Ecological control of non-point source pollution driven by soil and water erosion in China

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Abstract

Context

Emerging non-point source pollution (NPSP) driven by soil and water erosion (SWE) is a key factor affecting the environmental quality of many water source areas.

Objectives

Therefore, here we focus on NPSP driven by SWE, and critically review existing evidence of the spatial patterns and migration of N&P.

Methods

First of all, the occurrence of runoff-derived pollution under different land use and production strategies was probed, and the evidence for different forms of N&P loss from soils with varying vegetation covers was discussed. Then, the mechanism of N&P loss associated with SWE-driven NPSP was approached, and potential ecological control measures were concluded.

Results

Rainfall regimes, land use and terrain were the main factors affecting NPSP driven by SWE. Ecological treatment technologies such as ecological ditch interception technology and constructed wetlands can effectively reduce NPSP.

Conclusions

In water source areas, integrated protection, restoration, and management are needed to enhance the circulation capacity of the hydrological systems and maintain ecological balance. In particular, the greater protection of drinking water sources and construction of water-conserving forests are required.

1. Introduction

In recent years, continuous socio-economic development has resulted in serious water-related environmental problems in many parts of the world. In particular, non-point source pollution (NPSP) caused by the loss of soil nitrogen and phosphorus (N&P) has attracted increasing attention (Choi et al. 2016; Mcdowell 2015). For example, a study by Panagopoulos et al. (2011) in the small Arachtos watershed in western Greece showed that more than 80% of N&P pollutants in rivers in the region originate from agricultural activities. In Shandon, China, Zhang et al. (2018a) showed that in the Nansi

Lake Basin, the largest water source area in Shandong, 65.9% of the basin was affected by total nitrogen (TN) pollution and 66.8% of the area was affected by total phosphorus (TP) pollution. Srinivas et al. (2020) also note that agricultural NPSP is an important factor leading to the deterioration of water quality in most rivers in India, especially in the Ganges River Basin. It is clear that in water source areas, NPSP is in part driven by soil and water erosion (SWE), termed soil erosion-type NPSP, which typically occurs when heavy rain generates runoff and non-point source pollutants including N&P in the soil are mobilized, transported, and enter water bodies. In the southeast coastal areas of China, soil erosion-type NPSP is gradually becoming the dominant form of agricultural NPSP (Zhang 2018) and requires urgent attention. Understanding the migration of N&P via soil erosion-type NPSP and the potential forms of ecological control are, therefore, of great significance for environmental conservation and managing water-related public health issues.

2. Loss Of Soil N&p In Water Source Areas

NPSP is a regional-scale environmental problem. In the 1930s, the concept of NPSP was put forward, followed by a series of research studies (Novotny et al. 1993). According to the regional nature and process character of NPSP, two categories are commonly distinguished—agricultural NPSP and urban NPSP. Agricultural NPSP is typically the most important type, both because there are myriad potential agricultural pollution sources and, consequently, successful prevention and management are difficult to achieve (Wu et al. 2011).

In reservoir settings, the loss of soil N&P and the resulting eutrophication involve the interaction of surface soil, rainfall, and runoff (Xu 2011). Runoff is the transport medium of non-point source pollutants, and the calculation of runoff amounts and rates is a prerequisite for estimating NPSP outputs (Li et al. 2004). When the soil infiltration capacity is exceeded during a rainfall event, the generated runoff can mobilize and transport the N&P adsorbed on suspended particulate matter into water bodies. Currently, the effects of varying vegetation cover/land use and seasonal storm runoff dynamics remain understudied in the context of N&P in farmland runoff.

2.1 N&P loss under different land-use systems

Soil N&P exist in various organic forms; however, these forms vary as a function of environmental factors including land use, crop rotation, fertilization management, topography, and vegetation type. For example, Zhang et al. (2007) showed that changes in land can greatly affect the forms of N&P in soils and their spatial distribution in association with aggregates of different sizes. On the Sanjiang Plain in Northeast China, Lai et al. (2015) observed that among different land-use types and under average rainfall conditions, TN loss was highest from paddy fields (18.39 mg/L) with ammonium nitrogen and nitrate-nitrogen loss concentrations of 2.81 mg/L and 8.64 mg/L, respectively. In comparison, the lowest nitrogen losses were measured from forested land, with average runoff concentrations of 11.45, 1.64, and 4.04 mg/L of TN, ammonium nitrogen, and nitrate-nitrogen, respectively. Importantly, vegetation cover and species type strongly influence water regulation within catchments (i.e., water volume and quality), which can vary considerably between land-use types. For example, Li et al. (2018) found that the concentrations of nitrate-nitrogen and TP were significantly higher in dryland and paddy-upland rotation soils compared to forested land, and soil TN, nitrate-nitrogen, and TP generally decreased with soil depth.

