POLICY BRIEF

Key technologies and equipment for contaminated surface/groundwater environment in the rural river network area of China: integrated remediation

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Abstract

To realize the integrated remediation of SW/GW and soil in the rural river network area, the integrated remediation in rural river network area project (IR-RRNA), funded by the Ministry of Science and Technology of the People's Republic of China, has been launched. In eastern China, the rural river network area (RRNA) is an anthropic active area characterized by its rapid economic development and high gross national product. However, the water environmental pollution in these areas is increasingly severe, which has greatly hindered their sustainable development. Especially, the frequent interactions between surface/groundwater (SW–GW) have intensified the pollution migration and transformation in RRNA. The IR-RRNA (2019–2022) will apply the related interdisciplinary and methodological knowledge to elucidate the transportation and transformation of pollutants in water and soil during SW–GW interaction and develop remediation technologies of surface water, groundwater, and soil suitable for the RRNA. In this way, to realize the remediation technologies integration for surface/groundwater and soil in RRNA and implementing application demonstration. Meanwhile, a technical guideline will be compiled for the integrated remediation suitable for the RRNA. This project is conducive to addressing the urgent environmental problems as well as promoting rural economic revitalization and ecological environment optimization.

Keywords: The rural river network area, Environmental remediation, SW–GW interaction, Soil remediation, The integrated remediation

Introduction

The river network is formed by the river mainstreams and their tributaries in the river basin, which is the result of the interaction between the environment and human activities. River networks have both ecological and social benefits for regional development, in particular in the human-modified landscapes. However, in recent decades, river networks have suffered extensive destruction due to the anthropic activities of urbanization and industrialization, and this issue is especially serious in many developing countries [1–3].

Rural areas in plain river network areas possess an increasingly important status as they are the main producer of food and other natural resources for urban areas. The management of urban river systems is considered at an administrative region scale which plays a key role in the economic well-being of people living in both rural and urban areas. However, with the rapid urbanization and industrialization, rural communities face more
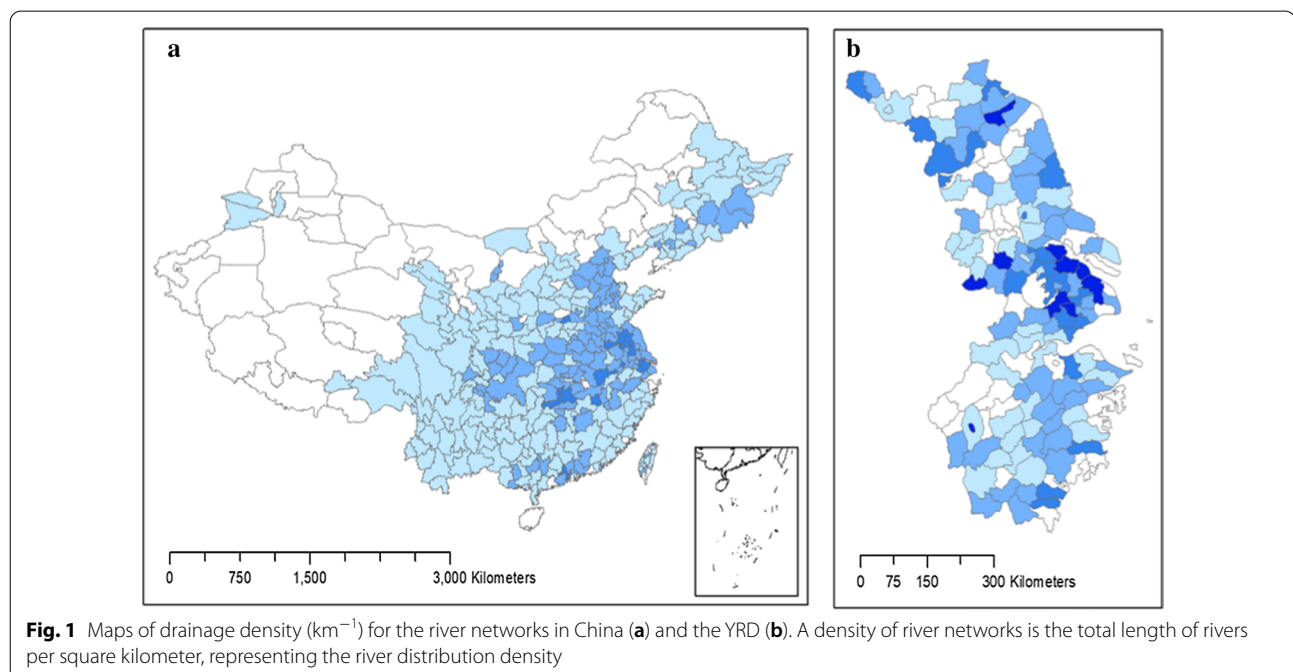
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pressures and risks from agricultural livelihoods, climate change, new technologies, commodity prices, environmental regulations, and economic conditions.

Rural development is hence a hot topic and challenging issue for human beings since the regional development has become more imbalanced between urban and rural areas in terms of population change, economic development, access to services, and social outcomes [4]. Accordingly, differential approaches have been proposed in worldwide for planning rapid and sustainable rural development. The strategies to cope with rural development have attracted wide attention and the differential approach for the planning of rural development has been proposed. For example, Participatory rural appraisal (PRA) has been launched, which describes approaches and methods for growing family to enable local people to share, to plan, and to act, by deep analyzing the status of the local people's life and living conditions, to plan and to act; Working With People (WWP) have been developed and implemented, and its connotation is that development projects, both in emerging countries and in the European Union, have to be developed by the people and not for the people [5, 6]. In China, the rural development means gradual change of developing rural villages into modern villages, as western developed countries have done. In 2013, the Ministry of Agriculture launched "the Beautiful Village Project" to promote sustainable development of rural areas, which has emphasized on the importance of protecting and preserving natural, landscape, and cultural resources protecting and preserving,

was hence developed. Therefore, the strategies to properly manipulate rural development are urgently required to effectively promote the environmental quality in the rural area.

