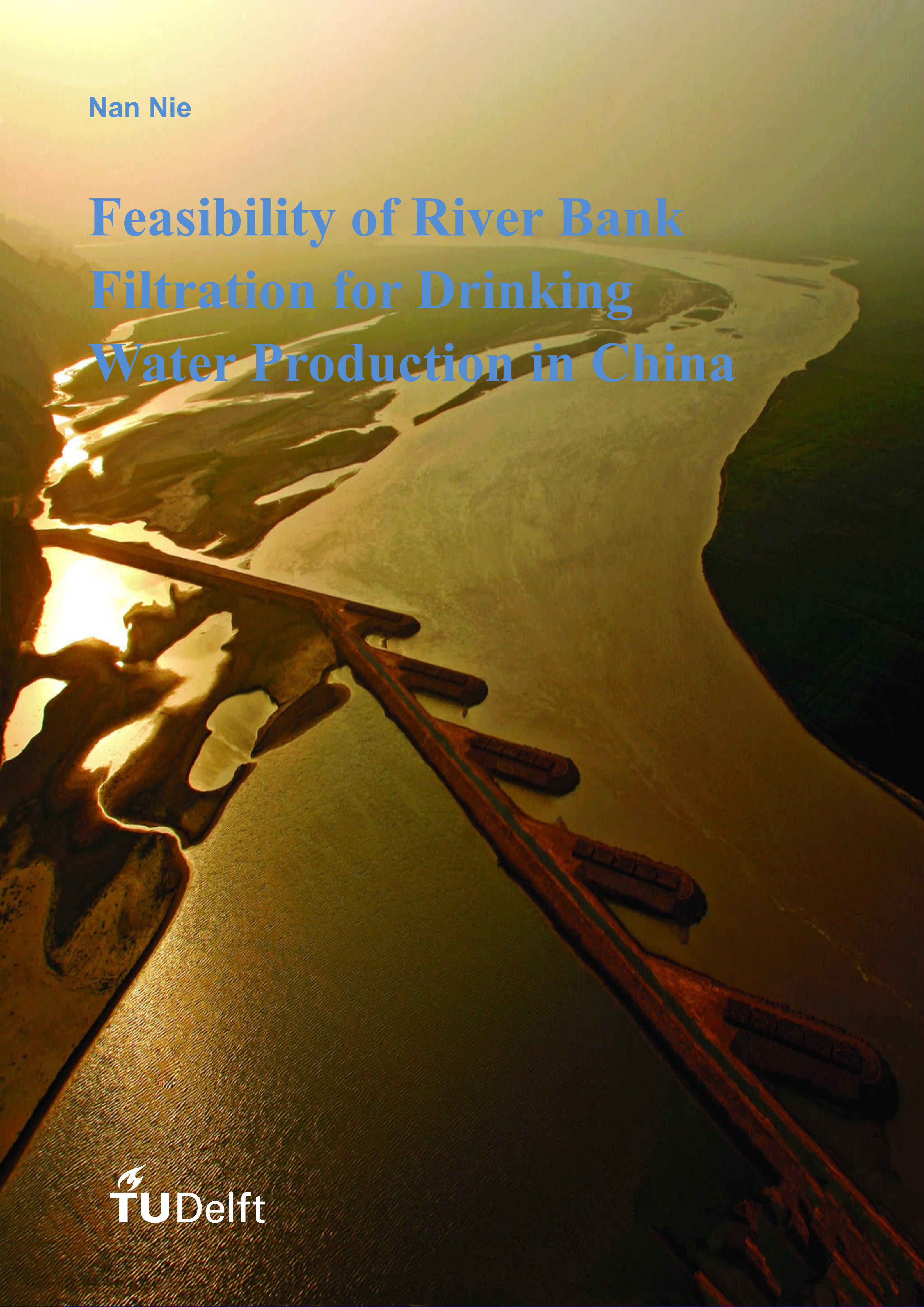
Nan Nie

Feasibility of River Bank Filtration for Drinking Water Production in China



TU Delft

Feasibility of River Bank Filtration for Drinking Water Production in China

By

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Preface

This report is the last work of my study in TUDelft. The new academic year 2016-2017 has already started with a large group of new faces just like me in the summer of 2014. I still remember extremely clear that I first felt hard to understand in lectures and then got better and better after efforts paid before and after the lectures. In the first year in my study, it is common to work in the water lab late and then go back home to finish the report. But all of these are passed and become my precious experience, an amazing experience in my life.

From November in 2015, I came to know this project about RBF and started to learn about it although actually it was rather new for me and somehow partly away from my subject. Because of the features of this project, I have to switch between Dutch or international conditions and Chinese conditions since China has its own methodology and hierarchy on engineering as well as scientific research. I have to admit that it is not only difficulty for me but also a great experience, the difference between China and the Netherlands on all education, engineering and the way of working. During finishing the report, I realized my shortages on scientific thinking and writing which take me more time to improve although it is still not perfect.

I would like to give my best gratitude to the chair of my committee, Prof. Gertjan Medema. Thank you for your supervision on my work and all the comments and suggestions on report. Harrie Timmer, thanks for your supervision in Oasen and many explanations or answers about technical questions. And other members of the committee, Prof. Pieter J. Stuyfzand, Gang Liu and Boris van Breukelen, thank you for your kind and meaningful help. Special thanks to Gang Liu for your help on connection with CAS in China and guidance on my study. Thanks for people who help me no matter in the Netherlands or in China.

At the end, thanks for my parents and girlfriend. Without your support, I cannot complete all of this. Hope to have a fantastic career in my life and say goodbye to Delft.

Abstract

River bank filtration (RBF) is scientifically and systematically developed in Europe and the United States for hundreds years. Researches on the processes in soil passage through RBF and also the requirements about hydrology and hydrogeology are closely compact to engineering application through well-design. Recently, the fast growing population and deteriorating water quality force China to pay more attention on safe water supply. Thus RBF is considered to bring in as a proven efficient natural water purification technique. Before introduce RBF to China, some preparation are needed at initial stage. After literature reviews, some knowledge gaps are found. Basic criteria for RBF site, current Chinese conditions, operating site situations are all needed to explore. Potential of RBF to help water challenges in China is needed to be elaborated on locations.

A site evaluation approach is formed as a core component including evaluation against criteria and a basic model for design and costing. Afterwards, hydrogeological Map Atlas (Chinese Academic of Geological Sciences, 1979) and information (hydrogeological and water quality) about operating site (Dongzhou Treatment Plant, Zhengzhou) are used for the site evaluation approach testing application on national level and on an operating site. The site evaluation approach is proved to be useful for further application to screen potential areas and cities as outcomes. With the help of Chinese Academic of Science (CAS), four sites are visited. Zhengzhou site has been operating for 16 years effectively producing improved drinking water which also proves the site evaluation approach but now facing problems such as attenuation of river and yield reduction. Jiaxing has less suitable hydrological conditions for RBF on two locations provided by Jiaxing Water Company but can be found some where nearby. In such case, an alternative transport design is made. Wuhu has no suitable hydrological conditions based on current drinking water treatment plant but has possibility to be found nearby according to general evaluation. Deyang site as an additional example to introduce conjunction system combining constructed wetland (CW), managed artificial recharge (MAR) and river bank filtration (RBF) which is one of prospective development directions. Outdated and incomplete data are main shortcoming of this thesis.

After all, the site evaluation approach with basic criteria and design model is possible to evaluate candidate locations and existing sites but local specific data are strongly recommended for a reliable evaluation. RBF has great potential to help solve the water challenges in China no matter in the north where quantity and quality are both serious or in the south where quality challenge is more serious. Meanwhile current operating site still has satisfied efficiency but facing some problems such as yield reduction. In the future, several opportunities are potential for RBF to develop in China together with detailed laboratory studies and pilot studies which are recommended based on selected location in China in further research.

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1. Introduction

1.1. River Bank Filtration

1.1.1. What is RBF?

River bank filtration (RBF) is a natural water purification process. In general, instead of taking river water directly, RBF is a soil passage process that lets the water flow through river bank soil to the collection wells before abstracting for drinking water production. RBF can remove suspended solids, organic matters, nutrients, pathogens, pharmaceuticals, pesticides and other emerging contaminants. Recently, RBF is combined with artificial recharge (AR), constructed wetland (CW) and other natural water purification processes. Comparing to direct intake of surface water as source water, RBF produces a higher and more stable quality which allows simpler post-treatment.

1.1.2. How does RBF work?

Basically, RBF contains two parts: soil aquifer and abstraction wells. The soil aquifer is hydraulically connected to the river on the one side, and the abstraction wells are connected on the other side. Once the abstraction starts, the groundwater level is lowered, and the water will flow from the river to the soil aquifer through the river bed towards the wells. In this way, the surface water is purified during its transport through the soil by several physiochemical and biological processes in the soil aquifer during the residence and transport, such as straining, (bio) degradation, sorption and ion exchange.

1.2. Development of RBF

1.2.1. History of RBF

RBF was firstly used in the Europe in 1800s and widely applied in the later 200 years. It is used for water purification as original purpose. According to C.Ray, the first site using RBF for water supply purpose was the Glasgow Waterworks Company in the United Kingdom (Ray, 2002). And in the mid-19th century, RBF was used by several European utilities to produce drinking water (Ray, 2002). Almost at the same time, RBF started to be applied in the Germany because of limited (fresh) groundwater availability in some places. An outbreak of epidemic cholera in Hamburg, Germany in 1892 pushed the implementation of RBF to replace the direct intake of surface water. In 1892 and 1998, the statistics of water source usage comparison offers an impression of RBF development in Germany (Table 1-1).

Table 1-1 RBF development in Germany Source: Ray, 2002

Type	1892 (%)	1998 (%)
Groundwater	63.6	33
Springs	7.8	1
RBF & groundwater recharge	15.3	49
Surface water	13.3	17

In the United States, RBF was developed in 1940s. The so called Ranney wells includes vertical, angle or collector wells, which have high yields and high intake capacity. In the Netherlands, the first RBF site for drinking water purification probably is in Nijmegen along the Rhine River (Stuyfzand, 2004). After more than 100 years development, RBF is now used at several locations. The annual capacity reached 80 Mm3 by 2002. It constitutes nearly 7% of the total drinking water production in the Netherlands (1200 Mm3/y).

1.2.2. RBF around the world

Surface water and groundwater are two main water sources for drinking water production around the world. However, on the one hand, surface water is limited in quantity and deteriorates in quality. On the other hand, the urbanization and civilization have led to the depletion and contamination of freshwater resources. Stable and reliable supply of high quality drinking water is essential to ensure human beings' health. With more than 100 years` experience and improvement, RBF has been recognized as a proven technology for drinking water purification in Europe and now is extended worldwide. Many countries and cities are using RBF or are testing RBF.

According to literature, the largest RBF system is located in Budapest, Hungary, with a capacity of 650,000 m^3/d. There are many small sites or pilot tests for future applications. For example, in Thailand 12 sites have been selected as potential sites to apply RBF (Srisuk, 2012). Similar action and research is ongoing around the world such as Egypt, Korea, India, New Zealand, Brazil and China (Hamdan et al., 2013; Lee & Lee, 2010; Boving et al., 2014; URS report, 2009; Freitas, et al., 2012; Zhai et al., 2015). In the future, there will be more large-scale RBF applications worldwide for reliable water supply.

1.3. Challenges in China

China is facing huge quantitative and qualitative challenges on water resources. Regarding the quantitative challenges, even though the birth rate in China is reduced in recent years, there are still around 16 million newborns per year. Along with the urbanization, 0.8 billion people are living in cities. The increasing population and urbanization are stimulating the water depletion and quality deterioration that creates stress to the water supply system. According to the database of the Ministry of Water Resources (MWR), 2/3 of the cities are facing water supply shortage in China, of which 110 cities face serious shortage. 30 cities with a population larger than 1 million are trapped into water shortage.

Ground water overexploitation is becoming a serious problem national-wide. In 2004, an (incomplete) investigation indicated that 76 groundwater depression cones were formed in 21 provinces, of which the total area is 72,000 km^2. Moreover, the overexploitation of groundwater has also caused surface subsidence in many cities.

Compared to quantity problems, the challenges are even worse when comes to quality aspects. In many cities, e.g. Chongqing, rivers run by the city and, theoretically, there should be sufficient water resources. But, in fact, there is no water source available for water supply because of the pollution of river water. In such cases, the government has to build hydraulic facilities to transport and store water, or to apply advanced treatment to produce high quality drinking water. The main reason for so called 'Quality-induced water shortage' is the discharge of domestic and industrial wastewater, where the contaminant-level exceed the self-cleaning capacity of the surface water body. 'Quality-induced water shortage' means water resource in a region is adequate in quantity but in reality it is unavailable because of insufficient quality that mainly happens in economically developed regions.

As indicate in 1.1.1., RBF can contribute to drinking water supply in China in the following ways: optimizing the proportion of surface water and groundwater; providing cleaner source water; allowing simpler post-treatments. Moreover, the introduction of systematic RBF technology will help China develop knowledge and experience in management and maintenance of RBF. In this master thesis, fundamental principles and basic criteria of RBF were studied to offer an insight of applying RBF in China.

1.4. Master thesis project

1.4.1. Project background

Since 2013, the Research Center for Eco-Environment Sciences of Chinese Academy of Science (RCEES, CAS), sanitary engineering of Delft University of Technology, KWR watercycle research institute and Oasen drinkwater have established collaboration on applying RBF as a reliable and natural option for drinking water purification in China. This master thesis project is a part of the cooperation, supported by all of the involved partners. The project includes theoretical (literature review, case studies and criteria development) and practical work (site visit, data collection and results discussion) in both China and the Netherlands.

1.4.2. Research questions

The main objective of this MSc research is to develop and apply an approach for successful RBF site selection in China. The evaluations of current RBF application in China and candidate sites are also part of the scope of this study. Through this thesis, data and results will be collected on the following research questions:

RQ.1. What are the basic criteria for RBF sites selection?

RQ.2. What is the potential of RBF to improve water quality?

RQ.3. What are the current conditions of RBF in China (operating sites)?
RQ.4. Where are the potential areas for applying RBF in China?
RQ.5. What are RBF future development opportunities in China?

1.4.3. Structure and chapter of this thesis

To achieve the above mentioned objectives and to answer the research questions, 6 chapters are included in this thesis as shown in Fig.1-1.

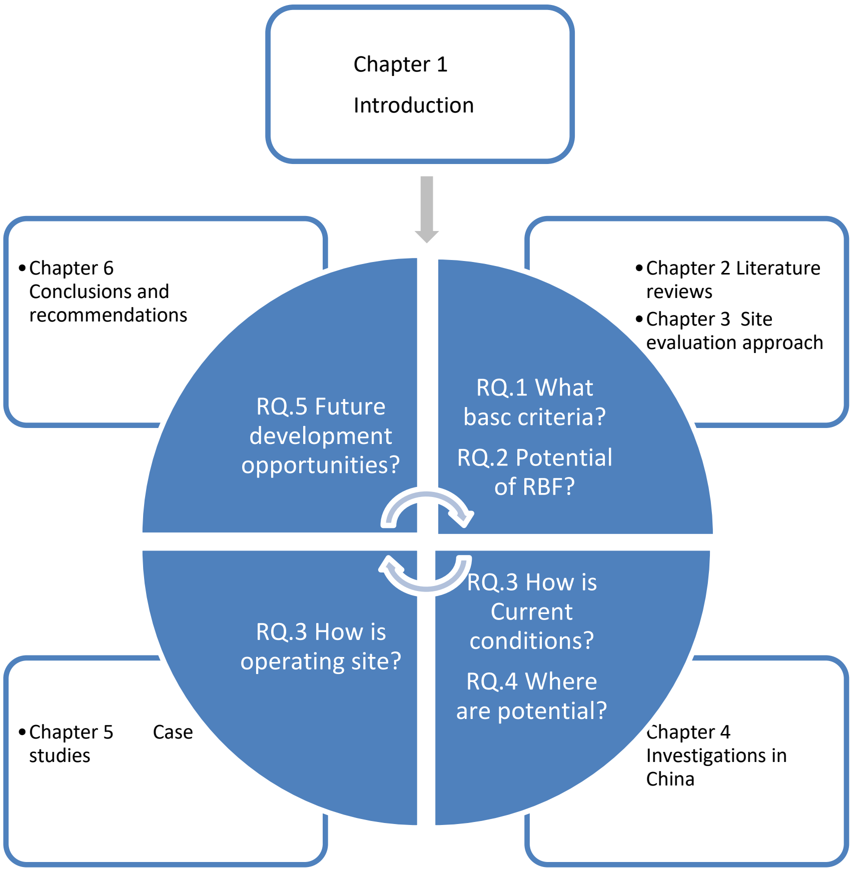


Figure 1-1 Chapter set up of thesis. Relationship of chapters and research questions shows in each combined quarter.

At first, RBF is generally introduced and the challenges in China are presented in chapter 1.
In order to understand RBF technique, basic knowledge of RBF is studied in chapter 2 through literature review to answer research question 1 and 2.
Then the site evaluation approach of RBF is developed including evaluation against criteria and basic model for design and costing in chapter 3.
Investigation on potential RBF sites in China start at the national level in chapter 4, to describe the current RBF conditions in China (answer research question 3) and to screen potential RBF areas (answer research question 4).
In four case studies, the approach is applied to the operating site and several candidate sites to answer research question 3.
Chapter 6 sums up the results from previous chapters in conclusions, recommendations and discussions.

2

2. Literature Reviews

2.1. Hydrological and Hydrogeological Conditions for Applying RBF

As a drinking water purification process, RBF hydraulically connects surface water body (e.g. river) with the abstraction wells through the soil passage in aquifer. As illustrated in Fig.2-1 and Fig.2-2, the surface water naturally infiltrates from the river bed to the adjacent aquifer.

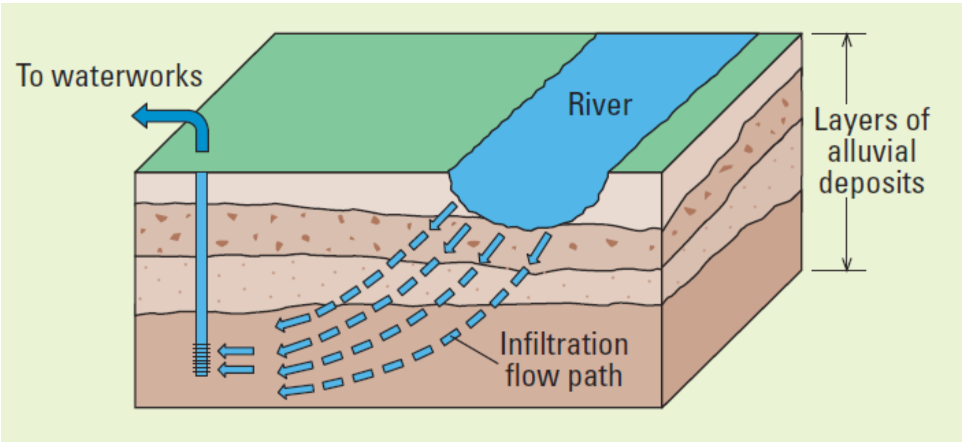
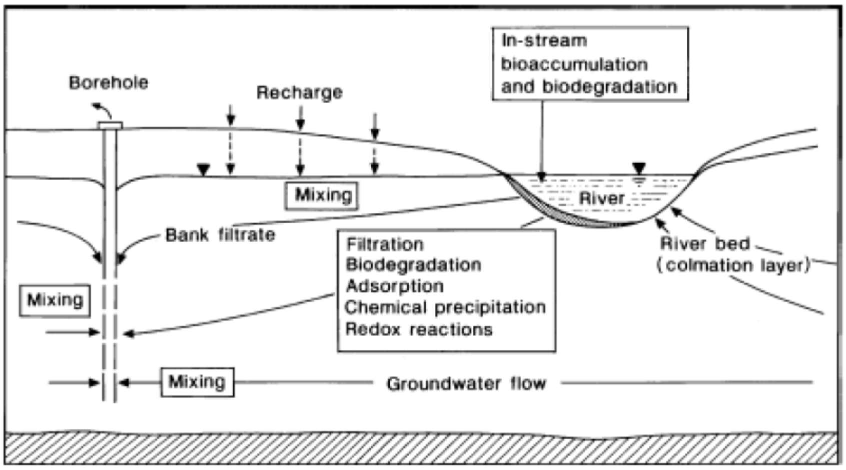


Figure 2-1 RBF scheme Source: Tufenkji, 2002

During this process that water flow through the aquifer from river to abstraction wells, a wide range of contaminants can be naturally removed. Therefore, only simple post-treatments are needed for drinking water production from RBF water (Tufenkji et al., 2002). From this perspective, RBF has been considered as a pre-treatment technique.

Driven by the abstraction of water from wells, the groundwater table becomes lower. The surface water starts to flow from the river to the wells and to mix with the local groundwater flowing from the land side at the wells. It is clear that the application of RBF is closely related to the subsurface conditions and the river hydrology on both water quantity and water quality. Therefore, sufficient hydrology and hydrogeology information and water quality data are critical to evaluate the suitability of a certain site for applying RBF.



Sources: Hiscock and Grischek (2002)

Figure 2-2 Illustration of RBF soil passage

2.1.1. Source

The availability of surface water is the most critical feature for a RBF site. In the target area, there should be water source available e.g. rivers. The river flow is not strictly required to be at a high level but stability is vital for its operation and performance. Besides, the river bed needs to connect to the aquifer that offers a soil passage as a route for the surface water transferring into groundwater.

During operation, groundwater level around the RBF wells should not decline below an ecologically and economically justifiable threshold value, otherwise, overexploitation will definitely damage the ecosystem (Techneau, 2009). To analysis and ensure the groundwater level, parameters such as transmissivity is needed to be declared. In basic design 3.3.1, acceptable drawdown is controlled by well yield.

2.1.2. River hydrology

The river hydrology information, including river velocity, river discharge, river flow duration and hydraulic gradient, provides the knowledge about the capacity of a river, transport conditions, runoff regime of a river and also the possibility and severity of clogging problems.

- The flow of a river will affects the hydrological connection between the river and the aquifer. The average parameters like maximum and minimum discharge can be used to determine the runoff regime of a river (Schon, 2006).
- River velocity can be used to estimate the shear stress on the river bed which relates to river bed clogging problem caused by sedimentation and remobilization of suspended particles (Schon, 2006).
- Particle load and flow of the river might also influence the restoration, infiltration capacity and RBF performance. Soil, rocks, particles, or other debris in flowing water near the river bed formed the bed load. The velocity of bed load movement influences

the self-cleaning process of the river bed (Ray et al., 2002).

- The hydraulic gradient of the river can provide rough information about grain-size distribution, mean flow velocity in the river, and the capability of bed load transport.
- Seasonal fluctuation is an important factor to precipitation and infiltration. The capacity of water storage in aquifer is also related to seasonal variations (Ray et al., 2002). The seasonal discharge and velocity variations will also affect the sediment, transport and deposition condition of the riverbed.

2.1.3. Aquifer

In reality, the flow direction of the groundwater is variable under natural conditions without any anthropogenic extraction (Schmidt et al., 2003). RBF will form an underground flow from river bed to abstraction well. The confined or unconfined aquifer is main water transport passage which is closely related to RBF and also is the pre-requirement for applying RBF. The type, porosity, material, thickness, permeability and hydraulic conductivity are important factors influencing application of RBF on site while some of them are critical.

- Material: preferably consisted of sand, silt, rock fragment, and pebbles (Tufenkji et al., 2002). It is discussable for limestone (karst and cavernous karst aquifers) and chalk (fractured aquifer) which are less favorable for RBF sites (Schijven et al., 2002). Because some cryptosporidiosis outbreaks appeared associated with failure of RBF in non-porous media aquifers reported by Schijven et al., 2002.
- Thickness: the thickness of aquifer can be used to calculate the volume of the aquifer for water storage and for the potential well yield.
- The costs for establishing RBF systems depend on many factors, including aquifer characteristics, type of well screen installation, facility design and distance to the consumers (Sharma et al., 2012).
- Conductivity [L/T] and transmissivity [L^2/T]: these two parameters are all representing the capability of water can move through soil passage while transmissivity is only on horizontal direction and hydraulic conductivity (K) is on all direction. In case the aquifer conductivity will not performance with an isotropic behavior and varies through the entire aquifer depth, the transmissivity is used instead (Schon, 2006).

An overview of RBF at different conditions is summarized in Table.2-1. Among those factors, river bed, flow velocity and redox environment are important for RBF`s water purification function. It will be important to collect information regarding those factors from potential locations. For example, to know redox environment is vital for predicting contaminants removals of different types of RBF (Stuyfzand, 2011).

Table 2-1 Classification of RBF from headwaters in the mountains to the river mouth in sea (source: Stuyfzand, 2011)

RBF Type (downstream direction)	1	2	3	4	5	6
Site characteristics	Mountains	Hills	Fluvial plain	Fluvial plain	Estuary / Delta	
	Alluvial fan	Valley	Upper	Lower	River	Lake
River type	Braided	Meandering		Anastomosing		-
River / Lake bed	Gravel		Sand	Sand	Sand	Silt / clay
Flow velocity	Extreme	High	Moderate	Slow	Very slow	
Flow drive behind RBF	G	P	P	D + P	D + P	
Infiltration regime	Periodical	Reversing	Constant	Constant	Constant	
River bed contact with aquifer	Direct		Direct	Direct	Intercalated aquitard	
Unsaturated zone below river bed	Yes		Rarely	No	No	
Redox environment	(sub)oxic		mixed	anoxic	deep anoxic	

**D = Drainage of adjacent land (polder)   G = Gravity   P = Pumping*

2.1.4. RBF site investigation methods

Pumping test

The aquifer hydraulic properties, aquifer boundaries (Duffield) and well performances can be evaluated by pumping tests, which is an experiment that a well is pumped at a controlled rate and the responses of water level are measured in one or more surrounding observation wells (may also be measured in the pumping well itself). In practice, the groundwater level could be read and recorded from piezometers installed around (Dunniclifs, 1998). For example, in the Malaysia case, 25 piezometers ad two test wells were installed to estimate the hydraulic features of the aquifer (Shamsuddin et al., 2014). Similarly, in Serbia, a two-month pumping test was conducted with four piezometers (observation wells) and one test pumping well, where a groundwater model was developed based on the obtained data simulating different extraction rates to estimate different scenarios (Stauder et al., 2011).

Modeling Analysis

Hydraulic models (e.g. MODFLOW, FEFLOW) can be used to analysis pumping test results and predict the groundwater conditions, so as to determine the parameters for building RBF site such as well location, pumping rate and level drawdown under steady-state conditions (Sharma et al., 2012).

MODFLOW is one of the hydraulic models requiring input of hydrological and hydrogeological data, such as river flow, groundwater table, ground layers, depth and type of aquifer, hydraulic conductivities and porosities. In the model, several scenarios could be placed as input (e.g. different pumping rates) and the results could be processed and displayed parallel. Criteria like minimum residence time and maximum allowable downward rates are variable for different locations. Therefore, decisions can be made balancing distance of wells from the source, residence time and drawdown. An example of MODFLOW results is shown in Table 2-2 under 1 m maximum allowable drawdown and 40 days minimum required residence time, the expected option can be 10 wells at distance of 100 from the source (Sharma et al., 2012).

Table 2-2 Example results of MODFLOW under 1 maximum allowable drawdown and 40 minimum residence time

No. of wells	Pump rate per well (m^3/d)	Distance of well from source = 50 m Time (days)	Drawdown (m)	Distance of well from source = 100 m Time (days)	Drawdown (m)	Distance of well from source = 150 m Time (days)	Drawdown (m)
4	9,700	9	2.8	18	2.5	36	2.7
10	3,880	26	0.78	46	0.5	68	0.2
20	1,940	41	0.7	70	0.18	120	0.01

Another model is NASRI (Natural Systems for Recharge and Infiltration) bank filtration simulator (version 1.3a) which has been developed during NASRI Project in Germany. It was used to determine the share (%) of filtrated water and local groundwater for given well settles. After inputting parameters such as number of wells, well spacing, distance of the wells from river bank, pumping rates, base flow and hydraulic conductivities, the share of filtrated water and local groundwater can be calculated.

