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Optimal resource utilization and ecological restoration of aquatic zones in the coal mining subsidence areas of the Huaibei Plain in Anhui Province, China

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ABSTRACT

Extensive land subsidence and submergence occurs in the coal mining areas of the Huaibei Plain in Anhui Province, China due to their unique geological features. It has significantly changed local landscapes and the implications for water conservation. The quantities and qualities of these subsidence waters were characterized, and recommendations for their ecological restoration were discussed. Quantitatively, numerous water storage spaces have been created. The water qualities show different patterns and degrees of pollution. The waters with less human disturbance show relatively lower nutrient concentrations. Different ecological restoration practices have been performed to suit local conditions. According to the water bodies, scales, locations, and hydrology, they are generally regulated as fishponds, wetland parks, and large plain reservoirs or ecological lakes. Continuous evaluation of landscape change and ecological functions within these waters will be necessary in future research.

Keywords: Coal mining; Ecological restoration; Land subsidence; Water environment

1. Introduction

Coal plays a predominant role in the energy structure of China. In 2010, raw coal production was more than three billion tons, accounting for over 70% of the total amount of primary energy consumed in the entire country [1]. There are many environmental issues surrounding the processes of coal mining, transport, and consumption, such as landscape damage, pollution of air, water, and soil; by mining wastes of coal gangue or fly ash of power plants, and other negative ecological impacts [2–4]. Among those, land subsidence is one of the most serious issues, since 95% of the coal is dredged from underground. Generally, every ten thousand tons of raw coal that is mined results in 0.2 hectares of land subsidence in

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China. Until 2006, the total land subsidence area was measured to be 11,000 km^2, and this is currently expanding at a rate of 200 km^2 per year [5]. The immediate effects of this are the loss of farmland and livelihoods of affected people. In addition, in many large-scale mining areas, it has even changed local hydrology and the ecological environment. For examples, some places have lost underground water, leading to desertification. In other cases, some have become more prone to flooding, which again harms agricultural activity [6].

The phenomenon of large-scale land submergence generally occurs in flooding plain areas in China with low topography and high groundwater tables. In these mining areas, coal deposits are covered by Quaternary sediments of several hundred meters to more than one thousand meters thick, which performs the function of a water-resistant layer (Fig. 1(a)). The coal mining areas located in the Huaibei flooding plain represent a typical case, as they have produced many subsidence water bodies due to continuous and extensive underground coal mining. Different landscapes are displayed within these waters, including collapsed ponds, reservoirs, and lakes; these classifications depend on their shapes, scales, and depths (Fig. 1(b)).

The ecological and environmental problems related to these types of water bodies have been addressed by local governments, coal mine operators, and habitants. On the one hand, they belong to the category of secondary geological disasters. One the other hand, their great potential in terms of use as water resources could benefit regional economies and environments. Concerning these unique water bodies, there are many successful examples to prove that ecological restoration or rehabilitation is viable. However, there remain considerable challenges both for the premining sites and for the current sites that are expected to continue expanding in the future. This paper characterizes these water bodies and discusses the best practices for tapping their resource potential as well as accomplishing ecological restoration.

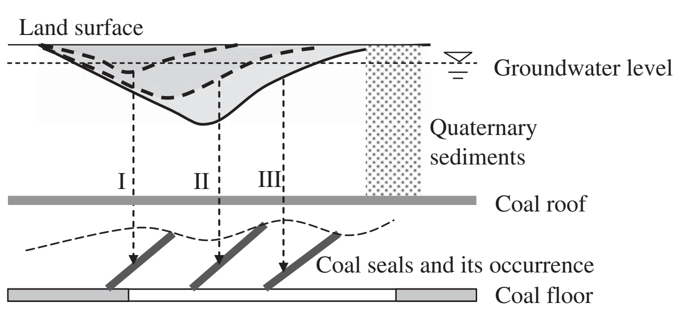
2. Features of subsidence waters

2.1. Geology, hydrology, and water quantities

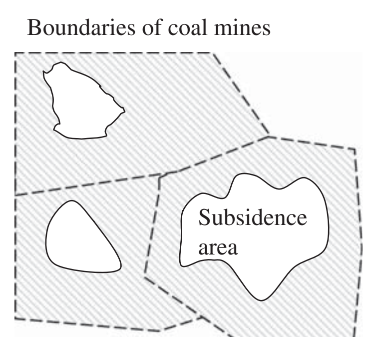
There are two typical locations exhibiting the presence of subsidence waters; these are distributed in the Huainan coal mining areas and Huaibei coal mining areas of the Huaibei Flooding Plain in Anhui Province (Fig. 2).