The Yangtze River Delta (YRD) and the Pearl River Delta (PRD) are two Chinese regions with the highest river network density (the total length of rivers per square kilometer) (Fig. 1). Specifically, the values of the river density for these two deltas are both above 2.0 [7, 8]. Take the YRD (with a high river density of 6.7), for example, the YRD is located in the plain river network area where major national city clusters bearing national strategies, but it faces the great challenge of the severe water environment pollution issue [9]. According to the measurement results reported by state of the environment in China by Ministry of Ecology and Environment of People's Republic of China (2019) (http://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/), most of the rivers and lakes in the Yangtze River Delta, such as Taihu Lake, exhibited mild eutrophication [10]. Compared with urban river network areas, rural rivers are generally more remote, narrower, and more complex. Due to the different investments in river restoration, the rural river restoration lags that of urban rivers, and the capital investment and daily management are also insufficient. Pollutants are usually discharged into the rivers through surface runoff or drainage ditches without treatment. Indeed, it is reported that the effective treatment of domestic sewage in rural areas of China was only 11% [11]. The main manifestations of the water environmental pollution are as follows: (1) the

Fig. 1 Maps of drainage density (km^{-1}) for the river networks in China (**a**) and the YRD (**b**). A density of river networks is the total length of rivers per square kilometer, representing the river distribution density

river system is seriously divided, leading to poor water connectivity and weak hydrodynamics; (2) the encroachment of river course frequently occurs due to the rapid economy development and the high pollution load into rivers; and (3) black and smelly water, and eutrophication problems of water bodies are prominent, and the water function areas that meet the national standard rate are few. Indeed, these problems have become the major bottleneck hindering the sustainable development of the plain river network area [12, 13]. In January 2019, a country-level action plan for the protection and restoration of the Yangtze River released by the Ministry of Ecology and Environment and the National Development of the People's Republic of China, which clearly declared that the ecological and environmental improvement of the Yangtze River will be at the core of future work. Therefore, efficient control strategies are urgently needed to promote the quality of the water environment in rural plain river network areas.

It should be noted that the boundary zone of surface and subsurface is a complex environmental system where the mass (including pollutant) transformation occurs actively because of the active exchange of surface water and groundwater [14]. This situation is especially significant in the plain river network area in China where the underground water tables are generally high at -1 to -3 m [15]. Surface water bodies, such as streams, lakes, and reservoirs, frequently interact with groundwater, and their interaction is of great importance in the hydrologic processes of river basins [16]. Even a small exchange between surface water and groundwater (SW–GW) can deliver a noteworthy contribution of solutes to a groundwater body, causing severe pollution interaction. Moreover, the surface runoff, unsaturated zone movement, and other actions can offer the way through which pollutants move from the surface/groundwater to soil [17]. The soil layer is an important ecosystem that protects both groundwater and surface water from contamination due to its good filtering function, but it can also be contaminated if the pollutant from groundwater or surface water exceeds its carrying environmental capacity. Therefore, if the surface water in plain river network area is contaminated with undesired substances (e.g., heavy metals, organic pollutants), it is likely that these pollutants can move to different environmental compartments, e.g., soil, surface, and groundwater, and ultimately produce great negative impacts on human health, climate change, biodiversity, and food safety. The changing and complex contamination status in RRNA requires the efficient integration of diverse environmental techniques and equipment.

In this circumstance, the Ministry of Science and Technology of the People's Republic of China (MOST) launched "green livable village program," to improve the rural living environment and to promote the coordination of agricultural production, living condition, and ecological conservation. In the environment monitoring and remediation in rural (EMR-rural) project, one of the subprojects in "green livable village program" is the restoration of the contaminated surface water and groundwater bodies to meet the requirements of water environment improvements in the rural river network areas [18]. This project focuses on research and development of the integrated remediation of key technologies and equipment for contaminated surface/groundwater environment in the rural river network area of China.

The integrated remediation in rural river network area (IR-RRNA) project duration is 38 months (2019–2022), consists of 3 partners from China, including Tongji University, Central South University, and Donghua University. The IR-RRNA will focus on to (1) apply interdisciplinary and methodological knowledge to elucidate the transportation and transformation of pollutants in water and soil during SW–GW interaction; (2) develop key technologies of surface water, underground water, and soil environmental remediation in rural river network area; (3) implement the remediation technologies integration for surface/groundwater and soil in rural river network area and implementing application demonstration; and finally (4) compile technical guidelines for integrated remediation of surface/groundwater and soil suitable for the rural river network area.

Current research status of environmental remediation in the rural river network area

The Web of Science Core Collection annually collects thousands of journals to provide various records for each publication, including author information, journals, citation, and institutional affiliation, from multiple disciplines for bibliometric analysis. Different keywords were set to search and collect publications in the past ten years (2010–2019); the number of environmental remediation publications is shown in Fig. 2.

In the present study, the search for "surface water remediation," "groundwater remediation," or "soil remediation" all resulted in high numbers of publications and a rapid growth rate. However, only less than 1% of the studies focus on the "rural" or "river network" area. Also, the studies aimed to the remediation technologies for combined pollution are only less than 300 in recent 10 years ("Surface water + Groundwater," "Surface water + Soil," or "Groundwater + Soil"), and there is still a lack of research on integrated Surface water/Groundwater/Soil remediation.
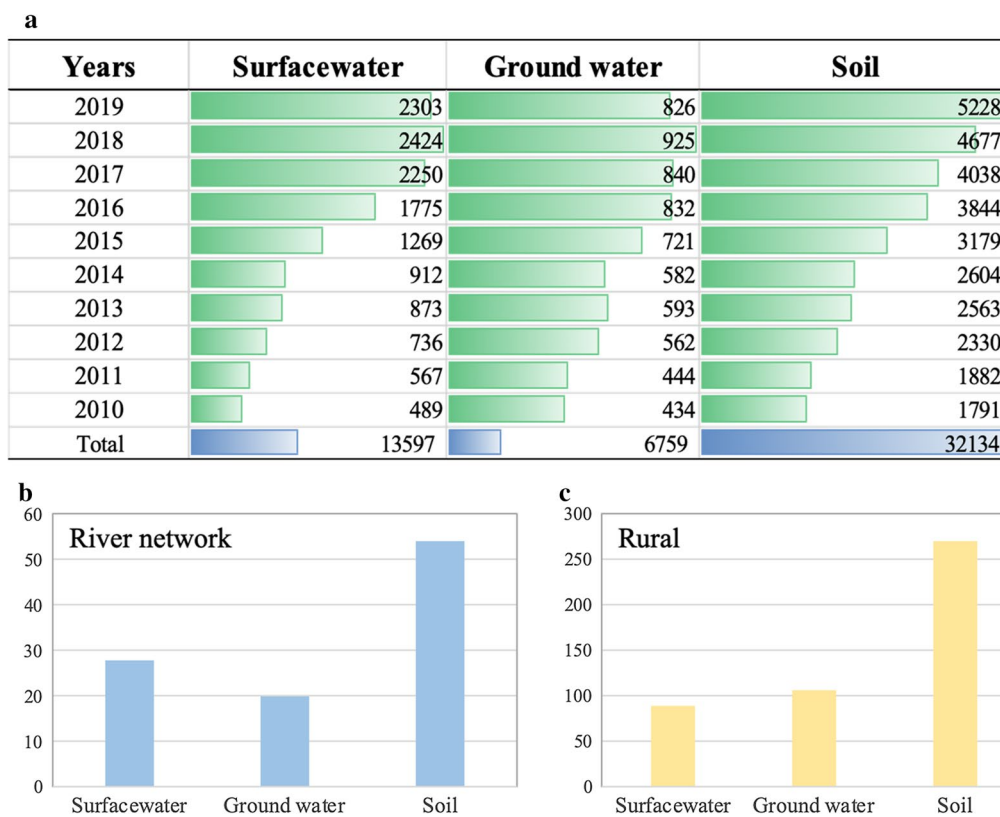
a