2.2. Water Purification Performance of RBF

2.2.1. Basic circumstances and parameters

Temperature and PH

The temperature of surface water and groundwater is a basic physical parameter for RBF. Regarding to geochemistry, temperature has a great impact on chemical and microbiological processes, e.g. solubility, redox zone formation, viscosity and microbial activities. Previous studies have proven that in temperature-controlled soil passages, both the organic matter degradation and mineralization of trace organics along infiltration path are promoted by temperatures (Grünheid et al., 2008). PH is another basic parameter for RBF which is temperature-dependent. It mainly affects dissolution of salts and then has impact on biochemical reactions. A clear advantage of RBF is stable temperature of abstracted water, which makes the post-treatment easier compared to the seasonal temperature variation of surface water.

2.2.2. Suspended solids

Suspended solids (SS) are usually mentioned as total suspended solids (TSS) and can be also related to and measured as turbidity in unit of nephelometric turbidity units (NTU). In surface water, suspended solids represent small particles (>0.45 μm) when mixed with aqueous solutions remain in suspension (Thibodeaux et al., 1993). Suspended solids is important in drinking water because it can be carriers for pollutants (e.g. heavy metals) and fecal contaminants, and it can protect fecal contaminants from disinfection during drinking water treatment and distribution (e.g. chlorination) (Guang-weil et al., 2005; Berman et al., 1988).
RBF removes suspended solids from water by the infiltration effects which mainly happen at the water-sediment interface (Techneau, 2009). Wang, 2002 found that turbidity in RBF

wells located in a sand-gravel aquifer was less than 1 NTU when the turbidity in the river water was even up to 1000 NTU (Wang, 2002). Besides, RBF has a strong adaptability to variations. In the River Rhine, suspended solids concentration varies between 10 g/m^3 and 400 g/m^3 (~1 and 100 NTU) while the turbidity in well water remained <0.05 NTU (Schubert, 2002). In Egypt, it is reported that RBF has strong TSS removal efficiency at a low SS concentration in the river Nile (~ 1NTU) (Hamdan et al., 2013).

However, although RBF can efficiently remove suspended solids, SS load will lead to clogging problems (e.g. riverbed clogging) which is a main problem for operation. Clogging is a process that river bed getting blocked by particle sedimentation. There will be serious clogging at slow flow velocity. The beneficial aspect is that the increased residence time can promote biodegradation, but more seriously, the problem is that the hydraulic conductivity of the infiltration zone will be reduced (Hiscock & Grischek, 2002).

2.2.3. Fecal contaminants

Fecal contaminants are mainly microorganisms such as bacteria, viruses and protozoa. It also contains larger parasites like helminths causing illness in humans and animals. The fate and transport of fecal contaminants like pathogens in the groundwater environment is foremost influenced by interactions with the solid passage (e.g. straining, filtration, sorption) and inactivation (i.e. die-off) (Tufenkji, 2007). Factors may influence the fate of fecal contaminants include physical force (Van-der-Waals forces, convective transport, dispersion, diffusion), hydraulics (flow velocity and direction), physic-chemical filtration and sediment texture, heterogeneity, association with suspended matter, inactivation kinetics and grazing activities, mechanism of microbial attachment and detachment (Techneau, 2009).

For RBF process, during soil passage, microorganisms can be removed from the aqueous phase firstly by straining, inactivation, and then attaching to the aquifer grains (in combination with inactivation) (Schijven et al., 2002).

Table 2-3 Example results of fecal contaminants removal (Source: Techneau report, 2009)

Pathogen or indicator	Travel time (d) or distance (m) to bank	Site	Removal efficiency (measured or estimated)	Reference
BACTERIA				
Bacteria spp.	2 m	"Bankside filtration"	3-$\log_{10}$	WHO, (2002a)
Bacteria spp.	4 m	"Bankside filtration"	4-$\log_{10}$	WHO, (2002a)
Total coliforms	11-19 d (84 m)	BF (Lake Naintal)	5-$\log_{10}$	Dash *et al.*, (2008)
Total coliforms	35 m	BF (Missouri River)	5.5 to 6.1-$\log_{10}$	Weiss *et al.* (2005)
Total coliforms	15 d (30 m) 63 d (25 m)	2 BF sites (River Meuse and River Rhine)	>5- $\log_{10}$	Schijven *et al.* (2002)
Faecal coliforms	11-19 d (84 m)	BF (Lake Naintal)	4-$\log_{10}$	Dash *et al.*, (2008)
Thermotolerant (faecal) coliforms	<15m	BF River Meuse, sandy gravel aquifer	4-$\log_{10}$	Medema *et al.* (2000)

Travel distance and travel time are two main parameters that influence the removal efficiency. The efficient fecal contaminants removal by RBF have been attributed to the long infiltration paths, low heterogeneity, fine to middle grained sediment, presence of complexing iron and aluminium hydro (oxides) and low flow velocities (Schijven et al., 2002; Schmidt, 2003).

As summarized in Table 2-3, under proper RBF design, the removal efficiency of bacteria contaminants can be 4-5 $\log_{10}$ normally. A minimum travel time between 50-100 days are suggested for an efficient pathogen removal (Grischek et al., 2002). In the least favorable conditions (anoxic conditions), a travel time of 110 days is suggested.

RBF also can remove part of virus such as adenoviruses and noroviruses. Sprenger et al. reported that after 50 m filtration and 119 days, they are undetectable since the initial concentration is in the range of 10^5 genomes/100 ml. As for pathogenic viruses, the removal efficiency is 3.3 $\log_{10}$ to 0.7 $\log_{10}$, decreasing with travel distance (Sprenger et al., 2014). RBF is effective to remove several kinds of viruses but also is influenced by the fluctuation of river level. The amplitudes of river water levels are more important than the duration and frequency of river floods. When the river level increases 1-5 m, the virus concentration in groundwater increased by a factor of 1.2 to 8 and the travel time is 30% shorter (Derx et al., 2013).

Bacteria are regular monitoring items in China usually including total bacteria count, coliform group and fecal coliforms. But viruses are not included in regular monitoring neither in standards and regulations for surface water and drinking water (GB3838-2002).

2.2.4. Nutrients

Carbon

The main problems for carbon are two aspects: a constituent of organic water pollutant and a precursor of disinfection by-products. The recommended maximum total organic carbon (TOC) value is <1.5 mg/l for copper-coated distribution systems for the risk of corrosion (i.e. PH⩽7.4) (TrinkwV, 2001). Regarding the biological stability of treated drinking water, it is required to obtain an assimilable orgnic carbon (AOC) concentration below 10μg C/l without disinfection residuals and 150μg C/l with disinfectant residuals. Numerous researches on dissolved organic carbon (DOC) removal report that the removal efficiency of DOC varies from 50% to 97.4% during RBF which is the main contaminant to be removed for Carbon (Lenk, 2005) (Kühn & Müller, 2000) (Weiss et al., 2004) (Alborzfar & Grøn, 2001) (Wilson, 1995). But redox conditions largely influence biodegradation during RBF and also complex compounds may require long retention times for degradation under anoxic or anaerobic conditions (Lenk et al., 2005). Under anoxic conditions, usually a long retention time is recommended whilst a short oxic passage can already reduce the DOC by 35~40% (Lenk et al., 2005).

RBF have been proven to be an efficient step for organic carbon removal. Its organic matter removal efficiency during RBF depends on the combination of factors such as initial concentration in surface water, aquifer (hydraulic conductivity) and travel time from river to the abstraction wells, temperature, redox condition and the composition of organic carbon (degradabale or non-degradeble) (Lenk et al., 2005; Jekel, 2006; Weiss et al., 2004).

Based on 100 years of experience in Berlin, it is believed that the removal of DOC is primarily ascribed to degradation process (Jekel, 2006). Lenk et al., 2006 proposed a formula to calculate the regression or removal efficiency of dissolved organic carbon (DOC). The formula was based on surface water DOC concentration, aquifer hydraulic conductivity and travel time. In total, 43 RBF wells from Germany, Austria, Switzerland and France with average concentration 4.39 mg/l are included (R^2=0.74). After combination and adjusted with observation wells they had, the formula below was concluded, with a maximum input DOC concentration of 8.0 mg/l suggested:

$$Y = -0.999 + 1.568\ln(X_1) + 0.033X_3^{0.737} + 3.807X_4$$

Y= DOC removal (mg/l)
X_1= DOC concentration in surface water (mg/l)
X_3= length of travel distance (m)
X_4=hydraulic conductivity (m2/s)
It is suggested that input concentration higher than 8.0 mg/l is a limitation. In this case, DOC removal increases as increased input concentration.

Nitrogen

Nitrogen (N) appears in all organisms, primarily in amino acids, in the nucleic acids and in the energy transfer molecule adenosine triphosphate. It is critical nutrient for microbes. The presence of nitrate and ammonium in groundwater is an indicator to an-anthropogenic pollution (Höll, 2002). In drinking water sector, there is a strict regulation on NH_4^+, NO_2^-, and NO_3-. Therefore, nitrogen removal is an important requirement for drinking water purification.
As N cycle, in aerobic condition, NH_4^+ transfers to NO_2^- and then NO_3-, this oxidation process is defined as nitrification. In anoxic or anaerobic condition, NO_3^- transfers to N_2 gas, named denitrification. It has been reported that RBF has a high efficiency on N removal. An example is the study conducted by Wu et al., 2007 in Xuzhou, Jiangsu, China where the surface water has been heavily polluted by nitrogen. The river water recharges the groundwater via RBF in unsaturated percolation along the Xucun section, and in saturated percolation along Huangqiao section. Wu et al., 2007 analyzed seasonal effects on nitrogen removal by RBF and concluded that RBF in the saturated percolation can improve remove nitrogen from the infiltrating water (with removal efficiency 98% in Table. 2-4). And the potential of nitrogen removal is not affected by the seasons and the interface thickness.

Table 2-4 Nitrogen removal efficiency monitoring data in Xuzhou, China

Monitoring date	II_1 (%)	II_2 (%)	II_3 (%)
2/21/2002	97.78	96.98	95.56
4/13/2002	98.38	98.30	97.65
6/29/2002	97.33	95.09	96.55
8/28/2002	98.50	97.65	97.67

Removal efficiency largely depends on the redox condition since it closely influences the chemical process in subsurface passage such as nitrification and denitrification. Thus, identifying the redox condition is a key issue for estimating and predicting the RBF nitrogen removal efficiency.

Phosphorus

In natural water system, phosphate concentration is about 0.1 mg/l and concentration higher than 0.3 mg/l in groundwater is considered as an indication for anthropogenic pollution. There is few literatures focusing specially on phosphorus removal by RBF but all the summaries indicate that RBF can efficiently remove phosphate by its precipitation with metals and cations which are rich in the soil passage (Techneau, 2009).

2.2.5. Cations and Anions

Components in water are divided into three parts (Höll, 2002): macro components (typically >10 mg/l); minor components (0.1-10 mg/l); trace elements (<0.1 mg/l). Marco components usually include sodium (Na^+), manganese (Mg^+), calcium (Ca^{2+}) and chloride

(Cl^-), Hydrogen-carbonate (HCO_3^-) and sulphate (SO_4^-). Minor components include potassium (K^+), manganese (Mn^{2+}), iron (Fe^{2+}), strontium (Sr^{2+}), nitrate (NO_3^-) and fluoride (F^-). Nitrite and nitrate have been discussed in the previous section, and heavy metals will be discussed afterwards in the section of heavy metal.

Cations

Cations like Na^+, Mg^{2+}, Ca^{2+} and K^+ are important salts in environment and maintain a stable condition basically related to the taste and order of water. From health perspective, high concentration of salts will influence the quality of water and break the water-electrolyte balance and kidney function. From the technical perspective, for filtration especially membrane filtration, high concentration of salts may lead scaling then fouling. Inorganic salts, such as calcium carbonate and barium sulphate have higher possibilities to form scaling (Lenntech).

Many studies show cations are difficult to be removed from water by RBF. Moreover, sometimes they are introduced into the water during RBF. In Egypt, the salt concentration in abstraction wells is higher than that in both surface water (the Nile River) and local groundwater in Table 2-5 (Hamdan et al., 2013).

Table 2-5 Uncertain cations removal results in Egypt. Ca, Na HCO_3, NH_3, NO_3 and SO_4 are introduced into abstracted water during RBF mixing with groundwater. Mg, K, Mn, NO_2, PO_4 and Cl are diluted by mixing of surface water and groundwater. Fe is variable during mixing.

Parameters	Units	Nile River	Riverbank filtrates			Groundwater wells	
		Inlet	Outlet 1	Outlet 2	Outlet 3	GW1	GW2
TDS	ppm	178	748	721	687	939	360
pH	–	7.9	7.4	7.4	7.5	7.3	7.8
EC	μmhos/cm	277	1168	1127	1074	1467	562
TH	ppm	105	476	464	462	565	553
Ca	ppm	21.6	100.2	98.7	97.5	81.9	80.0
Mg	ppm	12.3	54.8	52.9	53.1	87.6	85.7
Na	ppm	13.1	140.7	138.6	146.6	130.5	134.9
K	ppm	5.1	9.4	8.8	10.0	11.4	10.4
Cl	ppm	14.0	169.0	162.1	169.6	153.0	62.3
SO_4	ppm	14.6	241.9	242.1	234.9	353.9	350.5
HCO_3	ppm	118.6	335.0	313.3	349.3	268.2	235.9
NO_2	ppm	0.029	0.020	0.014	0.020	0.003	0.011
Mn	ppm	0.034	0.020	0.026	0.024	0.439	0.779
PO_4	ppm	0.065	0.033	0.024	–	0.002	0.001
Fe	ppm	0.031	0.025	0.017	0.295	0.046	0.014
NH_3	ppm	0.035	0.144	0.140	0.079	0.109	0.111
NO_3	ppm	1.267	1.987	2.119	2.513	1.797	1.183
Turbidity	NTU	157.9	269.0	283.0	1.3	0.9	0.3
Dissolved oxygen	ppm	7.63	6.40	6.25	5.46	6.53	7.33
Total. coliform	Colonies/100 ml	255	4.0	3.0	3.0	11.0	9.0
Total bacteria	Colonies/100 ml	1613	15.0	11.0	10.0	41.0	31.0

Similarly, data from RBF site near Opperduit also showed the same observation, as shown in Table 2-6 (Stuyfzand, 2006).

Table 2-6 Uncertain cations removal results in the Netherlands. Na, K, Cl, HCO_3, NH_4 are introduced during RBF mixing with groundwater. Ca, Mg, Fe, Mn, B, Ba, PO_4 vary between dilution and addition. Al, As, Cd, SO_4, NO_3 are diluted during RBF mixing with groundwater.

	Unit	Rhine (Lek)	291-b	292-b	293-a	294-a	Well field 15
Distance	m	0	10	100	220	675	581
Travel time	days	0	450	900	1800	2900	2000
Temp	°C	12.9	12.6	12.9	12.1	11.4	
EC (20°C)	µS/cm	690	797	863	871	837	828
pH	-	7.95	7.58	7.55	7.33	7.54	7.38
O2	mg/L	9.1	<1	<1	<1	<1	<1
DOC	mg/L	3.8	1.6	1.5	2.1	2.0	1.4
TIC	mmol/L	2.76	3.15	3.47	5.82	4.16	3.52
SI-calcite	-	0.33	0.04	0.11	0.11	0.03	*0.11
Cl	mg/L	111	145	166	144	154	145
SO4	mg/L	60	74	69	18	46	77
HCO3	mg/L	163	180	198	318	233	194
NO3	mg/L	15.5	<0.4	<0.4	<0.4	<0.4	<0.2
PO4-ortho	mg/L	0.32	0.35	0.37	0.34	0.73	
F	mg/L	0.15	0.28	0.30	0.14	0.08	0.18
Na	mg/L	61	86	82.9	81.1	84.8	80.5
K	mg/L	5.1	6.2	5.5	9.0	4.6	5.2
Ca	mg/L	72	77	89	92	82	84
Mg	mg/L	10.8	10.8	12.3	12.5	12.5	11.5
Fe	mg/L	0.98##	1.7	1.8	2.65	1.6	2.1
Mn	mg/L	0.13##	1.57	0.84	1.04	0.21	0.65
NH4	mg/L	0.18	0.34	1.21	5.04	2.9	1.19
SiO2	mg/L	4.6	7.3	7.7	9.2	11.1	10.7
Al	µg/L	225##	35	7	8	9	2
As	µg/L	2##	2	<1	<1	1.5	0.5
B	µg/L	100	96	113	158	110	120
Ba	µg/L	118	96	113	158	110	96
Cd	µg/L	0.03	0.04	0.02	<0.01	0.01	<0.05

Anions

Chloride is often used as tracer because of its non-reactive feature in RBF. The concentration of chloride in well abstraction water depends on its concentration in river water and groundwater. The condition of sulphate is more or less the same as chloride in RBF.

It also can be found in Egypt case (Table 2-5) and in the Netherlands (Table 2-6) that the anions concentration in abstracted water sometimes is higher than in river water and groundwater due to mixing. It is clear that some salts are introduced into water through the passage e.g. Fe and Mn as cations and SO_4^{2-} and Cl^- as anions.

2.2.6. Heavy metals

Heavy metals are usually found in trace concentration in earth`s crust and as components of other minerals. It is also widely used as pipe material for water distribution networks. Bourg & Ricour (1989) found that the river bed sediments can retain heavy metals, but re-mobilization can occur. It still depends on sorption, precipitation and ion exchange processes (Bourg & Ricour, 1989). For more detailed parameters, it also depends on pH and redox conditions, sediment texture, ionic strength and the nature of in/organic material present. It has been reported that oxic (aerobic) conditions are more favorable for heavy metals` removal because of the immobilization of hydroxyl (oxides) (Techneau, 2009).

An overview of heavy metals` removal by RBF is summarized in Table 2-7. However, for heavy metals such as F, Fe, Mn and U, RBF may not to be a good option to apply.

Table 2-7 Some of heavy metals removal results depending on specific type.

parameter	fate during BF & influencing factors
Pb	**removal** observed: 75% high affinity to sorb to colloids, fine sands, clay, organic matter and building complexes **remobilisation** possible, closely linked to the fate of particles/colloids during subsurface passage
Cd	**removal** observed: 29-99% depends on pH, redox potential, flow velocity, sorption to colloids (bacteria) and organic matter; organic matter may enhance Cd mobility; potential precipitation as carbonate and sulphide under anaerobic conditions **remobilisation** possible when Fe (hydroxy-)oxides become dissolved under anoxic conditions
Cu	**removal** observed: 77-90% depends on pH, redox potential, sorption to organic material, Fe (hydroxy-)oxides, precipitates with carbonates and sulphides (under anaerobic conditions), sorption/desorption and precipitation/dissolution reactions are major factors for retardation, **remobilisation** possible, pH changes due to mineralisation of organic matter under oxic conditions, remobilisation when Fe (hydroxy-)oxides become dissolved under anoxic conditions
Zn	**removal** observed: 75-82% good removal capacities suggested for BF (within 10 m), depends on pH, redox potential, temperature, ionic strength, sorption to clay, Fe & Al (hydroxy-)oxides, ferrihydrite potential precipitation as sulphide under anaerobic conditions **remobilisation** possible, remobilisation when Fe (hydroxy-) oxides become dissolved under anoxic conditions

In case of the Netherlands, the concentration of the majority of heavy metals increased after RBF as shown in Table 2-8 (Stuyfzand, 2006). It can be seen that RBF can remove As, Se and Cr but for F, Fe, Mn and Pb, the concentration in the abstracted water vary from dilution and addition. Differently, in Egypt (shown in Table 2-9), removal of Mn by RBF were observed where the heavy metal concentrations in river water was low but Fe sometimes is introduced into abstracted water (Hamdan et al., 2013).

Table 2-8 Heavy metal removal in the Netherlands. As, Se, Cr and Ni are diluted while F, Fe, Mn, Pb vary between dilution and addition.

	River	Well 1	Well 2	Well 3	Well 4	Groundwater
Distance	0	10	100	220	675	581
F mg/l	0.15	0.28	0.3	0.14	0.08	0.18
Fe	0.98	1.7	1.8	2.65	1.6	2.1
Mn	0.13	1.57	0.84	1.04	0.21	0.65
As μg /l	2	2	<1	<1	1.5	0.5
Ni	3.3	0.5	0.4	0.6	<0.5	<1
Pb	0.3	1.3	1.3	0.4	0.8	<1

Se	0.2	0.02	0.01	0.01	0.02	<1
Cr	4	<0.5	>0.5	<0.5	<0.5	<0.5

Table 2-9 Heavy metal removal in Egypt case. Mn is diluted while Fe varies between dilution and addition.

Parameters	River	Well 1	Well 2	Well 3	GW 1	GW 2
Fe ppm	0.031	0.025	0.017	0.295	0.046	0.014
Mn ppm	0.034	0.02	0.026	0.024	0.439	0.779

From discussion above, both ions and heavy metals are not only removed by RBF, but also might be introduced into the abstracted water. More attentions should be paid on the comparison of input concentration and limitation value in drinking water. A high input concentration and low limitation value means that the post-treatment might be stressful causing more costs.

2.2.7. Organic micro-pollutants

Pesticide

Pesticide is widely used around the world in agriculture field to replace manual treatment methods for crops and vegetables. WHO has a guideline limitation value for individual pesticides ranging from maximum 0.03 μg/l (aldrine/dierine) to 100 μg/l (dichlorpop) (WHO, 2006).

In soil passage, the behavior of pesticides depends on physical, chemical and biological processes in the aquifers. The main processes happened in soil passage are sorption and desorption, filtration, bio and abiotic degradation and volatilization (Verstraeten & Scheytt, 2002). In recent years, biodegradation is found to be the main mechanism for most OMPs removal during RBF influenced by redox condition (Bertelkamp, 2015). Redox environment is strongly influence the removal of pesticide based on different processes. Stuyfzand, 2011 reported that atrazine, diurone and carbendazim are removed between 0% to 40% by RBF under (sub)oxic but 60% to 100% under anoxic or deep anoxic (Stuyfzand, 2011). Bertelkamp, 2015 indicates that redox condition is vital for removal of organic micro-pollutants (OMPs). Redox dependent removal (dimethoate, diuron, and metoprolol) behavior with degradation rates larger in oxic zone compared to the suboxic/anoxic zone. But persistent behavior OMPs are not removed in both oxic zone and more reduced conditions (Bertelkamp, 2015).

Besides, there are huge differences among different pesticides` removals by RBF. Schmidt, 2003 found that the removal efficiencies of 13 pesticides vary from 0% to 99% shown in Table 2-10.

Table 2-10 Huge difference on removal efficiency by RBF towards pesticide

Pesticide	Removal efficiency	Conditions
2,4-D	86->97%	
Bentazone	0-60%	20 to >360 d
Bromoxynil	78-99%	
Dichlorprop-P (2,4-DP)	30-50%	
Flufenacet	63%	Suboxic RBF, 6d
Glyphosate	17->30%	Anoxic RBF, 30-300d
Isoproturone	10->75%	
MCPA	74%	
Mecoprop-P	0-80%	
Metazachlor	40->99%	
S-Metolachlor	0->70%	
Metalaxyl-M	>75%	
Terbuthylazin	10->70%	

Thus a complete water quality data on pesticides of potential RBF locations will give a chance to predict the removal of pesticides. Thus corresponding measures can be taken aiming at threaten types of pesticides.

Moreover, when pesticides retained in aquifer, it has a risk that contaminate the aquifer. Thus, the most important way is to limit from the source (Barbash, 1996).

Chlorinated hydrocarbons

Chlorinated hydrocarbons are a kind of chemical composed of carbon, hydrogen and at least one chlorine atom. Many contaminants are also chlorinated hydrocarbon such as pesticides and disinfection by-products (DBPs). Chlorinated hydrocarbon tends to accumulate in the food chain due to its hydrophobicity to be often toxic and persistent in the nature environment (Techneau, 2009).

Biodegradation is an important process on removal of chlorinated hydrocarbon which is influenced by the number of chlorine substituents. Chlorinated hydrocarbons with less substituent are predominantly biodegraded under oxic/aerobic conditions whilst with more substituents are rather biodegraded in the absence of oxygen (Techneau, 2009). It is also influenced by substrate-specifically by redox conditions and the availability of co-metabolites under a long retention time.

To explain this, Rivett et al., 2006 made a good conclusion that aerobic degradation processes are direct aerobic oxidation and co-metabolism both requiring an alternative substrate to be present (Rivett et al., 2006).

In general, it is difficult to predict the efficiency of RBF to chlorinated hydrocarbon because of the complex processes confirmed by observed results. Thus after specific test and operation, corresponding post-treatment is necessary.

Aromatic hydrocarbon

Aromatic hydrocarbons are compounds that are characterized by a cyclic C-H-ring structure that are hazard to ecosystem and human health due to their high toxicity combined with their persistence and spreading in the environment.

Monocyclic aromatic hydrocarbons

Common one ring structure aromatic hydrocarbons are benzene, toluene, ethylbenzene and xylene which are named in group BTEX. Degradation is still the main process for BTEX which was observed to occur rapidly under aerobic conditions. And then it is continued at a slower rate under nitrate-, iron-, and sulphate- reducing conditions (Gelman & Binstock, 2008). Degradation was observed to be best in the order: toluene> ethylbenzene> m-xylene> o-xylene> benzene> p-xylene.

Polycyclic aromatic hydrocarbons (PAHs)

Double or more rings structure, and is also a risk to wildlife and human health for their toxicity, persistence and tendency for bioaccumulation. 16 PAHs are listed by the US Environmental Protection Agency as "priority pollutants". Similar to other hydrocarbons, the main process degradation is also influenced by structure, redox condition and availability of co-nutrient for more. PAHs are less biodegradable compared with the BTEX group because of a more complex structure and their tendency to compact with solids and colloids. Jüttner (1999) assessed the removal efficiencies of fragrance compounds and aromatic hydrocarbons (menthol, limonene, a-terpineol, 4-tertiary butylcyclohexanol, 4-tertiary butylcyclohexanone) that are around 90% from 0.1 to 0.01 μg/l (Jüttner, 1999).

Although the removal efficiencies to different types of OMPs are variable, the organic carbon fractions of the river water will not affect the OMP biodegradation rates observed by Bertelkamp, 2015. Further she observed the resilience of RBF systems towards a DOC/OMP shock-load which may be important to the drinking water company during operating. Function groups are the factor that effect OMP biodegradation rates by a statistical significant relation. But redox dependent removal could not be explained by their physico-chemical properties or the function groups present in their molecular structure (Bertelkamp, 2015).

Endocrine disrupting chemicals

Endocrine disrupting chemicals (EDCs) are mostly anthropogenic appeared in various sources such as pesticides, metals, food, and personal care products (WHO). Most of EDCs are usually assembled in suspended solids or sediment rather than in the liquid phase, and the influence of EDCs towards groundwater is minimized by soil passage characteristics thus it is less influenced than surface water (Maeng, 2010).

It has been proved by many researchers that RBF is a promising technology for drinking water treatment to remove EDCs (Grünheid et al., 2005). Estradioles, estrones and estriols are sex hormones belonging to the group of human estrogens are reported to be reduced by RBF to limit concentration after 1 m (Zühlke, 2004).

For more quantified removal efficiency, Maeng, 2010 reported that in his batch experiments, most of remaining estrogenic activity in filtrates was eliminated by a significant removal of E2, E1 and EE2 and other estrogenic activity. Even redox conditions did not make effect on removal of E2 and EE2. Then because the removals of EE2 in abiotic and biotic are 67% and 87%, respectively, biodegradation also contributed to reduction of EE2 as well as the major mechanism adsorption (Maeng, 2010).

However, the removal efficiency of same EDC can be different according to Table 2-11.

