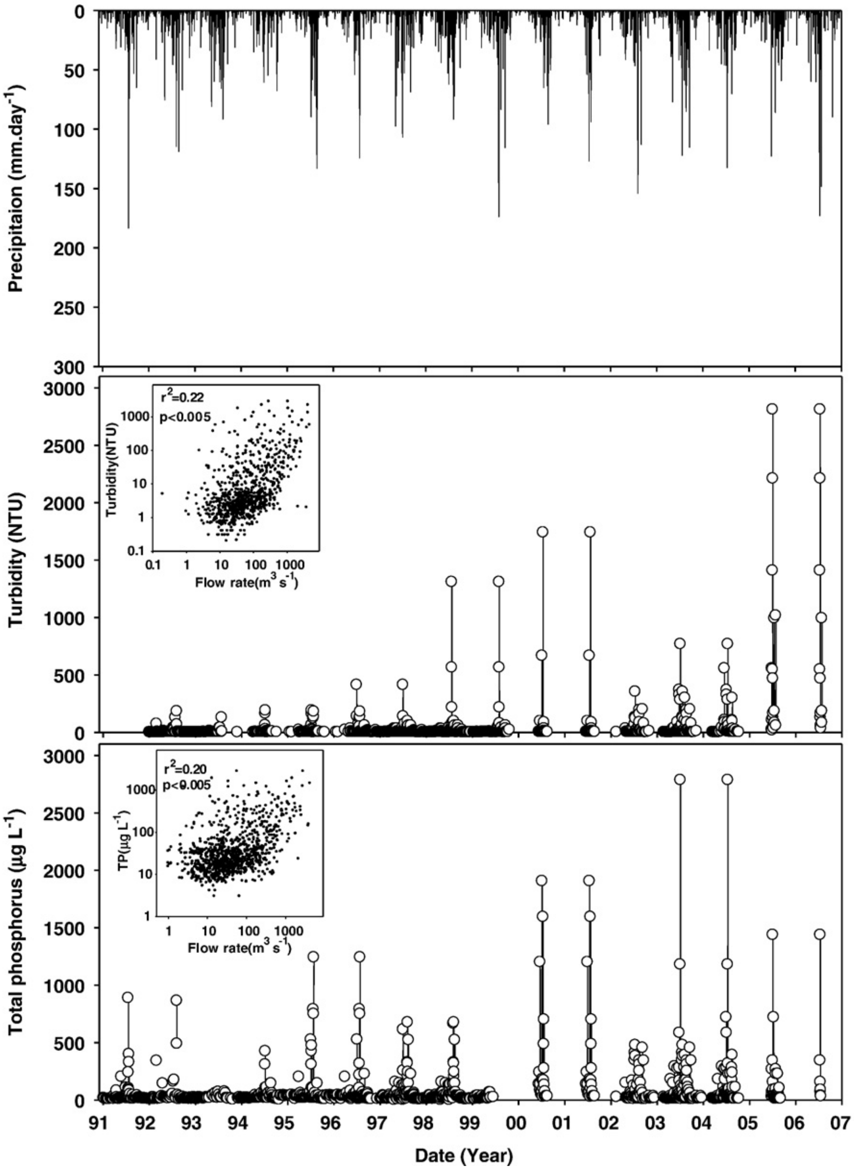

Fig. 5. Long-term variations in daily precipitations, turbidity and TP concentrations in the Soyang River from 1990 to 2006 (modified from Kim and Jung, 2007). Turbidity and TP concentrations were measured daily on wet days and otherwise weekly. Insets show the relationships between flow rates and turbidity ($r^2 = 0.22$, $P < 0.005$) or TP concentrations ($r^2 = 0.20$, $P < 0.005$).

are also high in storm runoff. Several episodes account for most of the annual phosphorus loading (Fig. 5). Concentrations of total nitrogen (TN) showed less variation (0.9 to 3.8 g N m^{-3}) than phosphorus, with 90% of TN in the form of NO_3^-. At a small forested watershed in Japan, Ide et al. (2007) also observed smaller fluctuations in dissolved TN concentrations compared to particulate P during precipitation events. Larger variations in TP compared to TN are likely associated with the large increases in suspended particulate P during storm events.