Years	Surfacewater	Ground water	Soil
2019	2303	826	5228
2018	2424	925	4677
2017	2250	840	4038
2016	1775	832	3844
2015	1269	721	3179
2014	912	582	2604
2013	873	593	2563
2012	736	562	2330
2011	567	444	1882
2010	489	434	1791
Total	13597	6759	32134

b River network

c Rural

Fig. 2 **a** Records for the environmental remediation terms, including surface water, groundwater, and soil, filtered by publication period (2010 to 2019); **b** records for environmental remediation in river network area; **c** records for environmental remediation in the rural area

Current research status of surface water remediation

Surface water pollution has become a severe threat to water resource sustainability and ecological safety in the world [19]. However, as surface water has a large amount and widely distribute, it could not be remediated by traditional centralized treatment technology, such as traditional coagulation sedimentation for the polluted surface water (e.g., adsorption, extraction, ion exchange, and membrane separation). Moreover, the contaminated surface waters are generally characterized by a relatively low concentration of pollutants compared to that of raw wastewater, e.g., total nitrogen (TN) < 10 mg/L and total phosphorus (TP) < 1.0 mg/L, so it might not be effective and economic to use the treatment technologies and equipment used for domestic sewage or industrial wastewater treatment [20]. Therefore, it is urgent to develop novel remediation technologies to prevent the deterioration of surface water quality (e.g., eutrophication) and maintain a healthy aquatic ecosystem.

In recent decades, a variety of studies have been carried out to remove contaminants from surface waters, including physical, chemical, and ecological methods (Table 1). Physical methods generally include dredging sediment,

mechanical algal removal, aeration, and water diversion, by which surface water pollution can be mitigated temporarily but without persistency effects [21, 22]. Chemical remediation requires chemical agents and adsorbents to change the redox potential and pH in surface water, by which suspended substances and organic matter in surface water can be adsorbed and precipitated [23, 24]. The chemical reaction between agents and pollutants will separate and recover harmful substances in water, or convert them into harmless substances. Although the chemical method can quickly function, it needs to add a large number of chemical agents that are expensive and prone to cause secondary pollution (e.g., chemical sludge). Moreover, the produced chemical sludge requires to be treated in the sewage treatment plants, which brings about a large amount of extra work and troublesome operation of sewage treatment plants.

Ecological remediation is a new in-situ remediation technology that plants and microbes work together to remove environmental pollutants [25–28]. The mechanism of the in-situ ecological remediation is mainly to use the metabolic activities of plants and microbes to absorb, accumulate, or degrade environmental pollutants. In-situ

Table 1 Key techniques for surface water remediation

| Remediation technique	Technique principle	Characteristics
Physic method		
Artificial aeration	Increase the dissolved oxygen of the water body, reduce the concentration of dissolved pollutants in water, improve the living environment for aquatic organisms	High cost, need to be combined with other methods
Sediment dredging	Dredging the whole or part of the river with serious deposition to restore the normal function of the river	A large amount of engineering, disrupt existing bio-systems
Mechanical algal removal	Using ultrasonic wave to make algal cell burst, break algal cell inside the airbag, make it lose float ability and precipitate	Unsustainable method
Chemical method		
Chemical precipitation	Adding iron salt or aluminum salt to produces chemical precipitation with inorganic phosphate through adsorption or flocculation, controlling the eutrophication	
Enhanced coagulation	Add the appropriate coagulant and the decontamination is carried out by adsorption, chemical precipitation, destabilization flocculation, and adsorption bridging	The addition of chemicals agents raises the cost and introduce secondary pollution
Acid–alkali neutralization	Acidic or alkaline substances are added to the water body to adjust the pH, meet the growing need and species reproduction in the aquatic ecosystem	
Chemical algal removal	Add chemical algal removal agent, the effect is remarkable	Water table damage, high risk
Ecological method		
Constructed wetlands	Simulates natural wetlands by extracting elements from them for artificial enhancement	Large floor space
Ecological floating bed	Using the principle of soilless cultivation, plants are planted in water and absorb nutrients directly from the water	Generally used to repair small rivers, lakes
Ecological revetment	Artificially reformed the river revetment to restore or strengthen the ecological capacity of water, which can protect the river bank and purify the water	Suitable for the long-term ecological remediation process

ecological remediation has many advantages when compared to other techniques, such as low costs, less adverse impacts on the environment, and no secondary production of pollutants. Indeed, many in-situ remediation processes, such as ecological floating bed techniques and constructed wetlands, have been developed for the bioremediation of polluted surface water and have exhibited satisfactory results [27, 28].

Ecological floating bed is a novel water remediation technology based on the traditional constructed wetland, which is featured with the dominant growth of aquatic plants or terrestrial plants on the surface of a water body. As an important component of the ecological floating bed, plants absorb the pollutant in water during their growth period and provide the attachment sites for microorganisms to grow through their developed plant roots. Sun et al. [29] investigated the remediation feasibility of ecological floating-bed systems using water spinach and sticky rice, and found that the total nitrogen removal rates reached 92.3% and 81.2%, respectively. Meanwhile, introducing the appropriate carrier in the ecological floating bed can promote the growth of plants and improve their ability to resist contamination stress. A study adopting plant *Acorus calamus* L. in the ecological floating bed demonstrated that the green zeolite was the best substrate for *Acorus calamus* L. to uptake metals, and the removal efficiencies of Cr and Cd were up to 95.24% and 91.8%, respectively [30].

Current research status of groundwater remediation

Groundwater and surface water have been managed as an isolated medium for a long time, but actually, they are hydrologically connected in terms of both water quantity and quality [31]. The physical interactions between groundwater and streams primarily depend on two factors: (i) the geological context and permeability degree of an aquifer in comparison to a streambed and (ii) the relationship between the river water level and piezometric level in the vicinity of the river. Generically speaking, the interactions between SW and GW take place in three basic ways: (i) steams gain water from the inflow of groundwater through the streambed (Gaining stream) (Fig. 3a); (ii) streams lose water to groundwater by outflow through the streambed (Losing stream) (Fig. 3b); (iii) do both (i) and (ii), gaining and losing stream. Thus, most of the groundwater contamination in shallow aquifers that are directly connected to surface water [32, 33].