Table 2-11 Removal efficiency of same EDCs under different conditions (source: Techneau, 2009)

Substance	Reduction	Days (d) or distance (m)	Conditions	Reference
BPA	> 99 %	n.a.	BF, c_o = 50 ng/l	Sacher *et al.*, (2001)
	50 %	0.2 to 4.1 d	oxic aquifer material columns	Ying *et al.* (2008)
	> 99 %	n.a.	oxic (BF)	Schmidt *et al.* (2003)
	>95%	60 to 100 d	oxic	Schmidt, (2003)
	> 99 %	n.a.	anoxic	Sprenger *et al.* (2009)
E2 and EE2	> 99 %	first metres of BF	oxic	Zühlke (2004)
	50 %	26 d for E2, 0.2 to 4.1 d for EE2	oxic aquifer material columns	Ying *et al.* (2008)
NP	50 %	14 to 99 d	oxic	Yuan *et al.* (2004)
	70%	14 m	c_o = 1 µg/l oxic?	Schaffner (1987)
	93%	5-14 m	c_o = 2.7 µg/l suboxic	Ahel (1996)
	50 %	0.2 to 4.1 d	oxic aquifer material columns	Ying *et al.* (2008)
	> 95%	n.a.	oxic (BF)	Schmidt *et al.* (2003)
NP M	50 %	1) 69 to 116 d	1) oxic	1) Yuan *et al.* (2004)
	98-99%	1-14 d	suboxic BF	Ahel (1996)

For example, NP is removed by 50% to >95% under different travel time (distance) or redox conditions. This indicates that RBF can remove many EDCs efficiently depending on travel time and redox conditions.

Pharmaceuticals (PhACs)

Pharmaceuticals are widely used in human medicals with large quantities and also as feed additives in animal production. Discharge of municipal sewage and effluent from hospital are two main ways for pharmaceuticals to enter water system. But there is no recommendation or threshold value for pharmaceuticals.

Biodegradation and adsorption are two main processes to remove pharmaceutical after a certain period of time. And in general RBF can remove most of PhACs that many researchers have already proved.

Maeng, 2010 did a lot of researches on OMPs in his PhD thesis. He found that the removal efficiencies of most selected PhACs are greater than 90% (Gemfibrozil, Ibuprofen, fenoprofen, bezafibrate, ketoprofen, naproxen, phenacetine, pentoxifyline, paracetamol and caffeine) in surface water and independent to redox conditions in soil. But wastewater effluent-impacted surface water will influence the overall removal efficiency which has more effluent organic matters (Maeng, 2010).

Stuyfzand, 2007 also reported some pharmaceuticals showing significant biodegradation removal higher than 90% (phenazone, iohexol, iomeprol and lopamidol in suboxic environment; sulfamethoxazole and amidotrizoic acid in anoxic environment). However, some of pharmaceuticals are very persistent in suboxic or anoxic environment (Stuyfzand, 2007).

Similarly, Benotti et al., 2012 found 22 of 29 compounds (including some EDCs) were removed greater than 90% following 36 days of treatment that across three sand and gravel columns simulating RBF treatment except carbamazepine and sulfamethoxazole which the removals are less than 20% (Benotti et al., 2012).

However, although many PhACs are removed effectively by RBF, there are some PhACs that are hardly removed, requiring special attention.

Disinfection by-product precursors

Disinfection by-productions (DBPs) are result of reactions between organic and inorganic matter after chemical treatment in disinfection process. DBPs have been associated with several health risks via drinking water such as bladder cancer. Not all DBPs have been identified and well-studied (Richardson, 2007). The main DBPs could be identified as, trihalogenmethanes (THMs), halogenated acetic acids (HAAs), (halo)acetonitriles, chloral hydrates, cyanogen chlorides, chlorophenols, chlorophenols and bromates.

To reduce DBPs formation, it is important to remove the precursors. Precursors for THMs and HAAs were removed between 50 to 80% and other DBP precursors between 30% and 100% in three observing sites (Weiss et al., 2004).

Wang, 2002 also reported that RBF can remove DBPs precursors such as THMs, HAA6 and TOXs through FP test shown in Fig 2-3.

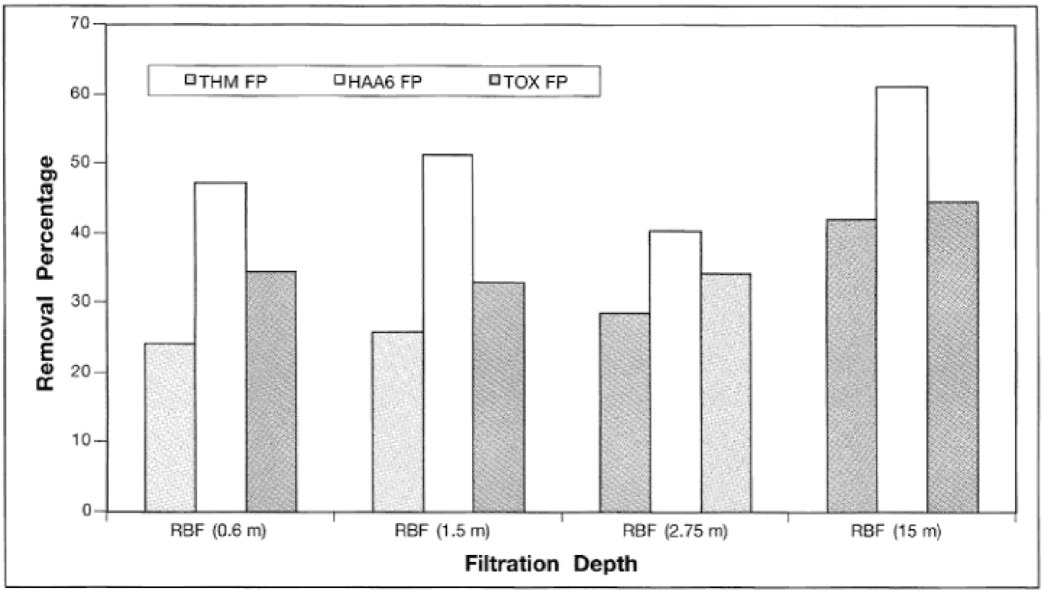


Figure 2-3 DBPs precursors (THMs, HAA6, TOXs) removal efficiencies through FP test under different filtration depth

Although RBF can remove all three types of precursors, removal efficiencies still vary with filtration depth and vary among types. Removal efficiencies increase with increasing filtration depth for all types but the removal of HAA6 is most significant reaching 60% after 15 m. Thus a longer travel time/distance is expected to improve the removal efficiency to a certain degree.

Soil type influences more on capacity of RBF than the OMP removal which is more influenced by aqueous phase (biodegradable dissolved organic carbon quantity/quality, nutrients) (Bertelkamp, 2015). This founding contributes to the function water quality improvement of RBF on OMP removal.

2.3. Will RBF Help to Water Quality Challenges in China?

In order to apply RBF to improve the water quality, many influencing factors are reviewed. Hydrological and hydrogeological aspects are the basic and also critical criteria. A proper aquifer linked with the river and adequate soil conditions are the most essential features for a RBF site. Meanwhile, from the literature review, it is clear that RBF can efficiently remove contaminants from source water and is resistant to variations such as temperature. Among them, TSS, nutrient, fecal contaminants, some ions (Cr, Al), many EDCs, PhACs and DBPs precursors are largely removed. The majority of ions and heavy metals are difficult to remove by RBF and may even be introduced into abstracted water during soil passage. The removal efficiencies for some OMPs e.g. pesticide are largely influenced by its type and by conditions such as redox, temperature and residence time/distance.

Thus a series of questions are proposed for RBF application in China since there are still some knowledge gaps when introducing RBF into China.

- What are the criteria for RBF in China? Many influencing factors are reviewed through literature but are them all proper in practice especially combining Chinese conditions?
- What are current situations in China? Is RBF already applied in China? How is the water quality condition?
- How can we use RBF in China? What are candidate locations?

Afterwards, a series of steps can be taken to overcome the gaps.

Firstly, the criteria for applying RBF in China are needed to evaluate sites against both critical and influencing factors. A site evaluation approach needs to be established to apply the criteria to potential sites and an additional design model helps to give a preliminary evaluation of the RBF site and cost estimation (in chapter 3). The site evaluation approach is the core component of this thesis.

Once a site evaluation approach is established, some questions may be asked. Is this model developed on European knowledge appreciated for Chinese conditions? For example: are the items and parameter values appropriate in Chinese practice? Thus learning about current RBF situation in China is important to tune the model. That can be done in two ways: investigations by information and literature review, and by site visiting. The former one gives an overall knowledge (in chapter 4.1) and the latter one is to acquire detailed conditions and data/information on site (in chapter 5.1).

The approach is applied to test at two levels: national application and site application. In the national application, the approach is applied to identify suitable sites for RBF. The outcome is potential areas for applying RBF in China (in chapter 4.2). In site application, the site evaluation approach can be fully applied by both criteria and design model. The validity of model can be tested by comparison of the model analysis and reality at the operating site in China to see if they are (reasonably) consistent. Feedback is also given after this application (in chapter 5.1).

If the criteria and design model are proper and consistent to reality, they can be applied to candidate locations for applying RBF. Alternative solutions are suggested relying on the model in case the candidate location is unsuitable for applying RBF. The outcomes are candidate location evaluations (in chapter 5.3 and 5.4).

Finally, after establishment of site evaluation approach, two testing applications and other case studies, the model is tuned according to Chinese conditions. Meanwhile, potential locations are proposed. The model can be applied further to other candidate locations.

The main question as title 2.3 can be answered and also how to apply RBF to help water challenges in China?

The logical thinking line of this series steps is shown in Fig 2-4.

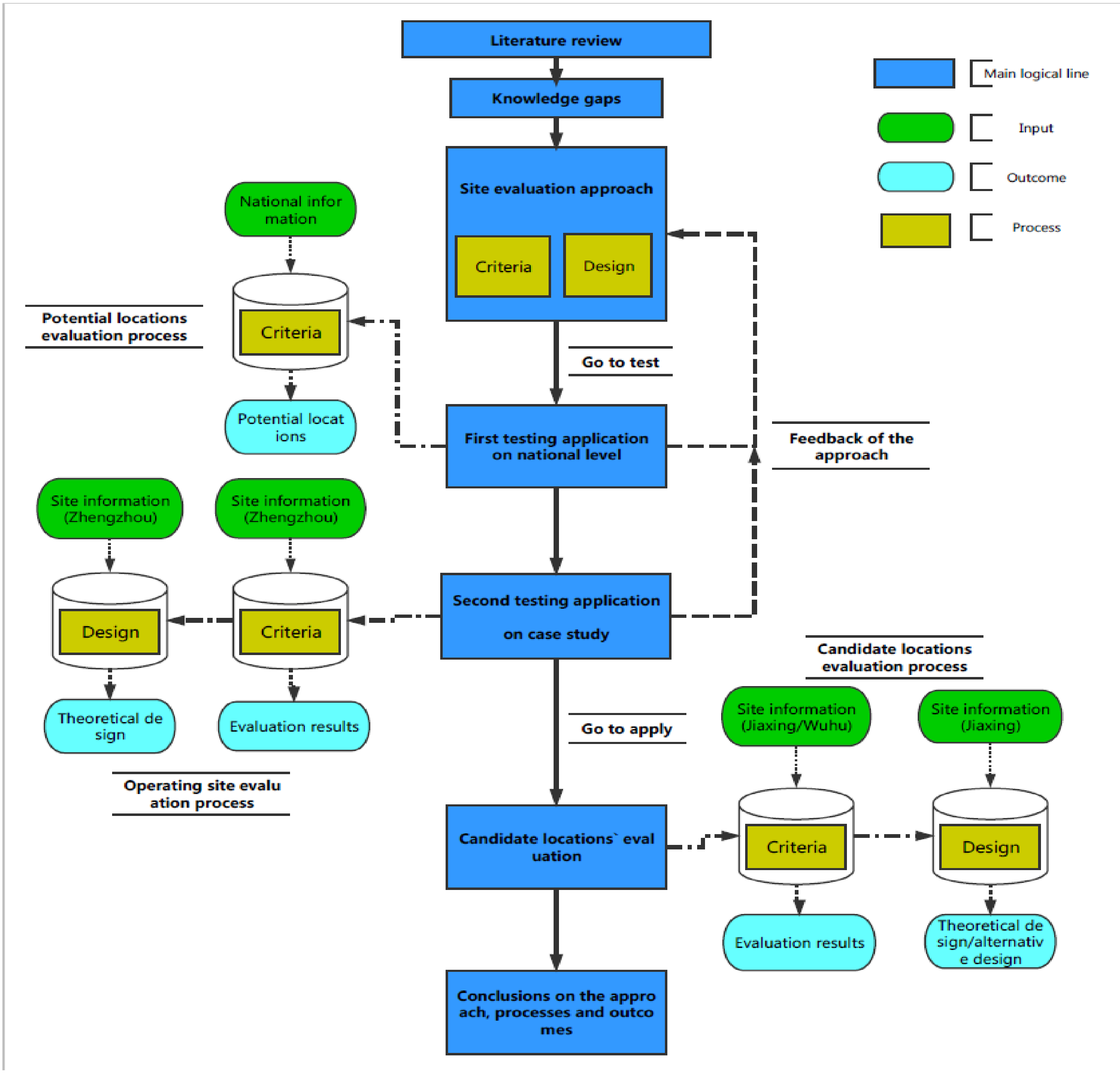


Figure 2-4 Illustration of logical thinking line including site evaluation approach and evaluation processes

3

3. Site evaluation approach for applying RBF

In order to screen and find potential sites in China using influencing factors summarized in chapter 2, a site evaluation approach is formed to fit in the factors.

The model includes 3 steps, 2 of them are screening criteria while the last step is a basic design Microsoft Excel model. The screening criteria are based on: RBF literatures reviews; case studies worldwide; discussion with experts in the Netherlands. The design model is for an insight to RBF site capacity, dimensions and costs to help decision making. In subsequent chapters 4 and 5, the site evaluation approach is applied to evaluate potential RBF sites and a national scale and specific case studies. Comparison against an existing RBF site provided information about the validity of the evaluation approach.

Two steps are applied: first step is a basic screening and second step is a more detailed evaluation against criteria.

Table 3-1 Criteria items overview

	Subject	Step 1	Step 2
Criteria		**Basic criteria**	**Classification Evaluation**
	Water source	River in region	River velocity River flow Streamline
	Water quality	Salinity No extreme pollutant	TSS Fecal contaminants Nutrients, Anions Cations & Heavy metal OMPs & Emerging contaminants
	Geo-hydrology	Aquifer material Aquifer thickness Hydraulic conductivity Connection	Aquifer thickness Aquifer hydraulic conductivity Soil texture

	Social	Water demand Finance Land	Current water supply & shortage Land use

Step 1 uses key parameters to identify the basic RBF potential of a location. This step is a strict 'Yes' or 'No' process which means in case any key parameter is insufficient, RBF application is not feasible. Meanwhile, step 2 is not a strict 'Yes' or 'No' process since there is more parameters are evaluated that provide a more enhanced evaluation.

3.1. Step 1: Basic Criteria

Four criteria are developed to evaluate the possibility (Table.3-2) based on information acquired in chapter 2.

Table 3-2 Site selection criteria Step 1

Subject	Criteria	Subject	Threshold	Subject	Criteria	Subject	Criteria
Water Source		Water Quality		Hydrogeology		Social	
Surface water	River	Fresh water At least III level[1]	Salinity (TDS): <1000 mg/l	Aquifer material	Sand, Gravel, Silt	Water demand	Extra water demand
Ground water	Adequate	At least IV level[2]		Thickness	>10 m	Finance	
				Connection	Connected river and aquifer	Land	Enough & Proper
				Hydraulic conductivity	>5 m/d		

1 Water Quality Standard for Surface Water GB3838-2002, Level III (China, 2002)

2 Water Quality Standard for Groundwater GB14848-93, Level IV (China, 1993)

3.1.1. Water source

Water source is vital for RBF that there should be a **river in this region as surface water source**. Moreover, **abundant groundwater source** is also an important feature for RBF. Besides, river with high stability flow is needed for a RBF site for sustainable operation.

3.1.2. Water quality

The second aspect, water quality, includes two main parts: surface water source and groundwater source. Fresh water is the first parameter to identify for surface water. This item is more vital to areas near sea side or estuary because sea water typically has a salinity

of around 35 g/kg, although lower values are typical near coasts where rivers enter the ocean. Rivers can have a wide range of salinity, from less than 0.01 g/kg to a few g/kg although there are many places where higher salinities are found (Eilers, 1990).
According to the standards for drinking water source in China, the water source should be above level III for surface water (Standard for Surface Water Environment Quality GB3838-2002(Appendix A.1)) and level IV for groundwater Level III (Standard for Groundwater Quality GB14848-93 (Appendix A.2)).

3.1.3. Hydrogeology

Hydrogeology aspect is to evaluate if the soil condition is suitable. Only unconsolidated, granular aquifer which means those comprising sand, silt, rock fragments, and pebbles—would be suitable for RBF (Tufenkji et al., 2002). Besides, karstified limestones and sandstone sometimes are also acceptable for RBF but not usual. **The main type of aquifer should be sand, gravel or silt.** To know the average value of parameters, several cases are studied around the world and summarized in Table.3-3.

Table 3-3 Aquifer cases information worldwide

			Malawi /Kenya	**India**	**Korea**	**Nile**	**Koblenz**	**Barcelona**
No	Name	Unit	Value					
1	Aquifer thickness	m	30~60	3~30	5~35	50~300	10~15	40
2	Aquifer material		Silty gravelly sands			Sand-gravel		Sand-gravel intercalated with silts-clay
3	Average hydraulic conductivity	m/d	4.92-143.42	5.44	112~6912	60-110	345.6-1728	2500
Reference			Sharma et al., 2012	Boving, 2014	Lee & Lee, 2010	Shamrukh et al., 2008	Schubert, 2006	Martín-Alonso, 2006

It is easy to see that the majority of thickness value is tens of meters. Therefore, **minimum 10 m thickness is selected as a strict value**. And for hydraulic conductivity (K), the majority of K values is bigger than 5 m/d. **Minimum 5 m/d is used as strict value.** When these three items are sufficient, the pre-conditions of RBF are satisfied.
Connection between river and aquifer is also a key point. The connection provides river water recharge to aquifer and influences the capability of water supply.

3.1.4. Social

Regarding to social part, the **water demand** in this region should reach beyond the water supply amount thus there is necessity to apply RBF. The **funds** for a RBF project should be available. Meanwhile, enough and proper **land** along the river is also required.

Then the site screening procedure will move to step 2 to classify the situation in more detailed since four aspects criteria are fulfilled.

Table 3-4 Step 1 summary table

Step 1				
	Criteria	Reality	Qualified	Remark
Water source	Rivers			
Water quality	Level III			GB3838-2002
Hydrogeology	Thickness > 10 m Connected K > 5 m/d			
Social	Water demand Land Finance			

3.2. Step 2: Classification in Degree

Although step 1 screens potential locations against basic criteria, different degrees of influencing factors will affect the performance of RBF and affect post-treatment.
Step 2 describes and evaluates a number of parameters that influence RBF and can be divided into four groups as in step 1. The results are in tables at the end of 3.3 with different points representing the score assigned to it. Point 5, 3 and 1 represent good, normal and poor, respectively. For some items, only two degrees are assigned: good by 5 and poor by 1.

Table 3-5 Site selection criteria step 2

Subject			
Water source	Geohydrology	Water quality	Social
Flow	Aquifer thickness	TSS	Current supply, shortage & future demand
Flow velocity	Hydraulic conductivity	Pathogens	Land use
Streamline	Aquifer soil texture	Nutrient	
		Cations & Anions	
		Heavy metals	
		OMPs & Emerging contaminants	

3.2.1. Water source

Flow

The discharge is the ability of the river to recharge an aquifer including the seasonal variety of water amount. The operation of RBF will be intermittent by the variety of flow in case it is very minimal. High and stable flow is 5 point to RBF. Fluctuate flow is 3 point and low flow is 1 point.

Flow velocity

Flow velocity is a key factor that influences the sedimentation of particles in the river to the riverbed. And it is also a factor to estimate the shear stress on the river bottom. The shear stress which is closely related to the flow velocity that generates the balance to renew clogged areas on the bottom of the river thus is an important factor to the yield of RBF systems (Schon, 2006). For example, the flow velocity of River Rhine is 1.0 to 1.4 m/s (Hunt, 2003) and the flow velocity of the Platte River, USA is about 2 to 3.5 kilometer per hour, 0.56 to 0.97 m/s (Schijven et al., 2002). Invoking the research from Thailand, the suitable river flow velocity is higher than 0.5 m/s and better around 1.5 m/s (Srisuk, 2012).

Streamline

Streamline is the meander of river flow as Fig. 3-1 shows.

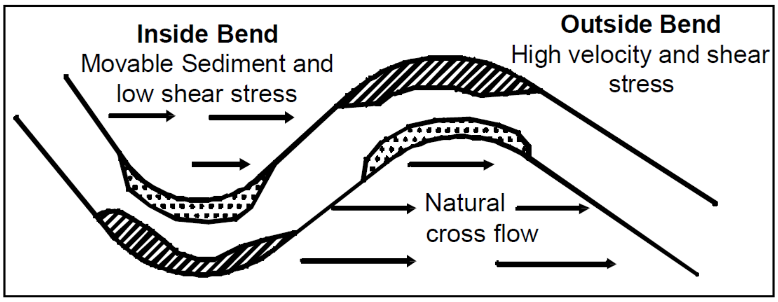


Figure 3-1 Streamline illustration map (Source: Caldwell, 2004)

The river meander is divided into the inside bend and outside bend. In the inside bend, the velocity is relatively low but it is easier to remove the sediment on riverbed when flood waves come. The yield is probably higher in the inside bend because of the natural cross flow to recharge the aquifer (Schon, 2006). Thus, the inside bend is a better choice to RBF site.

3.2.2. Hydrogeology

Aquifer thickness

Aquifer thickness is a key point to calculate the ability of water transport and the production of RBF together with hydraulic conductivity (K). After case studies and literature reviews, a thickness of 10 m is a minimum limitation for RBF site while 20 m or larger is preferred.

Hydraulic conductivity (K)

Hydraulic conductivity is a property of soil that describes the ability of fluid moving through pore space in soil. It is symbolically represented as K. K depends on the intrinsic permeability of the material, the degree of saturation, the density and viscosity of the fluid. Horizontal conductivity K is most used, although it is not an isotropic parameter and varies in different directions. The preferred minimum K value is higher than 5 m/d and larger than 10 m/d is preferred for RBF.

Aquifer soil texture

Soil texture can provide filter properties of the subsurface. Different type of soil will result in different reaction processes as well as efficiency of removal. Limestone and dolomite bedrocks, for instance, which are abundant in fissures, allow for rapid water travel times. These conditions are unfavorable for the removal of water contaminants although still some natural attenuation will happen. Moreover, the quality of water (e.g. salinity) and the soil at the geologic site (e.g. amount and solubility of arsenic content) are factors to be assessed prior to water abstraction for potable use (Techneau, 2009).

3.2.3. Water quality

Total suspended solids (TSS)

For the River Rhine, the removal efficiency reaches 99%, from 1~100 NTU to <0.05 NTU (Schubert, 2002). The filtrated water is also closely related to groundwater quality in which TSS is low. Besides, the S_{BF} is also an important factor representing the share of surface water contained in the overall produced Q_{BF}. Some removal efficiency examples are summarized in Table.3-6:

Table 3-6 Turbidity removal example cases

Sites	River (NTU)	Well (NTU)	Efficiency (%)	Reference
Rhine	1~100	<0.05	95%~99%	Schubert, 2002
Brazil	34.03	0.76	98%	D.A.Freitas, 2012
New Zealand	4.2~168	<2	53%~99%	Zeb Etheridge, 2009
Malaysia	699	11	98%	Shamsuddin, 2014

Generally speaking, RBF can reduce high turbidity to acceptable level under common conditions but when the turbidity exceeds normal values, post-treatment is required. A small calculation is made that assume the removal efficiency for RBF and conventional treatment to turbidity is 98% and 98%, respectively, while the limitation for turbidity is 1

NTU in GB5749-2006 (Zhao, 2015). Thus, a calculation value 2500 NTU is difficult to RBF and post-treatment because of more chemicals or advance processes. Meanwhile, high turbidity may cause problems in operation (e.g. clogging). For estimation, 1000 NTU is selected as criteria for RBF approximately.

Fecal contaminants

WHO (2002a) considers RBF capable to achieve a 3-$\log_{10}$ and 4-$\log_{10}$ removal after 2m and 4m respectively to both, viruses and bacteria. In order to achieve sufficient removal efficiency, long infiltration paths and retention time are needed. In case the concentration of fecal contaminants exceed the removal ability of RBF system even after maximizing resident time/distance, or due to the limitation of field space, additional post-treatment is necessary. Besides treatment technique such as flocculation, coagulation and sand filtration, chlorine dosing, ozone disinfection and UV are also effective techniques to remove fecal contaminants. Therefore, to ensure the water quality, at least **5-$\log_{10}$** is recommended, and a minimum travel time **30 days** is reliable.

Nutrients, Cations, Anions and Heavy metal

- **Nutrients**

WHO recommended 50 mg/l and 0.2 mg/l as the maximum acceptable level for nitrate and nitrite respectively under long–term exposure. Due to the 0.5 mg/l limitation for nitrogen in drinking water, concentration higher than **25 mg/l** cannot be treated sufficient directly by 98% removal efficiency.

For Phosphate, although there are few literatures focusing specially on phosphorus removal, all point out RBF is generally considered efficient to remove phosphate because of the precipitation with metals and cations which are abundant in the subsurface.

The removal efficiencies depend on redox condition and rely on retention time and travel distance. Thus the evaluation of nutrient concentration in surface water and groundwater is vital for RBF system. Once the concentration is too high to removal ability of subsurface, the concentration in filtrated water may exceed the limitation, especially when the concentration in groundwater is also high. In such case, enhanced post-treatment is necessary for RBF system. Wastewater treatment techniques are useful and effective in removal of nitrogen and phosphorus such as oxidation ditch, SBR, A^2O and other emerging techniques.

- **Cations and Anions**

The concentration of ions especially cations are largely depends on mixing of groundwater thus they are difficult to be removed by RBF (Hamdan et al., 2013). According to Hamdan et al., 2013, depending on the mixing rate, sometimes salt concentration (NO_3, Ca, Na, Cl) in filtrated water is higher than both river water and groundwater requesting for corresponding post-treatment. Ion exchange can be the first choice to reduce salts concentration such as Na^+, Ca^+, Mg^+ and K^+. Therefore, water source quality on and better than Level II is beneficial to post-treatment while water quality on Level III is normal. In case the water quality is on Level IV or worse, it is poor for RBF and post-treatment due to high concentration. Membrane filtration is another effective technique to remove salts but also with a high investment and operation fee.

- **Heavy metal**

In the Netherlands case (Stuyfzand, 2006) and Egypt case (Hamdan et al., 2013), RBF is a valuable treatment technique to remove heavy metal in generally but still some heavy metal such as Fe and Mn are rather difficult for RBF. According to the standard for drinking water, limitations for several heavy mental are calculated.

Table 3-7 Heavy metal removal example results

Heavy mental	Standard	Efficiency	Criteria value
As	0.01 mg/l	<50%	0.02 mg/l
Fe	0.3 mg/l	<20%	0.375mg/l
Mn	0.1 mg/l	<40%	0.17 mg/l

Concentration higher than criteria value listed in Table 3-7 is beyond the removal efficiency of RBF requesting corresponding post-treatment. Ion exchange is a desirable technique to remove several heavy metals and chemical deposition method is a traditional method and widely used. Membrane technique is an effective method but also with high investment.

Nutrients, ions and heavy metal are not only removed by RBF but also be introduced into the water during processes in the aquifer. Thus the criteria for these three items are summarized separately. Considering the conventional treatment processes, the concentrations for these three items should not beyond the limitation. Otherwise, the burden for post-treatment is huge.

For ammonia nitrogen, the limitation is 0.5 mg/l in GB3838-2002 and removal efficiency is 75% (Zhang, 2012). Thus, ammonia nitrogen concentration higher than 2 mg/l is difficult to post-treatment.

For ions, there is not specific limitation and information for conventional treatment processes.

