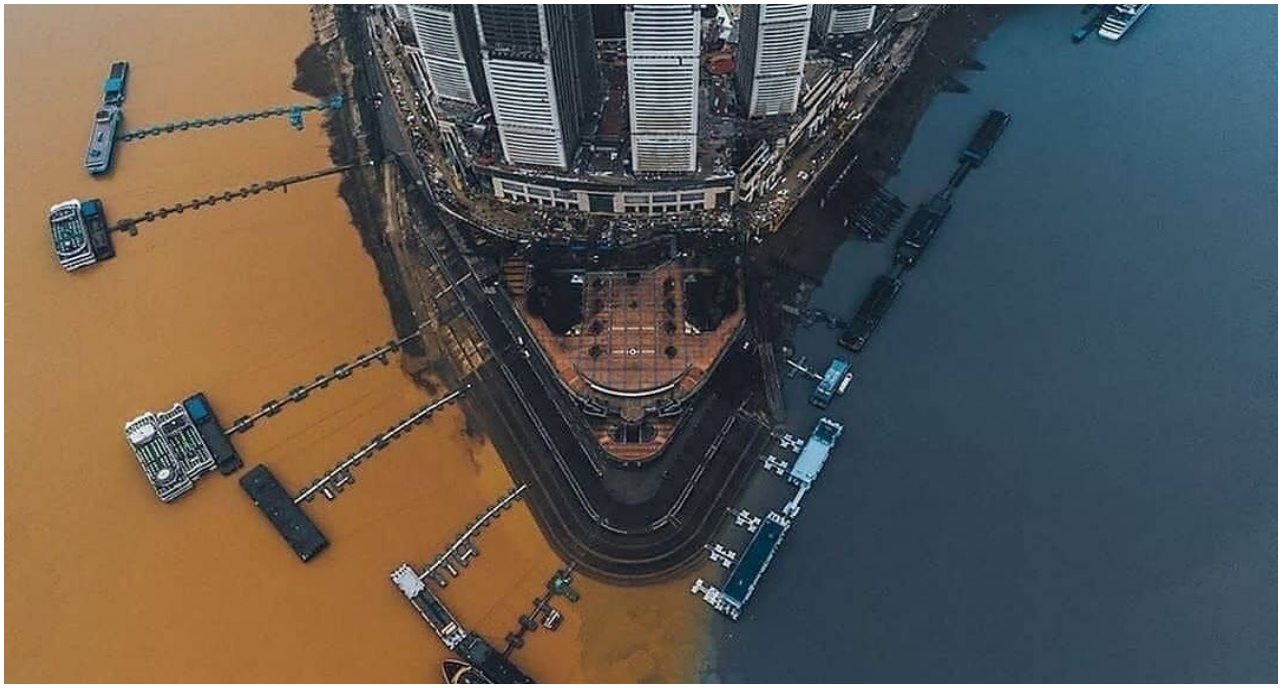
Surface Water Acidification from Air Pollution: Two Case Studies in China



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Executive Summary

Surface water acidification has had a huge impact on the ecology of Europe and America in the last century. In recent decades, this has started to influence China due to increasing acid pollution and acid deposition. The Jialing River and Taihu Lake, located in the three major acid rain zones, were chosen to be the areas for studying surface water acidification. Since acidification results from excessive acid inputs and high acidification sensitivity of the water body, the project focuses on acid gas emissions and the assessment of acidification sensitivity.

Air pollution in the Jialing River was historically high while the SO_2 emission has declined and NO_x emission has stabilized in recent years. Surface waters were not found being acidified in the two study areas according to the high pH values over the last 11 years. The probable reason why there was little evidence showing acidification could be the limestone formations in the watershed that provided sufficient buffer capacity to acidification. Another reason was the acid sensitivity maps that presented overall low sensitivity in the two regions with local sensitivity in the Jialing River, affecting the soil conditions but unlikely changing the water quality.

There is a great necessity for policymakers and environmental groups to take precautionary measures, referring to successful experiences from Europe. First and foremost, they are supposed to limit the emissions of SO_2 and NO_x from power plants and vehicles. In addition, a detailed acidification sensitivity map based on soil conditions, bedrock types, and land use types are helpful tools for identifying the likelihood of acidification. Moreover, strengthening monitoring by increasing monitoring sites and recording the quality and pH from wet and dry deposition could also help observe the acidification trend timely. It is believed that acidification would be effectively prevented if adequate mitigation measures are taken.

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1 Introduction

As is shown in figure 1, surface water acidification is a product of a series of processes. Acid deposition from polluted air is considered as the major factor that leads to surface water acidification (Van Breemen et al., 1984), because acidifying pollutants, such as sulphur oxide (SO_x) and nitrogen oxide (NO_x) produced by the burning of fossil fuels, could be easily dissolved in rainwater and accelerate the acidification in consequence (Ferrier et al., 2001). There is clear evidence that a large number of acid gas emissions will reduce the pH of rainwater the transformation to H_2SO_4 and HNO_3. These easily transported acid pollutants can affect large areas (Larssen, 2005). In addition, acidification also relates to various land use types and is influenced by other environmental factors such as buffer capacities of surrounding soils, weathering abilities of bedrocks, and vegetation coverage (Ye et al., 2002). In terms of the bedrock properties, rainfall that filters through granite and sandstone rocks usually has little buffer capacity. Therefore, water entering oligotrophic lakes is highly sensitive to acid rain inputs (Edmunds et al., 1986). There are other sources of acidification from different land-use activities, such as mining and chemical discharges. These impacts on water resources have are not specifically been addressed in this report.

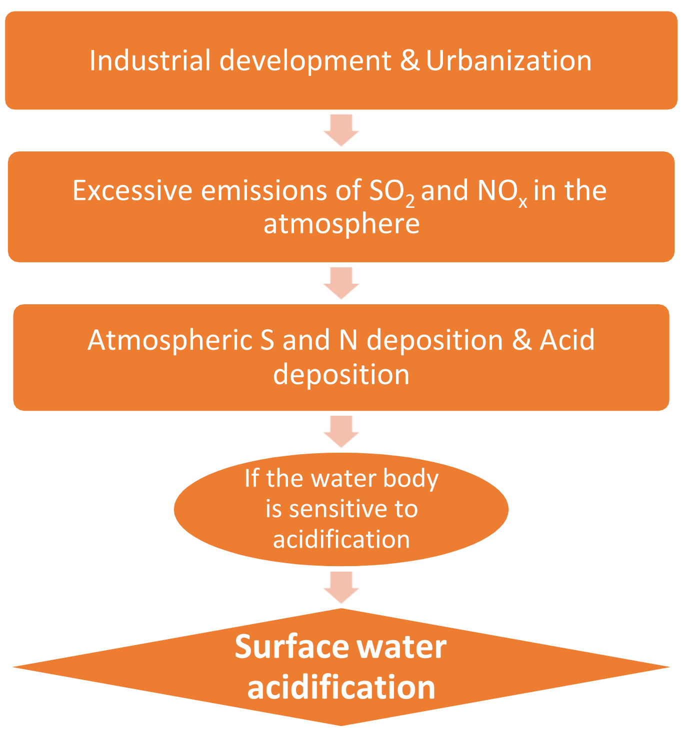


Figure 1. causes of surface water acidification

When the pH of a water body is below 6.5, surface water acidification occurs, including the acidification of lakes and rivers. If the pH keeps further falling below 5.5, a wide range of destructive consequences would develop (Hellstrom et al., 2012). A large number of aquatic organisms are highly sensitive to surface water acidification, particularly when pH keeps falling (Sullivan et al., 2000). For instance, when the pH ranges from 5.0-5.5, there will be a decrease in several important fish species and declines in species richness of phytoplankton and zooplankton. If the pH is less than 5.0, there would be a loss in most fish species, amphibians and plankton (Sullivan et al., 2000). Nevertheless, most surface waters have sufficient buffer capacity (alkalinity) to acidification that will slow down the acidification and the decrease in pH. As a result, sensitive aquatic species could be protected from the negative impacts of acidification due to the buffer capacity of surface water. Other environmental problems caused by surface water acidification include forest degradation (Fischer et al., 2007) and soil acidification (Matzner et al., 1995). Acidification may also be of concern for portable water use (Gee et al., 1989).

Since the 1950s, surface water acidification has become a major concern that influences the ecological environment in Europe and North America. Sweden, which suffered most from acidification, was found to have around 20,000 severely acidified lakes and large areas of acidified soils (Henrikson et al., 1995). In order to improve water quality, liming was implemented as a restoration strategy to counteract acidification in the 1980s. Functioning well in the short term, liming programmes have recovered 80-90% of surface waters from acidification in Sweden (Svenson et al., 1995). However, the long-term solution to acidification is the control of emissions of acid gas, so as to cut acid deposition (Henrikson et al., 1995). Evidence shows that surface water acidification has been reversed by the restriction of S and N emissions in Europe and North America since the 1980s (Skjelkvåle et al., 1999; Mitchell et al., 2011).