2.2 Runoff-driven loss of N&P in different soil-vegetation systems

Raindrops hitting the ground surface can destroy the surface structure of the soil, detaching soil particles, which can lead to soil erosion. Soil erosion is linked to N&P loss via runoff, which can reduce soil fertility and cause water pollution (Zhang et al. 2011). Many factors affect runoff-driven N&P loss from soils including slope gradient, rainfall regimes, fertilization regimes, and vegetation cover (Xu 2011). For example, Herve-Fernandez et al. (2016) studied the retention of N&P in evergreen primary forests, deciduous primary forests, and exotic eucalyptus forests during typical rainfall conditions in central and southern Chile, South America. Compared with exotic eucalyptus, soil nutrients (including N&P) were better retained by the evergreen and deciduous primary forests. Liao et al. (2017) found that soil phosphorus loss via surface runoff from seedlings in Changxing mainly occurred in the form of particulate phosphorus followed by dissolved phosphorus. Furthermore, most studies have shown that ground cover vegetation reduces the loss of soil N&P, at least to some degree, primarily by reducing soil erosion. For example, De Oliveira et al. (2017) found that forests effectively reduce the loss of non-point source pollutants in a small watershed of the Velhas River, Brazil, and Wang et al. (2020) used simulated rainfall experiments to show that *Quercus acutissima* Carr. and *Robinia pseudoacacia* L. forests reduce TP loss by 47.44% and 58.97%, respectively, relative to wasteland sites.

2.3 Leaching of N&P

Leaching is an important mechanism driving the transport of N&P from soils to water bodies. Cao et al. (2005) found that nitrogen leakage from vegetable plots in the suburbs of Shanghai accounts for more than 90% of nitrogen leaching losses, acting as an important source of nitrogen pollution in local water bodies. Zhang et al. (2018b) found that in addition to infiltration and leaching driving the loss of N&P during the runoff-generation process, surface runoff also transports N&P and can cause NPSP. Currently, soil leaching characteristics remain the focus of much soil science research (Gao et al. 2020; Laird et al. 2010; Lu et al. 2020; Yao et al. 2012). Much of this work demonstrates that N&P leaching is mainly associated with farmland soils, yet comparably little attention has been paid to the transport mechanisms involved or the factors influencing N&P mobilization in water source areas. This is particularly true in the case of the vertical migration characteristics of soil N&P with varying vegetation cover types.

3. Factors Influencing Soil Erosion-type Npsp

Many factors influence the mobilization and transport of non-point source pollutants from soils to water bodies including rainfall regimes, land use and land-management practices, and topography. Each of these factors is considered in the following section, with a focus on their implications for soil erosion-type NPSP.

3.1 Rainfall regimes

Precipitation is a prerequisite for runoff, and rainfall intensity and duration primarily control runoff generation and, consequently, associated erosion and nutrient mobilization (Zhang et al., 2010). For example, in the Erie Lake Basin, North America, Williams et al. (2020) showed that rainfall intensity and duration are important factors affecting phosphorus loss dynamics. In addition, Wang et al. (2014) and Ding et al. (2017) also demonstrated that rainfall intensity is an important factor affecting phosphorus loss.

During an individual rainfall event, N&P loss typically increases first and then gradually decreases and stabilizes over time (Wang 2019b). Importantly, runoff generation times are closely related to rainfall intensity; at higher rainfall intensities, runoff generation time advances with associated increases in runoff rates and N&P losses. For example, using rainfall simulation experiments, Wang (2019b) showed that rainfall intensities of 50, 75, and 100 mm/h produce runoff generation times of 1.5 min, 1.2 min, and 0.5 min, respectively. Furthermore, the same authors show that with increasing rainfall intensity, the loss of TN in surface runoff increased from 214.55 to 1,017.02 mg and the loss of TP increased from 5.63 to 48.85 mg.

Rainfall (such as rainfall intensity and rainfall duration) is a direct factor leading to the migration and loss of nutrients from soil, which is significantly positively correlated with TN, TP, soluble nitrogen, and soluble phosphorus. For example, Li et al. (2013) observed that pollutant (TN) losses via surface runoff from chestnut forests in the Fushi Reservoir catchment in Anji County, Zhejiang Province, China, were significantly positively correlated with rainfall.

