Geochemistry of the dissolved loads during high-flow season of rivers in the southeastern coastal region of China: anthropogenic impact on chemical weathering and carbon sequestration

Wenjing Liu1,2,3, Zhifang Xu1,2,3, Huiguo Sun1,3, Tong Zhao1,3, Chao Shi3, and Taoze Liu4

1Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China
2CAS Center for Excellence in Life and Paleoenvironment, Beijing, 100044, China
3University of Chinese Academy of Sciences, Beijing 100049, China
4State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, Guizhou 550002, China

Correspondence: Zhifang Xu (zfxu@mail.iggcas.ac.cn)

Received: 27 February 2018 – Discussion started: 20 March 2018
Revised: 4 July 2018 – Accepted: 27 July 2018 – Published: 22 August 2018

Abstract. The southeastern coastal region is one of the most developed and populated areas in China. Meanwhile, it has been severely impacted by acid rain over many years. The chemical compositions and carbon isotope compositions of dissolved inorganic carbon (δ13C\text{DIC}) in river water in the high-flow season were investigated to estimate the chemical weathering and associated atmospheric CO2 consumption rates as well as the acid-deposition disturbance. Mass balance calculations indicated that the dissolved loads of major rivers in the Southeast Coastal River Basin (SECRB) were contributed to by atmospheric (14.3 %, 6.6 %–23.4 %), anthropogenic (15.7 %, 0 %–41.1 %), silicate weathering (39.5 %, 17.8 %–74.0 %) and carbonate weathering inputs (30.6 %, 3.9 %–62.0 %). The silicate and carbonate chemical weathering rates for these river watersheds were 14.2–35.8 and 1.8–52.1 t km–2 a–1, respectively. The associated mean CO2 consumption rate by silicate weathering for the whole SECRB was 191 × 1012 mol km–2 a–1. The chemical and δ13C\text{DIC} evidence indicated that sulfuric and nitric acid (mainly from acid deposition) were significantly involved in the chemical weathering of rocks. There was an overestimation of CO2 consumption at 0.19 × 1012 g C a–1 if sulfuric and nitric acid were ignored, which accounted for about 33.6 % of the total CO2 consumption by silicate weathering in the SECRB. This study quantitatively highlights the role of acid deposition in chemical weathering, suggesting that the anthropogenic impact should be seriously considered in estimations of chemical weathering and associated CO2 consumption.

1 Introduction

Chemical weathering of rocks is the key process that links geochemical cycling of solid earth to the atmosphere and ocean. It provides nutrients to terrestrial and marine ecosystems and regulates the level of atmospheric CO2. As a net sink of atmospheric CO2 on geologic timescales, estimations of silicate chemical weathering rates and the controlling factors are important issues that are related to long-term global climate change (e.g., Raymo and Ruddiman, 1992; Négrel et al. 1993; Berner and Caldeira, 1997; Gaillardet et al., 1999; Kump et al., 2000; Amiotte-Suchet et al., 2003; Oliva et al., 2003; Hartmann et al., 2009; Moon et al., 2014). As an important component in the Earth’s critical zone (U.S. National Research Council Committee, 2001), rivers serve as integrators of various natural and anthropogenic processes and products in a basin, and as carriers, transporting the weathering products from the continent to the ocean. Therefore, the chemical compositions of river water are widely used to evaluate chemical weathering and associated CO2 consumption rates at catchment and/or continental scale and to examine their controlling factors (e.g., Edmond et al., 1995; Gisla-
W. Liu et al.: Geochemistry of the dissolved loads during high-flow season of rivers

The southeastern coastal region of China is one of the most developed and populated areas of this country, dominated by Mesozoic magmatic rocks (mainly granite and volcanic rocks) in lithology. Meanwhile, the southeast coastal area has become one of the three major acid-rain areas in China since the beginning of 1990s (Larssen and Carmichael, 2000). It is seriously impacted by acid rain, with a volume-weighted mean value of pH lower than 4.5 for many years (Wang et al., 2000; Larssen and Carmichael, 2000; Zhao, 2004; Han et al., 2006; Larssen et al., 2006; M. Zhang et al., 2007; Huang et al., 2008; Xu et al., 2011). Therefore, it is an ideal area for evaluating silicate weathering and the associated acid-rain effects. In previous work, we have recognized and discussed the importance of sulfuric acid on rock weathering and associated CO₂ consumption in the Qiantang river basin in this area (W. Liu et al., 2016). However, it is difficult to infer the anthropogenic impact on chemical weathering and CO₂ consumption in the whole southeastern coastal area from the case study of a single river basin, because of the variations on lithology, basin scale, runoff and anthropogenic condition in the large acid-deposition-affected area.

In this study, the chemical and carbon isotope composition of river water in this area were first systematically investigated in order to (i) decipher the different sources of solutes and to quantify their contributions to the dissolved loads, (ii) calculate silicate weathering and associated CO₂ consumption rates, and (iii) evaluate the effects of acid deposition on rock weathering and CO₂ consumption flux in the whole of the SECRB.

2 Natural setting of study area

The southeastern coastal region of China, where the landscape is dominated by mountainous and hilly terrain, lacks the conditions for developing large rivers. The rivers in this region have dominantly small- and medium-sized drainage areas due to the topographic limitation. Only five rivers in this region have lengths over 200 km and drainage areas over 10 000 km², and they are the Qiantangjiang (Qiantang) and the Oujiang (Ou) in Zhejiang province, the Minjiang (Min) and the Jialongjiang (Jiulong) in Fujian province and the Hanjiang (Han) in Guangdong province, from north to south (Fig. 1). rivers in this region generally flow eastward or southward and finally inject into the East China Sea or the South China Sea (Fig. 1), and they are collectively named Southeast Coastal Rivers (SECRs).