While there is a trend of recovery from surface water acidification in Europe and North America (Driscoll et al., 2001), the watersheds influenced by acid inputs continue to widen in China (Evans et al, 2001). The main cause is rapid development and increased industrialization, which resulted in heavy emission of SO_x and NO_x, speeding up the deposition of S and N (Larssen et al., 2006; Tang et al., 2010) and freshwater acidification. For example, the emission of SO_2 in China had increased from 12 Tg/year to 34 Tg/year from 1990 to 2005 (Xia et al., 2016), with only a slightly decreasing trend (by 14%) in recent years due to the emission abatement policies (Xia et al., 2016). There is also a rapid increase in NO_2 emissions from 1990- 2005, which increased from 12 Tg/year to 28 Tg/year (Yu et al., 2017). In addition to delivering acidic gas pollution, the acid deposition could accelerate surface water acidification as well.

A lot of concerns and efforts have been focused on acid rains and much less on water acidification. However, there are still some freshwater systems that might be sensitive to acidification (Zhen et al., 1991) and these may face the risk of acidification in the future. Feng (Feng et al., 1993) reported cases in some lakes at high elevation, which are low both low in pH and ANC. Although surface water acidification in China has not become a severe problem so far, acidification-sensitive areas may be stricken by accelerated acid gas inputs in the future. Therefore, it is of great importance to explore the trend of surface water acidification and acid air pollution in China with proactive measures to be taken.

2 Objectives

- Document the air-pollution history in the Jialing River watershed and Taihu lake area.
- Determine if these air pollution levels had an impact on the water quality of the pH and the acidification of the river and the lake.
- Identify the process and reasons why it is difficult to determine the impacts in the study areas.
- Develop a sensitive assessment for the two study areas that will determine how the water resources will respond if the air-pollution levels continue to increase.
- Review European literature that identify successful methods to assess areas that are sensitive to acid rain input and summarize some of the successful approaches that were used to rehabilitate acid impacted water resources.

3 Background

3.1 The Jialing River

The southwest region in China is one of the 3 major acid rain areas (Hao et al., 2007) and is seriously influenced by acidification. This study will focus on the lower Jialing River (the southern section of the Jialing River), located in Chongqing City, southwest China (see Figure 2).

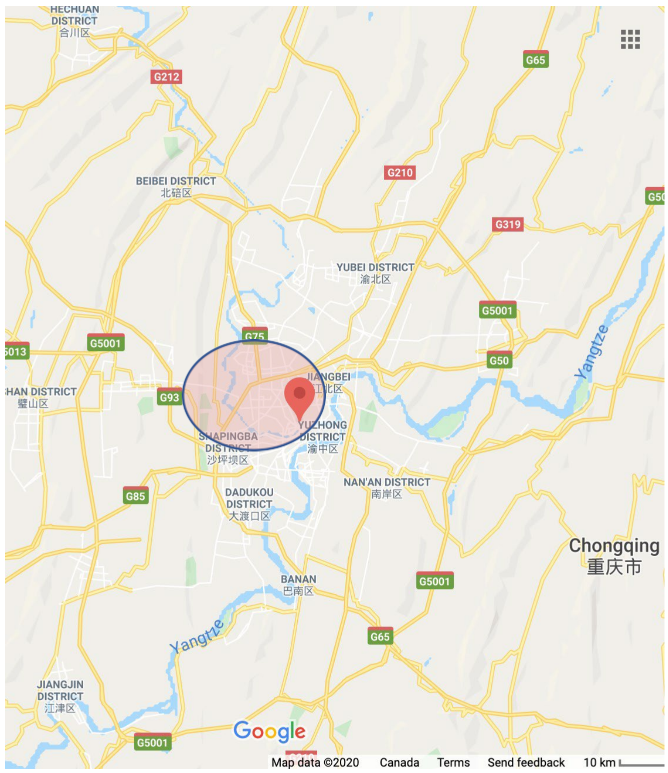


Figure 2. study area 1: the southern section of Jialing River (Source: Google Map)

Originating in the Qinling Mountains and joining the Yangtze River in Chongqing, the Jialing River forms the largest tributary of the former, with an area of 160,000 km^2 and a length of 1,119 kilometres. Also, it is an important waterway in Sichuan and accounts for one-fourth of the annual volume of inland waterway shipping activities. The watershed is ranked first among all rivers in Sichuan Province in terms of fish biodiversity and productivity, with some 163 different kinds of fish being identified. The annual precipitation of the Sichuan Basin is 1000 – 1300 mm/year, accounting for 7.7% of that of the Yangtze River basin. It is a rain-abundant region and delivers a total annual average surface water volume of 69.9 billion m^3, equivalent to 438.5mm runoff depth. The surface water resources available in the watershed vary greatly between years: In 1983, the number of surface water resources reached 106.4 billion m^3, while only 36.6 billion m^3 occurred in 1997 (Qin et al., 2008).

3.2 The Taihu Lake

Taihu Lake is one of the three major freshwater lakes in China, located in the lower reaches of the Yangtze River (Figure 3), covering an area of 2338 km^2 (Song et al., 2005). The population density in the lake area is high (910 people/ km^2) and the economy is well developed with the GDP accounting for about 10% of China.

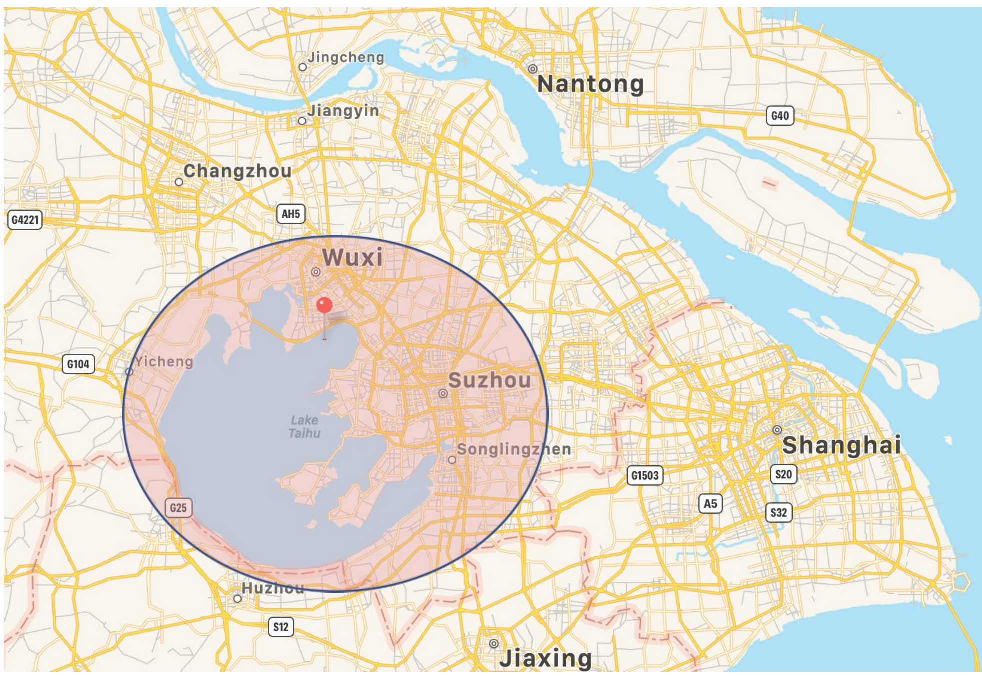


Figure 3. study area 2: Taihu Lake (Source: Google Map)

As a more static system, lakes are more likely to accumulate S and N deposition, compared to rivers, which are always flowing and can carry away acid deposits more easily. Taihu Lake is seriously affected by acid deposition: emissions of SO_x and NO_x in the lake region and resulted in a sharp increase of acid deposition over recent decades (Cui et al, 2014; Larssen et al, 2006). The SO_4^{2-} emissions account for approximately 50% of the total ions in the precipitation in Taihu Lake (Luo et al, 2007), and the concentration of NO_3^- has also increased rapidly over recent years (Zhao et al, 2019). As a result, the precipitation pH could sometimes be as low as

3.8 (Yang et al, 2014), and even a strongly acid deposition with a pH of 2.9 occurred in 2005. In addition, due to the long-term use of nitrogen fertilizers, such as ammonium nitrogen and urea, soil pH has decreased significantly, especially in southern and eastern China (Miao et al, 2011). Since Taihu Basin is located in a region where nitrogen fertilizers are applied frequently, water-soluble substances in the soil would be easily leached into Taihu Lake by runoffs and irrigations (Niu et al, 2011).