The Huainan coal mining areas are located on the flooding plain of the Huai River Watershed (near the Huainan City in Fig. 2), which is one of the seven biggest watersheds in China. The Huainan coal mining areas cover an average area of 865 km^2 with a maximum width of 6 km and a maximum length of 25 km [7]. Due to about 50 years of continuous exploitation, pockets of subsidence land with a total area of 150 km^2 have formed, of which two-thirds are submerged [8]. Obviously, the potential water resources in this area are significant. Assuming that the water bodies have a total area of 100 km^2 with an average depth of three meters, it translates to a total storage space for 300 million tons of water given an averaged water depth of three meters within these waters.

Several projects have been carried out by the Huainan Mining Group Company in recent years, aimed at investigating the potential use of water in these areas [9]. These evaluations have been based on surveys of local topography, water tables, hydrology, and mining areas through the employment of GIS tools. It also accounts for the possibility of further



(a) Temporal and spatial processes of land subsidence and submergence with mining activities. (I, subsidence scale after the first coal seal; II, subsidence scale the second coal seal; III, subsidence scale after the third coal seal.)



(b) Conceptual distribution of subsidence areas (top view)

Fig. 1. Occurrence processes of land subsidence and submergence.

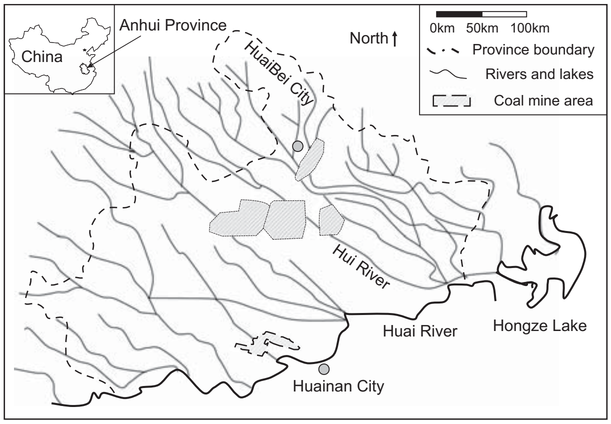


Fig. 2. Locations of the Huainan and Huaibei Coal Mine Areas, and the distribution of rivers in the north part of Huaibei Plain, Anhui Province.

land subsidence along with the continuation of mining activity. These areas were evaluated to have a total water volume capacity of 200 million tons by 2010. Furthermore, they are expected to expand and to achieve a total water storage capacity of 700 million to one billion tons by 2020.

These coal mining areas are located on the upper reaches of the Huai River. Four tributaries drain the mining areas from the northwest to the southeast before flowing into the Huai River (Fig. 3). Due to the low topography and high groundwater tables, these areas are easily subjected to flooding in wet seasons (Generally from July to September every year). Currently, some water bodies formed through subsidence have already become physically linked with local rivers, while some other water bodies remain separated.

These water bodies are expected to play significant future roles in terms of flood buffers and water storage. The Huainan section of the Huai River has approximately 1.5 billion tons of water available every year. These subsidence water bodies can supply comparable amounts of water storage space.

The Huaibei coal mining areas cover an area of 8,600 km^2 with estimated coal reserves of 37 billion tons. At present, 34 coal mines are distributed across four subsectors, namely the Zhahe, Suxian, Linhuan, and Guoyang districts (Fig. 4). The subsidence areas totaled 150 km^2, of which 38 km^2 (25.3%) were submerged by 2010. Furthermore, these areas are expanding at a rate of around 7 km^2 per year. At present, 30 large subsidence water bodies with a total capacity of 80 million tons exist, and this is predicted to increase to 148 million tons by 2020.