Fig. 3 The two type of interactions between SW and GW
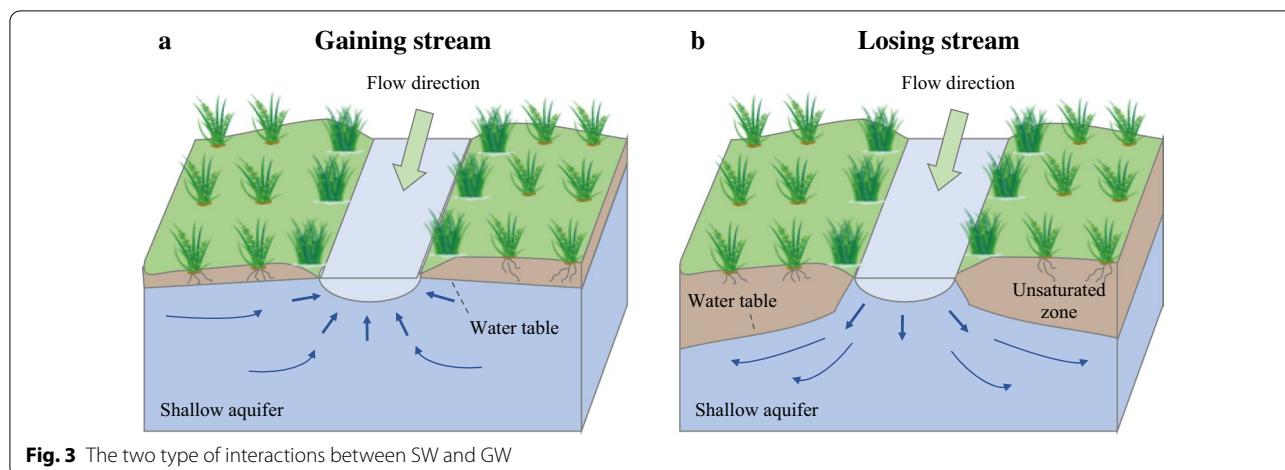
Groundwater is a very important source of agricultural irrigation and the domestic supply of drinking water for both human beings and animals in the world. To ensure the safety and sustainability of groundwater resources, numerous remediation technologies have been developed to remove pollutants from groundwater (Table 2). Pump-treat is one of the earliest groundwater remediation strategies that widely applied previously [34, 35]. However, some factors in terms of the treatable pollutants, cost considerations, cleanup efficiency, and secondary contamination have become limitations to the successful remediation of the contaminated sites. Therefore, in recent years, the combination of pump–treat with other alternative technologies has been proposed, such as chemical oxidation processes and bioremediation, to enhance the removal efficiency and lower the operational cost [36, 37]. Some novel techniques have also been developed by integrating conventional treatments with modern technologies, such as nano-material technology [38]. It is reported that permeable reactive barriers (PRBs) with nano zero-valent iron (nZVI) immobilization and packaging materials have a good capability to

Table 2 Key techniques for groundwater remediation

Remediation technique	Technique principle	Characteristics
Ex situ		
Pump and treatment	Groundwater is extracted and sent to the sewage treatment system for decontamination	Suitable for the treatment of soluble pollutants
Excavation method	The method of soil excavation can be used to treat and remediate the polluted groundwater	Only suitable for a small range of groundwater pollution
In situ		
Bioremediation	Utilize microorganisms to transform contaminants into less harmful daughter-products	Long processing time, need the integrated application
Air sparging	Inject air into the aquifer, and the pollutants in the groundwater move into the vadose zone with the air. Combine with the soil vapor extraction method to treat the pollutants in the groundwater	Suitable for soil with good permeability and homogeneous quality
Electrokinetic remediation	The charged ions of the metal undergo directional migration under the influence of the electric field force, and the pollutants eventually gather together for centralized treatment	Suitable for organic and heavy metal pollution
Chemical oxidation	Carried out by oxidizing reaction between oxidizing agent and pollutant in groundwater	Easy to affect the geological and ecological environment
Permeable reactive barrier	A trench is excavated downstream of the hydraulic gradient of the groundwater to form a reaction wall. When the sewage flows through the reaction wall, the pollutants in the groundwater are adsorbed, oxidized, and biodegraded	Low cost and large application scope

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improve the decontamination efficiency [39, 40]. Also, the performance of PRBs filled with nZVI was satisfactory in the removal of heavy metal ions, such as mercury, chromium, lead, zinc, nickel, and copper, and the percentage of removal was usually > 90% [40]. Traditionally, the PRBs have dimensions of < 5 m in width (parallel to flow), 10 m in depth, and 50 m in length (transverse to flow), and these barriers are filled with reactive media. There are two designing patterns of PRBs for the practical applications: the funnel-and-gate pattern which with relatively expensive construct fee but allows for pockets of plumes widely distributed to be captured for treatment; the other one is the continuous gate pattern, which are easy to realize but only suitable for plumes with narrow widths [41]. Recent studies have focused on the modifications of these two original PRBs designs, such as filling new remediation materials and adopting multi-barrier concept, to broaden the applicational area of PRBs.

Current research status of soil remediation

In the river network area, the riparian zone is the transition area between land and aquatic ecosystems (Fig. 4), and its ability to provide aquatic habitat and process chemical (including contaminants) varied along with the varying water source [42]. Soil filtration in the riparian zones can mitigate the negative effects of non-point source pollution on water quality, and plant absorption is capable of improving interactions between the roots and pollutants (e.g., nitrogen, subordinately phosphorous, and heavy mental) [43]. Thus, a better understanding of the riparian zone and create corresponding effective soil remediation technology is significant if the water quality requires to be effectively managing.
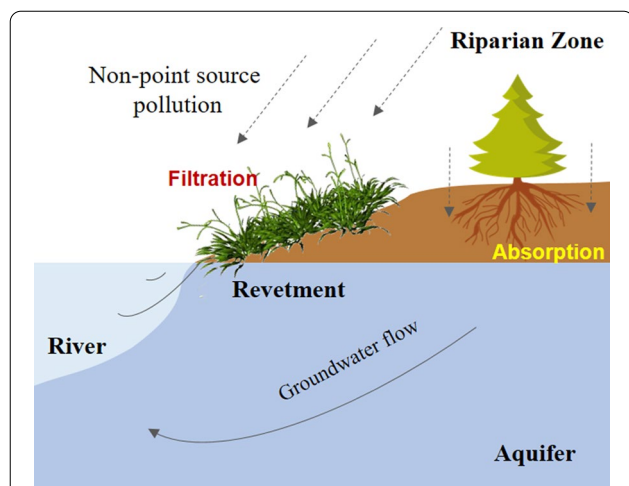

Fig. 4 Soil function on pollutant transfer between land and aquatic ecosystems in the riparian zone

Soil pollution could cause profound impacts on crop productivity and human health. Accordingly, investigation of the sources, fate, and occurrence of soil pollution, as well as the induced risks to human health, has been an important topic in the ecological environmental area [44]. The results of the National Soil Pollution Status Survey Bulletin show that the overall national soil environment is not optimistic and three main pollution characteristic have occurred. (i) The soil pollution in China is mainly inorganic pollution, followed by organic pollution; (ii) eight inorganic pollutants of cadmium, mercury, arsenic, copper, lead, chromium, zinc, and nickel have a point exceeding rate of 7.0%, 1.6%, 2.7%, 2.1%, 1.5%, 1.1%, 0.9%, and 4.8%, respectively; and (iii) the soil pollution problems in some regions such as the YRD and the PRD are more prominent (National Soil Pollution Status Survey Bulletin) [45]. For example, the Dabaoshan mining area in Guangdong province has caused serious pollution of surrounding farmland and crops, leading to frequent illnesses in the downstream Shangba Village. Moreover, pollutants in the soil could affect the reproduction of plants, soil animals, and microorganisms, endangering the normal soil ecological process and ecosystem service functions [46].