4 Method & Data Sources

4.1 Presenting changes in air pollution

The recent annual changes in acid air (SO_2 and NO_x) pollution in the Jialing River watershed were examined for the 2009-2019 period. Other historical air quality data including the SO_2 and NO_2 were documented for Chongqing City (2010 to 2019) based on the World Air Quality Index Project in 2020. Historical changes in SO_2 and NO_X emissions were also collected from Duan's report (2016).

4.2 Illustrating conditions in the Jialing River watershed

The conditions in the Jialing River watershed were specified using both the geological information and different land-use types. The geological information including bedrock and soil types as summarized from the literature review (Qin et al., 2008; Duan et al., 2002). The different land-use conditions were evaluated from data provided by the Government of Chongqing (2017) and a report by Li (2015).

4.3 Exhibiting changes in pH in the study areas

Scatter diagrams were used to display the weekly variations of pH in the Jialing River and the Taihu Lake over the past 11 years and trend lines were provided to show the overall acidification trends. The water quality data of the Jialing River was collected from the Automatic Water Quality Monitoring Weekly Report provided by the Ministry of Ecology and Environment of China. The chosen monitoring site was the Qingfeng Gorge, Sichuan Province.

The pH data in Taihu Lake was also collected from the above Weekly Report, with the chosen sites in Shazhu, Wuxi, and Xishan, Suzhou. 441 weekly reports were available from 2008 to 2018.

4.4 Assessing the acidification sensitivity of the two water sources

To produce an acid-sensitive evaluation, the acid-neutralizing capacity of water bodies and the acidification associated with nearby environmental conditions (soil, geology, and land-use types) formed the basis of the evaluation. The environmental factors that were used in Northern Europe (B Hankin et al., 2014; Langan et al., 1992) served as guidelines for this study. The Freshwater Sensitivity Classification (FWSC) developed by Hornung et al. (1995) was used for the lower Jialing River and Taihu Lake study.

First, the capacity to neutralize acidification of different soil and bedrock types were determined. For the bedrocks, the acidification sensitivity was classified according to their mineral composition, while for the soil, the pH, base saturation (BS), and weathering rate were used as the criteria for assessing acidification sensitivity (Ye et al, 2002). The details are provided in Tables 1 and 2.

Table 1. Acidification susceptibility classification of solid geology (Ye et al, 2002)

Acidification sensitivity	Bedrock type
High	Granite, acid volcanic rocks, coarse sandstone, quartz sandstone, decalcified sandstone, part of the quaternary sand
Medium	Neutral volcanic rock, metamorphic sedimentary rock without carbonate, impure sandstone and shale, sedimentary layer of coal
Low	Basic or ultrabasic volcanic rocks, calcareous sandstones, mudstones
Non-sensitive	Limestone, chalk, dolomite-bearing limestone and associated sediments

Table 2. Acidification susceptibility classification of soil (Ye et al, 2002)

Acidification sensitivity	BS%	pH	Weathering rate	Soil type
High	<20	<4.5	<0.2	Podzolic soil, latosol
Medium	20~60	4.5~5.5	0.2~0.5	Yellow soil, lateritic red soils, yellow-brown soils, acid brown forest soils, gleyed dark-brown forest soils
Low	>60	>5.5	>0.5	Brown soils, subalpine meadow soil, dark brown forest soils, cinnamon soil, meadow soil, torrid red soils, black soil, albic bleached soil, gray forest soil, paddy soil, desert soil, loess soil, chestnut soil

The bedrock and soil information were combined to create a map that provides the sensitivity of the base information for the study area (Table 3). This criterion was used to predict the possibility of surface water acidification in 4 classes: 1. 'extremely sensitive' – surface water acidification would occur; 2. 'sensitive' – acidification would likely occur; 3. 'medium sensitive' and 4. 'low sensitive' – the water acidification will not occur.

Table 3. A possible combination of geology and soil sensitivity and predicted likelihood of acid surface waters (Ye et al, 2002)

Soil sensitivity	**Geological acid susceptibility classes**			
	High	Medium	Low	Non-sensitive
High	Extreme sensitive	Sensitive	Medium sensitive	Low sensitive
Medium	Medium sensitive	Low sensitive	Low sensitive	Low sensitive
Low	Not sensitive	Not sensitive	Not sensitive	Not sensitive

In addition to the bedrock and soil, land-use could contribute to surface water acidification. Table 4 presents the acidification susceptibility classification of different land-use types and Table 5 provides the contribution rates of different land-use types.

Table 4. Acidification susceptibility classification of land use (Ye et al, 2002)

Type of vegetation and land use classification	Contribution level
Conifer	None
Shrubbery and grassland	Low
Deciduous tree	Medium
Agricultural land and deserts	High

Table 5. influence of land use contribution levels on surface water acidification sensitivity (Ye et al, 2002)

	Combined contribution level			
	None	Low	Medium	High
Effect on surface water acidification sensitivity	Up one grade	unchanged	Down one grade	Down to 'non-sensitive' grade

A grid was used to map the acid sensitivity and the soil/bedrock sensitivity and the vegetation sensitivity and the three layers were overlaid to arrive at the final surface water acidification sensitivity map. The basic soil and geological information of the lower Jialing River and the Taihu Lake Watershed were obtained from the Soil Map of Sichuan (Sichuan Agriculture and Herding Department, 1995), Chinese Soil Map (Xiong and Li, 1987) and The Geological Map of China (OSGeo China, 2020). The map of soil pH and base saturation was obtained from Xiong and Li (1987) as well as the vegetation information (Vegetation Map of China, Xiong and Li, 1987). The soil weathering rates were derived from the Distribution Map of Soil Weathering (Xie et al., 1998).

5 Results and Discussion

5.1 SO_x and NO_x emission

The emissions of SO_x and NO_x in Chongqing City, the major city located in the lower Jialing River are provided in Figure 4. The SO_2 concentration showed a continuously decreasing trend from 2009 to 2019, with the concentration dropping from 48 μg/m^3 to 7 μg/m^3. As a result, the emission of SO_2 had been reduced to low levels, indicating less S deposition. By contrast, the emission of NO_2 increased slowly as the main source of acid inputs. The annual average emissions of NO_2 ranged from 32 to 46 μg/m^3 and kept stable above 30 μg/m^3 in recent years. Although the emission of NO_2 had decreased from 2010 to 2011, the trend was reversed after 2011, especially until 2015. However, the concentration of NO_2 was below the national concentration limit – 50 μg/m^3 (MEE, 2016) and therefore the NOx level was not high enough to result in large N deposition and acid rain.