However, the nature of the water reserves in these areas is rather different from that of the reserves in the Huainan coal mining areas. These coal mining districts are relatively separated from one another (Fig. 4) and are distant from the Huai River. In addition, these areas have relatively smaller and fewer river systems, which are seasonally cut off and injected the Hongze Lake eventually (right part in Fig. 2). Moreover, there exists a shortage of water resources due to insufficient water storage space within these areas due to their geological conditions. The per capita occupancy of water is 398 tons, which is less than half of that in China and only one-fourth of that in Anhui Province. Utilization, protection, and preservation of these water resources are of strategic importance for Huaibei City.

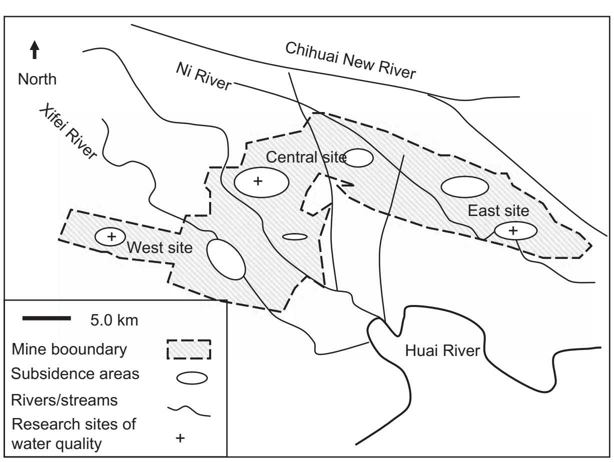


Fig. 3. The distribution of rivers and other water bodies in the Huainan Coal Mining Areas.

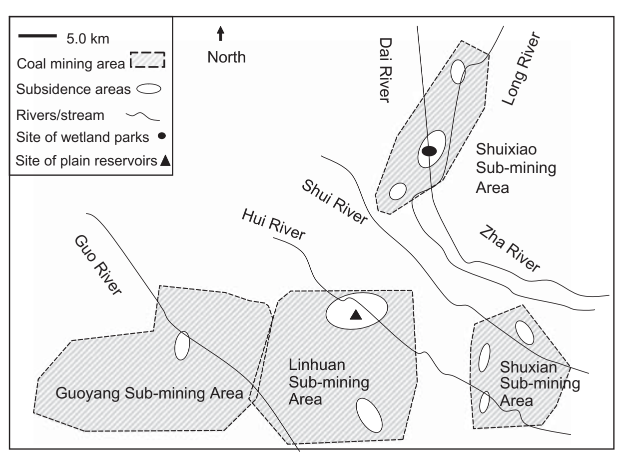


Fig. 4. Distribution of rivers and subsidence areas in the Huaibei Coal Mining Areas.

Table 1
Nutrient parameters in the selected research water bodies of the Huainan mining areas (mean values from nine sampling sites per studied site in 2012)

Sites location and their environment features		pH	DO (mg L^{-1})	SD[a] (cm)	SS (mg/L)	TP (mg/L)	TN (mg/L)	Chl[a] (mg/m^3)	TN: TP	DIN: TP	DIN: Pi	TSI[b]
East (3 km^2, Fishery, 20-year history)	Spring	8.90 ± 0.06	16.58 ± 1.29	79 ± 6	10.7 ± 4.7	0.119 ± 0.026	2.56 ± 0.52	23.0 ± 8.8	48	30	626	60
	Summer	8.47 ± 0.09	10.81 ± 1.64	79 ± 9	9.6 ± 6.3	0.100 ± 0.014	1.19 ± 0.12	59.8 ± 6.7	26	4	45	
Central (3 km^2, Fishery, 5-year history)	Spring	8.52 ± 0.02	10.41 ± 0.36	111 ± 9	3.4 ± 0.8	0.033 ± 0.005	0.75 ± 0.02	7.2 ± 1.4	50	14	126	50
	Summer	8.14 ± 0.10	4.92 ± 1.01	90 ± 14	11.3 ± 7.1	0.062 ± 0.010	0.80 ± 0.03	33.5 ± 4.5	29	6	116	
West(4 km^2, Fishery, 10-year history)	Spring	8.34 ± 0.17	9.25 ± 1.77	71 ± 12	11.7 ± 3.6	0.113 ± 0.012	5.96 ± 0.37	43.4 ± 13.6	50	14	126	64
	Summer	8.49 ± 0.05	0.01 ± 1.33	58 ± 4	11.7 ± 4.0	0.071 ± 0.008	1.36 ± 0.08	71.5 ± 13.8	29	6	116	