3.2 Impacts of land use and production methods on N&P loss

Farming methods affect the loss of N&P from soils by changing runoff generation times and intensities. For example, on the Sanjiang Plain in China, Huang et al. (2015) showed that organic phosphorus loss from drylands, rice fields, forested land, and wetlands was 2.30, 2.04, 0.99, and 0.69 kg/ha, respectively, and TP loss was 3.28, 3.04, 1.43, and 1.04 kg/ha, respectively. Yang et al. (2018) studied the loss of nitrogen and phosphorus under different farming modes (CNL-CK, corn + no straw application + longitudinal ridge; CSSC, corn + stubble standing + cross ridge; CSC, corn + straw application + cross ridge; SSC, soybean + straw application + cross ridge; ASC, alfalfa + straw application + cross ridge) in the Songhua River area. Compared with the traditional CNL, CSSC could reduce 53.8% soil nitrogen loss, 50.7% soil phosphorus loss, 52.8% runoff nitrogen loss and 46.9% runoff phosphorus loss. CSC could reduce 50.8% soil nitrogen loss, 50.7% soil phosphorus loss, 56.8% runoff nitrogen loss and 78.2% runoff phosphorus loss. SSC could reduce 62.1% soil nitrogen loss, 60.0% soil phosphorus loss, 46.1% runoff nitrogen loss and 67.2% runoff phosphorus loss. ASC could reduce 66.2% soil nitrogen loss, 66.7% soil phosphorus loss, 50.2% runoff nitrogen loss and 62.7% runoff phosphorus loss.

The type of crops planted in farmland soils has a direct influence on N&P losses. For example, in the Yujiahe River Catchment in Shaanxi, China, Chen et al. (2019) showed that while farmland only accounts for 28% of the land area, this accounted for 80.4% of the nitrogen loss in the catchment, and orchard soils accounted for 66.7% of the loss of available phosphorus. Furthermore, Wang et al. (2019d) conclude through simulation experiments in Henan Province, China that farmland is the land use most conducive to N&P loss followed by tea gardens and citrus orchards, while losses from forested land are comparatively low.

Most fertilizers contain N&P and, therefore, their application directly alters the concentrations of non-point source pollutants in agricultural soils. Bouraima et al. (2016) studied the loss of nitrogen and phosphorus under four fertilization methods (CK, without fertilizer; T1, combined manure with chemical fertilizer; T2, chemical fertilization; T3, chemical fertilizer with increasing fertilization) in Chongqing for five years (2010-2014). The study showed that compared with CK, T1 treatment can reduce 41.2% of TN loss and 33.3% of TP loss. In their study of 62 watersheds in Minnesota, USA, Boardman et al. (2019) found that fertilizer application at the crop-planting stage was the main cause of nitrogen pollution. Zhang et al. (2019) studied in Jialing River showed that N&P loss is positively correlated with fertilizer application rates; for every 10% increase in fertilizer application, N&P loss increased by 1% and 4%, respectively. Across China, Zou et al. (2020) showed that the application of chemical fertilizers has increased from 8.84 million tons in 1978 to 58.59 million tons in 2017, and the application of pesticides has also increased from 0.73 million tons in 1990 to 1.66 million tons in 2017. It can be seen that choosing the appropriate type and amount of fertilizer and applying it at the appropriate time are crucial to reducing water pollution.

3.3 Terrain

Topography determines the redistribution and intensity of runoff, which have a significant impact on slope erosion and nutrient transport (Zhao et al. 2016). For example, Wu et al. (2018) conducted artificial simulated rainfalls and found that as the slope rises, the dissolved TP lost with surface runoff increases significantly. Furthermore, in Tianmu Lake, East China, Zhang et al. (2020) report that variations in TN (7.0–10.0 mg/L) and TP (0.05–0.07 mg/L) concentrations entering the lake correspond to variations in the gradient of the surrounding slopes (8–16°). These studies also showed that topography (slope) is closely related to the loss of non-point source pollutants such as nitrogen and phosphorus. Bai et al. (2020) studied the characteristics of nitrogen and phosphorus loss in a special soil (degraded Ferralsols) under different slopes (10°, 15°, 20°) in Fujian, China. They found that when the slope is 15°, it is most beneficial to reduce the loss of nitrogen and phosphorus.