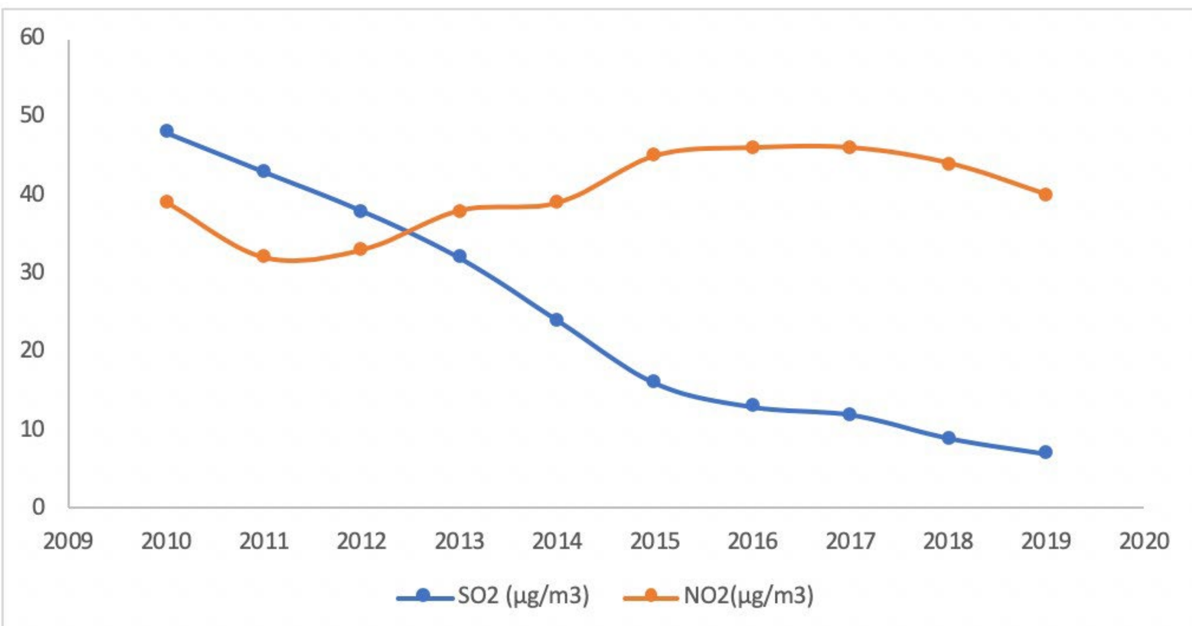
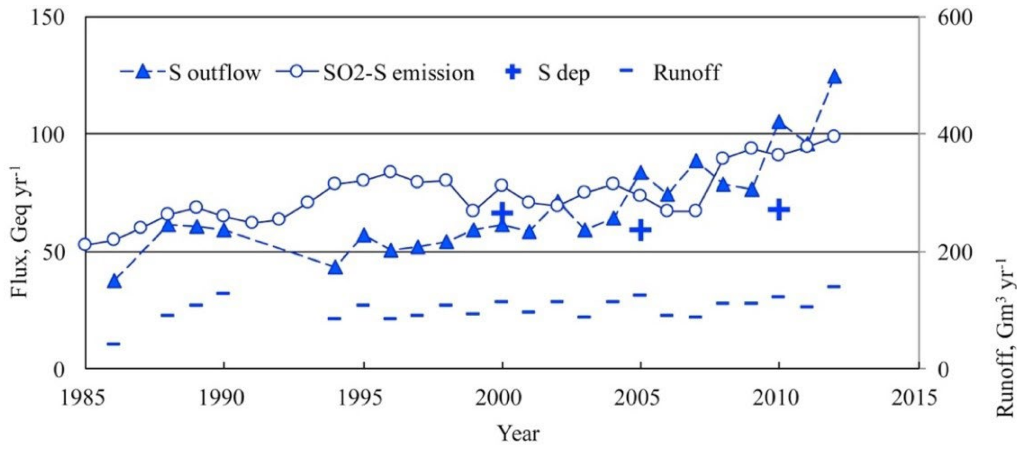
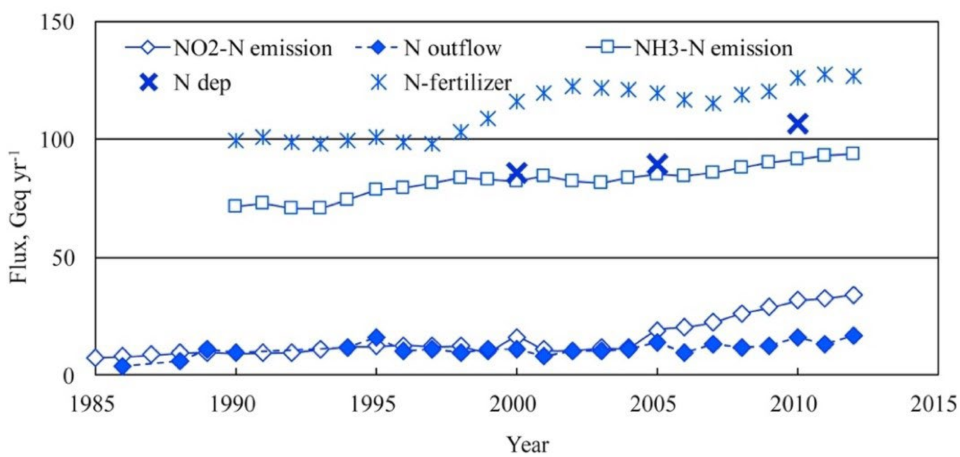


Figure 4. Annual average SO_2 and NO_2 emission in Chongqing City

Comparison between the recent trends of SO_2 and NO_2 to conditions between 1985-2012 (Figure 5) shows that the S and N emissions had increased significantly over the last 30 years (going up by 88% and 720%, respectively). The emission of NO_2 had not increased until 2005, after which the increasing trend was obvious. This might be related to the urbanization process, which has promoted the use of vehicles.



(a) S



(b) N

Figure 5. Total runoff and SO_4^{2-} and NO_3^{-} the outflow of the Jialing River during 1985-2012 compared with SO_2 and NO_X emission from the Sichuan Basin (Duan et al., 2016)

Although Sulphur has decreased in the air over recent years, the total S emission from the power plants is of concern (Duan et al., 2016). In addition, it is worth noting that the NH_3-N and N-fertilizers use have increased rapidly since 1985, due to the large demand in agriculture production. Therefore, extensive N-fertilizer applications have contributed a lot to the total N deposition. As a result, the large deposition of S and N could accelerate the surface water acidification in the Lower Jialing River. In contrast to the increase in NH_3-N, there was little change in N outflow because the low NO_3^- concentrations indicated large retention of N and low N leaching.

5.2 Conditions in the Jialing River watershed

In addition to acid air pollution, the local geology and land use types also play important roles in determining surface water acidification. The following part discussed the conditions in the Jialing River watershed in order to identify the possibility of the occurrence of acidification.

5.2.1 Geological information

The major bedrock type in the lower reaches of the Jialing River is the purple shale, which is easily weathered (Qin et al., 2008). Sandstones and limestones are also common in the lower part of the Jialing River, proving a good buffer capacity against surface water acidification. However, the concentrated distribution of calcareous purple soil with a high content of weatherable minerals in the Jialing River (Duan et al., 2002) might indicate the strong ability to buffer acidification of the watershed.

5.2.2 5.2.2 Different land uses

The land utilization in the Jialing River watershed includes 53% forests, 30% cultivation and 12% grassland, plus the urban industrial and mining land for 1.35% (Li, 2015). Agricultural production relies a lot on the water source of the Jialing River, and this also is a major source of pollutants. In addition, increased use of fertilizers could contribute to the acidification of soil and surface water.

Pollutants from urbanization are the major contributors to acidification. As an economic, technology and shipping center of southwest China, Chongqing is booming in both industrial production and manufacturing (Government of Chongqing, 2017). Therefore, increasing air pollution is caused by industrial activities, automobiles use and coal-fired power plants (Duan et al., 2011; Chen et al., 2012). This makes Chongqing one of the most serious acid rain areas in

China. The pH of rainwater ranges between 4.0-5.0 (Li and Chen, 1992) and the total emission of NOx in southwest China has continued to increase until 2011 (Yu et al., 2017).

5.3 Trend of pH

5.3.1 Trend of pH in the Jialing River watershed

As is shown in Figure 6, in general, there was a very small decrease in pH in the lower Jialing River from 2008 to 2018. In addition, there were both obvious interannual and seasonal variations of pH values -- pH was higher in winters and lower in summers. During the study period, the maximum value of 8.9 appeared in 2011, while a minimum of 6.7 in 2014. The abnormal high values of pH might be caused by industrial chemical pollution such as Na_2CO_3 from nearby plants. Despite the seasonal changes, the pH values remained high well above 7.5. From 2013 to 2018, there was a very small decrease and almost all values are above pH 7.

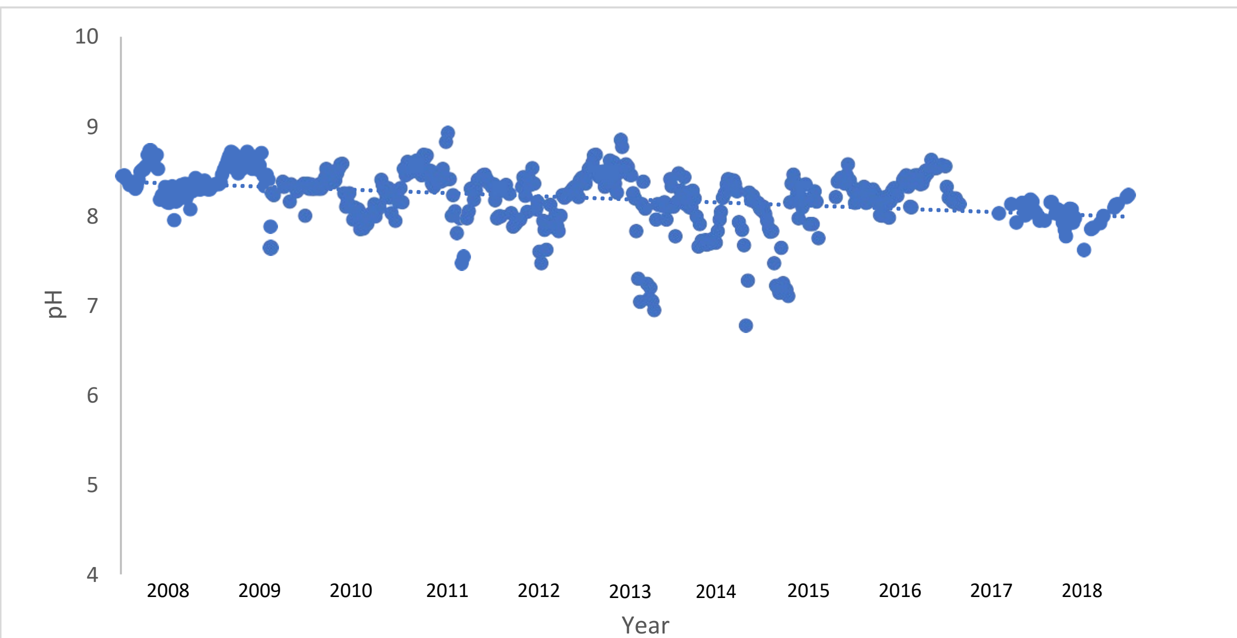


Figure 6. pH value of the Jialing River from the year 2008 to 2018

Given that the pH of the lower Jialing River is high (mostly above pH7), there is no evidence showing that surface water acidification is a serious problem in the Jialing River. This is probably because the major bedrock types in Chongqing are shale and limestones, both of which have great buffer capacity against acidification. As is reported, the acid-neutralizing capacity (ANC) of surface water is strong in southwestern China, especially in large rivers (Duan et al., 2000). However, the pH values were much lower in the soil waters than in the surface waters (Duan et al., 2016), similar to the acid-impacted soils in Europe (Van Breemen et al., 1984). Therefore, acidification was of concern locally.