The soil remediation techniques can be classified into two categories (i.e., in situ and ex situ), and are mainly affiliated to physical–chemical and ecological remediation (Table 3). The selection of the appropriate remediation technology depends on several factors, such as the characteristics of the hydrogeological environment, chemical and physical properties, of the contaminants, and financial resources. Due to the occurrence of complex compounds in soil, using the combined remediation technology (more than one) to comprehensively remediate the contaminated soil is often the case [47, 48].

Phytoremediation contains the processes of phytodegradation, phytoextraction, phytostabilization, phytostimulation, phytovolatilization, and rhizofiltration, to achieve extraction, degradation, or metabolization of toxic substances (Table 4). Phytoremediation has been increasingly used for soil remediation in recent years as it has a remarkable co-benefit, including providing a plant cover to the soil and reducing soil erosion. Cui et al. [49] conducted a phytostabilization experiment in polluted soil, and found that *Pennisetum sinese* successfully decreased soil availability of Cu and Cd. A study of the methylation process of 2,4-DBP by rice plants showed that phytovolatilization of 2,4-DBP contributed to 41.7% of their total volatilization, enhancing the emission of contaminant from hydroponic solution into the atmosphere [50]. Moreover, in the practical pollution remediation process, adopting multiple phytoremediation technologies are more favorable to the removal of

Table 3 Key techniques for soil remediation

Remediation technique	Technique principle	Characteristics
Physical–chemical remediation		
Vapor extraction	Drive air through the pores of the contaminated soil, thereby entraining VOCs to the extraction system, pumping to the ground, and then collecting and processing	Suitable for unsaturated areas, sites with strong permeability, and volatile organic pollutants
Thermal desorption	The organic pollutants in the soil will accelerate decomposition and volatilization during the heating process, and the contaminated gas is extracted and collected from the soil through the suction system to process	Suitable for volatile organic matter and semi-volatile organic matter
Immobilization/stabilization	Immobilization: encapsulating soil pollutants in a solid material with complete structure; Stabilization: transfer pollutants into a state or form that is not soluble, transportable, or less toxic, reducing the bioavailability of pollutants	Contaminants cannot be fundamentally removed
Chemical redox	Add oxidant or reducing agent to contaminated soil, through oxidation or reduction, so that the pollutants in the soil into non-toxic or relatively less toxic substances	Not suitable for remediation of heavy metal contaminated soil
Soil washing	The eluent is injected into the contaminated soil, with the help of chemical/biochemical solvents that can promote the dissolution or migration of pollutants, transfer pollutants from the soil phase to the liquid phase. The wastewater from the elution system should be further treated	Not suitable for soil with a fine (clay/powder) content of more than 25%
Ecological remediation		
Phytoremediation	Use plants for extraction, rhizosphere filtration, volatilization, and fixation to remove, transform, and destroy pollutants in the soil, so that the polluted soil can restore its normal functions	Long processing time and slow results
Microorganism remediation	The method of transforming, degrading, and removing pollutants in the environment by using indigenous microorganisms in the natural environment or artificially adding exogenous microorganisms	Suitable for integrated use with other methods

pollutants. For example, phytodegradation is always used to degrade organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), herbicides, and pesticides; simultaneously, *Sedum alfredii Hance* and *alfalfa* are the good remediation plants for the in-situ phytoremediation of polycyclic aromatic hydrocarbon in rural areas of North China; by adopting both phytodegradation and phytoextraction processes, the total PAH concentrations could be greatly decreased by 82.4% and 81.3% [51].

For heavily polluted soil cases, soil washing is an effective remediation approach [52, 53]. This technology combines physical and chemical processes to remove heavy metals from contaminated soil by ex-situ washing soil with the eluent. During the washing process, the polluted soil is excavated from the contamination site and is washed by the injected eluent, during which chemical/biochemical solvents are also added to promote the pollutants dissolution or migration. Thus, pollutions, such as heavy metals, can be transferred easily from the soil phase to the liquid phase. The remediated soil will be returned to the original site, and the wasted washing

effluent will be recycled for the subsequent soil wash processes or discharged to a wastewater treatment facility for disposal. Soil washing is of short duration and can be cost-effective, but not suitable for the soil with a fine (clay/powder) content of more than 25%.

Current research status of combined remediation technologies

In the practical remediation process, only using one technology has several disadvantages and limitations; thus, techniques using combined methods to remediate heavily polluted surface water, groundwater, and soils have been attracting increasing attention. The typical combined remediation technologies are shown in Table 5.

An appropriate use of combined remediation technology can greatly improve the environmental restoration performance, and has a good applicational potential as well. In-situ bioremediation has been developed for polluted water and soil, but they possess some disadvantages, such as being time consuming and limited removal rate for the heavily polluted sites. In the surface water

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Table 4 Types of phytoremediation technologies

Technique principle	Technique principle	Characteristics
Phytodegradation	Degrade the absorbed contaminants into less toxic compounds, either by plant's metabolic process or enzymes	Most suited for moderately hydrophobic organic chemicals
Phytoextraction	Absorb organic matter from the soil into the plant body through plants that have an enrichment effect on pollutants	Depends on the bioavailability of pollutants
Phytostabilization	Decrease the mobility and bioavailability of pollutants by root adsorption or insoluble compounds formed in the root zone, preventing pollutants leaching to ground water and the food chain	Does not reduce the concentration of pollutants but reduces the contamination of nearby media/area
Phytostimulation	Plants release specific root exudates (enzymes, organic acids, etc.) to enhance the growth and activity of microorganisms in the soil, accelerating the removal of pollutants	Cannot be done alone by the plant, always has close interaction between the microorganisms in rhizosphere
Phytovolatilization	Employs the plant-mediated uptake of pollutants, then transforms them into volatile compounds, and releases these compounds in the atmosphere by its metabolic and transpiration pull	Does not completely remove the pollutants from the environment
Rhizofiltration	Adsorption or precipitation of pollutants by plant roots	Requires a full understanding of the contaminant speciation and interactions of all contaminants and nutrients