For heavy metals, Fe and Mn are two items usually be introduced into the water during RBF. The limitation in drinking water is 0.3 mg/l for Fe and 0.1 mg/l for Mn and the removal efficiency is 90% (Su, 2012). Thus above 3 mg/l and 1 mg/l, it is difficult for post-treatment.

Table 3-8 Step 2 summary table for non-removable items

Step 2.a							
Items		Criteria			Reality	Qualification	Remark
Water quality	Nutrients Ammonia nitrogen	<2 mg/l*[1]	≥2 mg/l				
		5	5				
	Ions	Level I, Level II	Level III	Level IV, Level V			
		5	3	1			
	Heavy metal Fe/Mn	<3 mg/l, <1 mg/l	>3 mg/l, >1 mg/l				
		5	1				

**[1]2 mg/l is calculated by the 75% removal efficiency of traditional treatment processes and the limitation 0.5 mg/l in drinking water.*

**[2]limitation is calculated by the removal efficiency of 90% by traditional treatment processes to Fe and Mn. The standard for drinking water is 0.3 mg/l to Fe and 0.1 mg/l to Mn.*

3.2.4. Social

Current water supply & predicted demand

RBF has a great potential to apply in newly industrialized and developing countries where the safe and clean drinking water production shortage is a main problem for society. Current water supply conditions are important information to estimate the water supply shortage since water demand for clean drinking water is a basic requirement and driving-force to apply RBF when the future water demand is known the design capacity for RBF can be estimated. Then design capacity of RBF will determine the abstraction rate, number of wells, and working period.

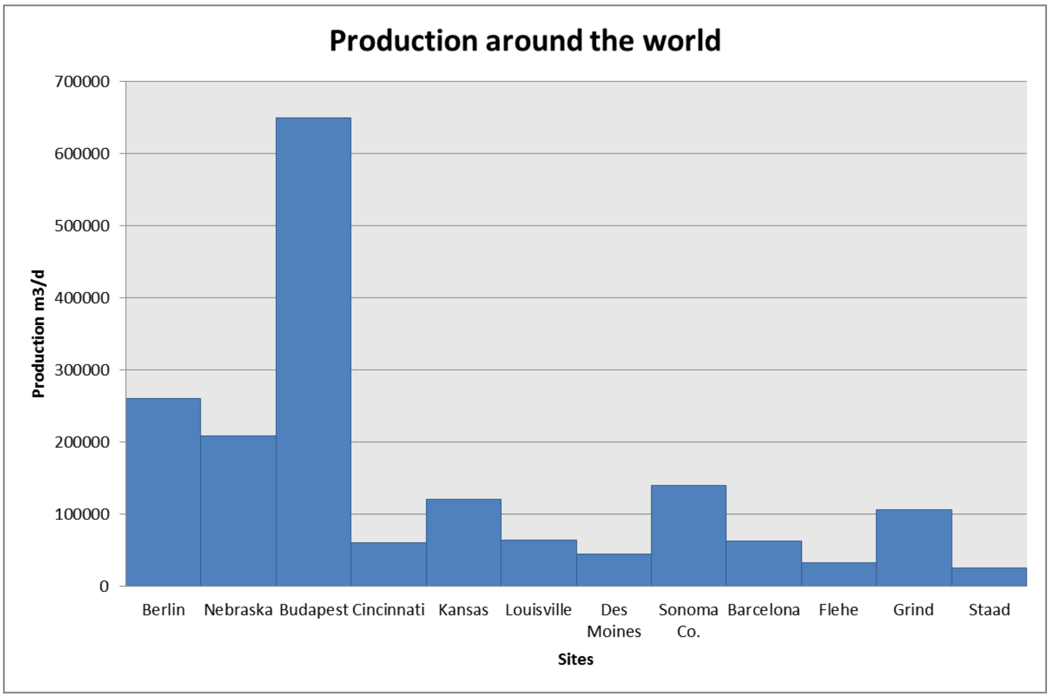


Figure 3-2 Production of RBF water plants around the world

According to the information collected now, the largest engineering production around the world is in Budapest with a capacity of 650000 m^3/d (Literathy, 1999). Other sites produce is less than 300000 m^3/d. The production of RBF is a main question to potential sites in China because the water demand in China is always extremely large. However, it is not necessary to meet all the water demand of a city by RBF.

Land use

The location of RBF is usually away from a river bank and need space for wells and equipment. The land use before construction is important; it may influence the groundwater quality and soil quality. The types of land use could be **open/public**, agriculture and industry. The worst situation is industry usage for the risk of pollution followed by agriculture because of the pesticides and fertilizer usage. Open and public use will be an advantage in RBF system site selection.

Table 3-9 Step 2 summary table on other items

Step 2.b							
Items		Criteria			Reality	Qualification	Remark
Water source	Flow	High flow	Fluctuant flow	Low flow			
		5	3l	1			
	Velocity	≥1.5 m/s	1-1.4 m/s	0.5-1 m/s			
		5	3	1			
	Streamline	Inside bend	Straight	Outside bend			
		5	3	1			
Hydrogeology	Thickness	>20 m	15-20 m	10-15 m			
		5	3	1			
	K	>15 m/d	10-15 m/d	5-10 m/d			
		5	3	1			
	Soil texture						
Water quality	TSS	<1000 NTU*	≥1000 NTU				
		5	1				
	Fecal contaminants	>30 d	<30 d				
		5	1				
Social	Land use	Open	Farm	Industry			
		5	3	1			

**2500 NTU is calculated from assumptions that the removal efficiencies for RBF and traditional treatment are both 98%. And the limitation for drinking water is 1 NTU. But consider the clogging problem, too high turbidity will cause clogging too fast thus a lower value 1000 NTU is expected.*

3.3. Step 3 Basic design model of RBF

In order to have a basic knowledge of capacity, dimensions and costs of a RBF site, a design model is developed on Microsoft Excel. It can be adjusted for different scenarios for future development. The model includes design of capacity, well yield, amount of wells, maximum drawdown, RBF cost, energy cost, possible transport pipeline, head loss, cost of pipes, etc.

3.3.1. RBF site design and costs estimation

RBF site design

- Capacity determination

To calculate the capacity of a RBF site, it is important to know the water demand of the customers. Basically, the customers are the citizens in the water supply city considering the population development and other water consumption. In practical, extra water demand is added for losses and peak value for hot day or other peak water consumption situation. For city A, the needed and produced parameters are shown in Table 3-10.

Table 3-10 Capacity design sheet

Item	Unit	Sign	Formular
City name		A	
Water demand	m3/d	D	D=q*Pf*(e%+1%)/1000
Capacity of RBF site	m3/d	C	C=D*R%
Population (Future)		Pf	Pf=Pc*a%
Population (Current)		Pc	
Water consumption quota	L/head/d	q	
Extra		e%	
Peak		P%	
Ratio of total demand		R%	
Population growth rate		a%	

Design model is used to calculate the capacity in different scenarios. Thus the capacity of RBF site is determined as example in Table 3-11.

Table 3-11 Capacity calculation examples

Item	Unit	Sign	Formular	Example		
City name		A		Zhengzhou		
Water demand	m3/d	D	D=q*Pf*(e%+P%+1)/1000	1,344,000	1,344,000	1,232,000
Capacity of RBF site	m3/d	C	C=D*R%	1,344,000	268,800	1,232,000
Population (Future)		Pf	Pf=Pc*a%	6,000,000	6,000,000	5,500,000
Population (Current)		Pc		5,000,000	5,000,000	5,000,000
Water consumption quota	L/head/d	q		160	160	160
Extra		e%		30%	30%	30%
Peak		P%		10%	10%	10%
Ratio of total demand		R%		100%	20%	100%
Population growth rate		a%		20%	20%	10%

- Well amount determination

The well amount mainly depends on the yield of each well which is limited by maximum acceptable drawdown. According to Hantush & Jacob,

$$s_m \approx \frac{2.30Q}{2\pi KD}\left(\log 1.12\frac{L}{r}\right)$$

Sm = stabilized drawdown in m in a piezometer at distance r in m from the well

Q = discharge of the well in m^3/d

L = √KDc, leakage factor in m^3/d

C = 100 d/m for clay layer on top

K = hydraulic conductivity in m/d

D = aquifer thickness

r = half of the diameter borehole, m

In Dutch experience, the usual maximum acceptable drawdown is 2-4 m and the well yield is 50-100 m3/h. But the drawdown and yield depend on local policy and environment protection. Well yield depends on soil conditions. Under the maximum acceptable drawdown, the yield can be larger than 100 m^3/h. Well yield is controlled by maximum acceptable drawdown as example shows in Table 3-12.

Table 3-12 Amount of well design sheet

Item	Unit	Sign	Example
Stabilized drawdown	m	Sm	3.96
Yield of well	m3/d	Q	3,600
Leakage factor	m3/d	L	447
Cover factor	d/m	C	100
Cover thickness	m	Hc	50
Hydraulic conductivity	m/d	KD	40
Radius of borehole	m	r	0.50
Thickness	m	D	25

Item	Unit	Sign	Example		
Capacity of RBF site	m3/d	C	200,000	300,000	400,000
Well yield	m3/d	Q	3,600	3,600	3,600
Amount of wells		N	56	83	111
Backup wells		n	6	8	11
Total amount		T	62	91	122

Besides the wells to fulfill capacity, several backup wells are needed to ensure the situation such as maintenance. The amount of wells is calculated by peak situation. Thus in normal days, not all the wells are operating. So management can be applied to well operation through programs.

RBF costs estimation

The costs estimation includes construction investment and operation costs which are mainly electrical energy costs.

➢ Construction investment

For construction costs, reference book 'Drinking water' (Verberk et al., 2006) is used.

Process / Process part	Cost factor (€ / m³ yearly capacity)
Production from groundwater	1.5 - 3.5
Production from bank filtration	2.0 - 4.0
Production from surface water (direct)	3.0 - 5.0
Production from surface water (soil aquifer recharge)	4.0 - 8.0
Groundwater abstraction	0.10 - 0.15
Aeration	0.10 - 0.15
Degasifying	0.20 - 0.30
Rapid sand filtration	0.30 - 0.55
Filter backwash water treatment	0.05 - 0.15
Raw water pumping	0.10 - 0.15
Microstrainers	0.05 - 0.15
Flocculation	0.10 - 0.25
Floc removal (sedimentation/flotation)	0.5 - 0.25
Rapid sand filtration	0.30 - 0.55
Activated carbon filtration (GAC)	0.50 - 0.90
Softening	0.35 - 0.60
Disinfection	0.05 - 0.20
Membrane filtration	1.00 - 2.00
Slow sand filtration	0.70 - 1.50
Clear water pumping station	0.40 - 0.70
Clear water storage	0.20 - 0.35

Figure 3-3 Cost factor for processes (Source: Verberk et al., 2006)

The cost factor of production from *bank filtration 2.0 – 4.0 € /m³ yearly capacity* is used. For a large capacity site, the low factor is applied while a high factor is applied to a small capacity. Example calculation is shown in Table 3-13.

Table 3-13 RBF cost estimation example

Item	Unit	Sign	Example		
Capacity of RBF site	Mm3/y	C	73.00	109.50	146.00
Cost factor	€/m3 yearly capacity	f	3.5	3.0	2.5
Investment	M€	i	255.50	328.50	365.00

➢ Electrical energy costs

Electrical energy is mainly power consumption of pumps. Formulas used are:

$$P_{net} = (P_t \times q_v) / (phi_{pump} \times phi_{motor})$$

Pnet=Energy per unit of time [W]

Pt=Pressure (Head) [Pa]

qv=Capacity well [m3/s]

phipump= Pump efficiency [-]

phimotor= Motor efficiency [-]

The electric price is 0.7 Yuan (0.1€)/kWh.

Table 3-14 Energy cost calculation sheet

Item	Unit	Sign	Example		
Well yield	m3/h	C	100	125	150
Pump efficiency		f	0.7	0.8	0.9
Motor efficiency		i	0.7	0.8	0.9
Pressure head	m	Pt	24	24	24
Drawdown	m	Hd	4	4	4
Extra head	m	He	10	10	10
Desired pressure	m	Hs	10	10	10
Energy per unit time	kW	Pnet	13.61	13.02	12.35
Electric price	€	e	0.1	0.1	0.1
Energy cost	€/h	E	1.36	1.30	1.23
	Yuan/h	E`	9.52	9.11	8.64

Item	Unit	Sign	Example		
Capacity of RBF site	Mm3/y	C	73	110	146
Well yield	m3/h	Q	100	125	150
Running hours	h/y	h	730,000	876,000	973,333
Energy cost	M€/y	Et	0.99	1.14	1.20
	Myuan/y	Et`	6.95	7.98	8.41

Example calculations are based on annual operating hours and the working strategy is managed by operators. All the costs estimations are strongly influenced by local situations. The price in the Netherlands can be extremely different from the price in China. Take rapid sand filtration as example, the difference of price is given in Table 3-15.

Table 3-15 Cost estimation comparison CN/NL

Item	Capacity		Factor		Cost		Country
Rapid sand filtration	109.50	Mm3/y	0.3	€per yearly capacity	32.85	M€	the Netherlands
RBF	109.50	Mm3/y	2	€per yearly capacity	219	M€	
Rapid sand filtration	300000	m3/d	13.4	€per m3/d	4.02	M€	China
					2.81	ten million Yuan	
RBF	300000	m3/d			26.8	M€	
					1.876	hundred million Yuan	

**Chinese cost factor: Municipal Engineering Investment Estimate, 2007, 3F-397 published by The Ministry of construction of the people's Republic of China*

According to the example, the RBF investment in China is clearly lower than in the Netherlands. There are a 8 times factor between NL and CN for rapid sand filtration that we used this factor also in the RBF cost model. But specific cost estimation in China needs further research. In case study in 5.1.3, cost estimation of the Zhengzhou site will be discussed to compare against the cost model. Moreover, the cost factor is variable and can be tuned in the model.

3.3.2. Transport design and costs estimation

Transport design

➢ Pipeline design

The type of transport is important for costs of the water supply. It influences the investment, operation and water supply reliability. Flow in pressurized pipe, partially filled pipe and open channel are the three most common phenomena in water transport. When an altitude difference is available to utilize, partially filled pipe is more recommended to apply. Otherwise, pressurized pipe is more likely to be used for water supply reliability. Considering the clean water after RBF, open channel flow is not suitable for transport.

In transport design, several parameters are needed including length of transport pipeline, and flow velocity in the pipeline to decide the diameter of the pipeline and costs of transport. In a rough calculation, average economic velocity is used as Table 3-16.

Table 3-16 Economic flow velocity in pipeline

Diameter (mm)	Average economic velocity (m/s)
D = 100 - 400	0.6 – 0.9
D ⩾ 400	0.9 – 1.4

According to the formula, $Q = Av = \frac{\pi D^2}{4} v$

A = Crossing area, m2

D = Diameter, m;

Q = flow, m3/s;

v = flow velocity;

Two pipelines strategy is applied to long distance transport. Each pipeline has to be able to transport 70% of total capacity.

➢ Head loss

Head loss of pressurized pipe is usually calculated by Darcy Weissbach

$\Delta H = 0.0826 \frac{\lambda L}{D^5} |Q| Q$, $\lambda = \frac{8g}{C^2}$ while D is the diameter of pipe and C is the roughness coefficient related to pipe material. In first estimation, the value of λ is 0.02.

Table 3-17 Transport head loss calculation sheet

Item	Unit	Sign			Example
Flow	m3/s	Q	3.47	4.63	3.47
Distance	km	L	10	30	50
Friction factor		λ	0.02	0.02	0.02
Velocity	m/s	v	1.37	1.34	1.37
Diameter	mm	D	1,800	2,100	1,800
Friction loss	m	Hf	10.57	26.07	52.83

The head loss is mainly friction loss as Table 3-17 shows and local loss is negligible in long distance transport. Friction loss is extremely influenced by distance and therefore, impact to costs. For desire pressure head of pump, the head from aquifer to surface is one part while another part is from the RBF site to the treatment plant. This part of pressure head can be applied by extra pumping station before pipeline according to the altitude difference between two cities. And additional pumping station may be needed to overcome the friction loss and local loss.

Transport costs estimation

For different material of pipe, the cost is different. The long distance transport pipeline cost estimation in China is based on the Municipal Engineering Investment Estimate, 2007, 3Z-005, published by the Ministry of construction of the People's Republic of China. Pre-stressed concrete pipe is used and in reality it can be replaced by other material. For capacity larger than 0.2 Mm^3/d, 412 € per 100 $m^3/d*km$ is used. The cost factors of both the Netherlands and China are around 2006-2007 that can be assumed in same price level. This way, the cost can be calculated through the model.

Table 3-18 Transport cost calculation sheet

Item	Unit		Example	
Distance	km	10	20	30
cost factor	€ per 100m3/d*km	412	412	412
Capacity	m3/d	150000	200000	300000
Cost	M€	6.18	16.48	37.08
	ten million Yuan	4.33	11.54	25.96

3.3.3. Comparison with direct surface water treatment

As discussed in 2.3, RBF is one possible technique to solve the water quality challenge in China. Compared to direct surface water treatment, RBF has several extra benefits on both technical aspect and cost aspect. Regarding to technique, RBF can dampen shock loads and temperature peaks caused by industry for example (Sharma et al., 2012). Oppositely, it is relatively easy to be influenced for surface water treatment. On costs aspect, using RBF as pre-treatment can simplify the subsequent processes or save chemical usage and extend service life (Schmidt et al. 2003). Adsorbents like PAC or zeolites and chemical oxidant are usually used to remove organic pollutants and control disinfection byproduct to enhance conventional treatment. Biological treatment like bio-filter and bio-fluidized bed are often used to control by-product and remove nutrients. High chemical consumption and maintenance fees are shortcoming of direct surface treatment compared to RBF.

In the following chapters, this model is going to be tested to give feedback during two applications. A potential and a candidate location are evaluated. The first application is on national level.

4

4. Investigations in China on national level

4.1. Current Conditions of RBF in China

RBF has been developed in the Europe and the United States for more than a hundred year. It is more and more systematic and complete on scientific research and engineering application. In China, although there is not a word 'RBF' and precisely description to be a technique, there are still some researches and engineering applications. To be one research question, understanding the overall conditions of RBF in China is the first action among investigations in China. The main method to do this is literature and information review together with communicating with researchers in China.

4.1.1. Scientific researches

Different from researches in Europe where RBF is proposed as a specific technique and a branch of natural water purification processes are developed. This kind of way to acquire water source is vague in China. Compared to the engineering application, researches about RBF starts late and grows slowly. In 1992, Senior Engineer Mr. Chen first proposed a method to acquire water from sand gravel river bed through infiltration galleries. After the proposal of this method, more than 20 engineering applications are established in Sichuan and Chongqing Provinces (Ren, 2007).

After reviewing the literatures related to this technique in China, the name of researches are mainly 'Infiltration by riverbed', 'Riverside tube well', 'Riverside abstraction', etc. The challenges for unconformable research are misunderstanding and unsystematic. The efficiency and outcome of researches are hard to generalize.

There are only around 30 papers about water abstraction from riverbank or riverbed and 25 papers about groundwater artificial recharge. After comprehensive analysis of literatures, the research is mainly focusing on the technical study and water amount calculation. But to the mechanism of aquifer clarification, the contaminants removal and processes in the aquifer, there are few literatures. For the design, construction and effluent relationship, there is hardly any research.

Recent years, there are more research appears in this field but a large part of them focus on mine area water abstraction. Mr. Zhai and other researchers from BNU (Beijing Normal University) proposed and registered a patent 'One method to evaluation riverside abstraction suitability'. This is a summarized paper to the site selection of RBF. But relevant applications cases are not observed (Zhai et al., 2015). Researchers including Wu et al., 2007 have done experiments on physicochemical processes underground (Wu et al., 2007) but they are still minorities of RBF researches.

4.1.2. Large-scale engineering applications

Compared to the scientific research of RBF in China, in engineering application, RBF is more widespread. But different from the long-term information collection, detailed field investigation and precisely design in Europe, the establishment strategy in China is relatively simple and crude. The purpose of establishing RBF site in China is more straightforward to acquire water with less consideration on service life and maintenance.

The engineering applications are mainly located in the north of China where the water source is limited. Many cities in this area have shortages on water source. From east to west, the cities are Harbin, Shenyang, Beijing, Jinan, Taiyuan, Zhengzhou, Luoyang, Xi`an, Lanzhou, Xining and so on. They are located in different section of the northern China with different hydrogeological features. According to the geological unit, Mr. Han summarized part of sites in China in 1996 (Han, 1996). Mr. Han`s investigation is years ago from the current conditions but is still meaningful to RBF development in China. Sites like Zhengzhou and Shenyang are still working regularly and producing safe drinking water for the city. Thus, Zhengzhou is one of the investigation sites will be visited as a representation. After Mr. Han`s investigation, there are several sites established continually.

Table 4-1 List of engineering application sites

	Site name	Consumers	Characteristics
Mountains valley	Taerheqiaotou plant Dagu River plant Xilipu plant, Qianan	Power plant City City	Sand gravel High yield
Mountains basin	Shalingzi plant Hanzhong city Yumenkou plant	Power plant City City	Medium-coarse sand Distribute along the river
Alluvial-proluvial fan	Hui River plant Matan, Cuijiatan and Yingmentan plant	City City	Sand gravel, coarse sand Great spread
Alluvial lacustrine and coastal plain	Jiuwutan and Beijiao plant Xibeijiao plant	City City	Fine-medium sand
New built sites after 1996	Liao River plant Xin County plant Sunwu County plant	City City Power plant	

For visual understanding of RBF in China, a map of sites is made as Fig.4-1.

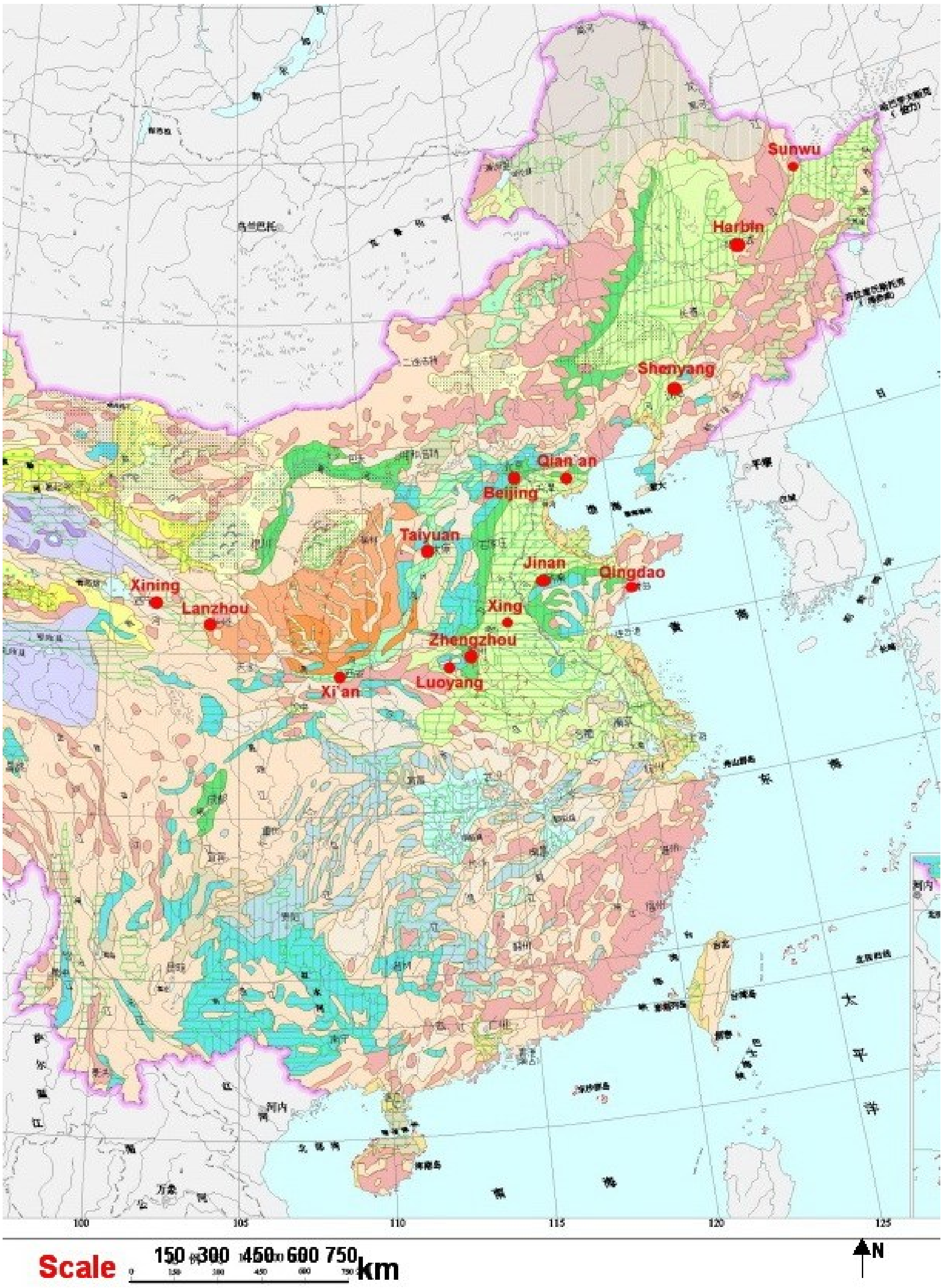


Figure 4-1 Map of RBF operating sites in China. Intercept from full map. Rad spot represents operating sites.

Fig.4-1 shows that the engineering applications are mainly in the north of China. It may because that surface water shortage challenge is more severe than in the south since modern society starts. Thus the attempt to acquire water other than surface water is more paid. But does the south of China is also suitable for applying RBF? Since the worsening water quality leads to 'Quality-induced water shortage' for many southern cities. In this chapter, the potential locations are screened on national level and in chapter 6, two candidate cities in south of China are evaluated as representative cities.

4.2. Potential Locations for RBF in China

To identify the potential locations in the entire China, a selection procedure below is proposed using site evaluation approach in chapter 3. The main materials to complete the procedure are mainly hydrogeological maps of China and each province or area. The maps opened to public is in 1980s since no other newest information are found. The quick selection procedure is based on the criteria in model step 1 after simplification for national level.

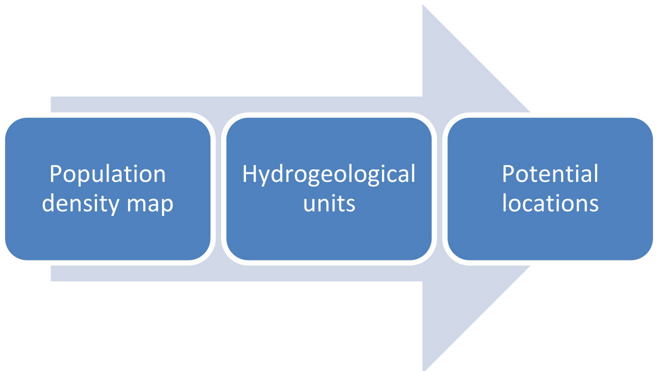


Figure 4-2 National level evaluation procedure

4.2.1. High water demand cities selection

It is rather hard to screen all the locations in entire China since all population, economy and topography are greatly different. The best option is that start from water demand which usually related to the population density. Thus a population density map is used as Fig.4-3.

Figure 4-3 Map of population density of China (except Taiwan). Outdated from 1980s for concept.

The population map shows an idea of urban population density of cities in China although the data is not accurate enough and outdated. According to latest statistics from National Bureau of Statistics of China, there are 17 cities with urban population larger than 4 million and 35 cities whose urban population are between 2 to 4 million. Larger urban population usually represents higher water demand. After all, 23 cities are included in the selection procedure after comprehensive consideration while the information of Hefei, Nanchang, Urumqi and Hong Kong is missing. Taiwan is also not included for discussion.

Then a combination of the population density map with national hydrogeological map (Appendix B only Chinese version) is made to predict high water demand areas. Following images are only for concept.

+

Population density map

Hydrogeological map

Some cities are in a same unit from conventional rules represented as 'Plain' or 'Basin' that are discussed below.