The Southeast Coastal River Basin (SECRB) is in the warm and humid subtropical oceanic monsoon climate. The mean annual temperature and precipitation are 17–21 °C and 1400–2000 mm, respectively. The precipitation mainly happens during May to September, and the lowest and highest temperatures often occur in January and July. This area is one of the most developed areas in China, with a population more than 190 million (mean density of ~ 470 individuals km⁻²),
Figure 1. Sketch map showing the lithology, sampling locations and sample number of the SECR drainage basin, and regional rainwater pH ranges are shown in the sketch map in the upper-left (modified from Zhou and Li, 2000; Shu et al., 2009; Xu et al., 2016, rainwater acidity distribution of China mainland is from State Environmental Protection Administration of China). (1) Shaoxing–Jiangshan fault zone, (2) Zhenghe–Dapu fault zone and (3) Changle–Nanao fault zone. The figure was created by CorelDraw software version 17.1.

but the population is mainly concentrated in the coastal urban areas. The vegetation coverage of these river basins is higher than 60%, mainly subtropical evergreen-deciduous broadleaf forest and mostly distributed in mountainous areas. Cultivated land, industries and cities are mainly located in the plain areas and lower reaches of these rivers.

Geologically, three regional-scale fault zones are distributed across the SECRB region (Fig. 1). They are the sub-EW-trending Shaoxing–Jiangshan fault zone, the NE-trending Zhenghe–Dapu fault zone and the NE-trending Changle–Nanao fault zone (Shu et al., 2009). These fault zones dominate the direction of the mountains ridgelines and drainages, as well as the formation of the basins and bay. The Zhenghe–Dapu fault zone is a boundary line of the Caledonian uplift belt and Hercynian–Indonesian depression zone. Mesozoic magmatic rocks are widespread in the southeastern coastal region with a total outcrop area at about 240 000 km$^2$. Over 90% of the Mesozoic magmatic rocks are granitoids (granites and rhyolites), with a minor amount of basalt (Zhou and Li, 2000; Zhou et al., 2006; Bai et al., 2014). These crust-derived granitic rocks are mainly formed in the Yanshanian stage and may have been related to multiple collision events.
between Cathaysia and Yangtze blocks and the Pacific plate (Zhou and Li, 2000; Xu et al., 2016). Among the major river basins, the proportions of magmatic rocks outcrop are about 36 % in the Qiantang catchment, over 80 % in the Ou, the Jiaxi and the Jin catchments and around 60 % in the Min, the Jiulong, the Han and the Rong catchments (Shi, 2014). The overlying Quaternary sediment in this area is composed of brown-yellow siltstones but is rarely developed. The oldest basement complex is composed of metamorphic rocks of greenschist and amphibolite facies. Sedimentary rocks are categorised into two types: one is mainly composed of red clastic rocks which cover more than 40 000 km² in the area and the other occurs as interlayers within volcanic formations, including varicolored mudstones and sandstones. They are mainly distributed on the west of Zhenghe–Dapu fault zone (FJBGMR, 1985; ZJBGMR, 1989; Shu et al., 2009).

3 Sampling and analytical method

A total of 121 water samples were collected from the major rivers and their tributaries in the SECRB in July of 2010 in the high-flow period (sample number and locations are shown in Fig. 1). For the river low-reach samples, the sampling sites were selected as far as possible from the tide-impacted area and the sampling was conducted during low-tide period (based on the daily tidal time, http://ocean.cnss.com.cn/, last access: 31 July 2010) on the sampling day. Besides, the salinity of the waters was checked by a salinometer (WS202, China) before sampling in the field. In addition, water chemistry data were double checked to make sure that the river samples were not contaminated by seawater. Water samples were collected in the middle channel of the rivers from bridges or ferries or directly from the center of some shallow streams. Temperature (T), pH and electrical conductivity (EC) were measured in the field with a portable EC/pH meter (YSI-6920, USA). All of the water samples for chemical analysis were filtered in field through a 0.22 µm Milli-Q 18.2 MΩ2 water. Alkalinity was determined by phenolphthalein and methyl orange end-point titration with dilute HCl within 12 h after sampling. The HCl consumption volumes for phenolphthalein and methyl orange end-point titration were used to calculate the HCO$_3^-$.

Cations (Na$^+$, K$^+$, Ca$^{2+}$ and Mg$^{2+}$) were determined using an inductively coupled plasma atomic emission spectrometer (ICP-AES) (IRIS Intrepid II XSP, USA). Anions (Cl$^-$, F$^-$, NO$_3^-$ and SO$_4^{2-}$) were analyzed by ionic chromatography (IC) (Dionex Corporation, USA). Dissolved silica was determined by spectrophotometry with the molybdate blue method. Reagent and procedural blanks were measured parallel to the sample treatment, and the calibration curve was evaluated by quality control standards before, during and after the analyses of each batch of samples. Measurement reproducibility was determined by duplicated sample and standards, which showed ±3 % precision for the cations and ±5 % for the anions. Analyzing water chemistry was conducted in the hydrochemistry and environmental laboratory at the Institute of Geology and Geophysics, Chinese Academy of Sciences.

Samples for a carbon isotopic ratio ($\delta^{13}$C) of dissolved inorganic carbon (DIC) measurements were collected in 150 mL glass bottles with air-tight caps and preserved with HgCl$_2$ to prevent biological activity. The samples were refrigerated until analysis. For the $\delta^{13}$C measurements, the filtered samples were injected into glass bottles with phosphoric acid. The CO$_2$ was then extracted and cryogenically purified using a high vacuum line. $\delta^{13}$C isotopic ratios were analyzed on Finnigen MAT-252 stable isotope mass spectrometer at the State Key Laboratory of Environmental Geochemistry, Chinese Academy of Sciences. The results are expressed with reference to VPDB (Vienna Pee Dee Belemnite) as follows:

$$\delta^{13}C = \left(\frac{\text{[^{13}C/^{12}C]_{sample}}}{\text{[^{13}C/^{12}C]_{standard}}} - 1\right) \times 1000.$$  

The $\delta^{13}$C measurement has a precision of 0.1 ‰. A number of duplicate samples were measured, and the results show that the differences were less than the range of measurement accuracy.