5.3.2 Trend of pH in Taihu Lake

As is shown in Figure 7, acidification was not found in Suzhou City due to the high pH values, most of which were above 7.0. The pH values of Taihu Lake as monitored in Suzhou City have remained almost unchanged for the past 11 years and the minimum coefficient of variation is insignificant. Similar to the Jialing River, Taihu Lake shows an obvious seasonal variation in pH values – higher in winters and lower in summers – fluctuating around 8.0, with a minimum value of 6.5 appearing in 2009, while the maximum of 8.5 in 2017.

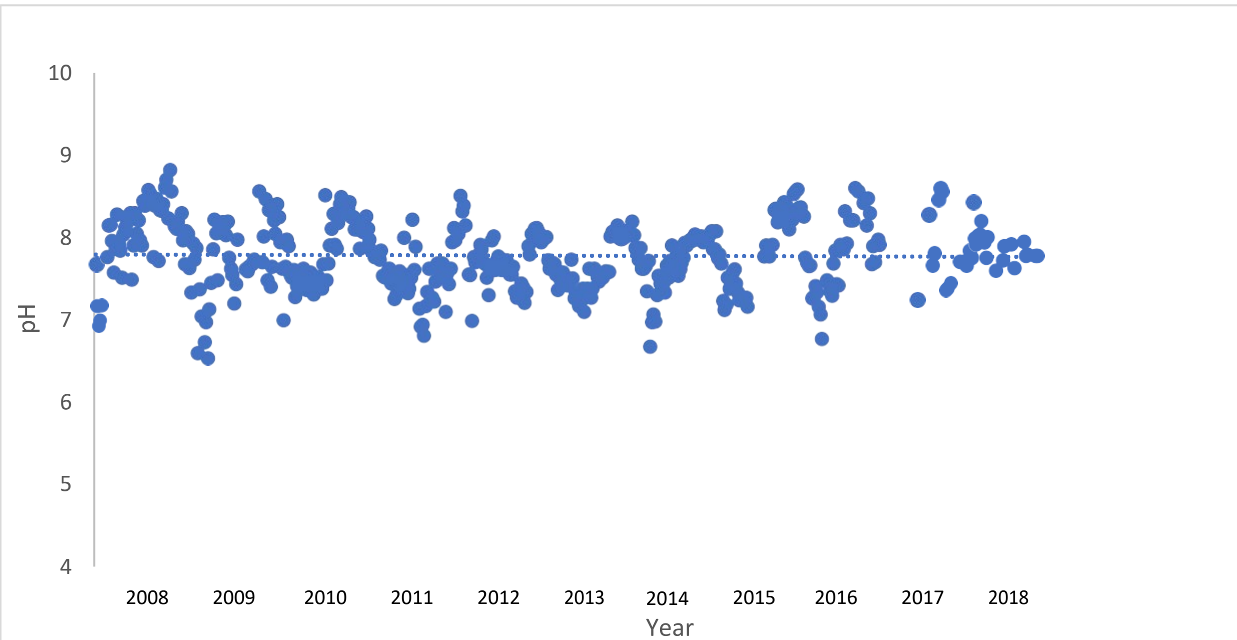


Figure 7. pH value of Taihu Lake (in Suzhou City) from 2008 to 2018

Similarly, figure 8 presents the high pH values monitored in Wuxi City indicated that no acid impacts were found in Taihu Lake. Although pH has dropped slightly for the last 11 years, the acidification trend is not observable. The changing range of pH in Wuxi is narrower than that in Suzhou, given that even the lowest pH is above 7.0 and the highest is 9.04.

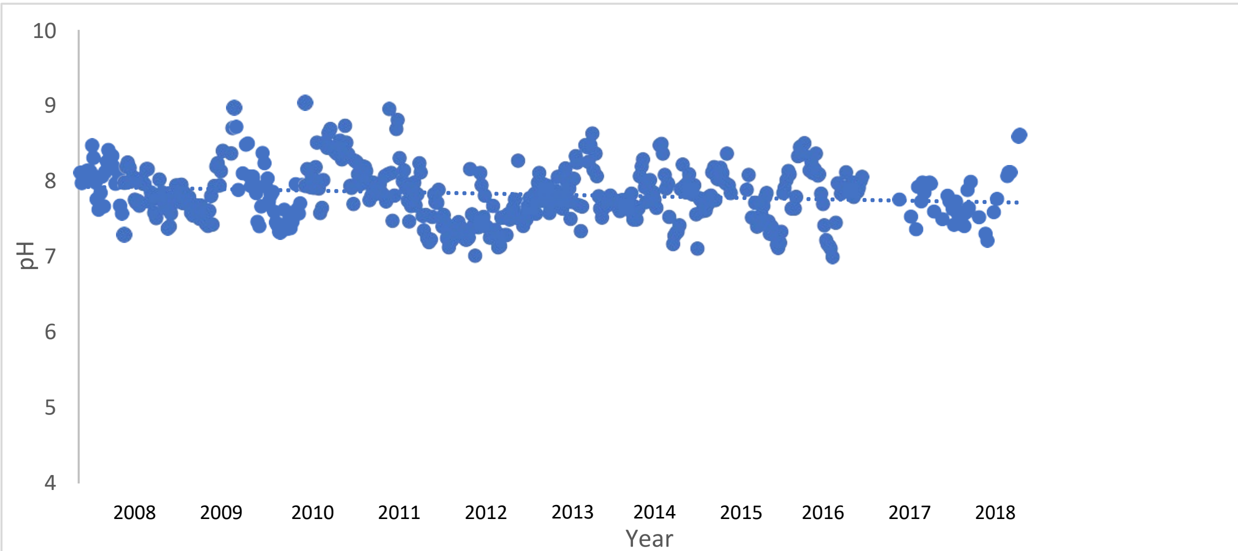


Figure 8. pH value of Taihu Lake (in Wuxi City) from 2008 to 2018

Compared to the lower Jialing River, Taihu Lake watershed shows a stable trend in pH. The reason why surface water in Taihu Lake was not easily acidified might be related to the lower acid inputs, including acid air pollution and acid deposition. In addition, the properties of the water bodies and surrounding soils play a key role, because the acidification sensitivity would differ, depending on various properties of the watershed.

5.4 Acidification risk assessment map

The fact that pH values are stable at well above a pH of 7 in these two areas was related to the geological conditions and land use types (as mentioned in 5.2). Acidification sensitivity maps helped visualize the influence of soils, bedrock and land use types so that the detailed acidification sensitivity in these two areas could be depicted.

The acidification sensitivity of soils in the lower Jialing River and Taihu Lake watershed is presented in Figure 9 (the legends ‘low’ ‘medium’ ‘high’ represents the level of sensitivity, the same in figure 10-13). As is shown in Figure 9(a), most of the soils in the watershed are in a low sensitivity class, while the soils in the eastern part of the watershed are in medium sensitivity class. On the other hand, the major types of soil in the Lower Jialing River are purple soil and yellow soil, both with great buffer capacity against acidification. However, laterite and brown soils, which are of medium sensitivity to acidification, are distributed in the east of the watershed. In general, surface water flowing through the Lower Jialing River watershed would not be acidified easily.

Figure 9(b) shows that all of the soils in the Taihu Lake watershed are in low sensitivity to acidification. The soil types in Taihu Lake watershed are all paddy soil. Since paddy soils have high ANC, water from these soils is resistant to acidification. The soils in the Taihu Lake area have an even stronger buffer capacity against acidification than those in the Jialing River watershed.