4.2.2. Units classification

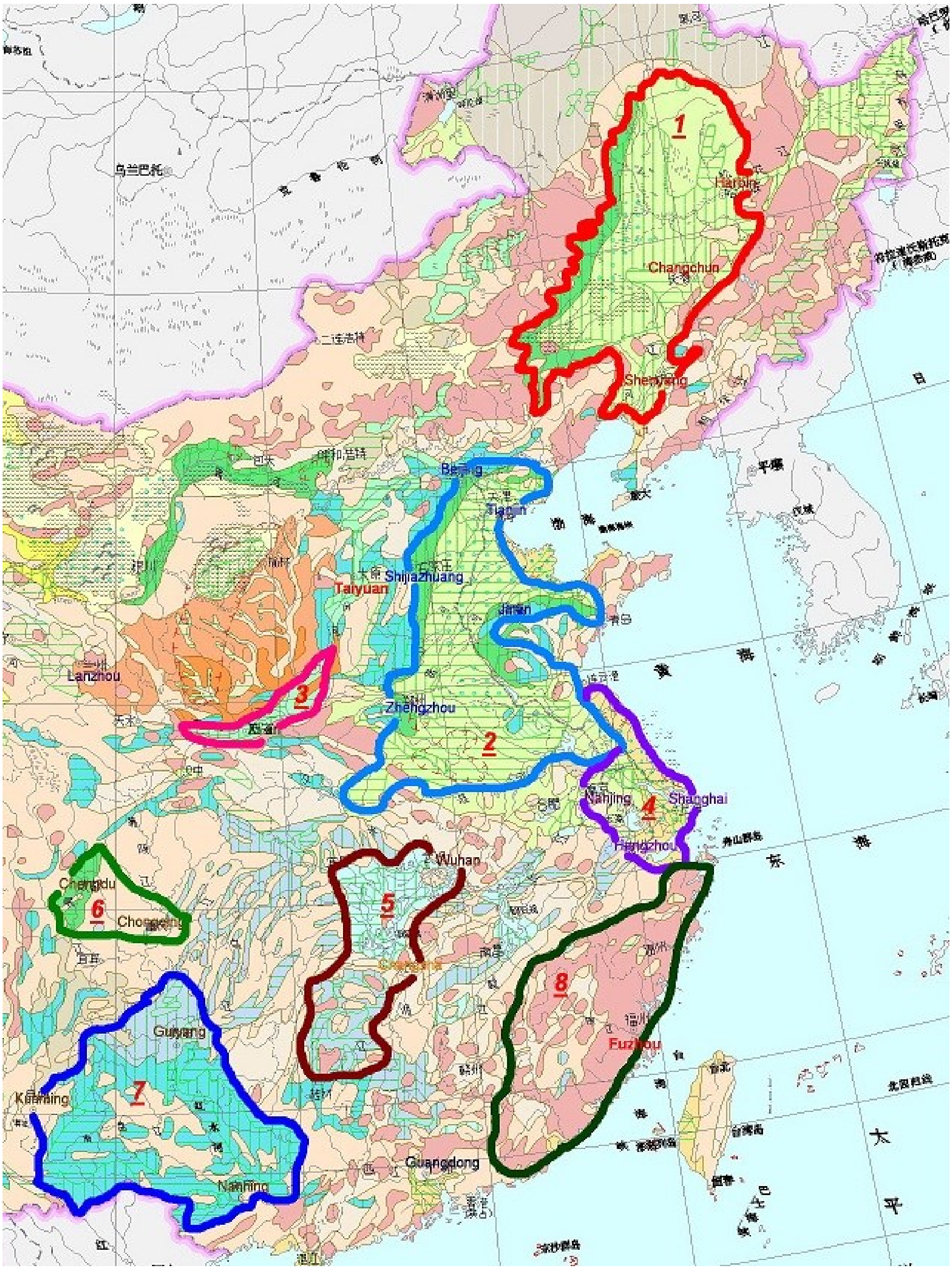


Figure 4-4 Units on national level. Different unit circled by different color and number.

Cities screened from 4.2.1 are in 8 units based on official classification in China Hydrogeological Map Atlas (Chinese Academic of Geological Sciences, 1979) combined with conventional rules. In this section, units on national level are listed and the geological or hydrogeological features are introduced.

Besides these 8 main units, three individual cities are also included. They are Taiyuan in Shanxi Province, Guangzhou in Guangdong Province and Lanzhou in Gansu Province.

Table 4-2 List of national level units and their characteristics

No.	Units	Including cities	Characteristics	
1	Songliao Plain	Harbin, Changchun, Shenyang	Alluvial plain	
2	North Plain	Beijing, Tianjin Shijiazhuang, Zhengzhou, Jinan	Alluvial plain	Thick silt and mud deposition
3	Weihe Plain	Xi`an	Lower valley Alluvial plain	Silt and mud deposition
4	Yangtze River Delta	Shanghai, Nanjing, Hangzhou	Lower fluvial plain (Liu, 1992)	Developed water system
5	Lianghu Plain	Wuhan, Changsha	Alluvial plain	Numerous lakes and rivers
6	Sichuan Basin	Chengdu, Chongqing	Alluvial plain Upper valley	
7	South Karst Region	Kunming, Guiyang, Nanning	Karst topography	
8	Southeast Hilly Region	Fuzhou	Hilly region	
9	Individual cities	Guangzhou, Lanzhou, Taiyuan		

After this unit classification computing by combination of population and hydrogeology, 8 units are selected thus the site evaluation approach can be applied more efficient.

4.2.3. Potential locations screening on national level

Basic items in the criteria will be used but simplified to fit national level:

- For water source, surface water and groundwater source are still important.
- For water quality, it will remain Level III which means there should be surface water that the water quality is on or superior to Level III. In Appendix A.1, the tables show differences between levels.
- For hydrogeology, on national level, the criteria could be potential suitable conditions like existence of proper aquifer.
- For social aspect, water demand will be the most important item.

Table 4-3 Simplified evaluation sheet step 1

Step 1					
	Criteria		Reality	Qualified	Remark
Water source	Rivers				
Water quality	Level III				GB3838-2002
Hydrogeology	(Thickness > 10 m Connected K > 5 m/d)	Proper Aquifer			
Social	(Finance Land)	Water demand			Depend on specific project and location

Use the simplified criteria step 1 to screen on national level to get potential units. The results are summary in the Table.4-4.

Table 4-4 National level screening results

National Level Screening						
Criteria		Water source	Water quality	Hydrogeology	Social	Remark
		Should be	Level III	Aquifer	Demand	
No.	Name					
1	Songliao Plain	√	Partly √	√	√	Water quality in Liao River is ✖
2	North Plain	√	Partly √	√	√	Water quality in Huai River is √ but in Hai River is ✖
3	Weihe Plain	√	Partly √	√	√	Wei River water quality is ✖
4	Yangtze River Delta	√	Partly √	√	√	Water quality in Tai Lake Basin and surrounding is ✖
5	Lianghu Plain	√	√	Partly √	√	Partly karst area
6	Sichuan Basin	√	√	Partly √	√	Partly clastic rocks
7	South Karst Region	√	√	✖	√	Mostly karst and clastic rocks
8	Southeast Hilly Region	√	√	✖	√	Mostly magmatic rock
City	Guangzhou	√	√	√	√	
City	Taiyuan	√	✖	√	√	
City	Lanzhou	√	√	√	√	

[1] *Water quality information here is from the National Surface Water Quality Report made by China National Environmental Monitoring Centre. Proportion of water quality in Level I-III higher than 50% is √.*

[2] *Hydrogeological information here is from the National Hydrogeological Map of China in Appendix A.1.*

South Karst Region and Southeast Hilly Region are out of selection because of the uncommon soil conditions for RBF (as indicate in 2.1.3) and need more researches about RBF built on karstified and limestone layers. For other units, it is possible for RBF but further location and detailed conditions should be screened. Locations around Guangzhou and Lanzhou are possible for RBF although the soil conditions are not perfect locally. Too much stress for post-treatment makes Taiyuan not possible because the water quality of surface water which is Fen River mostly fails to meet the standard.

In order to make a relatively complete list of potential locations, and to show the site evaluation approach in a detailed way using available information, individual discussion is applied. In this section, Songliao Plain, North Plain and Sichuan Basin are discussed individually because that Songliao Plain and North Plain are two largest units in this procedure and Sichuan Basin may be the only possible unit in southwest of China. The results of all individual discussions are in the Table 4-10.

4.2.4. Potential locations screening on unit level

All the maps in this chapter are intercepted from hydrogeological maps of each province from China Hydrogeological Map Atlas (Chinese Academic of Geological Sciences, 1979). Only related graphic symbols are translated and made for illustration.

Songliao Plain Unit

Three big capital cities are included into Sonliao Plain.

Harbin Area

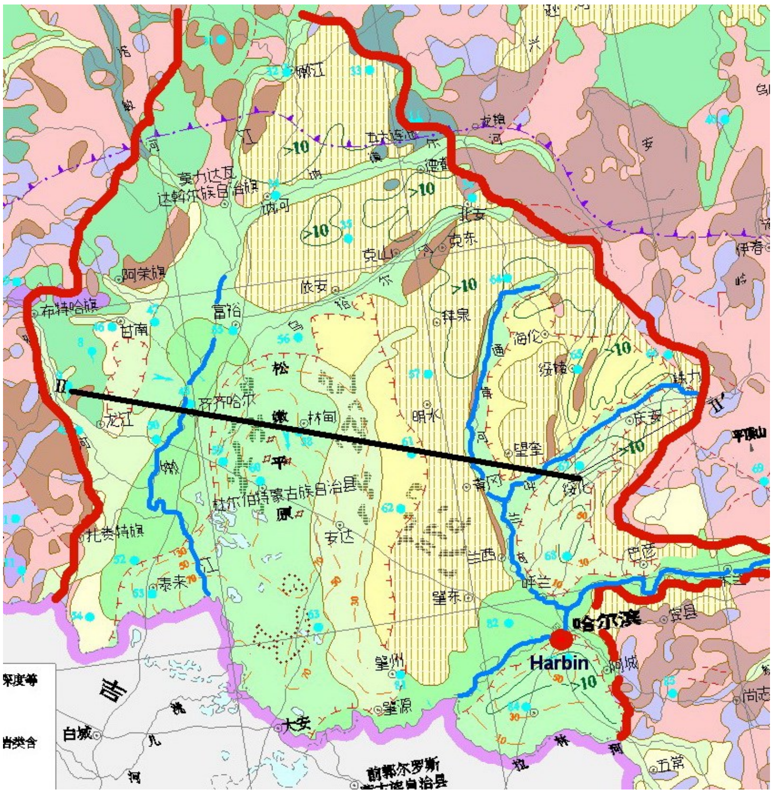


Figure 4-5 Harbin hydrogeological information. Intercept from full map. Black line represents

cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

In Fig.4-5 and later figure, the black line represents cross section and indicates the location of cross section profile in another map. The blue lines are rivers and the red point is the city.

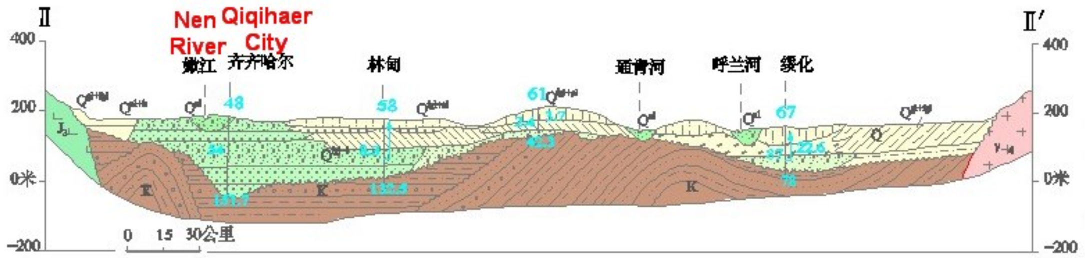


Figure 4-6 Cross section for Harbin area

Here are some legends and explanations of the maps. The horizontal scale of cross section is depth in meter.

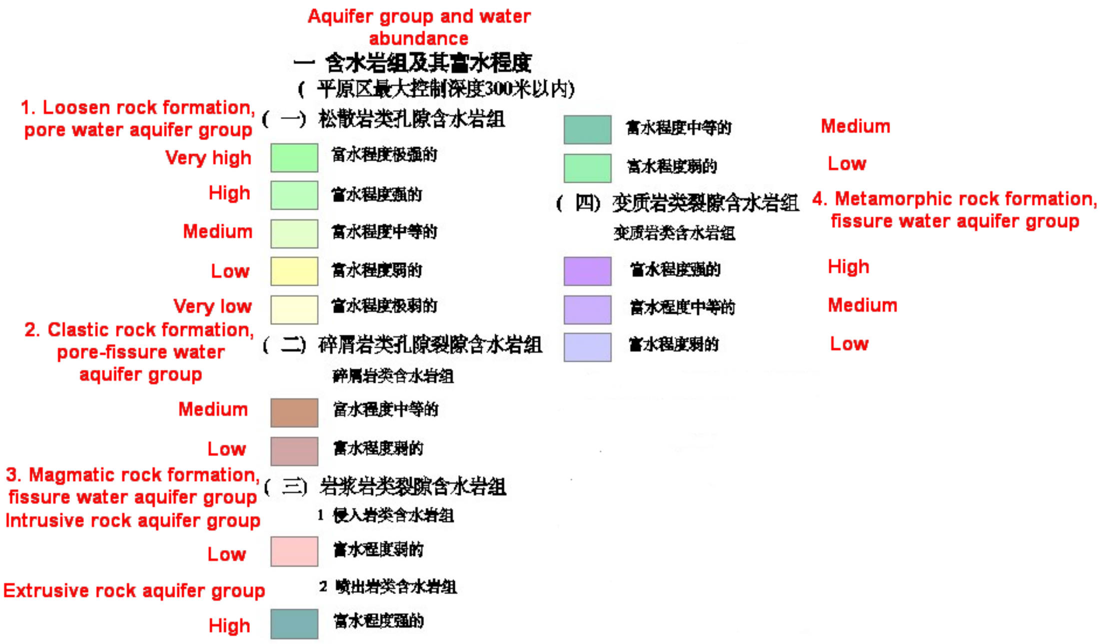


Figure 4-7 Legend of cross section map

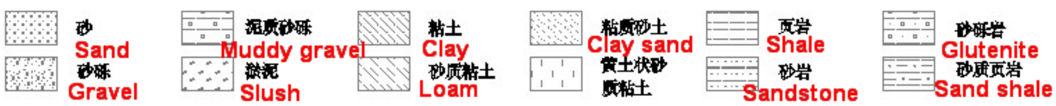


Figure 4-8 Legend of hydrogeological maps

The water abundance represents the yield property of aquifer group which influenced by the area, thickness, permeability and recharge conditions. The degrees of water abundance or yield property are classified in the Table.4-5.

Table 4-5 Water abundance classification

Degree	Name	Max discharge rate per well (m^3/d)
I	Very high	>5000
II	High	5000-1000
III	Medium	1000-100
IV	Low	100-10
V	Very low	<10
VI	Complicated	High variation

As it is shown from Fig.4-5 and Fig.4-6, Harbin is located on unconsolidated rock formation with pore-water aquifer. The water abundance is very high to high. Unconsolidated rock formation indicates that there are a large number of soft sediment which may has good permeability. And there is a big river Songhua River flows through the city with sufficient water quality. It has a high possibility for RBF site. In other locations in the map as Fig.4-6 shows, Qiqihar is located beside Nen River which has a great connection with a 200 m aquifer in west.

Changchun Area

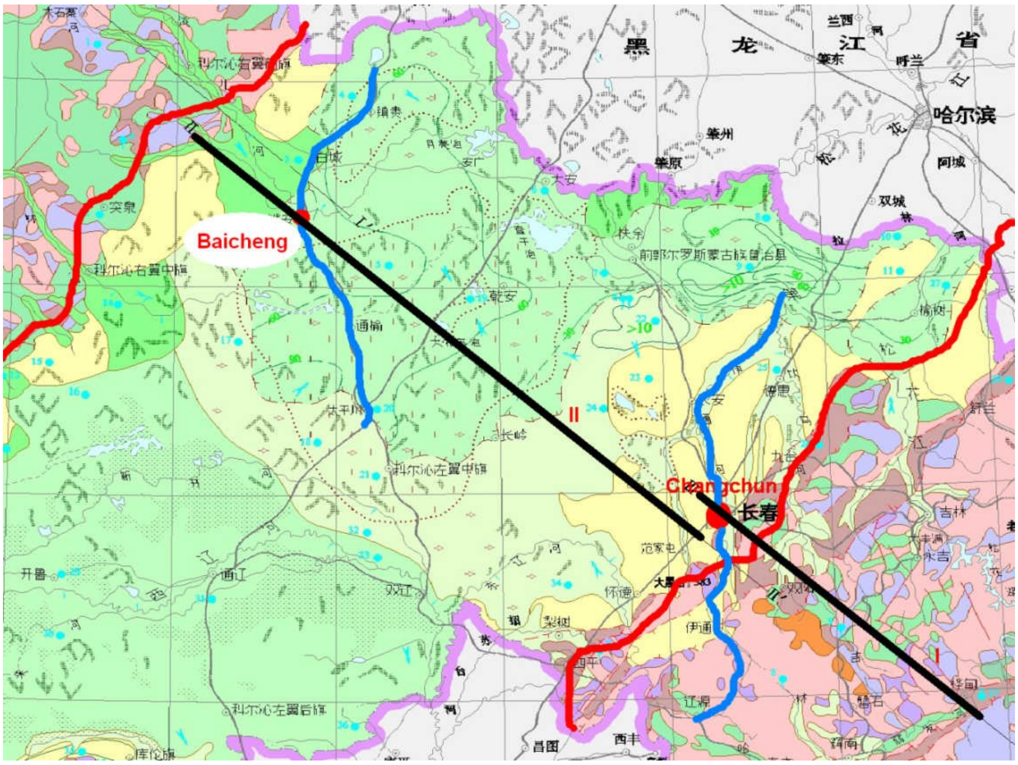


Figure 4-9 Hydrogeological map of Changchun area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

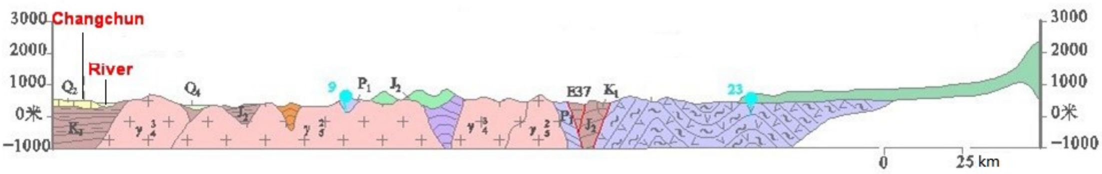


Figure 4-10 Cross section Changchun area I

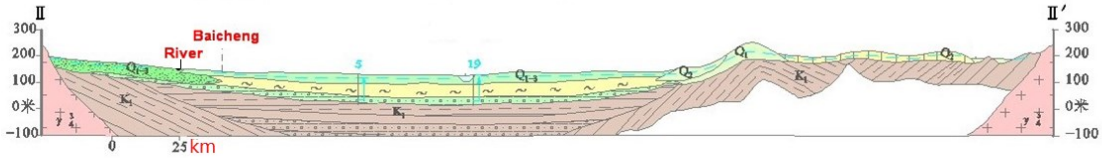


Figure 4-11 Cross section Changchun area II

Fig.4-10 shows that Changchun is also located on unconsolidated rock formation but with low pore-water abundance. In the cross section I, Changchun is located on a clay and limestone layer which is not very suitable for RBF although Yitong River flows through the city. The water quality of Yitong River is approximately sufficient for Level III. For other locations in this area, Baicheng-Tao`an surroundings is quite near to a sand gravel aquifer connected to Taoer River in the west with thickness more than 50 m. Nen River is also in this surrounding providing water source with an expected water quality above Level II. It can be a RBF drinking water site for city Baicheng.

Shenyang Area

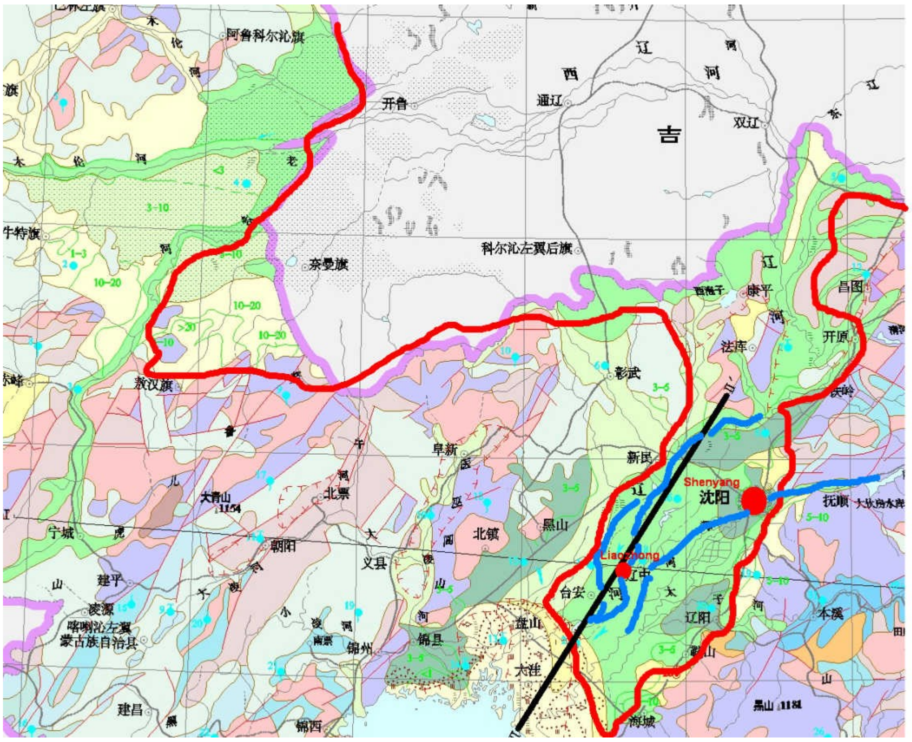


Figure 4-12 Hydrogeological map of Shenyang area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

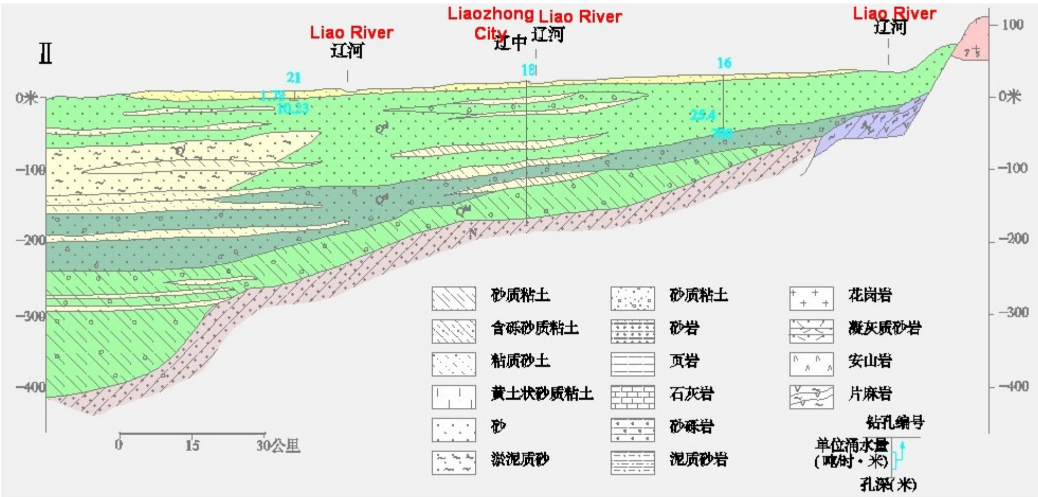


Figure 4-13 Cross section Shenyang area

As Fig.4-12 and Fig.4-13 show, Shenyang is located on unconsolidated rock formation with very high water abundance of pore-water aquifer group. And the Hun River flows just through the city but the water quality is not sufficient since it is Level IV or worse. Liaozhong is located on a sandy clay layer for less than 10 m and a huge sand aquifer behind. In the east, Liao River is just connected with this aquifer and the water quality for Liao River is Level III in most of time. The average thickness for this sand aquifer is around 50 to 100 meter. After all, locations around Liaozhong could be a better choice to establish RBF sites.

Table 4-6 Songliao Plain Section results

Songliao Plain Section							
Criteria			Water source	Water quality	Hydrogeology	Social	Remark
			Should be	Level III	Aquifer	Demand	
No.	Name						
1	Harbin area	Harbin	√	√	√	√	
		Qiqihar	√	√	√	√	
2	Changchun area	Changchun	√	√	✖	√	
		Baicheng	√	√	√	√	
3	Shenyang area	Shenyang	√	✖	√	√	
		Liaozhong	√	√	√	√	

As summary, Harbin and Qiqihaer, Baicheng and Liaozhong are suitable for RBF after quick selection. Changchun and Shenyang are less possible because of the water quality and soil conditions.

North Plain Unit

The North Plain is the biggest plain in the north of China involving several provinces. Five large provincial capital cities Beijing, Tianjin, Zhengzhou, Shijiazhuang and Jinan situates in this section.

Figure 4-14 Hydrogeological map of North Plain area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

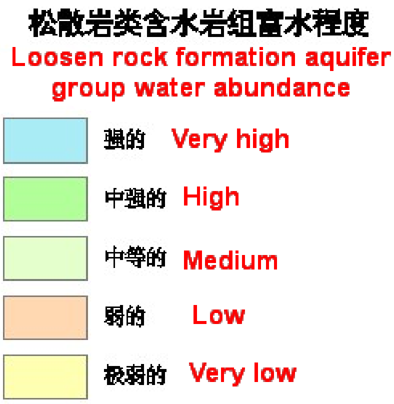


Figure 4-15 Legend of North Plain area map

Beijing Area

Figure 4-16 Hydrogeological map of Beijing area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

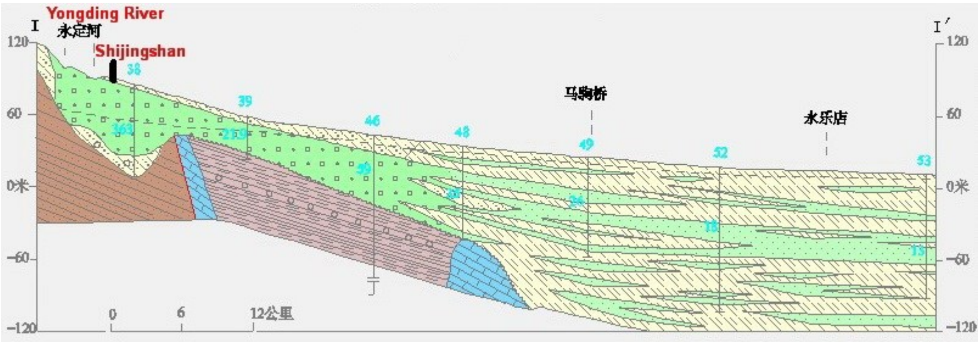


Figure 4-17 Cross section Beijing area

Beijing is situated in the most north of North Plain. And the soil is unconsolidated rock formation with high water abundance. From the cross section, in Shijingshan nearby Beijing, Yongding River is connected with a 40 m thick sandy gravel aquifer and the water quality is above Level II. It is a possible location for RBF site in Beijing area.