Table 5 Combined application of remediation technologies

Combined remediation technique	Technique principle
Surface water	
Ecological restoration—aeration	Aeration could improve the DO contents of polluted black-odor rivers to a certain extent, and had a significant effect on the transformation of all forms of N as well as the microbial activity
Ecological floating bed—biofilm	Make full use of water vertical space, and provide more attaching surface area for microorganisms
Ecological revetment—ecological floating bed	The ecological revetment intercepts a large amount of non-point source pollution carried by rainwater when it flows into the river, and the ecological floating bed further remediation river pollution
Groundwater	
Bioremediation coupled with nZVI	The corrosion of nZVI creates a suitable reducing environment for the growth of anaerobic bacteria and supplies electrons to the hydrogenotrophic bacteria and enhances the removal efficiency of pollutants
UV/H_2O_2 photo-oxidation—aeration	Volatilization, co-precipitation and biodegradation contributed to organic compounds removal during the combined remediation process
Bioelectroremediation	The combination of anodic and cathodic redox environments with microbial metabolism paves the way for the development of a variety of intriguing and beneficial removal pathways
Soil	
Phyto—microorganism	Microorganisms promote the extraction of heavy metals by plants and enhance the removal of heavy metals in the sediment; The compartmentalization of heavy metals in microbial cells, chelation, and fixation of metabolites can reduce the ability of heavy metals to migrate
Phyto—stabilizing agent	The chemical stabilizing agent can change the existing forms of heavy metals in the through adsorption or coprecipitation, improves the effect of phytoremediation of heavy metal polluted sites
Soil washing—effluent oxidation	The surfactant was selected as washing agents to extract pollutant from contaminated soil samples. After washing, the effluent containing surfactant and pollutants was collected further degradation treatment using effluent oxidation technique
Soil washing—freeze–thaw	Destroy the original structure of soil particles by freeze–thaw, help the eluent fully interact with pollutants, and thus improve washing efficiency

remediation process, the use of biofilm carriers in ecological floating bed could promote microbial richness and diversity, and many nitrifying and denitrifying bacteria would adhere to the biofilm carriers. Therefore, nitrification can be enhanced by 9–25%, and the emissions of N_2O and CH_4 were reduced by 11–70% and 7–59%, respectively [54]. For groundwater remediation, bioremediation was always combined with chemical remediation approaches using nanomaterials. The corrosion of nZVI could reduce the oxidation–reduction potential (ORP), which could create a suitable reductive environment for the growth of anaerobic bacteria, to completely degrade the contaminants into non-toxic or harmless substances [39]. In the process of soil plant–microorganism combined remediation, microorganisms can promote extraction and degradation of pollutants in the rhizosphere by changing the pollutant form and expanding the extension range of plant roots; meanwhile, plant root exudates in a natural environment can increase the organic matter content of the rhizosphere soil, contributing to a significant improvement in the activity of rhizosphere microorganisms as well as the biodegradation rate of pollutants in soil [55].

The other combined remediation techniques also developed successfully in recent years. For example,

ecological remediation technology is also often combined with artificial gas exposure to improve the remediation effect. Fan et al. (2016) examined a horizontal subsurface flow-constructed wetland with intermittent aeration and showed that the average removal rates of COD, ammonia nitrogen, and total nitrogen could be improved to 95.6%, 96.1%, and 85.8%, respectively [56]. Besides, aeration can strongly promote the removal efficiency of organic compounds in groundwater. The combination of UV/H_2O_2 treatment and simple aeration was also demonstrated to be very effective for monoaromatic compounds, including chlorobenzene [57]. Similarly, Yan et al. (2015) effectively remediated nitrobenzene (NB)-contaminated soil using combined surfactant-enhanced soil washing and degradation of nitrobenzene (NB) in effluent with persulfate, with the NB removal rate of over 97% [58].

Planning progress of IR-RRNA project
Case history and description
The main river network area YRD, located in East China, is one of the China's most developed, dynamic, densely populated, and concentrated industrial areas. In recent decades, the YRD has grown into an influential world-class metropolitan area and played an important role in China's economic and social development. In general, the

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boundary of the YRD varies from different perspectives in terms of its culture, economy, or geography. This paper refers to the area composed of Shanghai, Jiangsu, and Zhejiang provinces.

Since 1970, owing to the strong Shanghai's industrial base, the cities along the Yangtze River have caught up in the development of non-agricultural industries through rural collective accumulation. In these rural areas, the "five small industries" (small-scale steel, machinery, chemical fertilizer, coal, and cement industries) were allowed and started to grow [59]. Since then, those towns with more rural industries became ideal places for farmers to work or do business in the YRD. Without exception, the YRD's rapid industrialization has huge impacts on its natural environment, i.e., water pollution, groundwater levels decline, and soil pollution have become prominent problems. According to the Shanghai Environmental Protection Agency in 2007, non-point source pollution has become the main factor affecting the stream quality of rural river network area, outpacing industrial point source pollution in the 1990s. Notably, because stream order and catchment boundaries are difficult to delineate in these river networks, the effect of land use on water quality may be quite different than that in other areas. Furthermore, the ecological degradation in the YRD is also serious, and the involved issues in terms of land degradation, loss of biodiversity, and serious ecological damage all have brought serious threats to human survival and sustainable development [60, 61].

Research methodology and approach

The IR-RRNA project aims to develop effective integrated remediation techniques and equipment for water environment remediation. It should first clarify the basic information, such as the typical pollution in the YRD, the pollution distribution and interactions between water and soil, and the migration and transformation mechanism of pollutants in the water/soil. Accordingly, the literature survey and the typical pollution investigation will be conducted in the RRNA, combined with the collection of the village type and environmental pollution data. A comprehensive analysis will then be conducted to elucidate the distribution of typical pollutants over the RRNA. The scientific principles of ecology, microbiology, and hydrology will be applied to study the process of the pollutant migration and transformation between SW–GW–Soil. Finally, the field pollution survey, experimental methodology, and computer simulation models will be integrated to clarify the migration process of flux between SW/GW, the transformation mechanism of pollutants, and the characteristics of the inner relationship. By this way, the regulation principle of surface, soil,

and groundwater pollution remediation technology in RRNA will be revealed.

Based on the above theoretical study, bench-scale and pilot-scale tests will be conducted for polluted surface/groundwater and soil remediation in RRNA. Combining with the theoretical and process analysis, as well as fitness-for-purpose assessment, three key remediation technologies will be formed for three different media with the advantages of "high efficiency, environmental friendliness, and economy": (1) aquatic plants and microorganism coupling strengthening remediation technology for surface water; (2) nZVI coupled biochar sustained-release remediation system for groundwater; and (3) high efficiency multi-dimensional continuous pollution soil remediation technology using plant-microbial and chemical stabilization. Simultaneously, the outcome of the pilot study will be combined with the theoretical analysis of technology process and pollutant characteristics, to explore the economical, applicable, and easy to hand equipment for the different rural environment remediations. Finally, one or two pollution scenarios will be simulated in RRNA, and systematically study the feasibility of using integrated remediation technology to remediate the contaminated surface/groundwater and soil under different influencing factors, and then establish an efficient and sustainable integrated remediation pilot system.

Considering that the in-situ contaminated environments are complicated and hard to simulate in the laboratory, a field demonstration will be carried out in the project. This field demonstration is characterized by the integrated remediation technique and will be implemented in rural river network areas in Shanghai. In consideration of the natural climate conditions and hydrological characteristics, the project will make full use of the spillover effect and carry out integrated remediation in typical pollution sites in RRNA. This platform will take consideration into the complexity of environmental medium and natural biogeochemical processes to form an environmental restoration system that is suitable for the different time and spatial scales, and finally to realize the integrated remediation for contaminated surface/groundwater and soil in RRNA (Fig. 5).