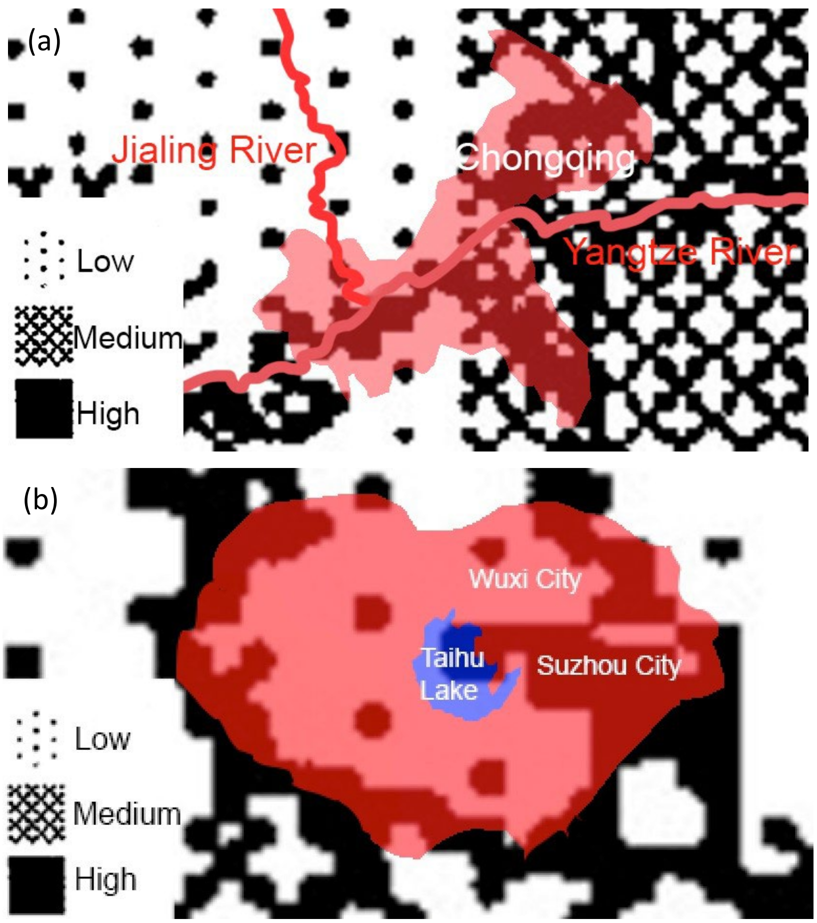


Figure 9. Mapping of acidification sensitivity of soils in (a) the Lower Jialing River; (b) Taihu Lake (adapted from Ye et al., 2002).

As is shown in Figure 10, the acidification sensitivity of the geology in both the Lower Jialing River watershed and Taihu Lake watershed is at a low level. The major bedrock types in the Jialing River are limestones and calcareous sandstones, which are easily weathered and have strong ANC. For the Taihu Lake, carbonatite and evaporite are most common in its watershed, resulting in a great buffer capacity against acidification.

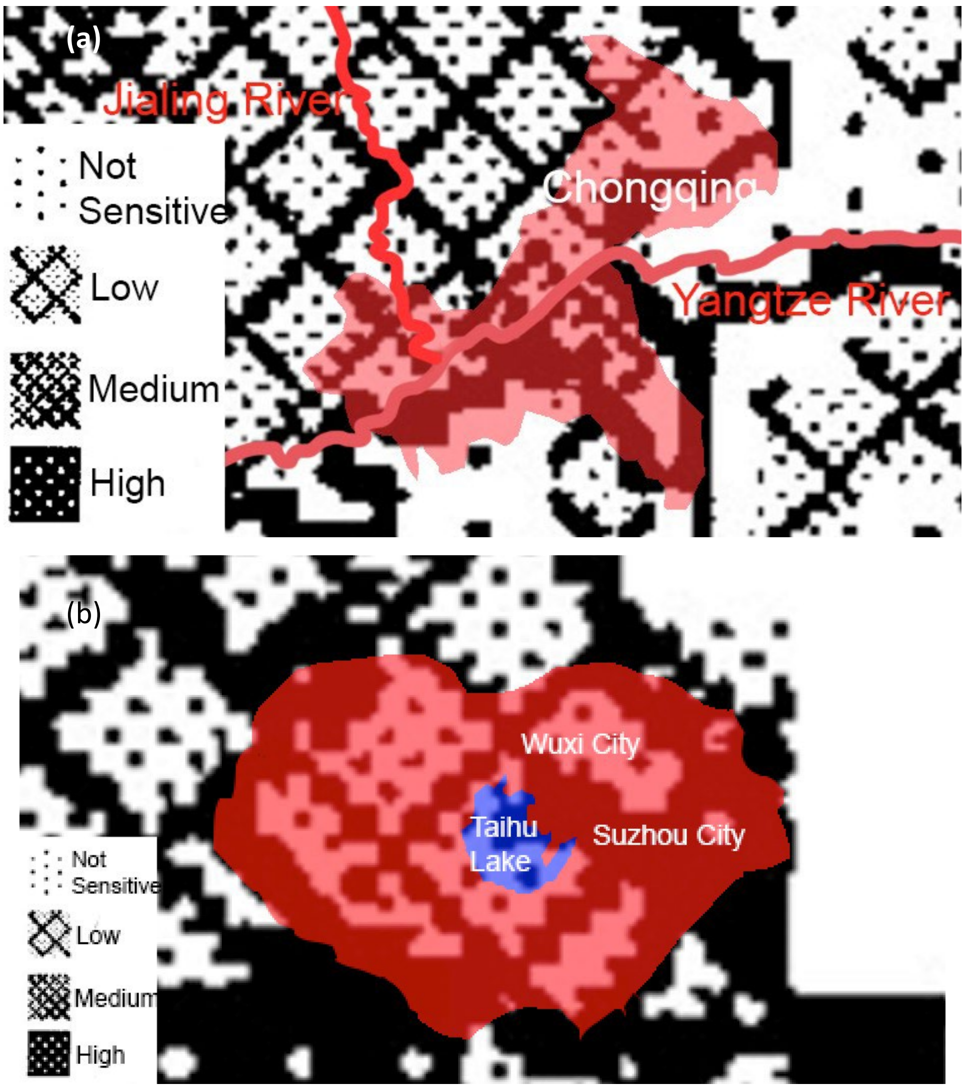


Figure 10. Mapping of acidification sensitivity of bedrock in (a) the Lower Jialing River; (b) Taihu Lake (adapted from Ye et al., 2002).

Soils developed on different bedrock types would respond differently to surface water flowing through them and their acidification sensitivity depends a lot on both the soils and the bedrocks. Figure 11 presents the acidification sensitivity of surface water by overlaying Figure 9 and Figure 10, in reference to the geological information of the two watersheds. Bedrock and soil properties play major roles in determining the acidification sensitivity of surface water, so the maps below show the sensitivity based on the geology information without considering different land uses. As shown in Figure 11(a), most of the surface water in the Lower Jialing River is not sensitive to acidification, while that in the east of Chongqing City is in the low sensitivity class, meaning that surface water acidification would only occur when there is an excess of acid inputs. As is shown in Figure 11(b), surface water acidification might not occur under any circumstances in the Taihu Lake watershed, due to the insensitivity of surface water.

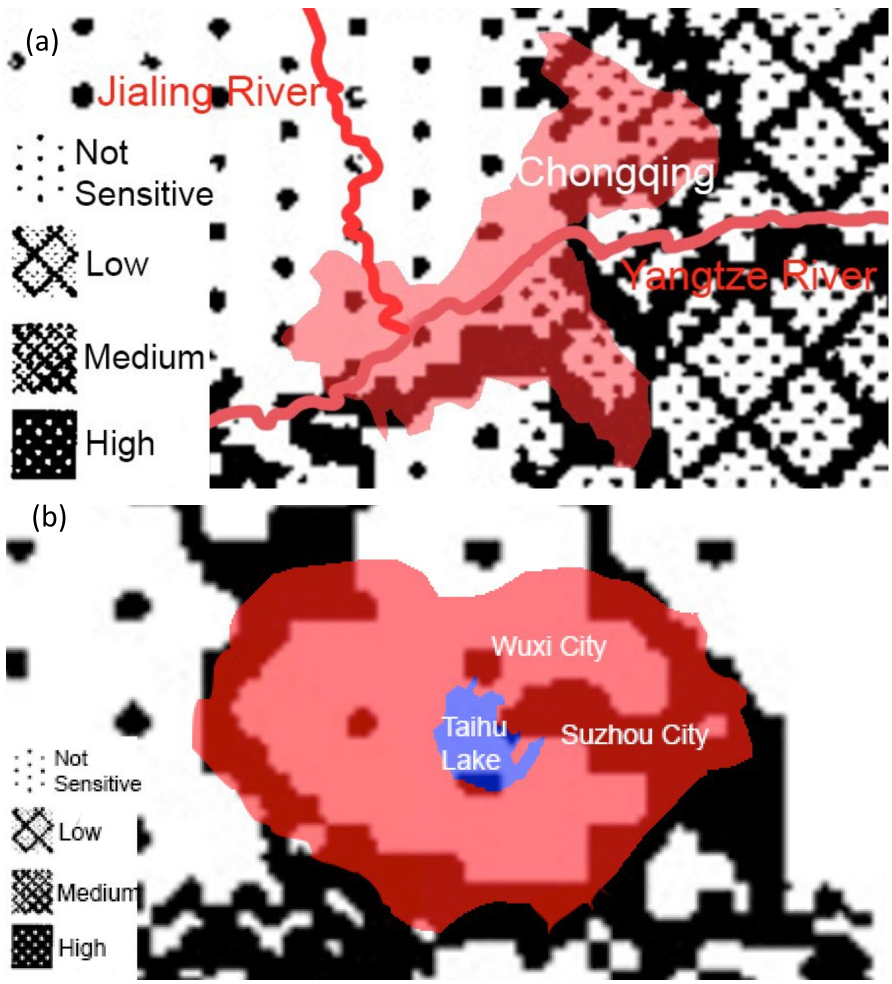


Figure 11. Mapping of acidification sensitivity of surface water in (a) the Lower Jialing River; (b) Taihu Lake decided by soil and bedrock properties (adapted from Ye et al., 2002).