4 Results

The major parameter and ion concentrations of samples are given in Table 1. The pH values of water samples ranged from 6.50 to 8.24, with an average of 7.23. Total dissolved solids (TDSs) of water samples varied from 35.3 to 205 mg L$^{-1}$, with an average of 75.2 mg L$^{-1}$. Compared with the major rivers in China, the average TDS was significantly lower than the Changjiang (224 mg L$^{-1}$), the Huanghe (557 mg L$^{-1}$), the North Han River in South Korea (75.5 mg L$^{-1}$), the Xishui (190 mg L$^{-1}$), the Amur (63 mg L$^{-1}$) and the Amur in northern China (70 mg L$^{-1}$), the Amur in central China (101 mg L$^{-1}$), the Qiantang (190 mg L$^{-1}$), and the Ou (70 mg L$^{-1}$), the Ou had the lowest TDS value (averaging at 48.8 mg L$^{-1}$).

Major ion compositions are shown in the cation and anion ternary diagrams (Fig. 2a and b). In comparison with rivers

Biogeosciences, 15, 4955–4971, 2018

www.biogeosciences.net/15/4955/2018/
Table 1. Chemical and carbon isotopic compositions of river water in the Southeast Coastal River Basin (SECRB) of China.

| Rivers | Sample number | Date | EC (μS cm⁻¹) | Na⁺ (μM) | K⁺ (μM) | Ca²⁺ (μM) | Mg²⁺ (μM) | F⁻ (μM) | Cl⁻ (μM) | NO₃⁻ (μM) | HCO₃⁻ (μM) | SO₄²⁻ (μM) | TZ (μg L⁻¹) | NRB (%) | δ¹³C (‰) | TDS (mg L⁻¹) |
|--------|---------------|------|-------------|----------|---------|-----------|-----------|--------|----------|-----------|-----------|-------------|-------------|----------|---------|----------|-------------|
| Quanztu | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Cao'e | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Feiyun | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Ling | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Cu'o | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Ou | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Fuyun | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Jiaori | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Huoting | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |
| Ao | | | 708-11 | 4.92 | 28.28 | 190 | 347 | 197 | 106 | 473 | 12.0 | 303 | 62.6 | 147 | 1130 | 148 | 1703 | 1789 | –5.0 | 19.0 | 144 |

W. Liu et al.: Geochemistry of the dissolved loads during high-flow season of rivers 4959

Biogeosciences, 15, 4955–4971, 2018

www.biogeosciences.net/15/4955/2018/
Table 1. Continued.

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Sample number</th>
<th>Date</th>
<th>T (℃)</th>
<th>EC (μS cm⁻¹)</th>
<th>Na⁺ (μmol L⁻¹)</th>
<th>K⁺ (μmol L⁻¹)</th>
<th>Mg²⁺ (μmol L⁻¹)</th>
<th>Ca²⁺ (μmol L⁻¹)</th>
<th>F⁻ (μmol L⁻¹)</th>
<th>Cl⁻ (μmol L⁻¹)</th>
<th>NO₃⁻ (μmol L⁻¹)</th>
<th>SO₄²⁻ (μmol L⁻¹)</th>
<th>HCO₃⁻ (μmol L⁻¹)</th>
<th>TEC (μmol L⁻¹)</th>
<th>NICB (%)</th>
<th>δ¹³C (%)</th>
<th>TDS (mg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jin</td>
<td>120</td>
<td>07-30-10</td>
<td>6.96</td>
<td>30.62</td>
<td>94</td>
<td>509</td>
<td>103</td>
<td>56.1</td>
<td>213</td>
<td>78.5</td>
<td>82.3</td>
<td>379</td>
<td>222</td>
<td>1150</td>
<td>1133</td>
<td>0.5</td>
<td>23.0</td>
</tr>
<tr>
<td>Huangang</td>
<td>120</td>
<td>07-30-10</td>
<td>6.77</td>
<td>28.19</td>
<td>65</td>
<td>132</td>
<td>93.6</td>
<td>52.7</td>
<td>60.6</td>
<td>78.8</td>
<td>75.4</td>
<td>333</td>
<td>243</td>
<td>627</td>
<td>630</td>
<td>2.8</td>
<td>23.1</td>
</tr>
</tbody>
</table>

Continued.

(e.g., the Wujiang and Xijiang) draining carbonate-rock-dominated areas (Han and Liu, 2004; Xu and Liu, 2010), these rivers in the SECRB had distinctly higher proportions of Na⁺, K⁺ and dissolved SiO₂. As shown in the Fig. 2, most samples had high Na⁺ and K⁺ proportions, with an average of more than 50% (in μmol L⁻¹) of the total cations, except for samples from the Qiantang. The concentrations of Na⁺ and K⁺ ranged from 43.5 to 555 μmol L⁻¹ and 42.9 to 233 μmol L⁻¹, with average values of 152 and 98 μmol L⁻¹, respectively. The concentrations of dissolved SiO₂ ranged from 98.5 to 370 μmol L⁻¹, with an average of 212 μmol L⁻¹, respectively. Ca²⁺ and Mg²⁺ accounted for about 38% and 11.6% of the total cation concentrations. HCO₃⁻ was the dominant anion, with concentrations ranging from 139 to 1822 μmol L⁻¹.

On average, it comprised 60.6% (36%–84.6%) of total anions on a molar unit basis, followed by SO₄²⁻ (14.6%), Cl⁻ (13.1%) and NO₃⁻ (11.8%). The major ionic compositions indicate that the water chemistry of these rivers in the SECRB is controlled by silicate weathering. Meanwhile, it is also influenced by carbonate weathering, especially for the Qiantang catchment.