Tianjin Area

Figure 4-18 Hydrogeological map of Tianjin area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

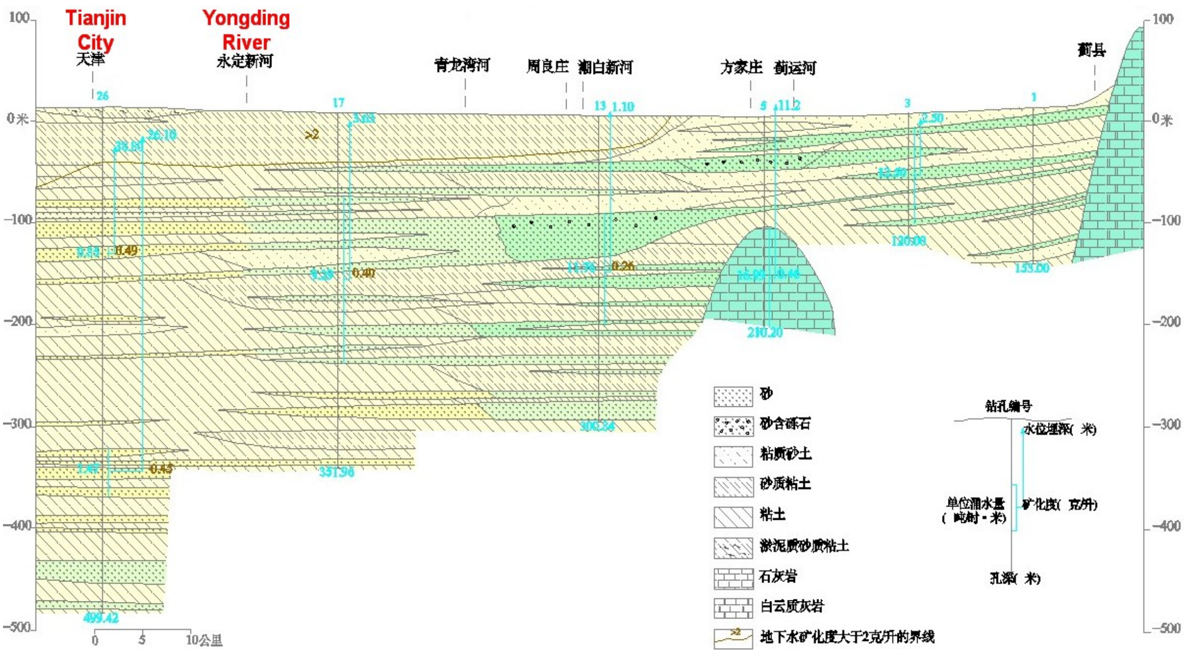


Figure 4-19 Cross section Tianjin area

From Fig.4-18 and Fig.4-19, Tianjin city is located on a thick clay layer and few sand aquifers around 100 m underground. And also the Yongding River is not connected with an aquifer although the water quality is sufficient.

As alternative solution, managed artificial recharge (MAR) is probably suitable because of the shown aquifer between 100 m to 200 m in deep.

Shijiazhuang, Zhengzhou Area

For Shijiazhuang city, Hutuo River flows through the city as well as several small rivers. The city is located on unconsolidated rock formation with pore-water aquifer with high water abundance. But the water quality of Hutuo River is less than Level V which won`t contribute to RBF.

For Zhengzhou city, detailed discussion is made in Chapter 5. From the map of North Plain, lands near the Yellow River are made of unconsolidated rock with medium water abundance. According to the data collected, it has a quite high permeability and large aquifers which are very suitable for RBF.

Jinan Area

Figure 4-20 Hydrogeological map of Jinan area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

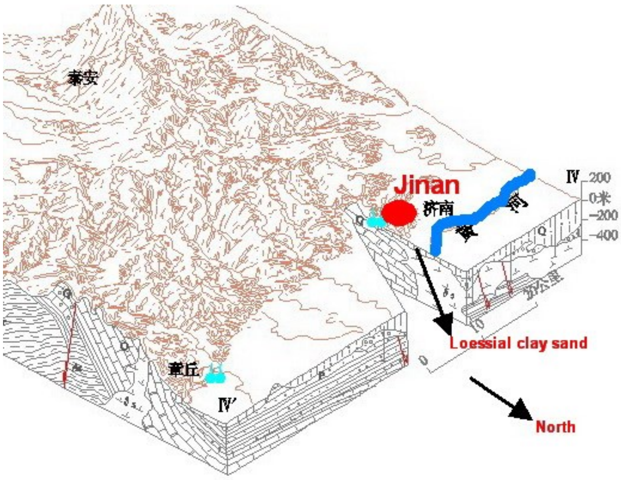


Figure 4-21 Cross section Jinan area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

For Jinan city, it is located on a loessial clay sand layer while the water abundance is very low.

Figure 4-22 Sand gravel area map. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

But in 10 to 20 km, an area consists of sand gravel with medium to high of water abundance is suitable location of RBF site for Jinan city. Similarly, Zibo has Zi River and other small rivers nearby as water sources. Sand gravel areas around the sufficient quality rivers are connected.

Table 4-7 North Plain Section results

North Plain Section							
Criteria			Water source	Water quality	Hydrogeology	Social	Remark
			Rivers	Level III	Aquifer	Demand	
No.	Name						
1	Beijing area		√	√	√	√	In Shijingshan nearby Beijing
2	Tianjin area		√	√	×	√	
3	Shijiazhuang area		√	×	√	√	
4	Zhengzhou area		√	√	√	√	
5	Jinan area	Jinan	√	√	√	√	In sand gravel area around the river
		Zibo	√	√	√	√	

As summary, in North Plain, Beijing, Zhengzhou and Jinan, Zibo are possible for RBF sites while Tianjin and Shijiazhuang are not suitable because of the water quality and soil conditions.

Sichuan Basin Unit

There are two large cities Chengdu and Chongqing in Sichuan Basin Section although only 300 km distance, the hydrogeological conditions are totally different.

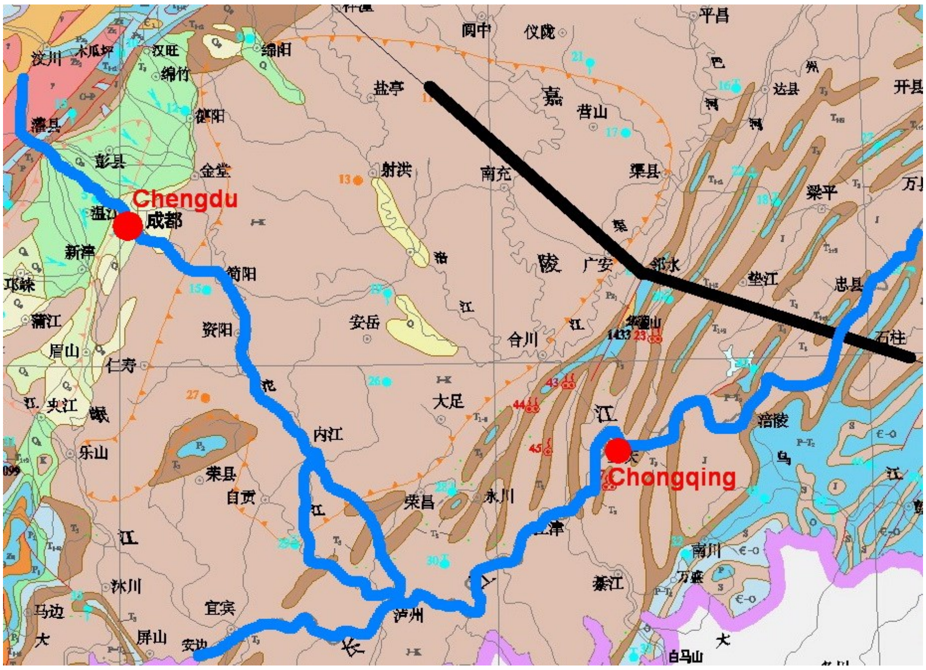


Figure 4-23 Hydrogeological map of Sichuan Basin Section. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

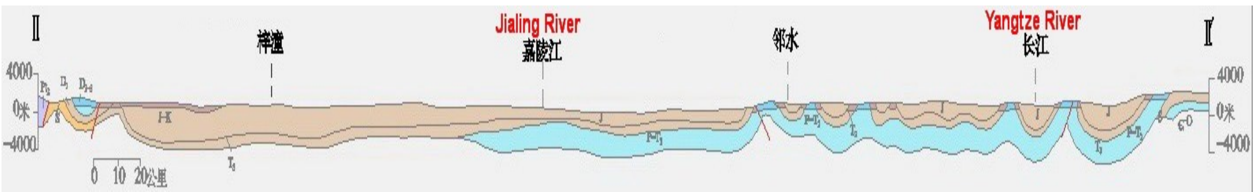


Figure 4-24 Cross section of Chongqing area

Figure 4-25 Legend hydrogeological map of Sichuan Basin Section

Chongqing Area

From Fig.4-23 and Fig.4-24, Chongqing is located on clastic rocks with fissure-water aquifer with medium to low water abundance. The water quality of Yangtze River in Chongqing is good as Level I. According to the cross section below, on the front of soil and connections with rivers, there are clastic rocks with fissure-water which is not typical for RBF because of possible low permeability.

Chengdu Area

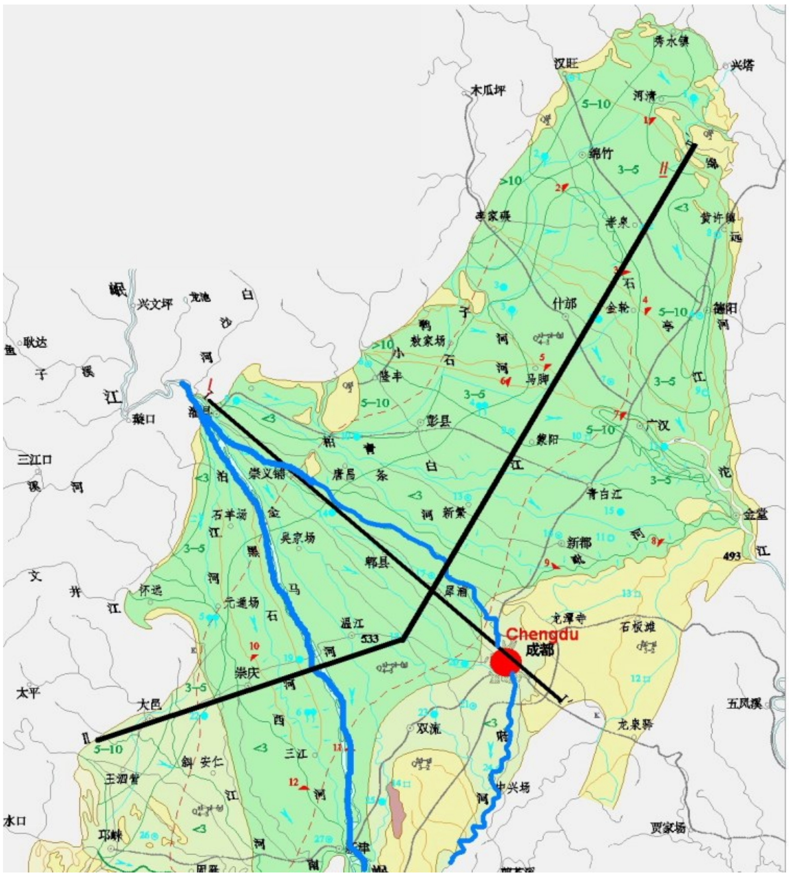


Figure 4-26 Hydrogeological map of Chengdu area. Intercept from full map. Black line represents cross section location and blue line represents river and red spot represents city location with name in black and red line represents edge of unit.

From Fig.4-26, Chengdu is located on unconsolidated rock formation with water abundance medium to high. Min River is on level II and flows from mountain area in northwest and through Chengdu and then together with the Yangtze River.

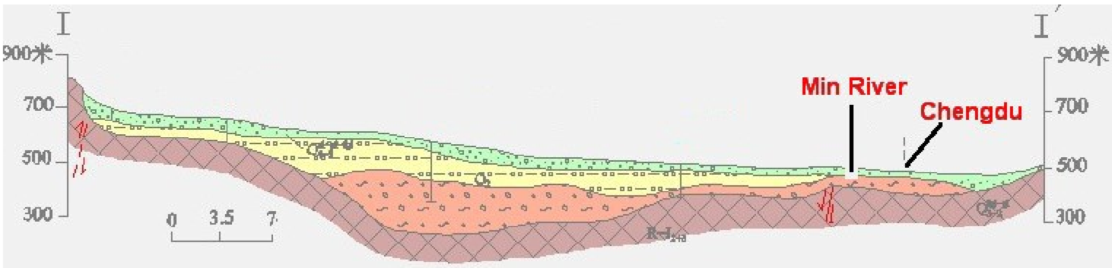


Figure 4-27 Cross section Chengdu area I

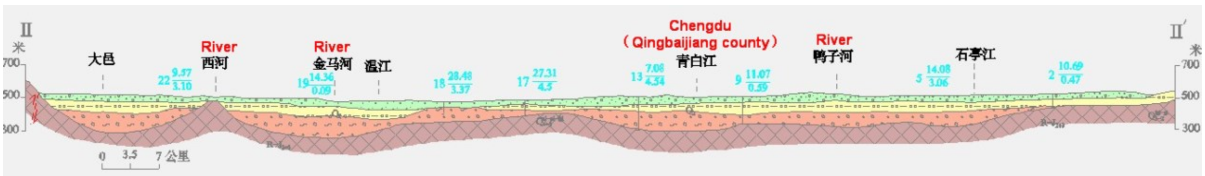


Figure 4-28 Cross section Chengdu area II

According to the cross section Fig.4-27 and Fig.4-28, it is clear that there is an entire sand aquifer on the front of soil for around 50 m thickness and silt sand/gravel aquifer in deep. Rivers are flowing through the whole area and all have good connections with the aquifer. The hydrogeological conditions are perfect for RBF. The water quality for this river system is sufficient as Level II.

Table 4-8 Sichuan Basin Results

Sichuan Basin Section						
Criteria		**Water source**	**Water quality**	**Hydrogeology**	**Social**	**Remark**
		Should be	Level III	Aquifer	Demand	
No.	**Name**					
1	Chongqing area	√	√	×	√	
2	Chengdu area	√	√	√	√	

As summary, the whole Chengdu area is entirely suitable for RBF considering the criteria but Chongqing area is less possible because of the poor soil conditions.

4.2.5. Results list and summary of potential locations

Potential units

As discussed on national level in 4.2.3, locations in some units are more possible for RBF than other units although shortcomings are still existed in this procedure. The results are in the Table.4-9.

Table 4-9 Possible and Less possible sections

Possible	Less possible
Songliao Plain, North Plain, Weihe Plain, Yangtze Delta Plain, Lianghu Plain, Sichuan Basin	South Karst Region, Southeast Hilly Region

Potential cities

All 23 large cities from national level are evaluated and screened by the criteria as individual discussion shows. And also some additional cities are added into the list during discussion.

Table 4-10 List of possible, less possible ad not suitable cities

No.	Unit	Possible	Less possible (Because of water quality)	Not suitable (Because of soil)	Remarks
1	Songliao Plain	Harbin, Qiqihar, Baicheng, Liaozhong	Shenyang	Changchun	
2	North Plain	Beijing, Zhengzhou, Jinan, Zibo	Shijiazhuang	Tianjin	
3	Weihe Plain		Xi`an		Good soil conditions but poor water quality
4	Yangtze River Delta	Yangzhong, Taixing	Shanghai	Hangzhou, Nanjing	Sea water problem for Shanghai
5	Lianghu Plain	Wuhan, Jiangling, Shashi		Changsha	Large area not possible, only several cities
6	Sichuan Basin	Chengdu		Chongqing	
7	South Karst Region	Guiyang, Liuzhou		Kunming, Nanning	
8	South Hilly Region			Fuzhou	
9	Individual cities	Guangzhou, Lanzhou	Taiyuan		

Summary of potential locations

Although cities in the list are evaluated, other locations in possible units still have opportunity to apply RBF after specific researches and investigations.

For cities Shenyang, Xi`an, etc. with proper soil conditions but lack in water quality, it is still possible to apply RBF but significantly the post-treatment can be more complicate to fulfill the standard for water quality. This may increase the investment of post-treatment. Besides, unexpected water quality may cause clogging problem. Therefore, the well yield may be influenced and the maintenance costs are increasing as well.

For cities Tianjin, etc. with improper soil conditions, it is not suitable for RBF because applications in these cities may fail to obtain satisfied well yield. As alternative solutions in case soil passage treatment is still applied, two options are provided.

- Search for suitable locations nearby and transport filtrated water

Pros: Better source water quality, stable water supply

Cons: Tremendous investment depends on distance

➢ Search for other soil passage treatment such as managed artificial recharge (MAR)

Pros: Better source water quality, potential combination with existed wetland (as many cities already have), potential combination with wastewater treatment

Cons: Extra investment, few engineering application in China, proper soil condition needed

4.3. Feedbacks of site evaluation approach after first application

The site evaluation approach is applied to national level with an original objective to give feedbacks on overall knowledge. After the whole process, some summary can be made:

- On national level, it is hard to acquire all detailed data at this stage. The screening of soil conditions strongly rely on hydrogeology maps of China, although information provided by maps are on quite large scale and few cross sections are provided.
- The items and specific values of criteria in site evaluation approach have to be simplified for fitting in general information. The most important items are sufficient river flow, proper soil type and aquifer connected to river bed that can apply on national level.
- The criteria for soil types are limited among sand, silt and gravel which are common in RBF application but limestone (karst) is also one important component in south of China.
- On water quality respect, some locations are suitable on soil conditions but with no sufficient water quality. In practice, less sufficient water quality is not critical criteria. So the site select model can still continue since hydrology and hydrogeology conditions are fulfilled. Corresponding solutions for worse water quality can be given in criteria step 2.
- Social part in first step is not a critical limitation in reality because the land and finance are all closely related to the specific project. For a potential location, area and finance may not be ensured or specified at the initial stage of whole project. So land and finance can be remark items but not critical limitations.

In next chapter, the site evaluation approach is fully applied to Zhengzhou site as second application. After the application, the results of theoretical evaluation are compared with reality to test the compatibility of the model.

5

5. Case Studies

In section 4.1.2, the engineering application conditions are discussed and several cities are mentioned to be visited in the investigations in China. The selection of visiting sites is strongly determined by the Research Center for Eco-Environmental Sciences, Chinese Academy of Science (CAS). The help from authorities and related departments greatly facilitates investigations in China. Even so, limited choices and data are available. CAS provided opportunities to visit Zhengzhou, Jiaxing and Wuhu. Among them, Zhengzhou is a representative operating site of RBF to learn the current conditions in China and an example to apply the site evaluation approach. Jiaxing and Wuhu are two cities where the local stakeholders including government and companies are interested in RBF. But the project is still in a very preliminary stage thus the information and data available are limited. Site evaluation approach is applied to evaluate the conditions of Jiaxing and Wuhu to provide relevant recommendations. Deyang is an example of conjunctive system which could be a way of developing for RBF.

5.1. Zhengzhou Site–Representative Operating Site in China

5.1.1. Introduction to Zhengzhou

Basic circumstances

Zhengzhou is the capital city of Henan Province in the east-central China. The city lies on the southern bank of the Yellow River with a population of 9.4 million inhabitants including 6.4 million urban populations.

Figure 5-1 China Water System map

Zhengzhou has a monsoon-influenced, four-season humid subtropical climate with cool, dry winters and hot, humid summers. The city has an annual mean temperature of 14.35 ℃. Average temperature in January is –0.2℃ while in July is 27.8℃. Annual average rainfall is around 640.9 mm and 220 days without frost-free. With the land within its administrative border generally sloping down from west to east, Zhengzhou is situated at the transitional zone between the North China Plain towards east and mountains towards west.

Figure 5-2 Location of Zhngzhou City. Red line represents distance and blue line is river.

The city center is situated to the south of the middle reach of the Yellow River, where its valley broadens into a great plain. The Yellow River is the main drinking water source for Zhengzhou city.

Zhengzhou drinking water supply condition

Two patterns of water supply are applied to Zhengzhou using surface water from the Yellow River and local groundwater.

- Zhengzhou Drinking Water Company

Shiyuan and Baimiao drinking water treatment plants use surface water from the Yellow River and 'South-to-north' water transfer. Shifo and Dongzhou drinking water treatment plants use RBF to abstract water while other two plants use groundwater from city center region.

- Permitted abstraction wells

In 2015, the total water supply amount is 505.7 Mm3 including 328.5 Mm3 from Zhengzhou Drinking Water Company.

5.1.2. Dongzhou drinking water treatment plant

General introduction

Dongzhou drinking water treatment plant is a plant invested by Zhengzhou government. The design water supply capacity is 0.2 Mm3 per day. The water source is RBF filtrated water from the Yellow River. The plant includes 72 abstraction wells and corresponding post-treatment.

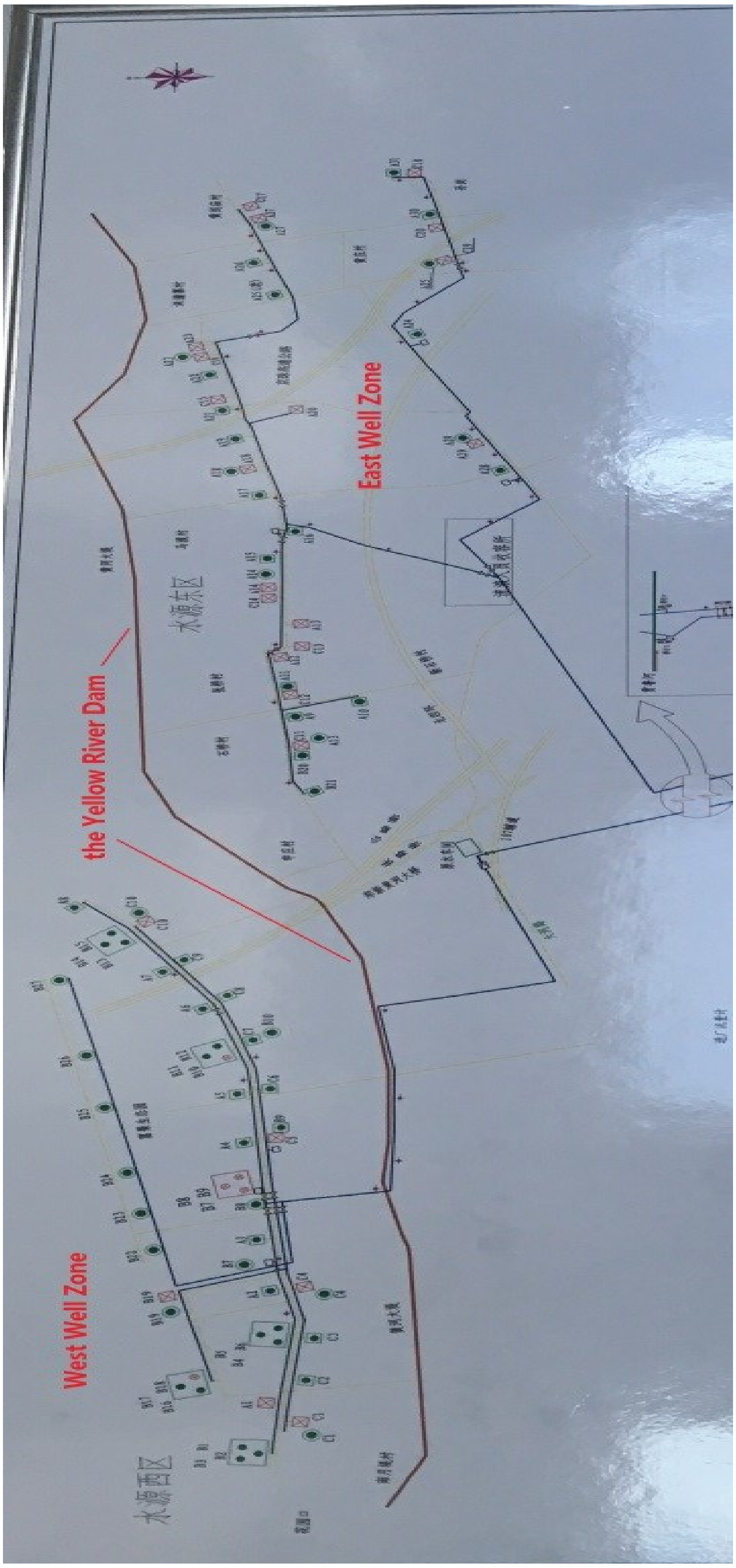


Figure 5-3 Wells distribution of Dongzhou DWTP. Black spot represents wells and black lines represents pipeline.

The whole wells group is divided into two zones and four units. Each unit has 15-23 wells and the distance between two wells is between 550 m to 600 m. The pumping station is located 3 km away to wells group and the treatment plant is far away from both.
After abstraction, the water is pumped to the treatment plant for several post-treatment processes including aeration, sand filtration and disinfection.

Figure 5-4 Conventional post-treatment processes in Dongzhou Plant, Zhengzhou

Figure 5-5 Pictures from abstraction wells in Zhengzhou

The water source of Dongzhou plant is confirmed to level I from Chinese Standard of drinking water source (GB3838-2002) thus after simple conventional treatment processes, the effluent water is sufficient to supply.

Hydrogeological, hydrological condition

➢ Geology

The whole area of water source shows a feature that west is higher than east connected by the Yellow River while hills are located more in west and east is relatively flat. To prevent the flood of the Yellow River, a large dam is built with a bottom size 58-61m and 5 m height on the river side and 9m outside.

➢ Hydrology

After the establishment of Xiaolangdi reservoir, the downstream flow of the Yellow River is more flat that the peak flow of the Yellow River is 23000 m3/s and lowest flow is 42 m3/s. in 1971-1983, average flow is 1280.8 m3/s. the sand content is 26.5 kg/m3 and the sand transport amount is 1.07 billion tons per year. The main sand material is suspended solids including 30.5% coarse sand larger than 0.05 mm and 69.5% fine sand smaller than 0.05 mm. In 1980 to 1989, the average water level is 93.3 m range from 95.17 m to 92.12 m. Because of the environment and climate, after successive 4-5 years for high water level, there will be 2-3 years with low water level. From October to June is low water level period and from July to September is high water level period.

According to Huayuankou monitoring station near Zhengzhou, the recent data of water flow and water level are summarized as Table.5-1.

Table 5-1 Annual flow of the Yellow River

Time	Flow m^3/s			
Month	**2015**	**2014**	**2013**	**2012**
1	512			
2	814			
3	1210			
4	1220			
5	1170			
6	1190	969	2120	2470
7	1580	1297	2380	2070
8	484	477	1330	1670
9	297	518	526	1320
10	292			
11	334			
12	332			

As shown in the Table.5-1, the flow of the Yellow River varies a lot from winter to summer. And also it is different from dry year and wet year. Recent years, the flow of the Yellow River drops a lot. It may because of the hydraulic construction such as dams in upstream but may also because of the feature of the river that has a large variation on flow. But the reduction of flow may lead clogging problem to river bed and the yield of wells may drop dramatically.

- Hydrogeology

In southwest part of water source area, slop is caused by gully and clough which contributes to the flow and discharge of groundwater. In east part, the slop is flat and the flow rate of both surface water and groundwater is low which benefit to store and recharge of groundwater.

- Shallow groundwater aquifer

Pore-water from aquifers contains sand and gravel sand

Under the benchland inside of dam and nearby plain outside of dam, the aquifers are mainly consist by medium sand, coarse sand and fine sand. The aquifer start from 6-15 m underground and thick 13-35 m. Water yield for single well can reach 5000 m3/d and average yield is 3000 m3/d with hydraulic conductivity (K) is 20-55.7 m/d.