The Lower Jialing River lies in Sichuan Basin, where limestone and calcium-based sandstones are widely distributed. Therefore, the purple soil and yellow soil developed on these bedrocks have a high base exchange capacity and great buffer capacity against acid deposition. Consequently, the lateritic red soil, yellow soil and brown soil developed on these bedrocks are not sensitive to acidification.

If taking into consideration the influence of land-use types, including vegetation and agricultural lands (Figure 12), the distribution of surface water acidification sensitivity would be different. A wide range of conifers might increase the acidification sensitivity of surface water (Duan et al., 2016), and human activities on farmlands would change the sensitivity as well.

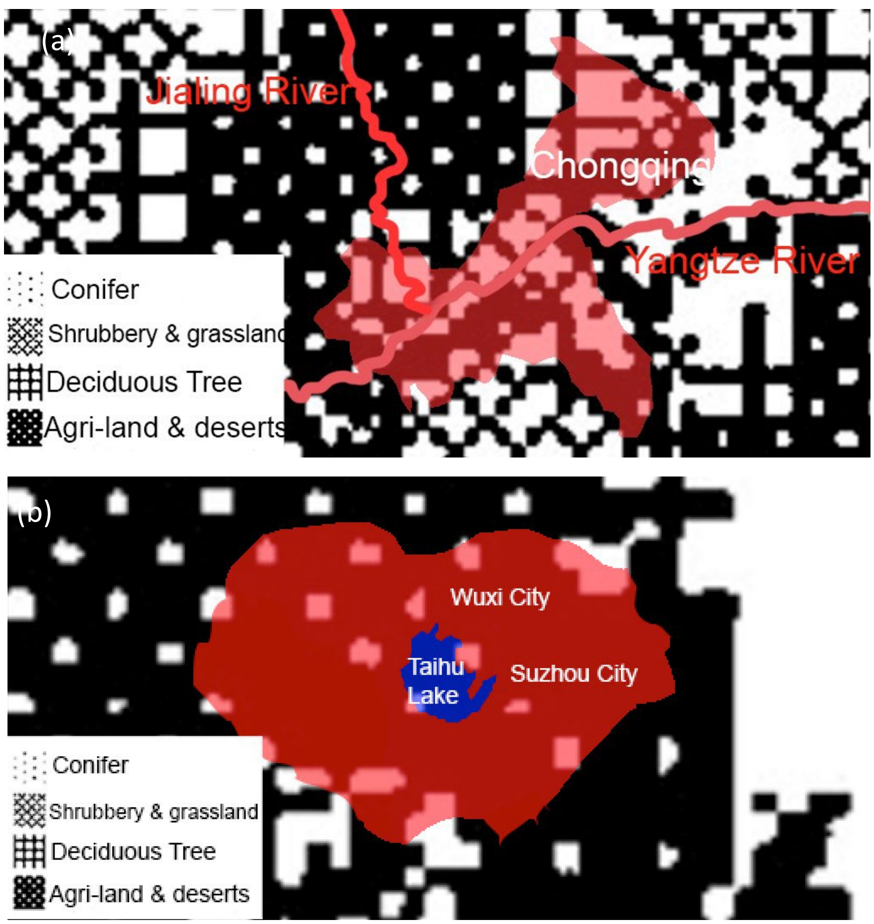
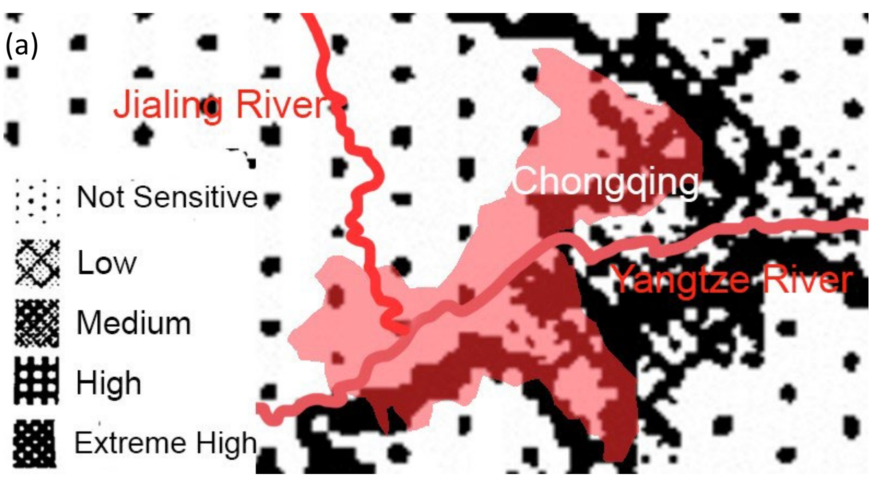


Figure 12. Mapping of land use types in (a) the Lower Jialing River; (b) Taihu Lake (adapted from Ye et al., 2002).

Figure 12(a) presents the major land-use types in the Lower Jialing River watershed. Agriculture and deciduous tree plantation are the main land use, with shrubbery and grassland also accounting for a portion. Compared to the combination of several land-use types in the Jialing River, the land use in Taihu Lake watershed is only agriculture, as shown in Figure 12(b). Since paddy soil is the most common agricultural land in these two watersheds, organic fertilization and lime application have maintained a high pH and base saturation in the soils. As a result, the acidification sensitivity of the surface water has been greatly reduced.

Figure 13 presents a comprehensive acidification sensitivity map, with the consideration of different land-use types. Most of the surface water in the Jialing River watershed is not sensitive to acidification, while a small part is in the low sensitivity class. Also, surface water in Taihu Lake watershed is considered to be insensitive to acidification. Although a large amount of acid deposition has been detected in these two areas, the acid-resistant soils and large areas of cultivated lands result in low acidification sensitivity of surface water. Therefore, the monitored pH values of the water body were higher than 7, and surface water acidification has not been found yet in these two areas.



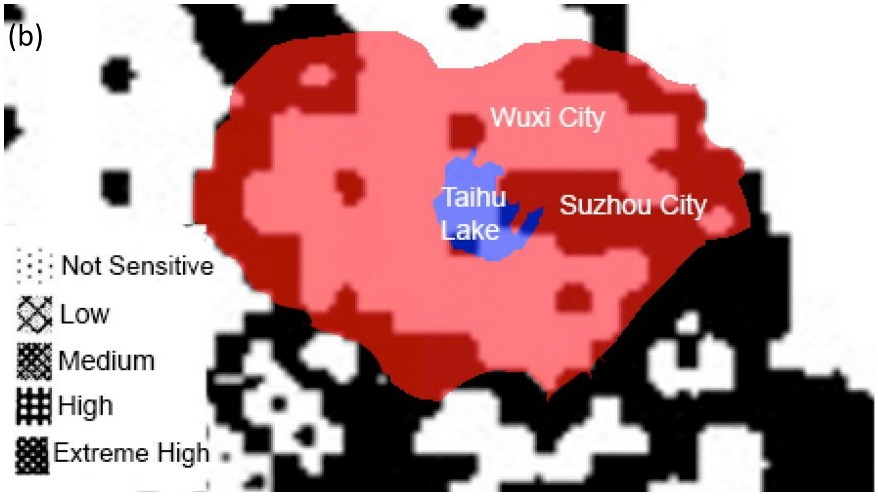


Figure 13. Mapping of acidification sensitivity of surface water in (a) the Lower Jialing River; (b) Taihu Lake considering land-use types (adapted from Ye et al., 2002).