The δ¹³C of dissolved inorganic carbon in the rivers of the SECRB are also given in Table 1. The δ¹³C of the water samples showed a wide range, from −11.0‰ to −24.3‰ (averaging at −19.4‰), and with a majority of samples falling into the range of −15‰ to −23‰. The values are comparable to rivers draining the Deccan Traps (Das et al., 2005).

Biogeosciences, 15, 4955–4971, 2018
www.biogeosciences.net/15/4955/2018/
5 Discussion

The dissolved solids in river water are commonly from atmospheric and anthropogenic inputs and weathering of rocks within the drainage basin. It is necessary to quantify the contribution of different sources to the dissolved loads before deriving chemical weathering rates and associated CO$_2$ consumption.

5.1 Atmospheric and anthropogenic inputs

To evaluate atmospheric inputs to river water, chloride is the most commonly used reference. Generally, water samples that have the lowest Cl$^-$ concentrations are employed to correct the proportion of atmospheric inputs in a river system (Négrel et al., 1993; Gaillardet et al., 1997; Viers et al., 2001; Xu and Liu, 2007). In pristine areas, the concentration of Cl$^-$ in river water is assumed to be entirely derived from the atmosphere, provided that the contribution of evaporites is negligible (e.g., Stallard and Edmond, 1981; Négrel et al., 1993). In the SECRB, the lowest Cl$^-$ concentration was mainly found in the headwater of each river. According to the geologic setting, no salt-bearing rocks were found in these headwater areas (FJBGRM, 1985; ZJBGMR, 1989). In addition, these areas are mainly mountainous and sparsely populated. Therefore, we assumed that the lowest Cl$^-$ concentration of samples from the headwater of each major river came entirely from the atmosphere.

The proportion of atmosphere-derived ions in river water can then be calculated by the element/Cl ratios of the rain. Chemical compositions of rain in the studied area have been reported at different sites, including Hangzhou, Jinhua, Nanping, Fuzhou and Xiamen (Zhao, 2004; M. Zhang et al., 2007; Huang et al., 2008; Cheng et al., 2011; Xu et al., 2011) (Fig. 1). The volume-weighted mean concentration of ions and Cl-normalized molar ratios are compiled in Table 2. Based on this procedure, 6.6%–23.4% (averaging 14.3%) of total dissolved cations in the major rivers of the SECRB originated from rain. Among the anions, SO$_4^{2-}$ and NO$_3^-$ in the rivers are mainly from the atmospheric input, averaging 73.2% for SO$_4^{2-}$ and 75.8% for NO$_3^-$, respectively.

As one of the most developed and populated areas in China, the chemistry of river water in the SECRB could be significantly impacted by anthropogenic inputs. Cl$^-$, NO$_3^-$ and SO$_4^{2-}$ are commonly associated with anthropogenic sources and have been used as tracers of anthropogenic inputs in watersheds. High concentrations of Cl$^-$, NO$_3^-$ and SO$_4^{2-}$ can be found in the lower reaches of rivers in the SECRB, and there is an obvious increase after it had flowed through plains and cities. This tendency indicates that the river water chemistry is affected by anthropogenic inputs while passing through the catchments. After correcting for the atmospheric contribution to river water, the following assumption is needed to quantitatively estimate the contributions of anthropogenic inputs, which is that Cl$^-$ originates from only atmospheric and anthropogenic inputs, and the excess of atmospheric Cl$^-$ is regarded to present anthropogenic inputs and is balanced by Na$^+$. 
5.2 Chemical weathering inputs

Water samples were plotted with Na-normalized molar ratios (Fig. 3). The values of the world’s major rivers (Gaillardet et al., 1999) are also shown in the figure. The best correlations between elemental ratios were observed for Ca\(^{2+}/\text{Na}^+\) vs. Mg\(^{2+}/\text{Na}^+\) \((R^2 = 0.95, n = 120)\) and Ca\(^{2+}/\text{Na}^+\) vs. HCO\(_3^-)/\text{Na}^+\) \((R^2 = 0.98, n = 120)\). The samples cluster on a mixing line, mainly between silicate and carbonate end-members, closer to the silicate end-member and show little evaporite contribution. This corresponds with the rock type distributions in the SECRB. In addition, all water samples have equivalent ratios of \((\text{Na}^+ + \text{K}^+)/\text{Cl}^-\) larger than one, indicating silicate weathering as the source of \(\text{Na}^+\) and \(\text{K}^+\) rather than dissolution of chloride evaporites.

The geochemical characteristics of the silicate and carbonate end-members can be deduced from the correlations between elemental ratios and referred to literature data for catchments with well-constrained lithology. After correction for atmospheric inputs, the Ca\(^{2+}/\text{Na}^+\), Mg\(^{2+}/\text{Na}^+\) and HCO\(_3^-)/\text{Na}^+\) of the river samples ranged from 0.31 to 30, 0.16 to 6.7 and 1.1 to 64.2, respectively. According to the geological setting (Fig. 1), there are some small rivers draining purely silicate areas in the SECR drainage basins. Based on the elemental ratios of these rivers, we assigned the silicate end-member for this study to Ca\(^{2+}/\text{Na}^+\) = 0.41 ± 0.10, Mg\(^{2+}/\text{Na}^+\) = 0.20 ± 0.03 and HCO\(_3^-)/\text{Na}^+\) = 1.7 ± 0.6. The ratio of \((\text{Ca}^{2+} + \text{Mg}^{2+})/\text{Na}^+\) for the silicate end-member was 0.61 ± 0.13, which is close to the silicate end-member for the world’s rivers ((\(\text{Ca}^{2+} + \text{Mg}^{2+})/\text{Na}^+\) = 0.59 ± 0.17, Gaillardet et al., 1999). Moreover, previous research has documented the chemical composition of rivers, such as the Amur and the Songhuajiang in northern China, the Xishui in the lower reaches of the Changjiang, and major rivers in South Korea (Moon et al., 2009; Liu et al., 2013; Wu et al., 2013; Ryu et al., 2008; Shin et al., 2011). These river basins have similar lithological settings to the study area, so we could further validate the composition of the silicate end-member with their results. Ca\(^{2+}/\text{Na}^+\) and Mg\(^{2+}/\text{Na}^+\) ratios of silicate end-member were reported for the Amur (0.36 and 0.22), the Songhuajiang (0.44 ± 0.23 and 0.16), the Xishui (0.6 ± 0.4 and 0.32 ± 0.18), the Han (0.55 and 0.21) and six major rivers in South Korea (0.48 and 0.20) in the studies above, well bracketing our estimation for the silicate end-member.