4. Ecological Treatment Technologies For Soil Erosion-type Npsp

Several studies have shown that increasing vegetation cover via measures including reforestation can be effective at reducing surface runoff and, thereby, reduce N&P losses and regulate NPSP (e.g., Hosseini et al., 2017). This has particular potential in water source areas as a means of controlling pollution inputs to rivers and lakes, and for improving water quality, reducing soil erosion, and maintaining biodiversity.

4.1 Ecological ditch interception technology

Ecological ditches (or vegetated agricultural drainage ditches; Fig. 1) are natural drainage ditches in which vegetation cover is increased to improve farmland drainage and stagnation (Zhou et al. 2008). Based on our synthesis of previous studies (Table 1), the TN removal efficiency of ecological ditches ranges from 10–80% depending on their length and type of vegetation. For example, Wang et al. (2019a) studied the pollutant-intercepting effects of three types of ecological ditches (soil eco-ditches, concrete eco-ditches, and concrete eco-ditches with holes in double-sided walls) planted with bitter grass (*Vallisneria natans*), finding that the latter type performed best. In another study by Nsenga kumwimba et al. (2020), ecological ditches planted with Japanese sweet flag (*Acorus gramineus*), parrot's feather (*Myriophyllum aquaticum*), and Siberian lag irises (*Iris sibirica*) reduced TN and TP pollutants by an average of 44% and 52%, respectively.

Table 1
Removal efficiency of non-point source pollutants in ecological ditches

Reference	Area	Type (Planting)	Removal efficiency
Nsenga kumwimba et al. 2020	Jialing rivers, China	200 m in length (*Acorus gramineus*, *Myriophyllum aquaticum* and *Iris sibirica*)	44% TN, 52% TP
Han et al. 2019	Erhai Lake irrigation zone, China	62 m in length (*Zizania aquatica*)	15.8% TN, 4.2%NO_3^--N, 22.8% NH_4^+-N
Han et al. 2019	Erhai Lake irrigation zone, China	58 in length (*Canna indica* L.)	11.6% TN, 8.4%NO_3^--N, 16.4% NH_4^+-N
Han et al. 2019	Erhai Lake irrigation zone, China	54 in length (*Pontederia cordata*)	27.9% TN, 17.8%NO_3^--N, 37.5% NH_4^+-N
Wang et al. 2019c	central Sichuan Basin, China	308 m in length (*Hydrocotyle chinensis* (Dunn) Craib and *Myriophyllum elatinoides* Gaudich)	47.97% TN in average, 49.79% TP in average
Vymazal et al. 2018	south-central Bohemia, Czech Republic	200 m in length (*Phragmites australis, Typha latifolia* and *Glyceria maxima*)	1070 kg $ha^{-1}yr^{-1}$ TN, 142 kg $ha^{-1}yr^{-1}$ TP
Soana et al. 2017	Milan, Italy	*Typhoides arundinacea* L. Moench and some submerged species	38–84 mmol N $m^{-2}d^{-1}$
Chen et al. 2015	Changsha, China	200 m in length (*Canna indica, Hydrocotyle vulgaris, Sparganium stoloniferum, Myriophyllum sp.*, and *Juncus sp.*)	75.8% TN, 63.7%NO_3^--N, 77.9% NH_4^+-N
Fu et al. 2014	Yixing, China	200 m in length [native plants (such as: Soybean, Bermuda grass, and Perennial ryegrass)]	31% NH_4^+-N, 27%TN, 26% TP

4.2 Purification by constructed wetlands

Constructed wetlands (CWs; Fig. 2) are a wastewater treatment and habitat restoration technology developed in the 1970s. The approach consists of a unique soil-plant-microbe-animal ecosystem composed of soil or substrate (e.g., slag and fly ash) in which aquatic plants are grown (Mander et al. 2015). Most studies of CWs have shown that TN and TP removal rates exceed 70% (Table 2). For example, Dzakpasu et al. (2015) studied the removal of N&P by reeds (*Phragmites australis*) and cattails (*Typha orientalis*) in CWs in the Zaohe River Basinr in Xi'an, China, finding that the N&P removal efficiency was 47.1% and 17.6% in the first year of operation and increased to 52.3% and 32.4% in the second year, respectively. This implies that the nutrient-removal efficiency increases over time in-step with plant establishment and growth. In the Erhai Lake area of Yunnan Province, China, Li et al. (2020a) showed that by the third year of operation, the removal efficiency of CWs with respect to non-point source pollutants reached 90%; nitrogen removal rates reached 43.3 g/day phosphorus removal reached 0.5 g/day, although seasonal effects were also observed.