The water quality in the Soyang River showed much higher concentrations of phosphorus, nitrogen, and suspended sediments than Lake Soyang and other nearby rivers (Kim and Jung, 2007). The volume-weighted mean of TP was 0.20–0.24 g P m^{-3}, which was much higher than the threshold level of eutrophication, contributing to the increase of phosphorus in summer in Lake Soyang and its downstream reaches. Suspended sediments in the range of 200–530 g m^{-3} contributed to the deterioration of stream habitats and also resulted in high turbidity in Lake Soyang. Because the thermal stratification is very stable in Lake Soyang and the inflowing storm runoff water is colder than the epilimnion, turbid storm runoff flows into the metalimnion of the reservoir, forming an intermediate layer of high turbidity and phosphorus content (Kim et al., 2000). Following extreme rainfall events in July 2006 turbidity in metalimnion remained high for an extended period until November (Kim and Jung, 2007; Fig. 6). The turbid water in the intermediate layer was eventually discharged from the reservoir through an outlet located at the middle of the dam, transporting turbidity downstream.

In highland agricultural fields that have been identified as a primary source of sediment and phosphorus export in LSW, the application of organic compost or manure and chemical fertilizer has increased markedly over the last couple of decades. In Korea, the application rate of chemical fertilizer has increased from 230 kg ha^{-1} yr^{-1} in 1980 to 450 kg ha^{-1} yr^{-1} in the mid 1990s and remained at the similar level thereafter (Shim, 1998; Statistics of Korea). In LSW pen-type livestock farming using imported animal feed has rapidly been replacing traditional cattle farms on pastures, adding large amounts of nutrients to streams draining agricultural fields (Kim et al., 2001). Top soils in highland croplands are annually replenished with soils excavated from nearby mountain slopes to improve the texture and fertility of arable soils after repeated erosion during heavy rainfalls. Eroded soils from

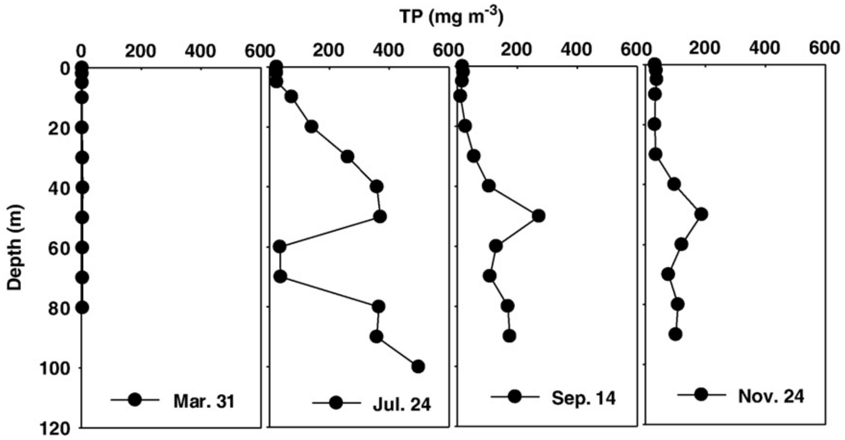

Fig. 6. Vertical profiles of phosphorus concentrations in Lake Soyang, showing fluctuations in phosphorus concentrations at the middle layer before and after summer monsoon in 2006 (modified from Kim and Jung, 2007).

these highland fields might play a key role in transporting phosphorus and other nutrients from croplands and cattle farms in LSW (Kim and Jung, 2007).