Key technologies and equipment for integrated remediation

The RRNA remediation project supports the overall target of developing key techniques and devices for rural environmental remediation in RRNA. The selected remediation techniques, such as phytoremediation, microbiological remediation, nZVI/biochar remediation, and chemical stabilization, will be combined, regulated, and optimized to effectively restore the polluted water and
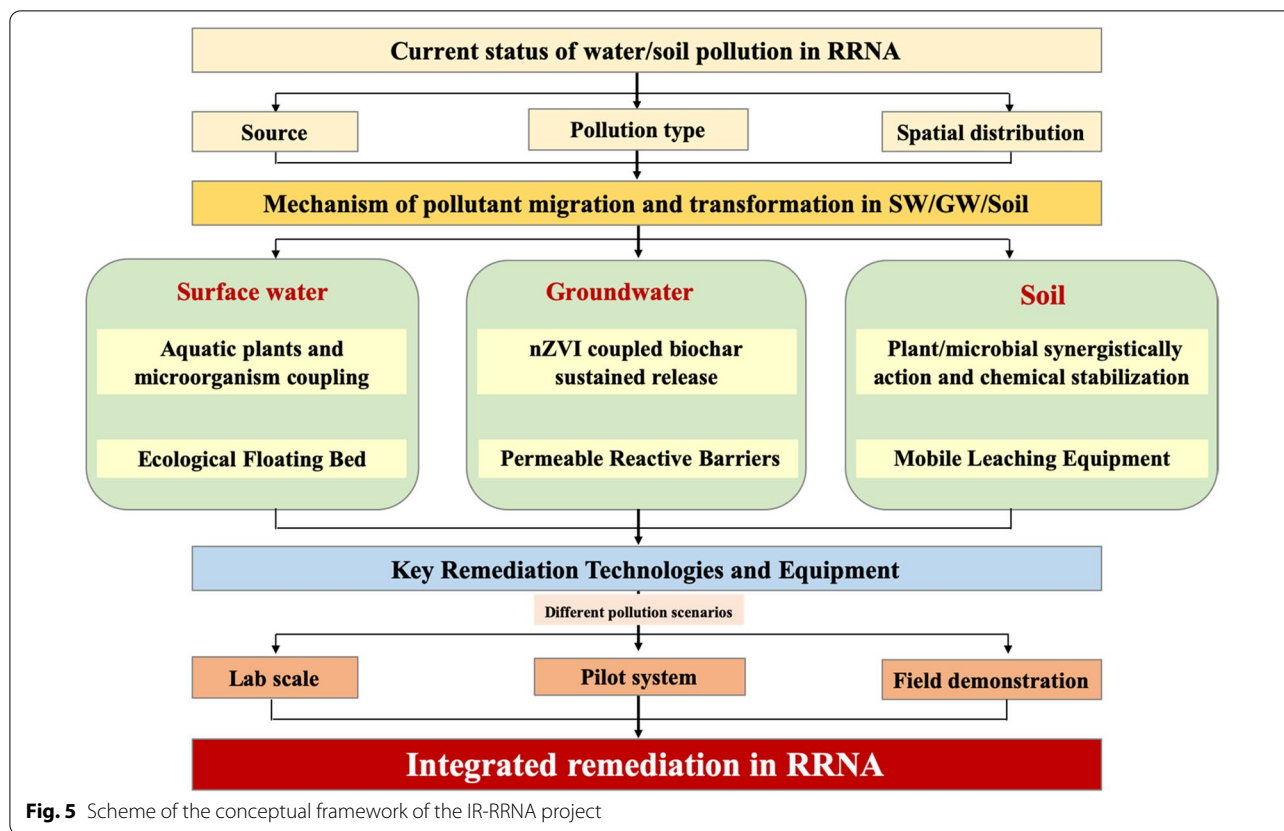
Fig. 5 Scheme of the conceptual framework of the IR-RRNA project

soil. Afterward, an integrated technical system will be created, including ecological reaction revetment, ecological floating bed, permeable reaction walls, mobile soil leaching device, and plant/roots–microorganism coupling remediation techniques, and ultimately to realize the efficient integrating of the plant, microorganism, and chemical stabilization for the contamination remediation in RRNA (Fig. 6).

River revetment is an important area of the land–water ecotone with comprehensive functions, such as safety protection, ecology, and landscape. It also acts as a connection channel between the river ecosystem and the terrestrial ecosystem. However, to accelerate the drainage of rainwater and protect the riverbank from soil erosion, a large number of riverbanks have been cut straight and channelized by constructing revetments in past years, resulting in serious damage of the ecological function of these riparian ecosystems [62]. Consideration of improved people's awareness in ecological and environmental protection as well as the preliminary filed investigation in RRNA, our project put forward an in-situ ecological reaction revetment construction plan. The outcome of this project could facilitate the sustainable circulation of SW/GW and river bank ecological restoration.

Eco-restoration materials for concrete revetment, aquatic plants, and PRBs are the main constitutes of the ecological reaction revetment. The native aquatic plants with a strong tolerance for pollutants will be selected to fix water pollutants via adsorption, accumulation, and degradation reactions. The plants' roots further provide a favorable habitat for microbial reproduction and stimulate microbial proliferation. Microbial consortia can help improve the water quality and maintain the stability of river slopes. In the laboratory, one or two native aquatic plants that with good pollution removal capacity will be chosen, and the plant/microbial interaction effect will be examined, based on which we attempt to develop an optimized strategy to effectively promote the mass and energy cycle among water/soil and plants/microorganisms.