Table 2
Removal efficiency of non-point source pollutants in constructed wetlands

Reference	Area	Type (Substrates)	Removal efficiency
Li et al. 2020b	Changsha, China	multi-stage surface flow constructed wetlands	1.0 g m^{-2} d^{-1} TN, 0.84 g m^{-2} d^{-1} NH_4^+-N, 61.3 mg m^{-2} d^{-1} NO_3^--N, 85.3 mg m^{-2} d^{-1} TP
Ge et al. 2019	32º07´56´´N, 118º56´56´´E	5640 mm×1480 mm×1200 mm (L×W×H) in total (pyrite)	87.7 ± 14.2% TP, 69.4 ± 21.4%
Xu et al. 2019		horizontal submerged constructed wetland with Ti-bearing blast furnace slag	77.54% NH_4^+-N, 71.07% TN
Gao et al. 2018		670 mm×300 mm×310 mm (L×W×H) in total (Electrolysis× biochar)	49.54% NO_3^--N, 74.25% TP
Dal Ferro et al. 2018	Venetian plain, Italy	semi-natural and reconstructed Free-Water Surface Constructed Wetlands	33.3–49.0% TN, 32.2–80.5% NO_3^--N
Vymazal et al. 2015		Hybrid constructed wetlands	92.5% BOD_5, 83.8% COD, 96.0% TSS, 88.8% NH_4^+-N, 79.9% TN

4.3 Deposition and purification in pre-reservoirs

In the late 1950s, pre-reservoirs began to be developed and researched as an effective technology for the control of NPSP. Pre-reservoirs provide water-storage functions to trap pollutants and subsequently discharge water into reservoirs following treatment by physical and biological techniques (Fig. 3). Zhang et al. (2006) proposed the ecological engineering of pre-reservoirs for NPSP control in the plain area including research on key technologies including ecological riparian construction, biological floating bed purification, biological manipulation, ecological permeable dams, and pre-reservoir operation control. After the implementation of the project, water quality and biodiversity have been significantly improved, and pollution loads have been reduced. For example, during dry and low rainfall periods, TN, TP, and suspended solids (SS) removal rates reached 65.1%, 45.3%, and 62.9% respectively. In comparison, during the initial stages of periods of heavy rain, the corresponding removal rates reached 70.5%, 84.6%, and 90.9%, respectively.

4.4 Vegetation buffer zones and biological interception technology

A buffer zone is a general term for a type of biological control measure for soil and water conservation and NPSP widely used in rural areas in China to control blockages and soil erosion, and improve channel stability (Liang et al. 2017). In most cases, vegetated buffer belts (Fig. 4) enhance the removal NPSP including N&P (Table 3). In the Valdivian area of Chile, South America, where a large number of natural forests have been converted to fast-growing eucalyptus plantations, Little et al. (2015) selected eight small watersheds to study the effect of natural forest buffer zones on nitrogen interception. They confirmed that as buffer zone width increases, the concentrations of pollutants including TN, dissolved inorganic nitrogen, nitrate-nitrogen, and particulate organic matter entering the local water bodies decreases. The same authors conclude that a 17–22-m-wide vegetated buffer zone is required to reduce the concentrations of TN and dissolved inorganic nitrogen to pre-plantation levels. In their study of the East African highlights, Alemu et al. (2017) also showed that a herb buffer zone of approximately 10 m can reduce TP, sediment, and nitrate-nitrogen losses by up to 99%, 94%, and 85%, respectively.

Table 3
Removal efficiency of non-point source pollutants in vegetation buffer zone

Reference	Area	Type	Removal efficiency
Jabłońska et al. 2020	Central Poland	wetlands	34-92% TN, 17-63% TP
Zak et al. 2019	Fillerup, Denmark	non-woody vegetation buffer zone (emergent plants, submerged plants, phytoplankton)	30±19% NO_3^--N, 31±16% TN, 44±10% TP
Zak et al. 2019	Fillerup, Denmark	woody plant vegetation buffer zone	37±17% NO_3^--N, 38±16% TN, 52±12% TP
Alemu et al. 2017	Sekoru, Ethiopia	10m herb	The concentration of TSS decreased by 0.775 mg/L, the concentration of TP decreased by 0.0653 mg/L, and the concentration of NO_3^--N decreased by 0.262 mg/L
Aguiar et al. 2015	Cará-Cará River, Brazil	woody	99%TN, 99%TP
Aguiar et al. 2015	Cará-Cará River, Brazil	sherb	66.4%TP, 83.9%TN
Aguiar et al. 2015	Cará-Cará River, Brazil	herb	61.6%TP, 52.9%TN