Since the amount and intensity of summer monsoon rainfalls are projected to increase in the northern part of South Korea (Im et al., 2008), future changes in monsoon rainfall patterns will play a more important role in both discharge and chemical export from LSW. Without considerable management and restoration efforts, intensive tilling activities in highland vegetable fields will render steep hillslopes more vulnerable to erosion during rain events, as observed in recurrent events of turbid waters in LSW and other big reservoirs in Korea over the recent years (An et al., 2006; Kim and Jung, 2007). These marked increases in turbidity during the monsoon period are posing a major challenge in the management of water quality of both reservoirs and rivers, including detrimental effects on aquatic organisms and sediment overloads in drinking water facilities.

5. Coupled effects of climate variability and acid deposition in Chongquing, China

5.1. Changing climate and its potential impacts on surface water quality in China

During the last 50 years the annual mean temperature has increased by 0.022 °C yr^{-1} in China (Ren et al., 2005). Over the same period, the annual mean precipitation has decreased by 50–120 mm in east of Northeast China, central and south of North China, and east of Southwest China, but increased by 60–130 mm in the north of Northeast China, west of Southwest China, and large areas in Northwest China, East China and Southeast China (Ren et al., 2005). Regional climate models predict that the temperature will increase by 2.2–3.0 °C at the end of the 21st century (Gao et al., 2003).

As in many other countries, more attention in China has been paid to the effects of climate change on the amount of water rather than water quality, despite the long-term economic and environmental impacts of water quality deterioration (Ren, 2008). Land use change and associated increases in pollutants will have more marked effects on water quality in many parts of China due to urbanization and intensive agricultural activities (Liu and Chen, 2006).

In arid northwestern China, increasing temperature has accelerated the melting of glaciers. This, combined with increased precipitation, has resulted in an increase of runoff and a decrease of salinity and hardness of some inland waters (Fan et al., 2005; Dang et al., 2006; Xu et al., 2006; Arkin et al., 2007; Bian, 2007; Chen et al., 2008). The Tarim River in the southern part of the Xinjiang Uygur Autonomous Region has an area of 1.02 M km^2 and is the longest inland river in China. The increasing annual mean temperature by ~0.02 °C yr^{-1} over the past 40 years has accelerated melting of glaciers in the Tarim River Basin, which is 0.2 M km^2 in area and represents 41.3% of total glacier volume of China (Wang et al., 2003). As a result, the total annual runoff of four main source tributaries, which are mainly fed by melting water of the glaciers, has increased from 21.6 B m^3/yr in 1957–1959 to 25.9 B m^3/yr in 2000–2005 by about 20% (Arkin et al., 2007), and the average salinity has accordingly decreased by about 15% (Chen et al., 2008). Although this enhanced melting is causing a temporary increase in discharge, this increase will not be sustained over the long-term as glaciers become depleted resulting in critical loss of water resources.

Warming-induced increases in glacier melting and runoff have not always led to the improvement of water quality of the impacted rivers, especially along the main stem and lower reaches downstream of large cities. Both salinity and hardness have recently been increasing in some rivers across northwestern China, including the Irtysh River, Ili River, Heihe River, Manas River, and Golmud River (Tan et al., 2001; Fan et al., 2005; Chen et al., 2006), and major lakes (Sun et al., 2005). Increases in salinity have been observed along the lower reaches of the Tarim River (Liu and Chen, 2006; Chen et al., 2008). This has been attributed to anthropogenic influences such as rapidly increasing water usage and irrigation return flow, together with increased evaporation and prolonged droughts as a consequence of regional climate change.

Linkages between climate change and water quality are currently less obvious in the warmer and humid parts of China, which are more populated and more economically developed compared to the arid Northwest. In eastern China, however, rapid expansion of urban and industrial areas has escalated water problems with concomitant increases in water demand and decreases in water quality. In these regions local human activities play a major role in water quality with climate change being a potential secondary effect. For the Yellow River, the second longest river in China, the increases in solute concentrations in the middle reaches have been attributed to the direct effects from local human populations (Zhang and Chen, 2000). However, the increased precipitation in southeastern China, especially in the Yangtze River basin, may be contributing to a reduction of solute concentrations but an overall increase in solute export (Xia et al., 2000; Zhang and Chen, 2000).