However, some samples show high concentrations of Ca\(^{2+}\), Mg\(^{2+}\) and HCO\(_3^-\), indicating the contribution of carbonate weathering. The samples from the upper reaches (Sample 12 and 13) of the Qiantang fall close to the carbonate end-member documented for the world’s major rivers (Gaillardet et al., 1999). In the present study, the Ca\(^{2+}/\text{Na}^+\) ratio of 0.41 ± 0.10 and Mg\(^{2+}/\text{Na}^+\) ratio of 0.20 ± 0.03 for the silicate end-member are used to calculate the contribution of Ca\(^{2+}\) and Mg\(^{2+}\) from silicate weathering. Finally, residual Ca\(^{2+}\) and Mg\(^{2+}\) are attributed to carbonate weathering.
Figure 3. Mixing diagrams using Na-normalized molar ratios: (a) \( \text{HCO}_3^-/\text{Na}^+ \) vs. \( \text{Ca}^{2+}/\text{Na}^+ \) and (b) \( \text{Mg}^{2+}/\text{Na}^+ \) vs. \( \text{Ca}^{2+}/\text{Na}^+ \) for the SECRB. The samples mainly cluster on a mixing line between silicate and carbonate end-members. Data for the world’s major rivers are also plotted (data from Gaillardet et al., 1999).

Figure 4. Calculated contributions (in %) from the different reservoirs to the total cationic load for major rivers and their main tributaries in the SECRB. The cationic loads are the sum of \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{Ca}^{2+} \) and \( \text{Mg}^{2+} \) from different reservoirs.

5.3 Chemical weathering rate in the SECRB

Based on the above assumption, a forward model is employed to quantify the relative contribution of the different sources to the rivers of the SECRB in this study (e.g., Galy and France-Lanord, 1999; Moon et al., 2007; Xu and Liu, 2007, 2010; Liu et al., 2013). The calculated contributions of different reservoirs to the total cationic load for major rivers and their main tributaries in the SECRB are presented in Fig. 4. On average, the dissolved cationic loads of the rivers in the study area originate dominantly from silicate weathering, which accounts for 39.5 % (17.8 %–74.0 %) of the total cationic loads in molar unit. Carbonate weathering and anthropogenic inputs account for 30.6 % (3.9 %–62.0 %) and 15.7 % (0 %–41.1 %), respectively. Contributions from silicate weathering are high in the Ou (55.6 %), the Huotong (54.5 %), the Ao (48.3 %) and the Min (48.3 %) river catchments, which are dominated by granitic and volcanic bedrock. In contrast, a high contribution from carbonate weathering is observed in the Qiantang (54.0 %), the Jin (52.2 %) and the Jiulong (44.8 %) river catchments.
The results manifest the lithology control on river solutes of drainage basin.

The chemical weathering rate of rocks is estimated by the mass budget, basin area and annual discharge (data from hydrological data of river basins in Zhejiang, Fujian province and Taiwan region, Annual Hydrological Report of 2010, P. R. China, Table 3), expressed in t km⁻² a⁻¹. The silicate weathering rate (SWR) is calculated using major cationic concentrations from silicate weathering and assuming that all dissolved SiO₂ is derived from silicate weathering (Xu and Liu, 2010), as in the equation below:

\[ \text{SWR} = ([\text{Na}]_{\text{sil}} + [\text{K}]_{\text{sil}} + [\text{Ca}]_{\text{sil}} + [\text{Mg}]_{\text{sil}} + [\text{SiO}_2]_{\text{LH}}) \times \text{discharge/area}. \] (2)

The assumption about Si could lead to an overestimation of the silicate weathering rate, as part of the silica may come from dissolution of biogenic materials rather than the weathering of silicate minerals (Millot et al., 2003; Shin et al., 2011). Thus, the cationic silicate weathering rates (Catₜₐₛ) were also calculated.

The carbonate weathering rate (CWR) is calculated based on the sum of Ca²⁺, Mg²⁺ and HCO₃⁻ from carbonate weathering, with half of the HCO₃⁻ coming from carbonate weathering and being derived from the atmosphere CO₂, as in the equation below:

\[ \text{CWR} = (\text{[Ca}]_{\text{carb}} + \text{[Mg]}_{\text{carb}} + 1/2\text{[HCO}_3^-\text{]}_{\text{carb}}) \times \text{discharge/area}. \] (3)

The chemical weathering rate and flux are calculated for major rivers and their main tributaries in the SECRB, and the results are shown in Table 3. Silicate and carbonate weathering fluxes of these rivers (SWF and CWF) range from 0.02 × 10⁶ to 1.80 × 10⁶ t a⁻¹ and from 0.004 × 10⁶ to 1.74 × 10⁶ t a⁻¹, respectively. Out of the rivers, the Min has the highest silicate weathering flux, and the Qiantang has the highest carbonate weathering flux. On the whole SECRB scale, 3.95 × 10⁶ and 4.09 × 10⁶ t a⁻¹ of dissolved solids originating from silicate and carbonate weathering, respectively, are transported into the East and South China seas by rivers in this region. Compared with the largest three river basins (the Changjiang, the Huanghe and the Xijiang) in China, the flux of silicate weathering calculated for the SECRB is lower than the Changjiang (9.5 × 10⁶ t a⁻¹, Gaillardet et al., 1999) but higher than the Huanghe (1.52 × 10⁶ t a⁻¹, Fan et al., 2014) and the Xijiang (2.62 × 10⁶ t a⁻¹, Xu and Liu, 2010).