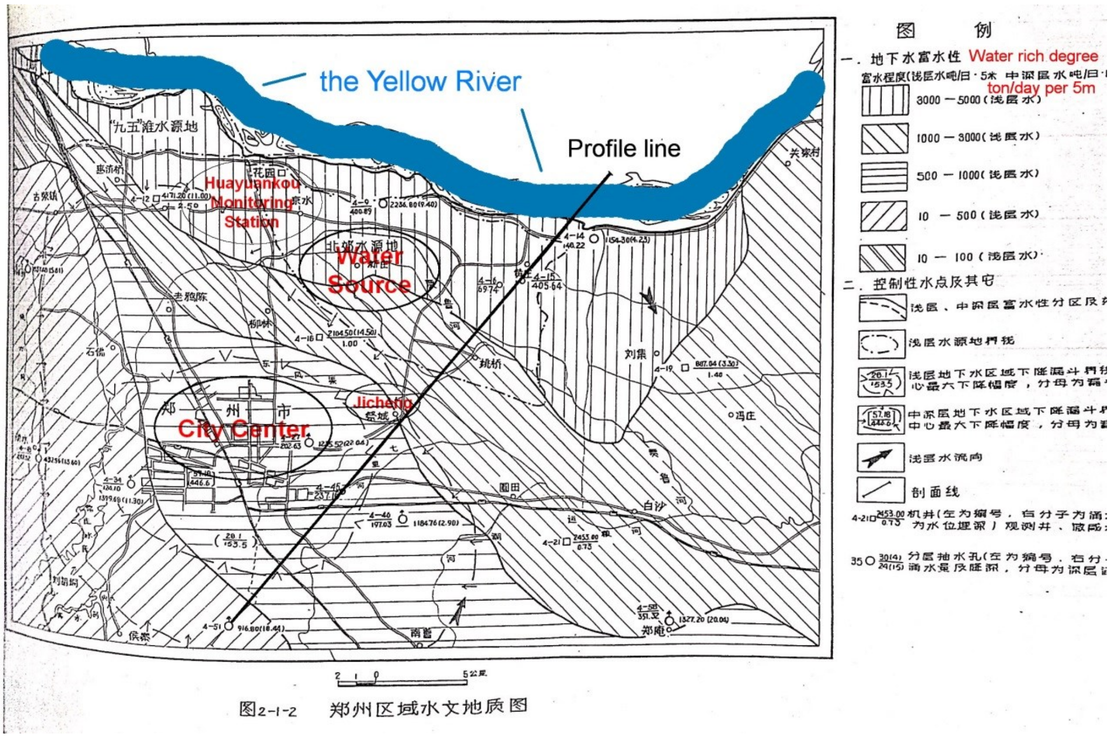


Figure 5-6 Hydrogeology map of Zhengzhou a

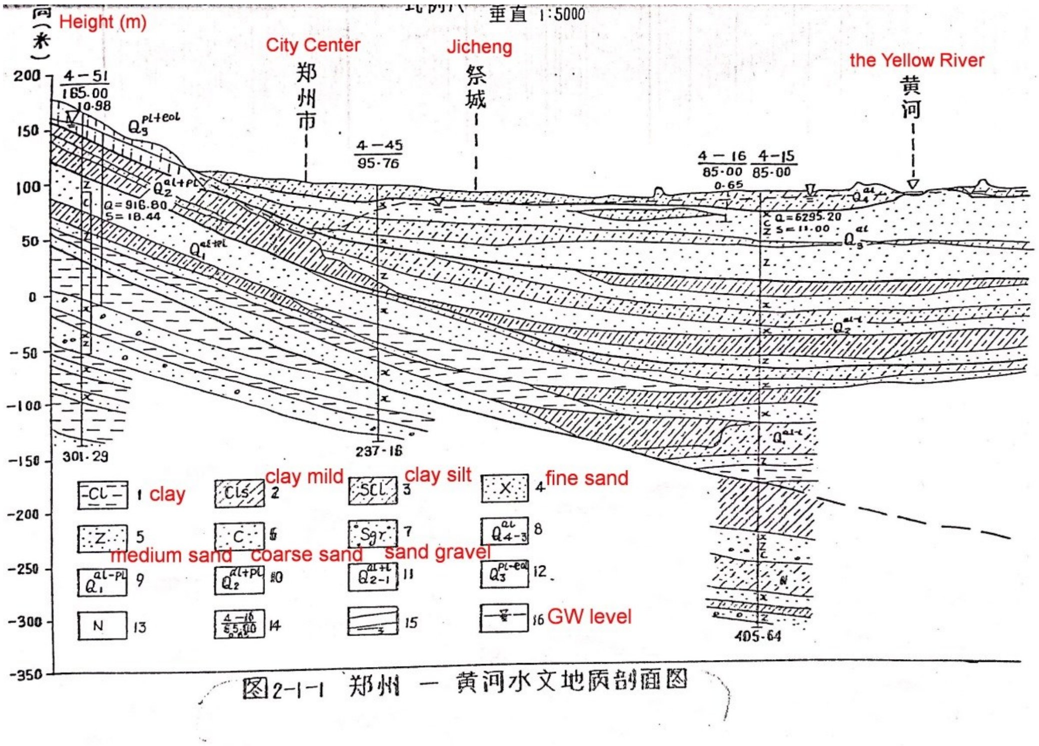


Figure 5-7 Hydrogeology map of Zhengzhou b

In the aquifer layer, 87.8-97.3% of sand is larger than 0.1 mm and the majority is between 0.1-1 mm. The whole aquifer layer is thicker in the west and south than in the east and north. Because of the advantages on sand size, distribution, conductivity and other features, this layer of aquifer is the main water source zone for RBF.

- Middle and deep groundwater

This layer of aquifer is under the shallow groundwater layer within 350 m consist of medium sand and the thickness is 20-50 m starting from 70-150 m underground. This aquifer is used in city center for groundwater abstraction. Well tests results are in Appendix C.1.

Specifically, all the data and information about hydrogeology are from 1970s to 1990s and mainly from 1990s when the construction of DWTP started which may cause uncertainty of analysis because the outdated data.

Water quality condition

- Surface water

Three types of data indicate the surface water quality of the Yellow River. Original data are in the Appendix C.2 to Appendix C.4

a) Data from Report of Field Investigation for Beijiao water source area (1995) (Appendix C.2)

In the report, the chemical compositions are analyzed. All the chemical parameters in this report are under limitation of Level III.

b) Water quality report of Government Office of the Yellow River (Appendix C.3)
In thereport, the monthly water quality for the Yellow River is summarized to be relatively stable on level II except exceeded parameter iron (Fe).
c) Real time monitoring (Appendix C.4)
In general, the water quality of the Yellow river is on Level II besides some sensitive parameters according to Huayuankou monitoring station.

Table 5-2 Exceeded contaminants in surface water source of Zhengzhou

Items	Standard	Data
Ammonia nitrogen	1.0 mg/l	1.18 mg/l
Iron	0.3 mg/l	1.66 mg/l
Mn	0.1 mg/l	0.47 mg/l

➢ Groundwater

The groundwater data is also from the Report Field Investigation for Beijiao water source area (1995). The whole groundwater is divided into shallow groundwater and medium-deep groundwater. The shallow groundwater has a difference between north and south. In the south area of Zhengzhou, the water is more mineralized and has a higher chloridion concentration because of the influence from wastewater. All the parameters are under limits of Level IV of groundwater (Appendix C.5).
Medium-deep groundwater quality is low-mineralized and alkalescenced thus it is mainly utilized as directly groundwater abstraction source in city center (Appendix C.6).

Water quality improvement

The water quality improvement is obviously for Dongzhou plant since the water abstracted through RBF is much better than the water source. Unfortunately, Dongzhou Drinking Water Treatment Plant only provides one day monitoring data (Appendix C.6) and annual text report while weekly, monthly or annual monitoring data are missing.

Table 5-3 Water improvement summary of Dongzhou Plant

Items	Standard (for drinking water GB5749-2006)	Intake	After RBF (Day ave.)	Removal efficiency
Turbidity(NTU)	1	114	2.08	98.2%
Chroma	15	15	<5	-
Oder and smell	No	Yes	No	-
PH	6.5-8.5	8.17	7.68	-
Ammonia nitrogen (mg/l)	0.5	1.18	0.06	94.9%
CODMn(mg/l)	3	3.02	1.41	-
Fe(mg/l)	0.3	1.66	0.71	57.2%
Mn(mg/l)	0.1	0.47	0.2	57.5%
Total bacteria	0	650	0	100%

court (CFU/ml)				
Total E-coli (MPN/100ml)	0	2300	0	100%
Thermo-tolerant E-coli (CFU/100ml)	0	200	0	100%

After RBF, water quality is improved on all parameters especially on fecal contaminants.

5.1.3. Criteria evaluation

Step 1: Basic criteria

- Water source

The Yellow River as the second large river in China has a great potential for water source but the attenuation of flow is sensitive to RBF. Including the Yellow River, there are also several small rivers flow through Zhengzhou city. Similarly, the groundwater source is also rich in this area. Meanwhile, an updated field investigation is needed since the overexploitation problem is raised.

- Water quality

The salinity is represented by conductivity in the Standard (GB5749-2006) under the limitation for total dissolved solids is 1000 mg/l that is 2000 μs/cm. And the water in the Yellow River is 1034μs/cm thus in general, the water quality is higher than Standard (GB3838-2002) Level III which is the limitation for drinking water source.

- Hydrogeology

The thickness is larger than 10 m in most part of area and well connected to the river bed which can be observed from the profile Fig.5-6. The hydraulic conductivity is fairly high to minimum 20 m/d because of the sand material.

- Social

High turbidity and large water level variety are two features for the Yellow River which is a main and indispensable water source for Zhengzhou city till recent. Dongzhou drinking water treatment plant is established in 90`s when the population is growing extremely fast. Therefore the water supply is hard to fit the population anymore. Till today, the water supply shortage is 200,000 m3/d in summer when water consumption is in peak. So RBF still can be a vital supplement to Zhengzhou city.
The result of step 1 is shown in the Table.5-4.

Table 5-4 Results of Zhengzhou site evaluation step 1

Step 1				
	Criteria	Reality	Qualified	Remark
Water source	Should be	The Yellow River	√	
Water quality	Level III	Level II	√	GB3838-2002
Hydrogeology	Thickness > 10 m Connected K > 5 m/d	Thickness > 20 m Yes Avg. K > 20 m/d	√ √ √	
Social	Water demand Land	Yes Yes	√ √	Depend on specific project and location

Step 2: Classification in degree

➢ Water source

a). Flow

From the hydrology data of the Yellow River, the monthly average flow is quite variable between years and sometime the river is lack of water. This condition is just 3 point for RBF.

b). Flow velocity

The water velocity of the Yellow River is between 0.8 m/s to 2.26 m/s except the section with no flow and the average velocity is 1.5 m/s. Thus the water velocity is 5 point for RBF.

c). Streamline

Streamline of the Yellow River in Zhengzhou area is tend to be straight but Dongzhou water source is in the side of outside bend. This is 3 point for RBF.

➢ Hydrogeology

a). Thickness

The thickness of the aquifer is larger than 20 m and the average value is 41.9 m. This is 5 point for RBF.

b). Hydraulic conductivity

The minimum K value is 2.3 m/d while the average K value is 20.3 m/d and majority is between 15-30 m/d. This is 5 point for RBF.

c). Aquifer soil texture

The materials of the aquifer are mainly sand and gravel which are 5 point for RBF.

➢ Water quality

a). TSS

The turbidity of the Yellow River is normally around 100 NTU but in the upstream of the river, the turbidity is as high as 5000 NTU during summer and 10000 NTU in peak. Although RBF is efficient to reduce turbidity, influence by extremely high turbidity like more than 5000 NTU is still need more research.

b). Fecal contaminants

Compared with Standard for Drinking Water Source (GB3838-2002) and Standard for Drinking Water (GB5749-2006), the water quality is sufficient to be water source at first and after RBF, the water quality is improved significantly to be drinking water indicating

RBF has good capacity to reduce fecal contaminants. The distance between wells and river bank is about 1 km but no specific information about all 72 wells. Thus the travel time is approximately 27 d using average K value 37 m/d to calculate.

c). Nutrients, Cations, Anions and Heavy metal

Nutrients, ions and heavy metal are not only removed by RBF but also may be introduced into the water during processes in the aquifer. Thus the criteria are summarized separately. Considering the conventional treatment processes, the concentrations should not beyond the limitation otherwise, the burden for post-treatment is tremendous.

Table 5-5 Results of Zhengzhou site evaluation step 2 on non-removal items

Step 2.a							
Items		Criteria			Reality	Qualification	Remark
Water quality	Nutrients Ammonia nitrogen	<2 mg/l*[1]	≥2 mg/l		1.18 mg/l	5	
		5	1				
	Ions	≥Level II	Level III	≤Level IV	Level II	5	
		5	3	1			
	Heavy metal Fe/Mn	<3 mg/l, <1 mg/l	>3 mg/l, >1 mg/l		1.66 mg/l 0.47 mg/l	5	Removal efficiency influenced by source water quality strongly
		5	1				

[1]2 mg/l is calculated by the 75% removal efficiency of traditional treatment processes and the limitation 0.5 mg/l in drinking water.

[2]limitation is calculated by the removal efficiency of 90% by traditional treatment processes to Fe and Mn. The standard for drinking water is 0.3 mg/l to Fe and 0.1 mg/l to Mn.

d). Organic micro-pollutants and Emerging contaminants

It is one of the shortcomings that monitoring data is absent.

- Social

a). Land use

For wells in the benchland, the land used to be open/public land which is 5 point to RBF. But now it is partly used as farm land without regulation.

Figure 5-8 Pictures from well field in Zhengzhou

For wells outside the dam, wells are surrounded by residential area which is 3 point to RBF. According to the criteria, the result of step 2 is shown in Table 5-6.

Table 5-6 Results of Zhengzhou site evaluation step 2 on other items

Step 2.b							
Items		Criteria			Reality	Qualification	Remark
Water source	Flow	High flow	Fluctuant flow	Low flow	Fluctuant flow	3	Seasonal and annual change
		5	3	1			
	Velocity	⩾1.5 m/s	1-1.4 m/s	0.5-1 m/s	1.5 m/s	5	
		5	3	1			
	Streamline	Inside bend	Straight	Outside bend	Straight	3	Depends on location
		5	3	1			
Hydrogeology	Thickness	>20 m	15-20 m	10-15 m	41.9 m	5	
		5	3	1			
	K	>15 m/d	10-15 m/d	5-10 m/d	20.3 m/d	5	
		5	3	1			
	Soil texture				Sand/Gravel		
Water quality	TSS	<1000 NTU*	⩾1000 NTU		100 NTU	5	Peak >5000 NTU
		5	1				
	Fecal contaminant	> 30 d	< 30 d		27 d	1	
		5	1				
Social	Land use	Open	Farm	Industry	Partly farm Rest open	5	Different location
		5	3	1			

**2500 NTU is calculated from assumptions that the removal efficiencies for RBF and traditional process are both*

98%. And the limitation for drinking water is 1 NTU. But consider the clogging problem, too high turbidity will cause clogging too fast thus a lower value 1000 NTU is expected.

Step 3: Basic design and comparison

After two steps` evaluation, the basic conditions as well as water quality of Zhengzhou site are highly suitable for RBF which is consistent with the reality. This supports the application of the evaluation approach developed in this thesis. In step 3, the design model is applied to evaluate the amount of wells and cost of RBF in Zhengzhou. At first, RBF is design theoretically using the model, resulting in the required amount of wells.

Table 5-7 RBF Capacity design of Zhengzhou

Item	Unit	Sign	Zhengzhou
Stabilized drawdown	m	Sm	3.82
Yield of well	m3/d	Q	3,600
Leakage factor	m3/d	L	195
Cover factor	d/m	C	100
Cover thickness	m	Hc	10
Hydraulic conductivity	m/d	KD	38
Radius of borehole	m	r	0.50
Thickness	m	D	24
Cpacity of RBF site	m3/d	C	200,000
Well yield	m3/d	Q	3,600
Amount of wells		N	56
Backup wells		n	6
Total amount		T	61

**The well yield and amount of wells can be adjusted to fulfill the requirement of drawdown and capacity.*

Under the limitation of drawdown 4 meter, total 61 are established including backup with a well yield 150 m^3/h. In reality, there are 72 wells including some abandoned wells because of low yield due to improper maintenance.

Table 5-8 Amount of wells design in Zhengzhou

Well amount	Theoretical	Reality
N	61	72

The results are reasonable considering the variety of drawdown and well yield. For further comparison, a specified management report is needed for Dongzhou Drinking Water Plant.

Regarding to cost, the cost of RBF site in Zhengzhou can be calculated by the design model.

Table 5-9 Theoretical Cost estimation Zhengzhou site

Item	Unit	Sign	Zhengzhou
Capacity of RBF site	Mm3/y	C	73.00
Cost factor	€/m3 yearly capacity	f	3.0
Investment	M€	i	219.00
Investment combine CN/NL	M€	i`	26.71
	hundred million Yuan	ic	1.87

**Factor CN/NL is calculated in 3.4.2 and the cost factor can be adjusted according to capacity.*

In reality, the total investment for Dongzhou plant, Zhengzhou site is approximately 64 M € (4.4 hundred million Yuan) including well drilling, post-treatment and other fees in 2000. Considering the price difference of time and entire investment, the theoretical calculated cost is smaller than the actual cost but still in same order of magnitude. Therefore, when discuss about the cost difference CN/NL of RBF, a value smaller than 8 (calculated in 3.4.2) can be used.

5.1.4. Problems, Conclusions and Recommendations

Problems

During communicating with technicians and staffs from Zhengzhou Drinking Water Company and their branch design institute, some problems are collected in design, construction and operation.

At first, when the wells system was designed, the scientific investigations and analysis are missing thus the design is relatively uncomplete and inaccurate. The understanding of RBF is lacking, therefore, the way now is to trial and error. So the service life of wells is relatively short.

Regarding to construction, more detailed questions on engineering are proposed to the well itself. For example, how to improve the stability of the well? How to improve the well yield? How to prevent and recovery clogging?

At last, accidents also appeared for example the water level and flow of the Yellow River vary a lot during a year or a period. Sometime the water level increased a lot to submerge the wells which are in the benchland of the river. And the attenuation of the river is an uncertain threat.

Conclusions

Zhengzhou site

Zhengzhou is the first site in the investigations in China, because it has a 200,000 m3/d scale engineering application on RBF. Nowadays, Zhengzhou has built a channel transporting water from Danjiang River far away but not continuing using RBF. This may be because of the decreasing yield of the Yellow River and improper maintenance and operation of the RBF site. The utility is more experienced on surface water treatment than RBF, but it is still a vital supplement to the city for now. Proper water source, soil passage and successful experience all indicates that RBF is effective to improve the water quality especially to turbidity, ammonia nitrogen and fecal contaminants. But due to the soil passage and combination of groundwater, the concentrations of iron and manganese not decrease too much and even sometime increase. Unfortunately, the outdated data and lack of information in worse or peak situation may lead to ignorance to real current condition and result of bad situation.

Site evaluation approach

Zhengzhou site is the only full application of site evaluation approach. From the results of application, the model has realized its function that evaluation a potential site of RBF. The first two steps are able to evaluate the basic conditions and distinguish different water quality condition to help make preliminary decision. Basic design model is able to have an insight at the RBF site and cost estimation although it is a rough order of magnitude type calculation. Later in other cases, this model can be used to theoretically evaluate case study sites.

Recommendations

Considerable potential is still available to develop RBF in Zhengzhou. Therefore the following recommendations are given.

- Designers need to have a better understanding to RBF. It includes the processes underground and influence factors to water quality.
- More specific investigations on operating wells. To clarify the location of each well, and the distance between river bank and wells.
- Scientize and systematize the whole well system. Use scientific method to analyze problems.
- Update the current condition on hydrogeology and pay more attention to peak time and bad situation, not only to the normal situation.
- Research and predict the trend of the Yellow River because it is an uncertain threat in case RBF is still developing in Zhengzhou.

5.2. Feedback of site evaluation approach after second application

Different from the application on national level, the second application is fully based on an operating site. Besides feedbacks from first application, some other detailed feedback is given:

- The criteria of water flow are relatively simple since the fluctuation and attenuation of rivers are not discussed specifically. These two phenomena will influence the performance of RBF and more importantly will cause clogging problems during operation.
- On water quality respect, turbidity is capable to be removed efficiently by RBF but exceeded turbidity will cause clogging problems in peak time. Criteria on turbidity should be adjusted to give warnings or solutions.

- Ions and heavy metals may be introduced into abstracted water during soil passage, thus as criteria they are limited by the removal of post-treatment efficiency for now. More proper criteria are needed to evaluate water quality condition on these items.
- Organic micro-pollutants (e.g. pesticide, EDCs, PhACs and DBPs) are not included in regular water quality monitoring in many sites. Therefore, these items are cannot be used for now.
- The results of the theoretical evaluation by the site evaluation approach are consistent with reality situations. After evaluation, Zhengzhou site is suitable for RBF theoretically. In reality, Zhengzhou site has been operating RBF for twenty years to obviously improve the water quality.
- Output of the design model is in a reasonable range to reality (61 wells and 72 wells, respectively). Costs estimation of RBF is in a same order of magnitude to real investment although it is half of the price. The reason can be: the price of RBF in China is derived by the proportion of rapid sand filtration that can cause inaccuracy; the factors (e.g. cost factor) are selected simply in the range; the real investment of Dongzhou plant, Zhengzhou is an overall value including post-treatment and other fees.

After the second application especially the full application of criteria and design model, the site evaluation approach can be applied to candidate locations for preliminary decision-making. It can be more accurate and applicative for more locations by further modification. For example, a pilot RBF site may give a real cost in China other than conversion from cost in the Netherlands.

5.3. Jiaxing Site — candidate location in China

5.3.1. Introduction to Jiaxing

Basic circumstances

Jiaxing is a city of Zhejiang Province and an important component of the Yangtze River Delta city series. The city situated in several connections of rivers, lakes and sea it is a vital transportation central of the Taihu Lake basin.

Figure 5-9 Location of Jiaxing

In the east of Jiaxing is the East Sea while in the north is the Taihu Lake and the Qiantang River is in the south. The whole city is fully flat.

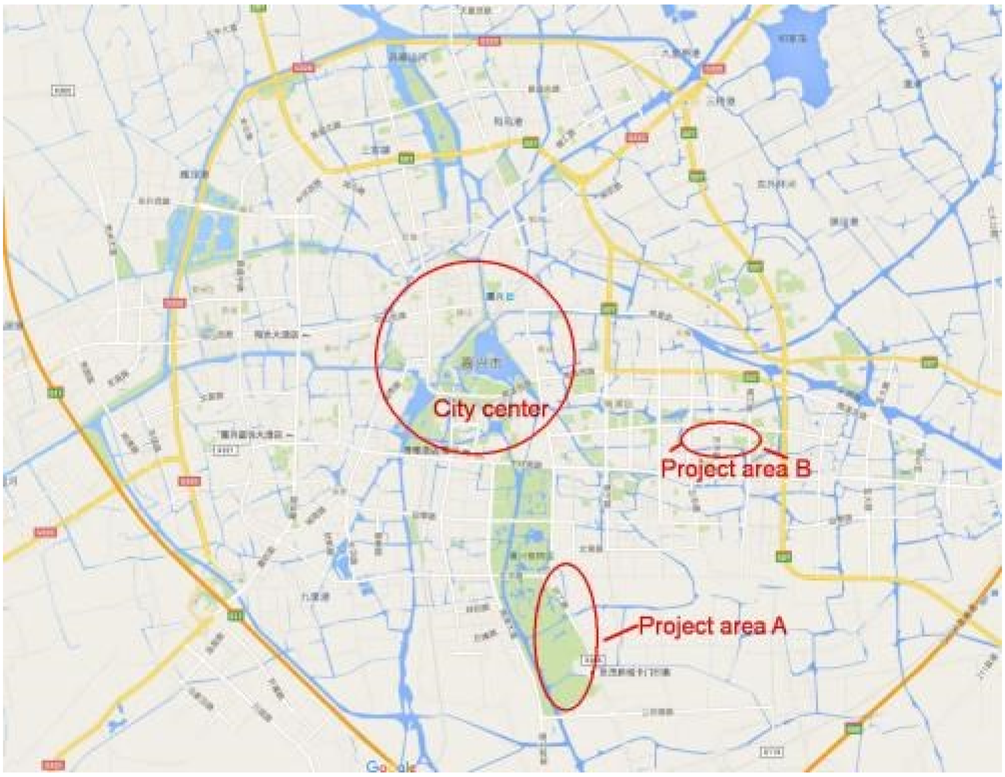


Figure 5-10 Project areas locations in Jiaxing

Jiaxing is monsoon climate with sufficient rainfall and sunshine. The annual average temperature is 15.9℃ and annual average rainfall is 1168.6 mm. According to the Zhejiang Provincial Bureau of Statistics, the total population of Jiaxing is 4.585 million with a proportion of 60.9% urban population. Both of the two project areas are outside of downtown and have plenty of land with natural landscape. Data and information are collected about these two areas and attentions mainly focus on the project area A where there is constructed wetland.

Current water supply condition

Jiaxing is situated in the Taihu lake basin where a large number of rivers and cannals settled. The river water in Jiaxing is polluted for more than thirty years and becoming worse. Till this century, the water quality upper than Level V (GB3838-2002, Appendix A.1) is only 20% since most of the water sources are Level V or less. Only water from Taipu River, North Lake and South Lake are generally meet the requirement. According to monitoring data, the pollutants in Jiaxing are mainly organic pollutants and ammonia nitrogen pollutants caused by three sources industry, municipal and agriculture areas. In such cases, the drinking water treatment processes are more complicate to produce clean water. Two drinking water treatment plants use advanced treatment to treat water clarified by constructed wetlands and produce 550,000 m3/d drinking water.

Problem clarification and motivation

As discussed in 5.2.1.2, the water quality in Jiaxing is difficult to drinking water treatment. Guanjinggang Drinking Water Treatment Plant is an example. The water source is Level IV-Level V with several features such as exceeded concentrations of iron and manganese. Fe is as high as 2.5 mg/l and Mn is as high as 0.8 mg/l. Besides, the most troublesome items are ammonia nitrogen and CODMn. The average ammonia nitrogen concentration is 1.1 mg/l and average value for CODMn is 6.35 mg/l. Although constructed wetland is introduced to improve the source water quality, the drinking water treatment processes in the plants still have to be complicated and advanced. Through over two year`s test, the efficiency of the wetland is found not sufficient and not capable to the treat worse source water. Therefore, Jiaxing is eager to introduce RBF to further improve the source water quality.

5.3.2. Background condition

Guanjinggang Wetland

Guanjinggang Wetland is 3 km^2 wetland constructed in project area A including three sections. The first one is buffering self-cleaning section after the water intake point. And then is plant cleaning section using designed plants to treat water continued by advanced cleaning section.

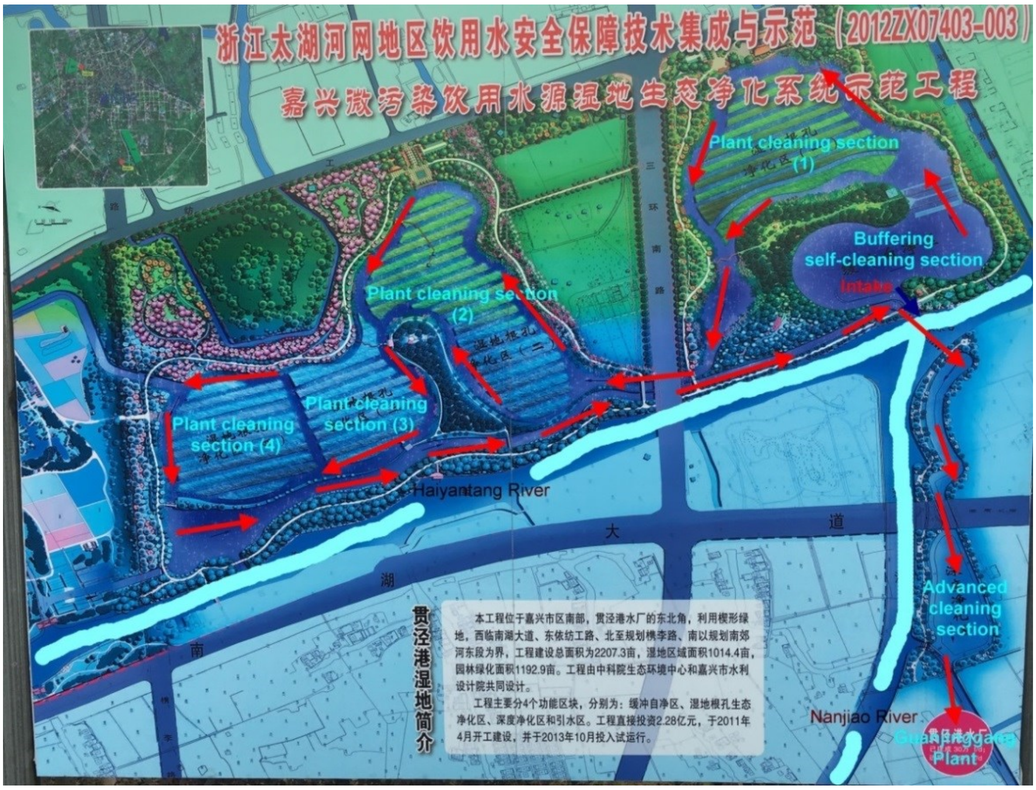


Figure 5-11 illustration of Guanjinggang wetland structure. Arrow represents flow direction of water.