5. Conclusions

In the face of global socio-economic development, the need for environmental protection is growing. To effectively address emerging environmental problems in drinking water source areas, connected elements from upper and lower mountain areas, above and below ground stores, and upstream and downstream parts of watersheds should be considered holistically. In water source areas, integrated protection, restoration, and management are needed to enhance the circulation capacity of the hydrological systems and maintain ecological balance. In particular, the greater protection of drinking water sources and construction of water-conserving forests are required.

To achieve this, continued research is needed on (1) the forms and distribution of soil N&P with different vegetation cover types, (2) the effects of varying vegetation covers on soil N&P loss via surface runoff and soil flows, (3) the transport pathways and vertical movement of different forms of N&P within the soil, and (4) the accumulation and transport mechanisms of different forms of N&P in the soil in water source areas. Such work is required to provide the theoretical basis on which suitable technical interventions can be developed for the management of soil erosion-type NPSP in water source areas.

Declarations

-Ethical Approval

Not applicable

-Consent to Participate

Not applicable

-Consent to Publish

Not applicable

-Authors Contributions

CC and JZ designed the research. SS collected the data. RW analyzed the data and wrote the manuscript. All authors read and approved the final manuscript.

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-Competing Interests

The authors declare that they have no competing interests.

-Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1

Ecological ditches in Anji, Zhejiang, China

Figure 2

Constructed wetland in Anji, Zhejiang, China

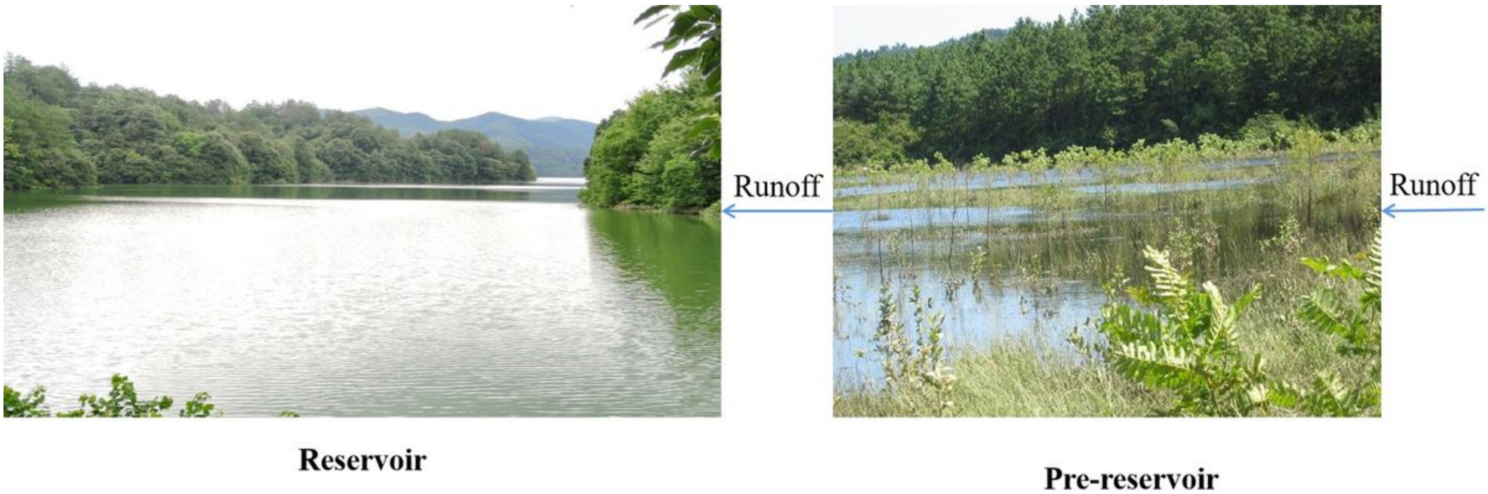

Figure 3

Schematic diagram of pre-reservoir

Before the runoff enters the reservoir, it is purified in the pre-reservoir to reduce the pollutants flowing into the reservoir

Figure 4

Vegetation buffer zone in Anji, Zhejiang, China