The silicate and carbonate chemical weathering rates for these river watersheds were 14.2–35.8 and 1.8–52.1 t km⁻² a⁻¹, respectively. The total rock weathering rate (TWR) for the whole SECRB is 48.1 t km⁻² a⁻¹, higher than the world average (24 t km⁻² a⁻¹, Gaillardet et al., 1999). The cationic silicate weathering rates (Catₜₐₛ) range from 4.7 to 12.0 t km⁻² a⁻¹ for the river watersheds in the SECRB, averaging at 7.8 t km⁻² a⁻¹. Furthermore, a good linear correlation \( R^2 = 0.77, n = 28 \) is observed between the Catₜₐₛ and runoff (Fig. 5), indicating that silicate weathering rates are controlled by runoff as documented in previous research (e.g., Bluth and Kump, 1994; Gaillardet et al., 1999; Millot et al., 2002; Oliva et al., 2003; Wu et al., 2013; Pepin et al., 2013).

5.4 CO₂ consumption and the role of sulfuric acid

To calculate atmospheric CO₂ consumption by silicate weathering (CSW) and by carbonate weathering (CCW), a charge-balanced state between rock chemical weathering-derived alkalinity and cations was assumed (Roy et al., 1999).

\[ [\text{CO}_2]_{\text{CSW}} = \text{[Na]}_{\text{sil}} + [\text{K}]_{\text{sil}} + 2[\text{Ca}]_{\text{sil}} + 2[\text{Mg}]_{\text{sil}} \]

\[ [\text{CO}_2]_{\text{CCW}} = [\text{HCO}_3^-]_{\text{sil}} = [\text{Ca}]_{\text{carb}} + [\text{Mg}]_{\text{carb}} \] (5)

The calculated CO₂ consumption rates by chemical weathering for the rivers in SECRB are shown in Table 3. CO₂ consumption rates by carbonate and silicate weathering are from 17.9 to 53.0 mol km⁻² a⁻¹ (averaging at 206 × 10² mol km⁻² a⁻¹) and from 167 to 460 × 10² mol km⁻² a⁻¹ (averaging at 281 × 10² mol km⁻² a⁻¹) for major river catchments in the SECRB. The CO₂ consumption rates by silicate weathering in the SECRB are higher than that of major rivers in the world and China, such as the Amazon (174 × 10³ mol km⁻² a⁻¹, Mortatti and Probst, 2003), the Mississippi and the Mackenzie (66.8 and 34.1 × 10³ mol km⁻² a⁻¹, Gaillardet et al., 1999), the Changjiang (112 × 10³ mol km⁻² a⁻¹, Chetelat et al., 2008), the Huanghe (35 × 10³ mol km⁻² a⁻¹, Fan et al., 2014), the Xijiang (154 × 10³ mol km⁻² a⁻¹, Xu and Liu, 2010), the Longchuanjiang (173 × 10³ mol km⁻² a⁻¹, Li et al., 2011), the Mekong (191 × 10³ mol km⁻² a⁻¹, Li et al., 2014), three large rivers in eastern Tibet (103–121 × 10³ mol km⁻² a⁻¹, Noh et al., 2009), the Hanjiang in central China (120 × 10³ mol km⁻² a⁻¹, Li et al., 2009) and the Sonhuajiang in northeastern China...
<table>
<thead>
<tr>
<th>Major river</th>
<th>Location</th>
<th>Discharge (m$^3$ s$^{-1}$)</th>
<th>Area (10$^3$ km$^2$)</th>
<th>Rainfall (mm a$^{-1}$)</th>
<th>Anth.</th>
<th>Sil.</th>
<th>Carb.</th>
<th>Weathering rate (10$^{-1}$ km$^2$ a$^{-1}$)</th>
<th>Fluxes (10$^{-1}$ km$^2$ a$^{-1}$)</th>
<th>Weathering rate by silicate weathering (10$^{-3}$ km$^2$ a$^{-1}$)</th>
<th>Weathering rate by carbonate weathering (10$^{-3}$ km$^2$ a$^{-1}$)</th>
<th>Weathering rate by catenate weathering (10$^{-3}$ km$^2$ a$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qiantang</td>
<td></td>
<td>43.81</td>
<td>38.32</td>
<td>1143</td>
<td>43.81</td>
<td>38.32</td>
<td>1143</td>
<td>43.81</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Han</td>
<td></td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Liao</td>
<td></td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Fuhe</td>
<td></td>
<td>3.100</td>
<td>2.645</td>
<td>126.6</td>
<td>3.100</td>
<td>2.645</td>
<td>126.6</td>
<td>3.100</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Han</td>
<td></td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Liao</td>
<td></td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Fuhe</td>
<td></td>
<td>3.100</td>
<td>2.645</td>
<td>126.6</td>
<td>3.100</td>
<td>2.645</td>
<td>126.6</td>
<td>3.100</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Han</td>
<td></td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>3.100</td>
<td>89.9</td>
<td>2.736</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Liao</td>
<td></td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>3.043</td>
<td>85.8</td>
<td>2.630</td>
<td>8.3</td>
<td>27.3</td>
<td>0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Tributaries**

- **Qiantang**: Qiantang, Han, Liao, Fuhe
- **Han**: Han, Liao, Fuhe
- **Liao**: Liao, Fuhe

**Anth.** for anthropogenic, **Sil.** for silicate, and **Carb.** for carbonate.
(66.6 × 10⁹ mol km⁻² a⁻¹, Liu et al., 2013). The high CO₂ consumption rates by silicate weathering in the SECRB could be attributed to extensive distribution of silicate rocks, high runoff and favorable climatic conditions. The regional fluxes of CO₂ consumption by silicate and carbonate weathering are about 47.9 × 10⁹ mol a⁻¹ (0.57 × 10¹² g Ca⁻¹) and 41.9 × 10⁹ mol a⁻¹ (0.50 × 10¹² g Ca⁻¹) in the whole SECRB.