[a]Secchi disk transparency.
[b]Trophic state index.

2.2. Water qualities

Water qualities within these subsidence water bodies are also important. As these water bodies have mainly originated from agricultural land prior to subsidence and are still influenced by surrounding agricultural activities, the general pollution patterns can be defined as typical nonpoint source (NPS) pollution. Some water bodies receive local domestic sewage or mine drainage. At present, most of these water bodies are used for fisheries with or without additional feeding of fishes. In recent years, some researches have been investigating the water qualities in both the Huainan and Huaibei Mining areas, mainly concerning organic matters, nutrients, and heavy metals etc. [10]. In order to pursue the further scientific perspectives, concerning of the pollution patterns, nutrient states at present and in future development across these regions, we are undertaking some innovated researches. These researches will be concentrated on their trophic state trend, resource utilization and water management within these water bodies, emphasizing their ecosystem-response to the stressed human activities.

Three water bodies were selected in the eastern, central, and western parts of the Huainan mining areas (see research sites of water qualities in Fig. 3). The work in the Huaibei Mining areas will be undertaken from 2013. Table 1 lists the selected water quality parameters, N/P ratios, and the trophic state index (TSI) in the spring and summer during our research in 2012. For the sake of comparison, this research differentiated among the water bodies based on their history or on human activities.

The eastern body of water formed 20 years ago. It was used as crop land prior to subsidence. It is currently used primarily for aquaculture by local farmers, without fish food dosing. This water body is connected with the Ni River, which receives mine drainage, rural NPS pollutants, and domestic sewage from surrounding villages. The central water body formed in recent years. In this area, surface water already occupies an area of over 10 km^2, being separated by the roads of the mining areas. One of them was selected as a representative research site. Before subsidence, it also presented a history of use as cropland. Finally, the western water body has existed for around ten years, before which it was a rice-growing area. It is also a selected area for the research to represent the western water bodies. It is currently used for fisheries with fish food dosing.

Until now the investigations into water qualities were conducted in growth seasons of May and August 2012. Briefly, surface water samples were taken in nine sampling sites of each studied waters. Then water parameters, including pH, dissolved oxygen (DO), total suspended solids, total phosphorus (TP), soluble reactive phosphate (SRP), total nitrogen (TN), nitrogen species including nitrate (NO_3–N), nitrite (NO_2–N), and ammonium (NH_4–N), chlorophyll-*a* (Chla), were examined, according to a previously published method [11]. Means of the values and their viabilities in each of the investigated water bodies are summarized using the statistical software SPSS v. 11.0. The ratios of TN to TP (TN/TP), dissolved inorganic nitrogen to TP (DIN/TP), and DIN to dissolved inorganic phosphorus (DIN/P_i), were calculated to analyze the nutrient balance and limitation potential on primary production, according to these indicators discussed by the Ptacnik et al.[12]. While the TSI within these waters were judged by the method proposed by Carlson in 1977 [13].

The average water depths in the study area ranged from 3 to 6 m, akin to shallow lakes, but some water bodies displayed greater depths. They were found to be abundant in dissolved oxygen with a weakly alkaline chemistry. The water qualities appear to be significantly influenced by human activities. Overall, our research revealed fairly high contents of nutrients and chlorophyll-*a*. Averaged TN concentrations were 2.56 mg/L, 0.75 mg/L, and 5.96 mg/L in the east, central, and west water bodies in the spring season, respectively, while their concentrations were 1.19 mg/L, 0.80 mg/L, and 1.36 mg/L during the summer investigations.