The PRBs that consist of nZVI/biochar sustained-release materials will be installed parallel to the revetment, in the path of a plume of contaminated surface and groundwater. Compared with the previous vertical installation method, it can dramatically drive down treatment costs and achieve better interception of pollutants in surface water. As the contaminants move through the nZVI/biochar material, the reaction occurs that transforms the contaminants into less harmful (non-toxic) or
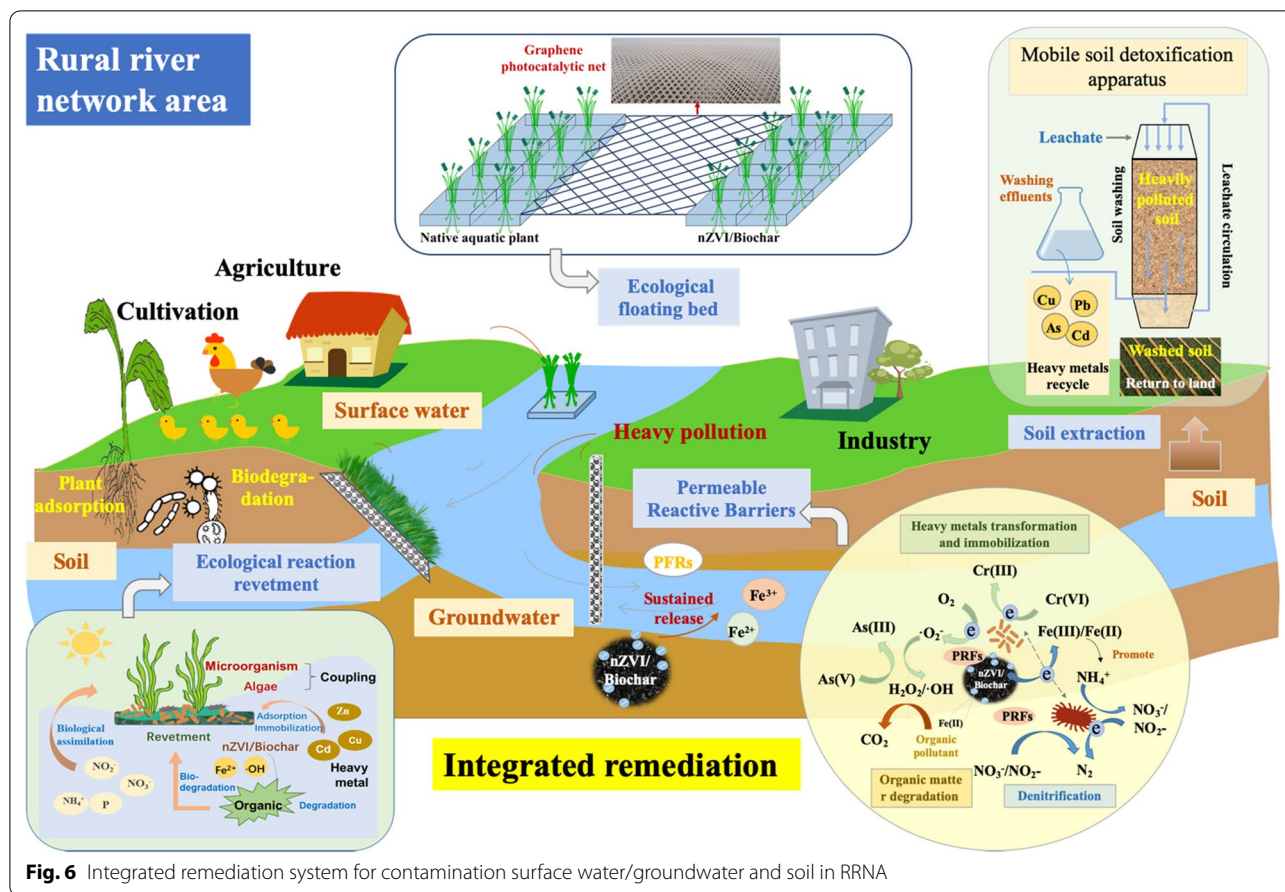
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Fig. 6 Integrated remediation system for contamination surface water/groundwater and soil in RRNA

immobile species. For instance, nitrates will be reduced to N_2 and/or NH_4^+ by nZVI and the addition of biochar could be favorable for this process, as NO_3^- can be selectively reduced to N_2 instead of NH_4^+ [39, 40]. The PRBs are a barrier to the contaminants rather than a barrier to the groundwater. Therefore, PRBs should be designed to be more permeable than the surrounding aquifer materials so that the contaminants are removed as groundwater readily flows through but without significantly altering the groundwater hydrogeology.

Phytoremediation can improve the biological quality of the soil and has been recognized as a benign technology, so it has been selected for our project to degrade, accumulate, or stabilize of contaminants in the polluted aquatic systems. Prior to establishing the demonstration project, the native plant species that have an extremely high capacity of adsorption of metals will be selected firstly, affiliated with the microorganism-based remediation technologies to decompose, transform, and absorb pollutants. For the heavily polluted regions caused by long-term industrial production, the contaminated soil will be moved to a mobile

soil washing device (a kind of ex-situ technique), and the contaminants (heavy metals) will be extracted and washed from soils by physical and/or chemical procedures. Meanwhile, a novel ecological floating bed has been proposed in our project that integrates graphene photocatalytic materials, act as a net between ecological floating bed.

The graphene, as a two-dimensional monolayer of sp2-bonded carbon atoms, was used for contaminants removals due to its large specific surface area, good charge transportation, and mechanical strength [63]. Then, the purification capacity and the stability of the ecological floating bed system can be greatly promoted, which favors flexibly to cope with the fluctuation of the water quality of the polluted river.

It should be noted that the integrated remediation system proposed in IR-RRNA project will fully consider the impact of pollution types, pollution levels, and hydrological conditions in different scenarios, and flexibly control the operation of the remediation system, to realize the optimal integration of surface/groundwater/soil remediation in the RRNA in China.

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Research prospect

The implementation of the IR-RRNA project will form several key technologies, equipment, and integrated technical systems. These outcomes can more effectively support environmental monitoring and restoration in (Chinese) rural areas or (in China), ultimately favoring construction of "green livable village" of China. The benefits of this research mainly include the following: (i) The developed novel technologies, products, equipment, and remediation systems will be continuously applied to demonstration and supporting projects, which will create investment benefits by several times the research investment. (ii) The improvement of the water and soil environment quality in the rural area will greatly improve the people's quality of life which provides significant social benefits. (iii) The practice of the novel remediation technology will remediate the polluted environment, increase the value of natural resources in the environment and ecology, and provide a beautiful environment for the sustainable development of the rural area, which have good ecological benefits.

China is a large country with a vast land area, so the climate, hydrogeological conditions, and developing history in different Chinese regions vary greatly. Future research will take into consideration of the complex environmental medium and natural biogeochemical processes in different rural areas, to form an environmental restoration system that is suitable for different spatial scales in China, such as mountain areas and cold regions. Also, comprehensive environmental management and government policy are important means to achieve the harmony between human beings and nature. The effectively environmental management system will be perfected continuously in practice, and further serves for the construction of rural revitalization and eco-environment improvement.

Conclusions

In our project, multiple research methods, such as the multi-disciplinary theory application, in-situ sampling investigation, lab-/pilot-scale experiment, and integrated field determination, will be applied to develop an applicable integrated remediation technique and equipment for complex rural river network. The IR-RRNA project will clarify the key factors affecting the rural environment and address the urgent environmental problems in rural areas, based on which effective integrated remediation techniques will be developed to realize the integrated remediation of surface water/soil/groundwater. Our work highlights the importance of integrated environment remediation in the rural river network area. The outcome of the project hopes to favor realization of rural economic revitalization and ecological environment optimization.

Abbreviations

IR-RRNA: The integrated remediation in rural river network area project; RRNA: The rural river network area; SW: Surface water; GW: Groundwater; PRA: Participatory rural appraisal; WWP: Working with people; YRD: The Yangtze River Delta; PRD: The Pearl River Delta; MOST: The Ministry of Science and Technology of the People's Republic of China; EMR-rural: The environment monitoring and remediation in rural; PRBs: Permeable reactive barriers; nZVI: Nano zero-valent iron; NB: Nitrobenzene.

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