However, in addition to CO₂, the anthropogenic-sourced proton (e.g., H₂SO₄ and HNO₃) is well documented as significant proton providers in rock weathering processes (Galy and France-Lanord, 1999; Karim and Veizer, 2000; Yoshimura et al., 2001; Han and Liu, 2004; Spence and Telmer, 2005; Lerman and Wu, 2006; Xu and Liu, 2007, 2010; Perrin et al., 2008; Gandois et al., 2011). Sulfuric acid can be generated by natural oxidation of pyrite and anthropogenic emissions of SO₂ from coal combustion and subsequently dissolve carbonate and silicate minerals. The riverine nitrate in a watershed can be derived from atmospheric deposition, synthetic fertilizers, microbial nitrification, sewage and manure, etc. (e.g., Kendall, 1998). Although it is difficult to determine the sources of nitrate in river water, we can at least simply assume that nitrate from acid deposition is one of the proton providers. The consumption of CO₂ by rock weathering would be overestimated if H₂SO₄- and HNO₃-induced rock weathering was ignored (Spence and Telmer, 2005; Xu and Liu, 2010; Shin et al., 2011; Gandois et al., 2011). Thus, the role that anthropogenic-sourced protons play on chemical weathering is crucial for an accurate estimation of CO₂ consumption by rock weathering.

Rapid economic growth and increased energy needs have resulted in severe air pollution problems in many areas of China, indicated by high levels of mineral acids (predominately sulfuric) observed in precipitation (Larssen and Carmichael, 2000; Pan et al., 2013; L. Liu et al., 2016). The national SO₂ emissions in 2010 reached 30.8 Tg a⁻¹ (Lu et al., 2011). Previous studies documented that fossil fuel combustion accounts for the most sulfur deposition (∼77 %) in China (L. Liu et al., 2016). The wet deposition rate of nitrogen is the highest over central and southern China, with mean values of 20.2, 18.2 and 25.8 kg N ha⁻¹ a⁻¹ in Zhejiang, Fujian and Guangdong provinces, respectively (Lu and Tian, 2007). Current sulfur and nitrogen depositions in the southeastern coastal region are still among the highest in China (Fang et al., 2013; Cui et al., 2014; L. Liu et al., 2016).

The involvement of protons originating from H₂SO₄ and HNO₃ in the river water can be illustrated by the stoichiometry between cations and anions, shown in Fig. 6. In the rivers of the SECRB, the sum of the cations released by silicate and carbonate weathering could not be balanced by HCO₃⁻ only (Fig. 6a), but were almost balanced by the sum of HCO₃⁻, SO₄²⁻ and NO₃⁻ (Fig. 6b). This implies that H₂CO₃, H₂SO₄ and HNO₃ are the potential erosion agents in chemical weathering in the SECRB. The δ¹³C values of the water samples showed a wide range, from −11.0 ‰ to −24.3 ‰, with an average of −19.4 ‰. The δ¹³C from soil is dominated by the relative contribution from C₃ and C₄ plants (Das et al., 2005). The studied areas have subtropical temperatures and humidity, and thus C₃ processes are dominant. The δ¹³C of soil CO₂ is derived primarily from δ¹³C of organic material, which typically has a value between −24 ‰ and −34 ‰, with an average of −28 ‰ (Faure, 1986). According to previous studies, the average value for C₃ trees and shrubs are from −24.4 ‰ to −30.5 ‰, and most of them are lower than −28 ‰ in southern China (Chen et al., 2005; Xiang, 2006; Dou et al., 2013). After accounting for the isotopic effect from the diffusion of CO₂ from soil, the resulted δ¹³C (from the terrestrial C₃ plant process) should be ∼−25 ‰ (Cerling et al., 1991). This mean DIC derived from silicate weathering by carbonic acid (100 % from soil CO₂) would yield a δ¹³C value of −25 ‰. Carbonate rocks are generally derived from marine systems and typically have a δ¹³C value close to zero (Das et al., 2005). Thus, the theoretical δ¹³C value of DIC derived from carbonate weathering by carbonic acid (50 % from soil CO₂ and 50 % from carbonate rocks) is −12.5 ‰. DIC derived from carbonate weathering by sulfuric acid are
Figure 7. (a) $\delta^{13}C_{\text{DIC}}$ vs. HCO$_3^-$/(Na$^+$ + K$^+$ + Ca$^{2+}$ + Mg$^{2+}$)$^*$ and (b) (SO$_4^{2-}$ + NO$_3^-$)/(Na$^+$ + K$^+$ + Ca$^{2+}$ + Mg$^{2+}$)$^*$ equivalent ratio in river water draining the SECRB ($^*$ noted concentrations corrected for atmospheric and anthropogenic inputs). The plots show that most water deviates from the three end-member mixing areas (carbonate weathering by carbonic acid and sulfuric/nitric acid and silicate weathering by carbonic acid).

all from carbonate rocks; thus the $\delta^{13}C$ of the DIC would be 0‰. Based on the above discussion, sources of riverine DIC from different end-members in the SECRB were plotted in Fig. 7. Most water samples drift away from the three end-member mixing areas (carbonate and silicate weathering by carbonic acid and carbonate weathering by sulfuric acid) and towards silicate weathering by sulfuric and nitric acid area, clearly illustrating the effect of the anthropogenic-sourced protons (sulfuric and nitric acid) on silicate weathering in the SECRB.