Mean TP concentrations were 0.119 mg/L, 0.033 mg/L, and 0.113 mg/L in the spring, while they were 0.100 mg/L, 0.062 mg/L, and 0.071 mg/L in the summer within these studied sites, respectively. The mean chlorophyll-*a* concentration followed the same trend, where the western water body exhibited the highest content of 43.4 mg/m^3, while the central water body had the lowest value of 7.2 mg/m^3, which was predictable, given its lowest contents in the spring. The eastern water body exhibited intermediate chlorophyll-*a* concentration of 23.0 mg/m^3. In the summer, the mean chlorophyll-*a* concentrations were 59.8 mg/m^3, 33.5 mg/m^3, and 71.5 mg/m^3, respectively.

Newly formed water bodies that were maintained in a virgin state or otherwise left undisturbed exhibited lower nutrient status. Meanwhile, the ratio of nitrogen to phosphorus concentrations in the spring was greatly exceeded that in the summer from the indicators of TN/TP, DIN/TP and DIN/Pi. Based on the perspectives supposed by Ptacnik et al. [12], the best overall performing indicator, DIN: TP, had chlorophyll-response with the thresholds of N limitation below 2:1 and P limitation above 5:1 (by atoms). It seemed that the limiting nutrient element was P. DIN and TN contents during the spring were greatly higher than that during the summer season (Fig. 5). DIN/P_i is particularly high, especially because very low SRP values were observed (Fig. 5). This is probably because SRP was assimilated through algal growth. However, organic phosphorus could be hydrolyzed for their bioavailability by the alkaline phosphatase from phytoplankton or bacteria [14]. Although lowest SRP concentrations exist, high Chlorophyll-*a* consents were still observed.

On the spring sampling trips, algal communities were also investigated (data not shown). The eastern and western sites showed significantly more abundant and diverse phytoplankton species than those in the nutrient-poor central site. Involving the comprehensive TSI indicator, the central site was in light-trophic state (TSI = 50), while the other two were in meso-trophic states (TSI = 60 in the east site and TSI = 64 in the west site). In a previous study concerning phosphorus fractions and migration in the sediments of the eastern water bodies [10], a high content of total iron and iron oxides was observed to be a limiting factor, as it was responsible for phosphorus immobilization. However, if limitations in phosphorus occur within these waters, they have to be well addressed since both carry very important implications for future water management and practices for ecological restoration.

3. Practices for ecological restoration

Mine-site rehabilitation has been presented as an ideal case study for the development of an ecosystem beginning from point zero on 'terra nova' [15]. During the past few decades, many new approaches and technical methods for land reclamation have been developed [16,17]. As a general principle, a variety of restoration measures should be applied to these subsidence waters. This is because any such measures should suit the local environment based on the water qualities and quantities of the concerned water bodies. There are four main strategies for accomplishing resource utilization and ecological restoration.

First, there exist certain small and shallow water bodies which experience seasonal flooding in their marginal zones. Based on local topography, they are regulated as fish ponds to compensate local farmers for their loss of farmland. Typically, the soils in the shallower water areas have been excavated to deepen the existing depressions, enabling their use as intensive fish ponds, while the raised ridges on the edges are still used for crop cultivation (Fig. 6). This is recognized as one of the best examples of reclamation

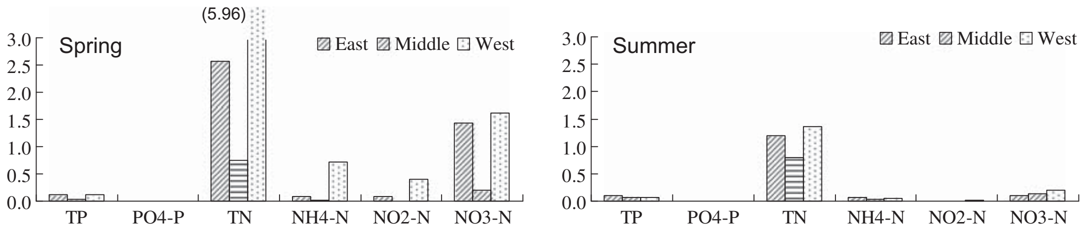


Fig. 5. Distribution of nitrogen and phosphorus species in the spring and summer of 2012.