5.2. Implications of changing precipitation for acid deposition effects on forested watersheds in southwestern China

The issue of “acid rain”, with a particular focus on soil and water acidification as major consequences, has gained considerable attention in China over the last decade (e.g., Hao et al., 1998, 2001), because emissions of acid rain precursors (SO_2 and NO_x) have been increasing markedly. Although water acidification has not been found widely in China (Larssen et al., 2004), a continuously decreasing trend of pH has been observed in the Yangtze River (Xia et al., 2000; Zhang and Chen, 2000). There are important interactions between climate change and acidic deposition including the suggestion that recovery of surface waters from acidification may be delayed by climate change due to reductions in the total amount of precipitation in the summer, or more frequent storms in the winter (Aherne et al., 2006; Evans et al., 2007; Laudon, 2007).

The effects of acidic deposition on five forested watersheds in southern China and southwestern China were monitored from 2001 to 2004 in a Sino-Norwegian collaboration project entitled "Integrated Monitoring Program on Acidification of Chinese Terrestrial Systems" (IMPACTS) (Larssen et al., 2004, 2006). The monitored watersheds include Tieshanping in Chongqing province, Luchongguan and Leigongshan in Guizhou province, Caijiatang in Hunan province, and Liuxihe in Guangdong province. At these sites intensive monitoring was conducted including precipitation, throughfall, soil water, and surface water chemistry. Among the five IMPACTS sites, the Tieshanping watershed in Chongquing province in southwestern China was most severely impacted by acidic deposition. At this forest dominated by Masson pine trees, severe defoliation has been observed for 40–50% of the area and tree mortality reached 6% (Larssen et al., 2004). The monthly mean pH in the stream water decreased from 2001 to 2004, with values in the later years being below 5.0, pointing to a possibility of intensifying acidification at this watershed (Fig. 7).

High amounts of precipitation at Tieshanping in summer and autumn were associated with lower sulfate concentrations in precipitation (Fig. 7). The seasons with higher precipitation also coincided with lower SO_4^2 concentrations in soil water. The seasonal patterns of Ca^{2+} concentrations were similar as those of sulfate (Fig. 7). The pH values in throughfall were lower in winter and spring compared to summer and autumn (Fig. 7). The average pH of surface waters was ~5.0 and much higher than that of soil waters (~4.0), suggesting the importance of acid consumption as water percolated through the mineral soil and bedrock of this watershed. Unlike SO_4^2 and Ca^{2+}, high precipitation in summer and autumn did not always lead to lower concentrations of total inorganic nitrogen (TIN, mostly NO_3^-) in soil water (Fig. 7), presumably due to accelerated N mineralization in the soil under hot and moist conditions in the subtropical region. Similarly, high NO_3^- concentrations in soils and surface waters have also been found in some Japanese watersheds during the summer, a period with high temperatures and high precipitation (Ohrui and Mitchell, 1997; Ohte et al., 2001a,b).

Throughfall results suggest substantial amounts of sulfur dry deposition with SO_4^{2-} concentrations in throughfall being five-fold greater than in wet only deposition (Fig. 8). Other studies have indicated that throughfall SO_4^{2-} fluxes in forest ecosystems provide good estimates of total sulfur deposition (Lovett et al., 1992). The nine-fold increase in Ca^{2+} flux between wet deposition and throughfall would be the combined effect of canopy leaching and dry deposition (Lindberg and Lovett, 1992). The relative increases for N solutes were substantially lower at around two times suggesting the possible importance of N retention in the canopy as has been found in other studies (Lovett and Lindberg, 1993).