Considering the H$_2$SO$_4$ and HNO$_3$ effects on chemical weathering, CO$_2$ consumption by silicate weathering can be determined from the equation below (Moon et al., 2007; Ryu et al., 2008; Shin et al., 2011):

$$[\text{CO}_2]_{\text{SNSW}} = [\text{Na}]_{\text{sil}} + [\text{K}]_{\text{sil}} + 2[\text{Ca}]_{\text{sil}} + 2[\text{Mg}]_{\text{sil}}$$

$$- \gamma \times [\text{SO}_4^{2-} + \text{NO}_3^-]_{\text{atmos}},$$

where $\gamma$ is calculated by $\text{cation}_{\text{sil}} / (\text{cation}_{\text{sil}} + \text{cation}_{\text{carb}})$.

Based on the calculation in Sect. 5.1, SO$_4^{2-}$ and NO$_3^-$ in river water were mainly derived from atmospheric inputs. Assuming that SO$_4^{2-}$ and NO$_3^-$ in river water derived from atmospheric input (after correction for sea-salt contribution) are all from acid precipitation and considering H$_2$SO$_4$ and HNO$_3$ effects, CO$_2$ consumption rates by silicate weathering (SNSW) are estimated between 55 $\times$ 10$^3$ and 286 $\times$ 10$^3$ mol km$^{-2}$ a$^{-1}$ for major river watersheds in the SECRB. For the whole SECRB, the actual CO$_2$ consumption rate by silicate is 191 $\times$ 10$^3$ mol km$^{-2}$ a$^{-1}$ when the effect of H$_2$SO$_4$ and HNO$_3$ is considered. The flux of CO$_2$ consumption is overestimated by 16.1 $\times$ 10$^9$ mol a$^{-1}$ (0.19 $\times$ 10$^{12}$ g Ca$^{-1}$) due to the involvement of H$_2$SO$_4$ and HNO$_3$ from acid precipitation, accounting for approximately 33.6 % of the total CO$_2$ consumption flux by silicate weathering in the SECRB. It highlights the fact that the drawdown of atmospheric CO$_2$ by silicate weathering can be significantly overestimated if acid deposition is ignored in long-term perspectives. The result quantitatively shows that anthropogenic activities can significantly affect rock weathering and associated atmospheric CO$_2$ consumption. The quantification of this effect needs to be well evaluated in Asia and globally, taking into account current and future human activity.

It is noticeable that the chemical weathering and associated CO$_2$ consumption rates for the study area were calculated by the river water geochemistry of high-flow season. As a subtropical monsoon climate area, the river water of the southeastern coastal rivers is mainly recharged by rain, and the amount of precipitation in the high-flow season accounts for more than 70% of annual precipitation in the area. The processes in the low-flow season might be different to some extent. It is worth making further efforts to investigate the hydrological and temperature effects on weathering rate and flux, as well as evaluate the anthropogenic impact in different climate regimes and hydrology seasons.

6 Conclusions

River water in the southeastern coastal region of China is characterized by high proportions of Na$^+$, K$^+$ and dissolved SiO$_2$, indicating that the water chemistry of the rivers in the SECRB is mainly controlled by silicate weathering. The dissolved cationic loads of the rivers in the study area originate dominantly from silicate weathering, which accounts for approximately 39.5% (17.8%–74.0%) of the total cationic loads. Carbon-
ate weathering, atmospheric and anthropogenic inputs account for 30.6%, 14.3% and 15.7%, respectively. Meanwhile, more than 70% of $\text{SO}_4^{2-}$ and $\text{NO}_3^-$ in the river water is derived from atmospheric input. The chemical weathering rate of silicates and carbonates for the whole SECRB are estimated to be approximately 23.7 and 24.5 $\text{km}^{-2} \text{a}^{-1}$. About $8.04 \times 10^6 \text{t a}^{-1}$ of dissolved solids originating from rock weathering are transported into the East and South China seas by these rivers in the SECRB. With the assumption that all the protons involved in the weathering reaction are provided by carbonic acid, the CO$_2$ consumption rates by silicate and carbonate weathering are 287 and $251 \times 10^3 \text{mol km}^{-2} \text{a}^{-1}$, respectively. However, both water chemistry and carbon isotope data provide solid evidence that sulfuric and nitric acid from acid precipitation serve as significant agents during chemical weathering. Considering the effect of sulfuric and nitric acid, the CO$_2$ consumption rate by silicate weathering for the SECRB is $191 \times 10^3 \text{mol km}^{-2} \text{a}^{-1}$. Therefore, the CO$_2$ consumption flux would be overestimated by $16.1 \times 10^3 \text{mol a}^{-1} (0.19 \times 10^{12} \text{g C a}^{-1})$ in the SECRB if the effect of sulfuric and nitric acid is ignored. This work quantitatively illustrates that anthropogenic disturbance by acid precipitation has a profound impact on CO$_2$ sequestration by rock weathering.

Data availability. The data in this study have been presented in the tables of the article and can also be requested from the corresponding author.

Author contributions. WL and Z.X designed the study. WL., HS, TZ and CS carried out the study. WL, Z.X, HS and TL contributed to data treatment and calculations. WL and Z.X prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue “Human impacts on carbon fluxes in Asian river systems”. It is not associated with a conference.

Acknowledgements. This work was financially supported by the Strategic Priority Research Program of Chinese Academy of Sciences (grant nos. XDB26000000 and XDB15010405), and Natural Science Foundation of China (grant no. 41673020, 91747202, 41772380 and 41730857).

Edited by: V. V. S. S. Sarma
Reviewed by: Shouye Yang and two anonymous referees

References


Millot, R., Gaillardet, J., Dupré, B., and Allègre, C. J.: Northern latitude chemical weathering rates: clues from the Mackenzie


Xiang, L.: Study on Coupling between Water and Carbon of Artificial Forests Communities in Subtropical Southern China, Master Dissertation, Institute of Geographical Sciences and Natural