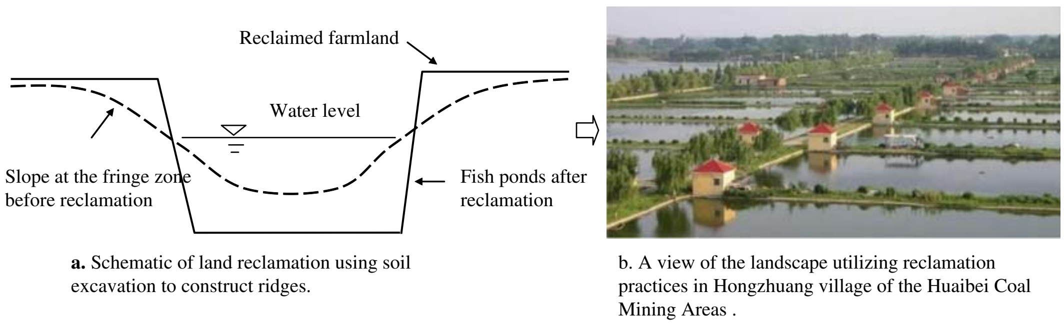


Fig. 6. Utilization of water bodies as fish ponds.

methods in rural areas, which even can be performed through the appropriate excavation and deposition of topsoil before initiating premining activities. This is a simple process to minimize reclamation costs with little or no land loss.

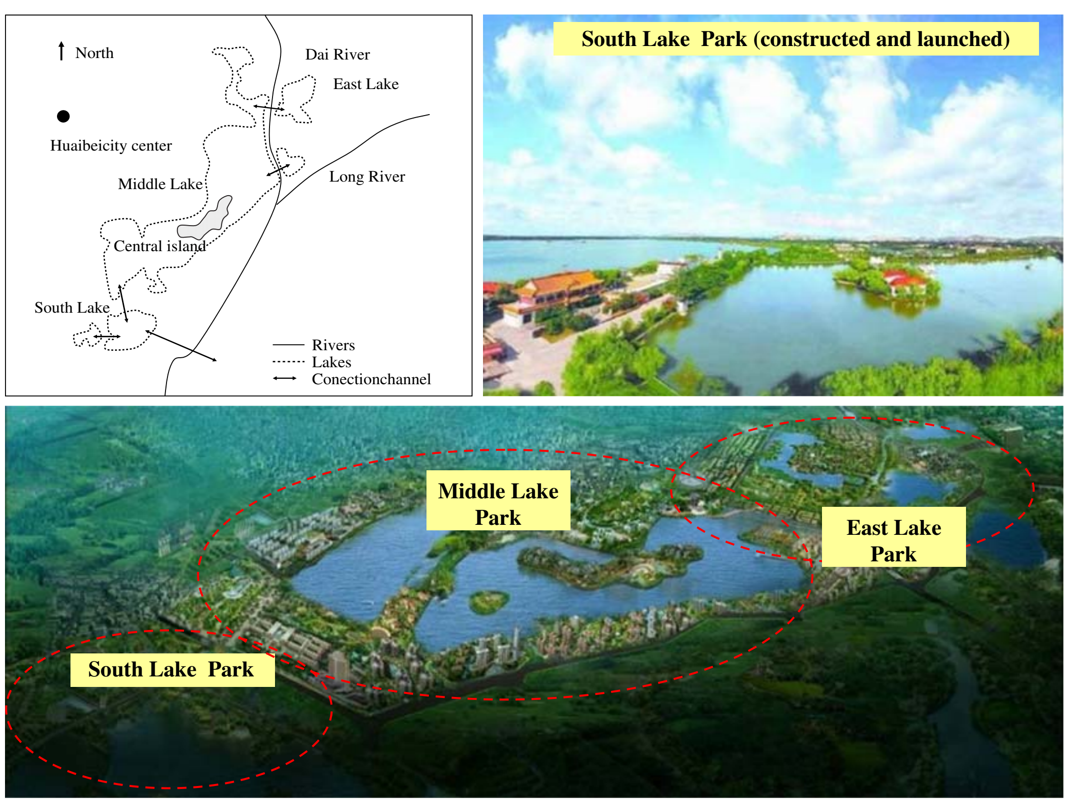


Fig. 7. Wetland parks linked with local rivers.