Highest total deposition was found in wet years due to greater inputs of wet deposition (Fig. 8). Although soil was a sink of the inputs SO_4^{2-} and NO_3^- via throughfall with a relatively small export in stream water throughout the monitoring period, the export of SO_4^{2-} and NO_3^- in stream waters draining the watershed was higher in wet years (2002 and 2004) than dry years (2001 and 2003) (Fig. 8). Higher runoff in wetter years might have led to a larger export of SO_4^{2-} from soil sources. There was also higher mobilization of N solutes from the soil in wet years, some of which can be attributed to enhanced N mineralization from litterfall (Chen and Mulder, 2007a,b). In relatively dry years, when mineralization rates were reduced, more N was retained in the soil (Fig. 8). Although the pH of surface waters showed a generally decreasing trend over the entire measurement period, pH values were even more depressed during the wet years of 2002 and 2004 than during the dry years of 2001 and 2003 (Fig. 7). In Chongquing province the annual mean precipitation has decreased by about 10% over the past 50 years and is projected to continue to decrease in the future (Gao et al., 2003; Ren et al., 2005). This changing rainfall pattern, together with the monitoring results, suggests that future changes in moisture regime including precipitation inputs can affect forest S and N dynamics, with potential changes in acid neutralizing capacity of headwater streams in this region as a consequence.

6. Summary and implications for future research

In contrast to relatively uniform patterns of climatic warming, the variability in both summer and winter precipitation patterns has been increasing across NE Asia over recent decades and this variability is predicted to accelerate in the coming decades (Chung et al., 2004; Im et al., 2008). Although it is difficult to predict accurately the temporal and spatial patterns of precipitation for NE Asia, major changes in the water cycle in NE Asia will likely lead to more frequent occurrence of extreme monsoon rainfalls, as predicted for other parts of the world (Knapp et al., 2008). For those regions particularly in northern latitudes with substantial snowfall, climatic warming is predicted to reduce snowfalls and/or snow depth via increased winter minimum temperatures (Im et al., 2008).

As shown for the Hokkaido region in Japan, winter snowpack dynamics and soil freeze–thaw cycles play a pivotal role in the release of solutes from steep hillslopes in northern Japan. In this region more extreme freeze–thaw cycles under thinner snowpacks and earlier snowmelt, are predicted to increase the mobilization of solutes from soil and into headwater streams. This mobilization would affect the availability of nutrients in soils and surface waters, but would not have a substantial impact on either chronic or episodic acidification due to the relatively high buffering capacity of soils compared to acid sensitive areas of North America and Europe (Shibata et al., 2002).

In South Korea increasing intensity of monsoon rainfalls during recent decades has contributed to the deterioration of water quality in many reservoirs and rivers. The export of sediments and nutrients from these erosion-prone mountainous watersheds during storm events has been exasperated by the rapid expansion of intensive farming and other forms of deforestation on steep terrain. It is predicted that South Korea will exhibit a marked increase in the occurrence of siltation, impacting rivers and reservoirs that provide potable water supplies for large metropolitan populations. The large dams that have been built along the major rivers of South Korea also affect material transport, and the transformation of nutrients and pollutants. Marked increases in the export of carbon and nutrients from mountainous watersheds have also been observed in Japan and Taiwan during recent typhoons (Zhang et al., 2007b; Goldsmith et al., 2008). Understanding the effects of these extreme hydrologic events is needed for understanding how climate change is affecting key watershed processes including the fate of eroded sediments, nutrients and pollutants.

Recently in many parts of southern China, lower annual precipitation amounts have been combined with large year-to-year variations. This variability in precipitation has a substantial influence on year-to-year variations in acidity and nutrient fluxes in soils and stream waters of forested watersheds subjected to increasing levels of acidic deposition. Long-term monitoring studies in Europe and North America have suggested that climate change can delay the recovery of acidified forest ecosystems through complex temperature- or