6 Successful precedents

Given the air pollution issues in the lower Jialing River, policymakers and environmental groups are required to take action to prevent the occurrence of acidification. Once a water body is found acidified, remediation practices should be implemented. As a serious problem, surface water acidification has caused damage to ecological environments, so multiple ways have been tried to deal with the problem, and some approaches have worked well, including the following successful precedents that could provide helpful guidance to mitigating surface water acidification.

6.1 Acidification risk assessment in Wales

In order to predict the possibility of future acidification, a program of Acidification Risk Assessment was made for all kinds of surface water in Wales in 2014 (B Hankin et al., 2014). They tabulated the sensitivity of water to acidification by creating chemical and biological impacts and sensitivity metrics. To evaluate the impacts, the critical load exceedance was the key to assessing impacts. This was accomplished by the Centre for Ecology and Hydrology and was based on the projected atmospheric deposition with the use of the MAGIC model (a model used for estimating atmospheric deposition of SO_2 and NO_x emissions). Other factors that were considered included local geological characteristics, pH of a water body, the buffer the capacity of local environments, changes in flora and fauna, different land-use types, and the emission of sulphur and nitrogen from power stations, traffics and shipping. Evaluation of sensitivity was made based on the Freshwater Sensitivity Class (FWSC) and the Steady-State Water Chemistry (SSWC) Critical Load Exceedance for 2027 were projected. Finally, the overall risk score could be obtained by combining the weighted impact scores and the sensitivity scores.

The outcome of the programme is the acidification risk assessment map that presents the detailed acidification sensitivity of Wales in 2027. The map shows that the majority of water bodies were at low risk, and the areas at risk were mainly distributed in the northwest and centre of Wales. In conclusion, local acidification risk assessments could help predict the likelihood of acidification in a specific watershed before the acidification actually happens, and protection measures could be implemented in sensitive areas.

6.2 The Swedish liming programme

Over 20,000 lakes in Sweden were found to be largely influenced by acidification in the 1970s. In order to mitigate surface water acidification, the Swedish government had funded a liming programme with US$ 200 million during 1976-1995 (Svenson et al., 1995). The principle of liming was to apply limestone powders ($CaCO_3$) and dolomite powders ($CaMg(CO_3)_2$) to 95% of the surface water in Sweden and to apply sodium carbonate ($NaCO_3$) to waters of low retention time (Henrikson and Brodin, 1995). The specific operations included the direct liming and the dose liming, which were appropriate for lakes and running waters, respectively. The first method allowed limestone to be mixed with lake water or dispersed by boats. The other method considered the proportion of flow, water level, water speed or pH when applying limestones into the watercourse, and the locations of applying should be a few hundred meters upstream to the target watershed. The utilization of these two methods was 50-80% and 70-90%, respectively. In addition, wetland liming was used as a supplement to mitigate surface water acidification.

After liming in 1982, the pH of the lakes increased quickly from 5.8 to 6.6 and had stayed above 6.2 for the next 10 years. The alkalinity also showed a similar trend to pH, indicating the recovery from acidification in Sweden was successful. In addition, the liming programme resulted in the improvement of biodiversity and avoided the elimination of endangered species in over 8,000 lakes and watercourses. The fish production had been boosted, while the toxic level of metals (Al, Mn, Fe and Cd) in surface water had been dampened as a result of lime application as well (Svenson et al., 1995). Therefore, if large-scale acidification is identified in a watershed, liming would be the most effective way to mitigate the problem in a short time.

Nevertheless, it should be noted that liming comes with potential side effects, including changes in water chemistry and short-term damage to biology. There might be an increase in conductivity and phosphorus might concentrate in oligotrophic waters especially in mountain areas (Henrikson and Brodin, 1995). In addition, liming could considerably damage the vegetation and stimulate algal blooms, occasionally in the watershed (Henrikson and Brodin, 1995). Moreover, liming costs a lot and it is reported that approximately 300,000 tons of limestone were spread in surface waters every year which costs $40-50 million (Henrikson et al., 1995) to raise the pH. The timing and the amount of lime released are also critical factors to consider because a high done application with little mixing in the water can create a temporary shock to the system. One other successful approach in rivers is to apply pebble size limestone into the river, which slowly releases Ca and carbonates over time.

7 Suggestions

Surface water acidification is mainly caused by human activities, such as the acid air emission from power plants, industrial operations and transport. Therefore, by strict restrictions on some activities and strengthened monitoring of surface water quality, an increase in acidification would be likely to be reduced. Since the Lower Jialing River watershed and Taihu Lake have not been affected by surface water acidification despite high air pollution levels, suggests that there is sufficient buffer capacity in these two systems. However, preventive measures need to be in place in those areas where the buffer capacity could decline as acid inputs continue to rise.

7.1 Controlling the emissions of SO_x and NO_x

Acid gas emissions could be reduced by reducing vehicle exhausts and applying improved combustion technologies, such as the application of clean energy and the SNOX process. Low sulphur coal, coal with a sulphur content of less than 0.51-1% by weight (Fan et al, 2003), can deliver 1-3% lower sulphur content than the normal coal. It is reported that the emission of SO_2 could be reduced by 6% when using low sulphur coal (You and Xu, 2010). Therefore, replacing normal coal with low sulphur coal as fuels is an effective way to control the emission of SO_2. Another way to reduce acid air pollution is to remove sulphur dioxides and nitrogen oxides from flue gases of combustion, a process called SNOX. Since the process mainly contains catalytic reactions (e.g., catalytic reduction of NOx and catalytic oxidation of SO_2 to SO_3) and does not need water and absorbents, almost no waste will be produced (Laursen and Karavanov, 2006).

7.2 Strengthening monitoring

In the lower Jialing River watershed and Taihu Lake, only a few monitoring stations have been built to record daily information on water quality and acid deposition. This makes it difficult to monitor pollutions comprehensively. Enhancing the density of monitoring stations could help study the dynamics of water quality more accurately. For instance, there are 87 stations on the west coast of Southern Norway (Raddum et al, 2001) for monitoring the acidity of precipitation. This allows environmental groups to initiate targeted prevention measures promptly.

The monitoring should focus not only on the quality of surface waters but also measuring the quality of wet and dry deposition in the watershed because atmospheric deposition was the major pathway to import air pollution into surface water (Erisman et al., 1995). This requires monitoring and recording NH_4, NO_2 and SO_2 emissions to calculate the acid inputs. Once the N and S deposition has reached a critical value, it is necessary to check for the occurrence of surface water acidification. Moreover, since many aquatic organisms are not tolerant of acidic water (with pH lower than 5.5), identifying abnormalities in precipitation or water acidity is crucial.

7.3 Creating acidification sensitivity maps

Surface water acidification is an outcome of both acid inputs and geological sensitivity. This is the reason why acidification is not found in those areas with high acid deposition but also high buffer capacity. However, the continuous acid inputs could exhaust this buffer capacity over time.

Assessment of acidification sensitivity of water sources is a good preventative measure when incorporation the soil, geological and land use in a watershed. There are already nationwide acidification sensitivity maps of surface water in China, but there is a lack of local tests for different watersheds. The specific methods and models could refer to those used in Europe, as mentioned in Section 6.1. The acidification maps are great tools that allow us to identify where land and water conditions are sensitive to acid inputs.

8 Limitations

This study is mainly focused on changes in water acidity over the past decade but should be extended to show long term changes. Unfortunately, data for only 441 weeks were available to show the pH trends. Water quality data (cations, carbonate and alkalinity) should also be considered in such studies but were not available. Other areas in China with high air pollution issues and low buffer capacity in the bedrock are likely susceptible to acidification and those should be given priority for developing acid-sensitive maps.

9 Conclusion

Air pollution is a serious problem in China and is posing a great threat to the ecological environment in many freshwater systems as a result of acid deposition. The acidification determining factors in a watershed and a lake were studied in this report and the main findings include:

1) Air pollution in the Jialing River watershed was historically serious, but the NOx emissions stabilized and the SOx emissions were well controlled and declined in recent years.
2) Surface water was not found being acidified in the two areas so far because the pH levels have shown small changes over 2008-2018 and are still mostly above 7.0. However, decreases in pH in the Jialing River watershed are of concern if acid inputs continue at a high rate.
3) There are many reasons why there is little evidence of acidification in the Jialing River watershed and this is primarily since there are limestone formations in the watershed that provide sufficient buffer capacity to mitigate the acid input. However, the acid sensitivity map shows that some areas in the watershed are locally sensitive to acid input. This is primarily affecting the soil conditions but is unlikely to change the pH and overall water quality of the river and the lake.
4) Acid sensitivity maps based on geology, soil conditions, vegetation cover and land use activities are good tools to identify where the acid impact on water resources is likely to occur.
5) Experiences from Europe where acidification of water resources was problematic in the 1980s served as good examples of how to identify sensitive areas of acid input. Some of the lessons learned on how to mitigate impacted water sources were highlighted in this report.

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