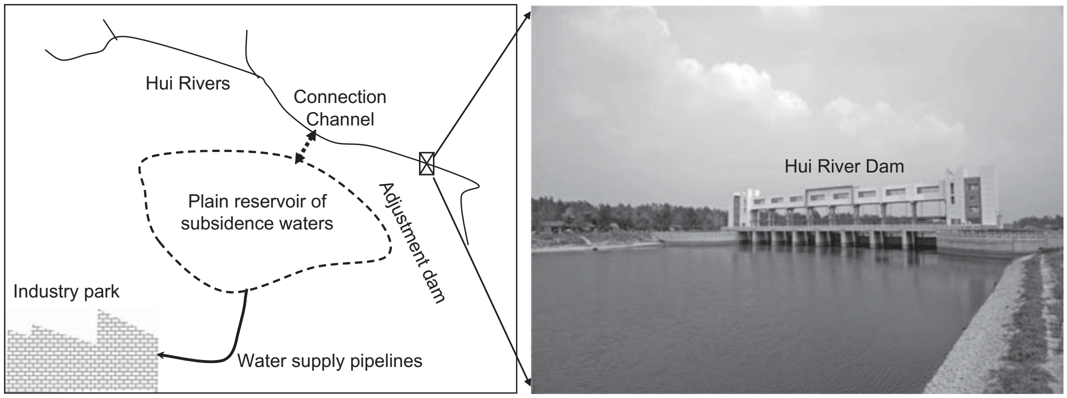


Fig. 8. Plain reservoir for water storage and supply adjusted with the local river dam.

Secondly, larger bodies of water close to urban centers are ideally developed as wetland parks. The first case of city wetland parks being constructed on mining subsidence areas is the South Lake National City Wetland, with an area of 5.2 km^2 in the Huaibei Coal Mining areas (upper right photo in Fig. 7). Subsequently, the East Lake Park and the Middle Lake Park are under construction or have been planned for the future, respectively. They represent key projects of geological environment rehabilitation in the Huaibei Coal Mining Areas, where 700 million Yuan have been invested for appropriate engineering practices. They are designed to maximize the resource potential of the wetland landscape, assist in ecological rehabilitation, and enable urban development; the latter is supposed to play an important role in terms of eco-service functions for the sustainable development of Huaibei City [18].

This project involves subsidence areas exceeding 30 km^2 with one-third of this area covered by water with a total water volume capacity of 25 million tons. It was designed to interlink the Dai River, East Lake, Middle Lake, South Lake and Long River to form a series of lakes (upper left and bottom photos in Fig. 7). The water flow is designed to be controlled, by the difference in water levels, from the northeast to the southwest. This is to improve water recycling and purification. It also plays a role in storm water storage during the wet season; therefore, this area has been designated as a source of water for Huaibei City in cases of water shortage. For the important reasons indicated, these water bodies have been maintained in a virgin state with minimal disturbance or influence by humans. Therefore, their water qualities are in a good state with low levels of pollutants.

Thirdly, for large water bodies linked to local rivers, plans have been laid for their regulation as large plain reservoirs or lakes. Several major projects for plain reservoirs are under construction or have been planned in recent years. It is envisaged that they would perform the functions of water storage and water supply to surrounding industries or towns. The construction of local river dams will influence local water conservation by diverting storm water into these lakes during wet seasons.