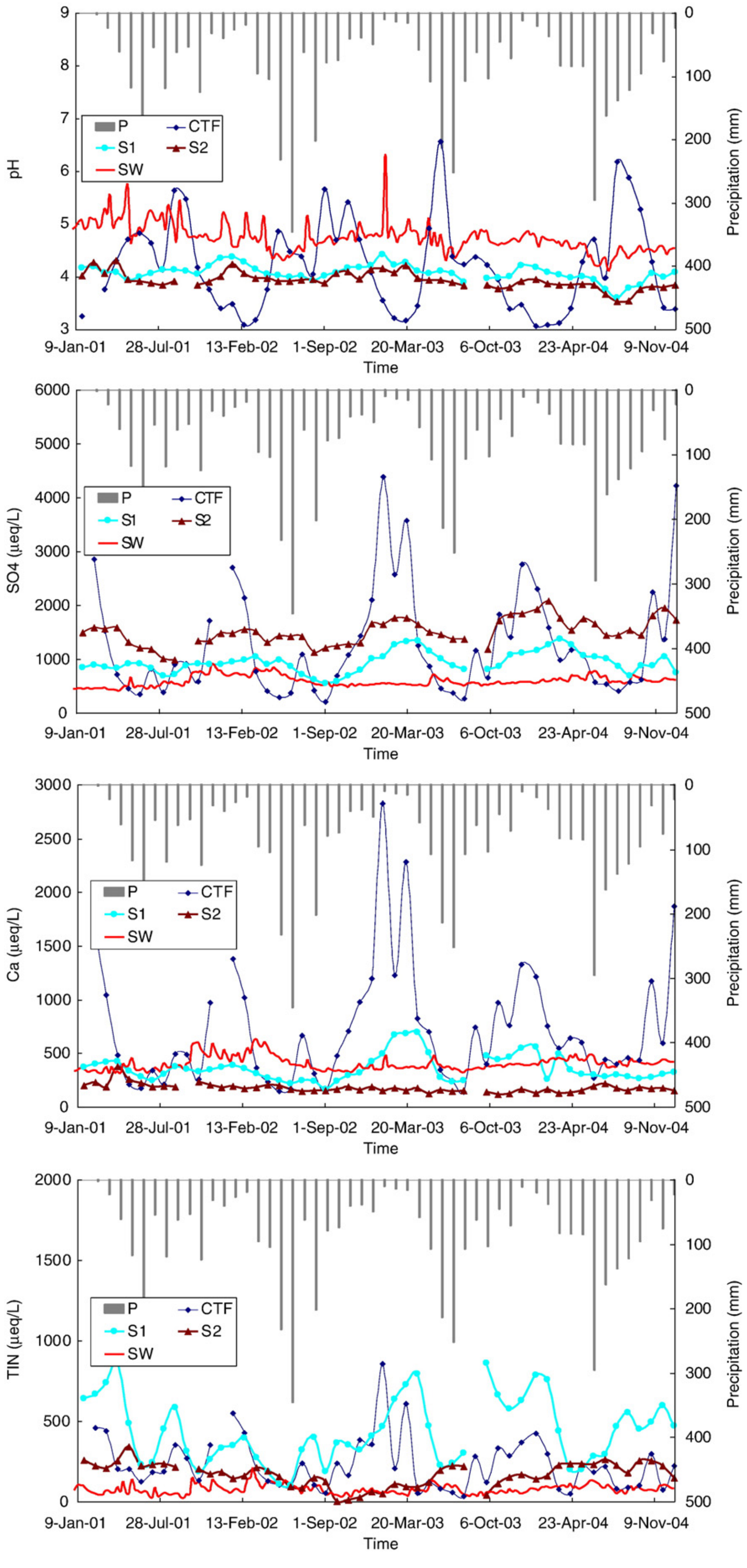

Fig. 7. Monthly variation of precipitation (P) and SO_4^{2-}, Ca^{2+}, TIN, and pH in throughfall (CTF), soil water (S1 for upper layer 0–15 cm and S2 lower layer 15–30 cm) and surface water (SW) (unpublished data).

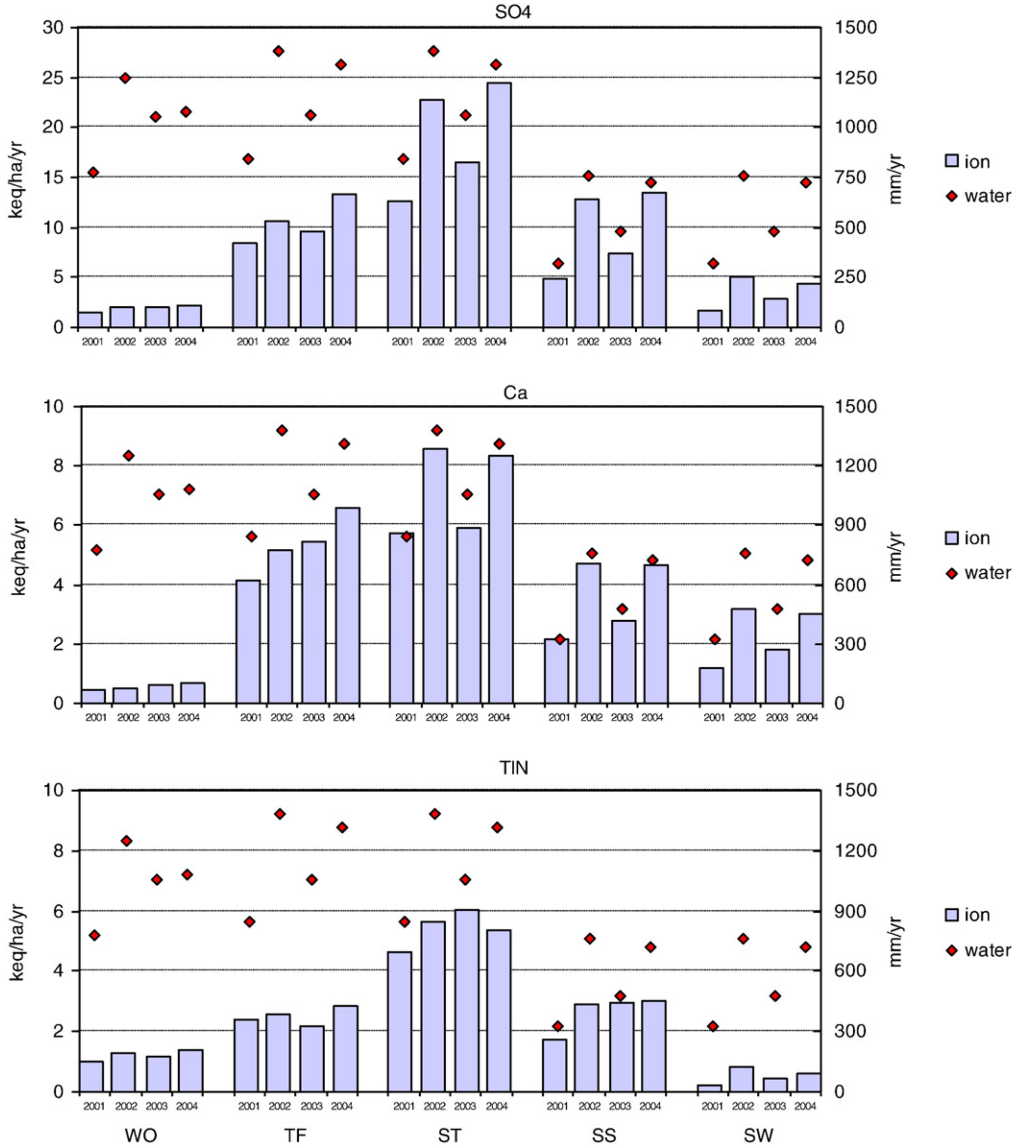

Fig. 8. SO_4^{2-}, Ca^{2+}, and TIN fluxes in wet deposition (WO), throughfall (TF), soil water (ST and SS) and stream water (SW) (unpublished data).

precipitation-mediated processes (Murdoch et al., 1998; Park et al., 2005; Laudon, 2007). These changes in precipitation amounts and patterns have important implications for the future changes in acidification and nutrient release especially in those watersheds already severely affected by acidic deposition. However, the complex interactions between climate, atmospheric deposition, and watershed biogeochemical processes present a major challenge in separating out the relative influence of each of these factors. Hence future studies need to include long-term monitoring combined with more detailed process-level studies and modeling efforts that together will help provide better predictions in the changes of water quality to concomitant changes in acidic deposition and climate.