One example of a plain reservoir is the Linhuan Industry Parks, which is the largest domestic coal coking base with a maximum water demand of 70 million tons per year. A guarantee of a stable water supply is of strategic importance for the industry park. Three projects have been designed for water sequestration and supply. The first project has a designed volume treatment capacity of 80,000 tons daily, using water from the Hui River and mine drainage. The second project uses a daily amount of 15,000 tons of untreated water from the relatively distant Huai River. The third project is the construction of a plain reservoir, located 1,500 m upstream of the Hui River Dam (see Hui River crossing the Linhuan Sub-mining Area in Fig. 4 and 8). This reservoir will supply available water resources of 25, 56, and 76 million tons in the next 5, 10 and 20 years, respectively, concomitant with expansions in area due to continuous land subsidence forecast in the future [19].

In the Huainan coal mining areas, as discussed above (Fig. 2 and Fig. 3), abundant river systems are present due to their unique geographical and geological conditions. These subsidence areas are planned to be treated as large ecological lakes (or reservoirs), which will perform significant ecological functions of buffering floods for the section of the Huai River, and benefit local industries, agriculture, fisheries, and towns. This will be the largest project using the coal subsidence areas in China.

4. Discussion and conclusions

Mining activities have changed the landscapes and ecological environments in the coal mining areas in the Huaibei Plain of Anhui Province. As a result, the traditional agricultural ecosystems have been transformed into freshwater ecosystems within these areas. Besides its negative effects, the positive aspects also need to be characterized. Small water bodies can be restored to the farmland areas that existed before subsidence. Consequently, it will be easy to evaluate these changes if only the output values of farming were compared to those of aquaculture. In all probability, the reclamation may lead to improved incomes for local farmers.

However, for wetland parks, plain lakes or reservoirs, their water resource potentials and ecological functions will tend to be emphasized over their direct economic benefits. Therefore, methods to accurately evaluate and characterize their benefits or losses are necessary goals for future research. There are many trials that have evaluated post-mining landscapes, and which have typically considered their ecosystem service functions, such as climate regulation, biodiversity, food production, freshwater provision, etc. [20–23]. In some case, new tools have been developed to evaluate mining landscapes [24–27]. In other cases, negative environmental impacts or economic losses arising from improper restoration of coal mining areas have been addressed [28–30]. Therefore, development of proper and quantitative tools suited to these aquatic areas will be immensely useful in assisting appropriate ecological restoration and resource management.

Another important fact is that these water bodies are generally physically linked to local river systems. Large-scale subsidence could greatly change the regional hydrology cycles in mining areas. There are links between surface waters, groundwaters and rivers, which should be considered as the basis for regional biotechnological remediation. Many studies indicated that they will eventually affect one another if just one or two of the water bodies are polluted [31,32]. In recent years, due to the requirements for convenient acquisition of coal resources, many power plants and coal chemical processing plants have been built in coal mining areas. Accordingly, pollutants from these industrial sources complicate local environmental problems. In order to manage the risk of water pollution, it is necessary to find appropriate solutions to address complex environmental problems, as opposed to solely relying on the efforts of mining companies. Incorporating current scientific research into engineering practices will improve the likelihood of future restoration projects succeeding.

For water qualities, emphasis should be placed on the issue of eutrophication, since prior studies indicated that human efforts improved the nutrient status of water bodies [33]. However, we still have insufficient information about the changes in ecosystems that are directly attributable to changes in their history or in specific patterns of human involvement. Increased knowledge will guide decision-making with respect to ideal water management practices. Moreover, the mined areas underground can also store water through the formation of secondary cracks after mining activity has ceased. It is important to emphasize the differences in water quality and water chemistry created by variation in local surrounding rock or environmental conditions. It is particularly important to analyze the impact of past mining activities on the quality of surrounding water and soils [34].

Overall, the phenomena of land subsidence and submergence in the coal mining areas of the Huaibei Plain in Anhui Province are rather unique, and they cause significant changes in local landscapes and in the nature of water conservation. These phenomena create numerous storage spaces for storm water and also perform useful ecological functions. This is despite the fact that they were initially regarded as an environmental and geological disaster. If the selected array of restoration practices is appropriate, it could improve regional environmental quality. To some extent, land subsidence can result in other positive effects as well, such as the creation of a more diverse and attractive local landscape.

Acknowledgments

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