Strong seasonal variability inherent in the monsoon climate and unique geomorphological characteristics associated with mountainous terrain in NE Asia necessitate different research emphasis than studies in Europe and North America. For example, the typhoons of NE Asia have a marked influence on biogeochemical processes and water quality and require new study approaches that are applicable to these extreme wind and precipitation events. The development of sensor techniques that are operative under these extreme conditions is a major need for research in this region. Understanding climate effects on the land-water biogeochemical linkages in this region is also essential in predicting changes in water quality and ecological processes of aquatic systems in response to more variable and extreme rainfall patterns. Future studies should include an evaluation of changes in organic matter deposition and CO_2 out gassing in aquatic systems as a consequence of changes in hydrologic export of terrestrially derived carbon and nutrients under altered hydrologic regimes (Dean and Gorham, 1998; Battin et al., 2008; Williams et al., 2008).

Another important issue is the synergy and feedbacks affecting watershed biogeochemical processes among the primary large-scale environmental factors: climate change, land use, and atmospheric deposition (Williams et al., 2008). There is an increasing interest in the interactive effects of changing land use and atmospheric deposition on the responses of the sediment, nutrients and other contaminants to altered hydrologic regimes under a changing climate. Although a warmer and wetter climate has been predicted to increase nutrient leaching from many watersheds under intense land use change in NE Asia, the lack of integrated approaches still poses a major challenge for quantitative prediction of expected environmental impacts such as eutrophication of downstream lakes and reservoirs. As observed in Korea, agricultural expansion following deforestation on steep hillslopes increases the vulnerability of soil erosion in response to an intensifying monsoon rainfall regime. In an ongoing research project comparing the export of sediments and nutrients from forested and agricultural watersheds during storm events, concentrations of suspended sediments in the streams draining arable lands on deforested hillslopes have been higher by one order of magnitude than the natural level at the forest stream (Park, unpublished data). Mitigation of predictable deleterious consequences of this interaction between climate change and land use requires novel land management strategies, such as alternative agricultural practices and reforestation of erosion-susceptible arable lands on steep slopes.

Understanding these synergies and feedbacks between climate change and other environmental factors is central to a more accurate prediction of water quality changes in response to future climate changes in NE Asia where rapid economic development is accelerating both land use change and the emissions of air pollutants. A combined approach of linking model predictions with field monitoring of biogeochemical processes and environmental controls will facilitate the prediction of watershed biogeochemical processes to multiple stresses. Another challenge is the spatial interpolation or extrapolation of the results from case studies from local to national and regional scales. Spatial patterns of climate change and other environmental factors show considerable diversity across NE Asia. Comparisons of results from both within and among East Asian regions are needed to evaluate climate response in the context of other changes in the landscape. The further development of integrated tools combining modeling, GIS spatial analysis and remote sensing for watershed biogeochemical studies in NE Asia is a critical need for aiding watershed management and evaluation of climate-related risks to water quality.

Acknowledgements

This work was supported by the Asia-Pacific Network for Global Change Research (ARCP2007-11NMY-Park) through START (global change SysTem for Analysis Research and Training). Institute of Forest Science, Kangwon National University, organized the workshop presenting the three case studies. Additional support to JH Park was provided by Korea Forest Service via ‘Forest Science & Technology Project’ (S21080L010) and a National Research Foundation of Korea (NRF) grant (ERC 2009-0093460). The case study in Japan was conducted in the Uryu Experimental Forest of Hokkaido University as part of the Japan Long-Term Ecological Research Network core-site, North Hokkaido Experimental Forests. Hideaki Shibata's work was partly supported by the Research Institute for Humanity and Nature (Project No. 5-2). The case study in China is part of the IMPACTS project, supported by the Norwegian Agency for Development Cooperation, coordinated by the Chinese Research Academy of Environmental Sciences, Beijing and Norwegian Institute of Water Research.

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