The water abstracted from the Haiyantang River and flows into the buffering self-cleaning section to sedimentation naturally. Then it flows into four plant cleaning sections and turns back into a canal to the intake point but separated to it. Through the underground canal, the water is introduced to another side of Haiyantang River to the advanced cleaning section Guanjinggang Drinking Water Treatment Plant.

Figure 5-12 Haiyantang River in Jiaxing

Figure 5-13 Intake point of wetland

Figure 5-14 Plant cleaning section in wetland

The wetland makes an improvement to the source water quality according to monthly water quality monitoring data from October 2013 to October 2015. Take the summary for January and August as examples to analyze the operation condition of the wetland (Appendix D.1) as shows in Table 5-10.

Table 5-10 Removal efficiency summary of wetland in Jiaxing

Item	Month	Removal%	On Standard
Turbidity (NTU)	1-2	18.7	
	7-8	5.0	
Ammonia nitrogen (mg/l)	1-2	28.5	IV
	7-8	53.5	III
COD (mg/l)	1-2	7.3	III
	7-8	7	III
DO (mg/l)	1-2	-7.4	II

	7-8	7.5	III
Fe (mg/l)	1-2	17.1	Unqualified
	7-8	-1.6	
Mn (mg/l)	1-2	25.3	Unqualified
	7-8	17.3	
Total P (mg/l)	1-2	15.8	III
	7-8	28.5	III
Total N (mg/l)	1-2	16.6	VI
	7-8	15.9	VI

From the data, several summaries can be made.

a) The first one is that there are some items that are exceeded the standard for drinking water source. They are ammonia nitrogen, Fe, Mn and total N.

b) The second one is that the removal efficiency in winter is much worse than in summer.

c) The third one is that the removal efficiency is decreasing along the decreasing of concentration.

d) After treatment of wetland, the source water becomes better but still not qualified to be the water source basically.

Hydrogeological and water quality condition

➢ Hydrogeological condition

Borehole test in project area A shows that the soil is divided into 8 layers in total.

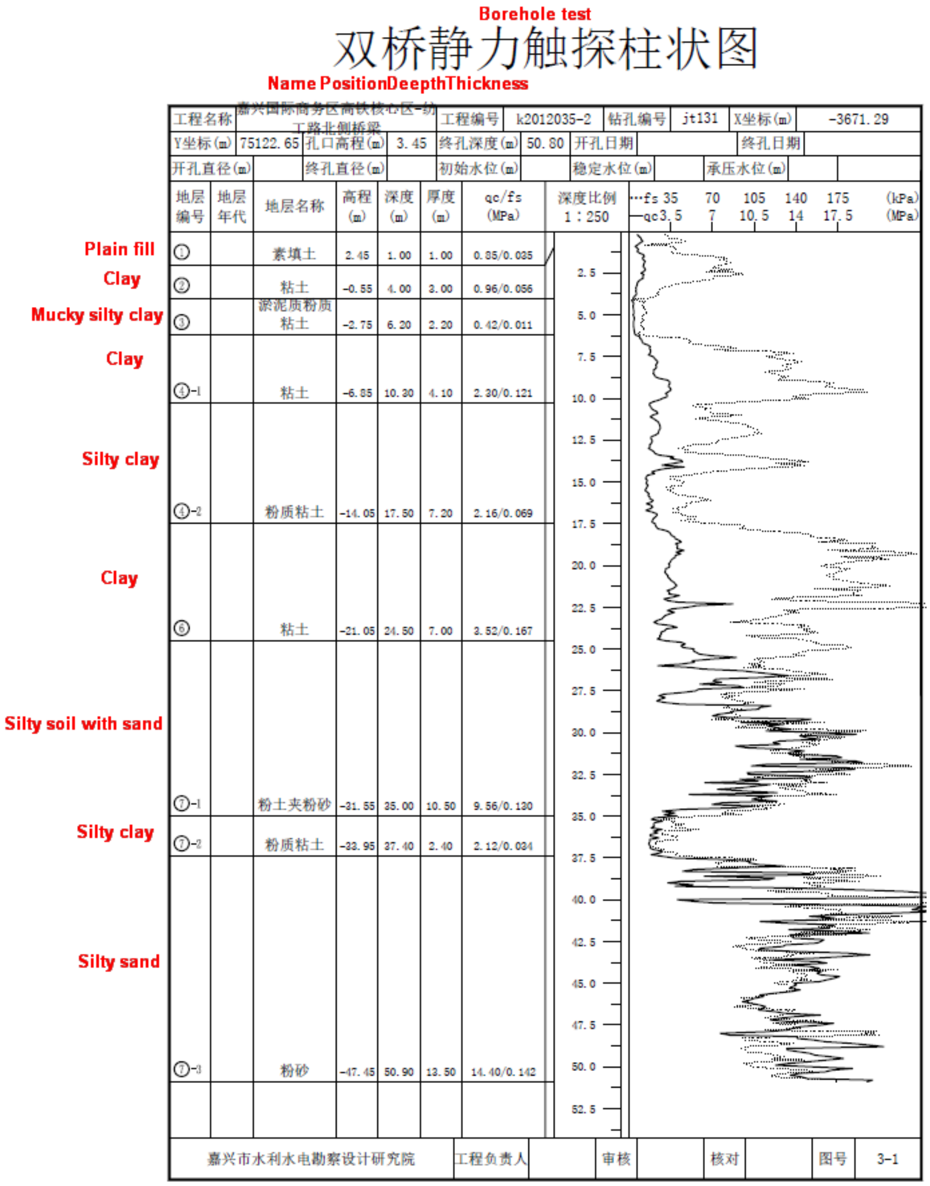


Figure 5-15 Borehole test 1 in Jiaxing

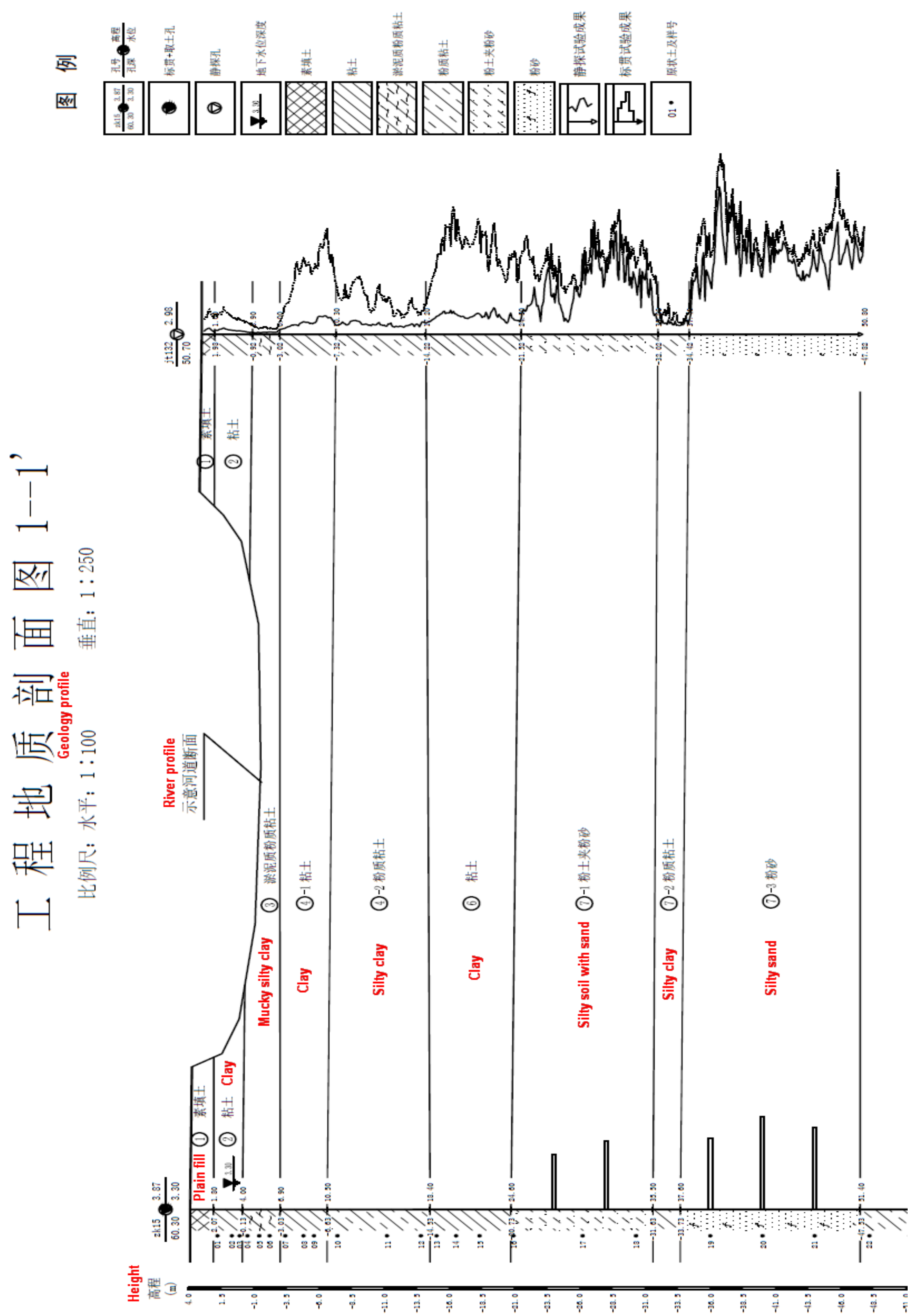


Figure 5-16 Borehole test 2 in Jiaxing

The first part of soil is mainly clay until 25 m underground where sand appears gradually after 25 m. Between 27 m to 50 m, silt sand fills a possible aquifer layer. The soil is porous unconfined with a depth between 2.8 m to 3.3 m but the permeability is extremely low. According to the report of Summary for Geology Condition in Jiaxing, 6 layers of 3 group aquifers are in project area A. The first group is 24 m thick silt aquifer starts from 26 m underground and 21 m thick silt aquifer from 68 m. The second group has highest water content among three groups including 17 m thick aquifer from 108 m and 27 m thick aquifer from 128 m. The third group layers start from 166 m and 193 m and the thickness is 12.8 m and 7.5 m, respectively.
From the profile, it indicates that the river is not connected to the aquifer. The soil connected with the river bed is mainly clay. This makes Jiaxing not suitable for RBF but there are aquifers available in deep underground. Thus, techniques such as Managed Artificial Recharge (MAR) could be possible in these soil conditions.

- Water quality condition

The water source for Guanjinggang DWTP is Nanjiao River and wetland water as addition. One of the monthly reports in August and January are used for comparison. Complete data is in Appendix D.2 and only exceeded parameters are in Table 5-11.

Table 5-11 Water quality data of Nanjiao River in Jiaxing. Red number is exceeded the standard

Item	January	August	Standard Level III
DO (mg/l)	5.58	3.1	5
Ammonia nitrogen (mg/l)	1.54	0.19	1.0
Total N (mg/l)	5.35	2.89	1.0
Fe (mg/l)	0.49	0.76	0.3
Mn (mg/l)	0.14	0.05	0.1

For groundwater, no complete water quality data except a part of the report from a bridge construction project is collected as shown in Table 5-12.

Table 5-12 Corrosivity Analysis to Construction Material of Jiaxing groundwater

Type			Groundwater	Groundwater
No.			ZK32	ZK39
Cation	K^+	mg/L	6.72	6.90
		mmol/L	0.27	0.24
	Na^+	mg/L	40.1	41.3
		mmol/L	1.75	1.80
	Ca^{2+}	mg/L	39.3	40.6
		mmol/L	1.96	2.03
	Mg^{2+}	mg/L	10.22	11.53
		mmol/L	0.83	0.95
	Sum.	mg/L	96.45	100.03

		mmol/L	4.81	5.02
Anion	HCO_3^-	mg/L	112.9	126.4
		mmol/L	1.84	2.05
	SO_4^{2-}	mg/L	40.8	43.4
		mmol/L	0.84	0.91
	CL^-	mg/L	51.6	50.8
		mmol/L	1.47	1.43
	NO_3^-	mg/L	7.91	8.99
		mmol/L	0.13	0.15
	Sum.	mg/L	214.36	229.12
		mmol/L	4.31	4.58
Total hardness (Ca CO3)		mg/L	143	151
Gas	Free CO_2	mg/L	14.52	19.10
	Ero CO_2	mg/L	10.14	15.26
Mineralization		mg/L	48.68	51.68
PH			6.92	7.03
Hydrochemical type			$-HCO_3^-$- CL^-- Ca^{2+} -Na^+	$-HCO_3^-$- CL^-- Ca^{2+} -Na^+

According to information collected above, the criteria are going to be used to evaluate in case project area A in Jiaxing is suitable to introduce RBF.

5.3.3. Criteria evaluation

Step 1: Basic criteria

- Water source

Plenty of stable surface water sources are in Jiaxing area including the river Nanjiao and Haiyantang. But the groundwater source is not rich in this area.

- Water quality

Even though numerous small water systems are present around Jiaxing, the water quality is not sufficient to use as water source for most water systems. The water source Nanjiao River and Haiyantang River are basically conform to the standard for Level III but several items exceed the standard thus enhanced post-treatment is needed.

- Hydrogeology

Three aquifer layers are in project area with thickness larger than 10 m but in deep underground which means no connection between the river bed and the aquifer.

- Social

Water demand is obviously required by Jiaxing because of the lack of clean water source.

And also open land is available for RBF.

The result of step 1 is shown in the Table 5-13.

Table 5-13 Result of Jiaxing site evaluation step 1

Step 1				
	Criteria	Reality	Qualified	Remark
Water source	Should be	Nanjiao River	√	
Water quality	Level III	Less Level III	×	GB3838-2002
Hydrogeology	Thickness > 10 m	Thickness > 10 m	√	
	Connected	No	×	
	K > 5 m/d			
Social	Water demand	Yes	√	Depend on specific project and location
	Land	Yes	√	

After the evaluation step 1, the result is obviously not suitable for RBF. The water quality and hydrogeology are both not sufficient. Thus the evaluation procedure will end up here and alternative solution is given in 5.3.5.

5.3.4. Conclusions and Recommendations

Conclusions

According to the data and information collected till now, project area A in Jiaxing fails to fulfill the basic criteria of RBF since its unsuitable hydrogeology conditions and undesirable source water quality. In such case, other techniques should be introduced to produce superior source water.

Recommendations

The most important issue to RBF is the hydrogeology condition generally. As for water quality, the efficiency of RBF will influence the post-treatment but a worse water source is acceptable. Thus, a detailed hydrogeological investigation is strongly recommended on a specific project area.

Techniques to improve the performance of the wetland are first option to obtain superior water source especially measurements aiming at the worse circumstances in winter.

Managed Artificial Recharge (MAR) is one of the alternative solutions because there are deep aquifers in Jiaxing although they do not have connections with the river. Dune filtration is a solution to replace RBF. There is a case in Xi`an city using dune filtration to obtain superior water source from Chan River.

Looking for a suitable location to build RBF site and transporting the water to Jiaxing is also an alternative solution.

5.3.5. Alternative solution

Since Jiaxing is not suitable for RBF locally, an alternative solution is given to continue using soil passage treatment. In order to find a suitable location for RBF site around Jiaxing, the hydrogeological map of the Yangtze Delta area is used.

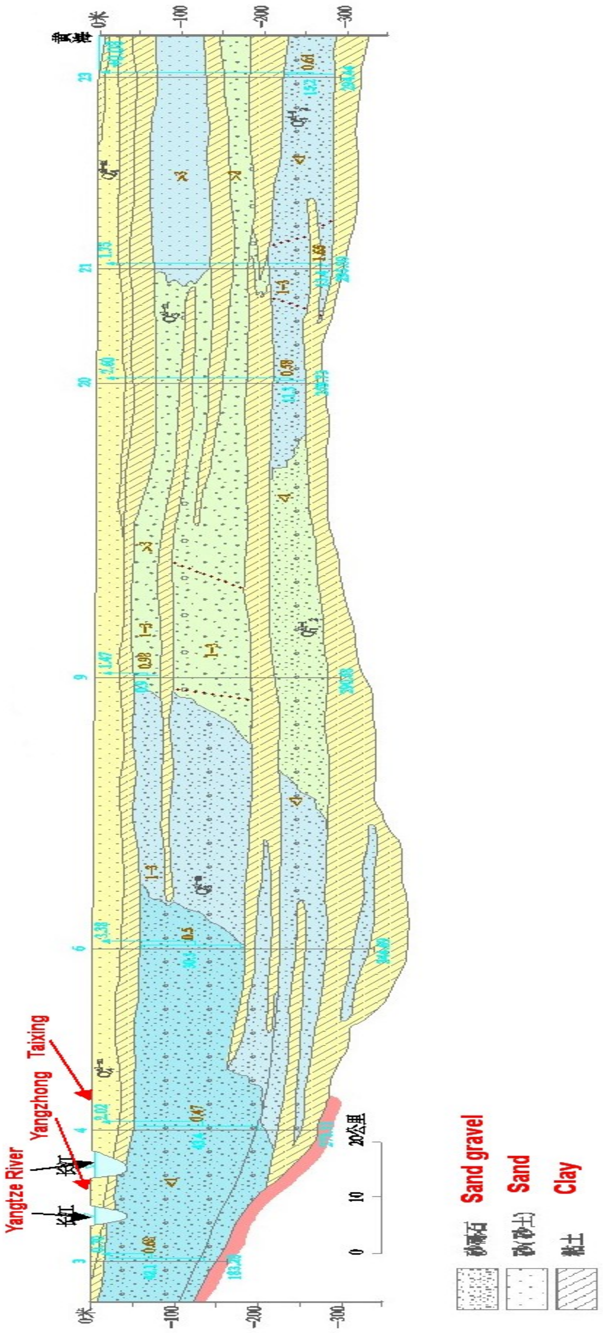


Figure 5-17 Cross section Jiaxing area

From this cross section, it`s easy to find that the Yangtze River has two connects to a huge aquifer around Yangzhong City. The aquifer layer is made by sand gravel and covered by a clay layer of around 20 m thick. The location of Yangzhong City and Taixing City are shown in Fig 5-17.

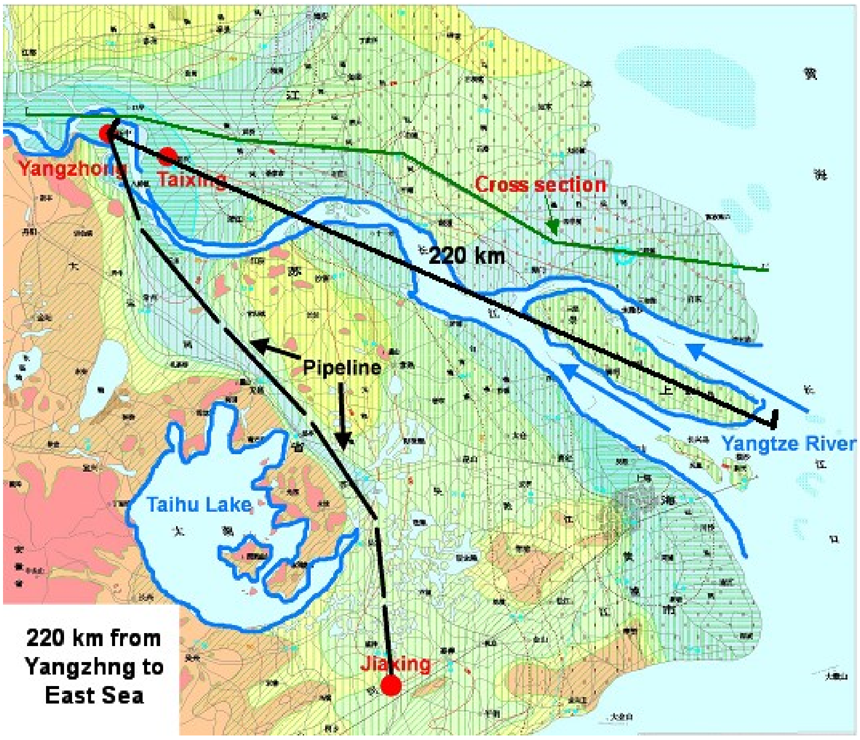


Figure 5-18 Transport pipeline design from Yangzhong to Jiaxing. Blue line represents edge of rivers or lakes.

The idea for alternative solution is to build a RBF site around Yangzhong or Taixing City and transport filtrated water to Jiaxing for post-treatment. The investment is two main parts including abstraction wells and transport pipelines. In such case, the length of pipeline is estimated as 190 km (Alternatively, the RBF could be used to supply Yangzhong or Taixing).

RBF system basic design

Applying the model developed in 3.4, the results of basic design are given in Table 5-14. The population of Jiaxing for now is 4.85 million and the growth rate is assumed to be 20% at the end of the design period. All other assumptions and results are in Table 5-14.

Table 5-14 RBF Capacity design of Jiaxing

Item	Unit	Sign	Jiaxing
City name			Jiaxing
Water demand	m3/d	D	1,155,420
Capacity of RBF site	m3/d	C	231,084
Population (Future)		Pf	5,502,000
Population (Current)		Pc	4,585,000
Water consumption quota	L/head/d	q	150
Extra		e%	30%
Peak		P%	10%
Ratio of total demand		R%	20%
Population growth rate		a%	20%

**Factors such as extra, peak and growth rate can be adjusted.*

The capacity of RBF site is assumed to be 0.23 Mm^3/d. Some assumptions for calculating amount of wells are made as below based on the hydrogeology map:
K value: 25 m/d (because of sand and gravel aquifer)
Thickness of aquifer: 40m (100 m available from cross section Fig 5-16)
Cover thickness: 20 m (from cross section Fig 5-16)

Table 5-15 Amount of well design in Jiaxing

Item	Unit	Sign	Jiaxing
Stabilized drawdown	m	Sm	3.56
Yield of well	m3/d	Q	3,600
Leakage factor	m3/d	L	224
Cover factor	d/m	C	100
Cover thickness	m	Hc	20
Hydraulic conductivity	m/d	KD	25
Radius of borehole	m	r	0.50
Thickness	m	D	40
Cpacity of RBF site	m3/d	C	230,000
Well yield	m3/d	Q	3,600
Amount of wells		N	64
Backup wells		n	6
Total amount		T	70

As an example design, a total 70 wells is applied including 6 backup wells. Because of the large aquifer, thickness is as thick as 100 m, the yield of wells can be improved further. Thus the well amount could be reduced in case the drawdown is still acceptable.

RBF system costs estimation

- **Investment**

Table 5-16 Investment estimation of RBF in Jiaxing

Item	Unit	Sign	Jiaxing
Capacity of RBF site	Mm3/y	C	83.95
Cost factor	€/m3 yearly capacity	f	2.5
Investment	M€	i	209.88
Investment combine CN/NL	M€	i`	25.59
	hundred million Yuan	ic	1.79

**Cost factor can be adjusted according to capacity mentioned in 3.4.2*

- **Energy costs**

Table 5-17 Energy costs estimation of RBF in Jiaxing

Item	Unit	Sign	Jiaxing
Well yield	m3/h	C	150
Pump efficiency		f	0.7
Motor efficiency		i	0.7
Pressure head	m	Pt	33.56
Drawdown	m	Hd	3.56
Extra head	m	He	10
Desired pressure	m	Hs	20
Energy per unit time	kW	Pnet	28.54
Electric price	€	e	0.1
Energy cost	€/h	E	2.85
	Yuan/h	Ec	19.98

Item	Unit	Sign	Jiaxing
Capacity of RBF site	Mm3/y	C	83.95
Well yield	m3/h	Q	150
Running hours	h/y	h	559,667
Energy cost	M€/y	Et	1.60
	ten million Yuan/y	Etc	1.12

The investment is influenced by the capacity and cost factor. To build a bigger site, the factor can be lower thus the increase of investment will not be proportion with capacity.

Pipeline basic design and cost estimation

To transport water from RBF site to Jiaxing, pipelines are used.

Table 5-18 Transport head loss calculation in Jiaxing

Item	Unit	Sign	Jiaxing
Flow	m3/s	Q	1.86
Distance	km	L	190
Friction factor		λ	0.02
Velocity	m/s	v	0.73
Diameter	mm	D	1,800
Friction loss	m	Hf	57.82

Because of the long distance, the friction loss is tremendous. The average altitude of Yangzhong and Jiaxing are 4.25 m and 3.7 m respectively. The applicable head is scarcely any. Therefore, additional pumping station is needed although investment will increase.

Table 5-19 Transport costs estimation of Jiaxing

Item	Unit	Jiaxing
Distance	km	190
cost factor	€ per 100m3/d*km	412
Capacity	m3/d	230000
Cost	M€	180.04
	hundred million Yuan	12.60

From Table 5-19 and Table 5-16, the cost of transport pipeline is much higher than the RBF site itself (180.04 M€ to 25.59 M€) because of the long distance. Thus a closer suitable location around Jiaxing is more cost effective for transport. The example location is selected by regional hydrogeological map. A more detailed map of the Jiaxing surroundings is needed to evaluate if suitable locations are nearby.

5.4. Wuhu Site — candidate location in China

5.4.1. Introduction to Wuhu city

Basic circumstances

Wuhu is a city in Anhui Province located in eastern China and south of the Yangtze River connecting Qingyi Rver and Yangtze River. 3,654,000 inhabitants live along the Yangtze River and other rivers and lakes.

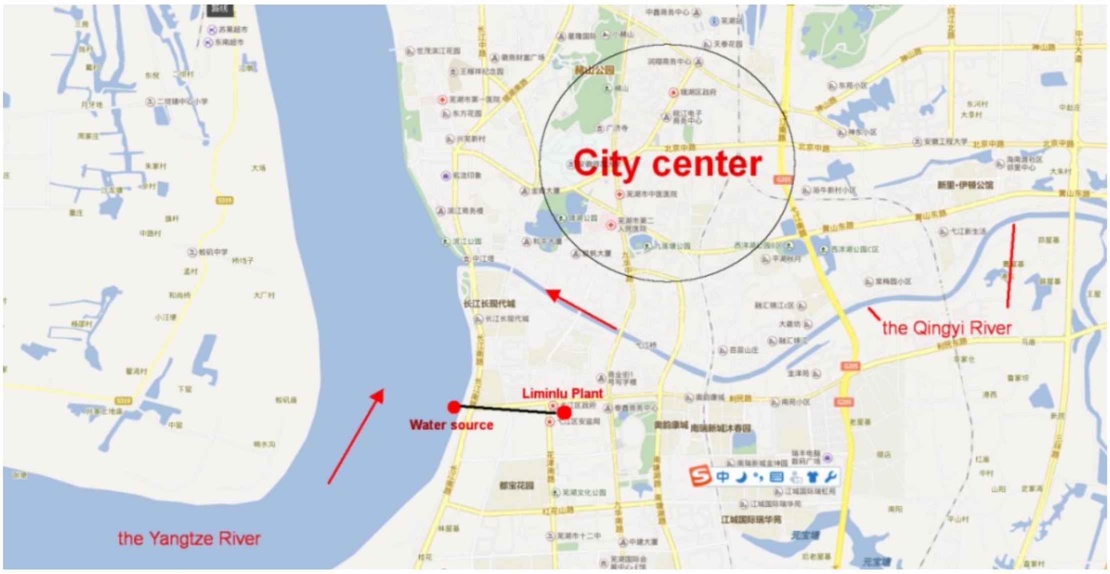


Figure 5-19 Water supply conditions in Wuhu

The annual average temperature is 15-16℃ and sunshine time is 2000 hours. The annual average rainfall is 1200 mm but contributes not equal and mainly concentrates on spring, autumn and early winter. Water source is not the only function of the Yangtze River to Wuhu, but also the important transport and economy support.

Wuhu current water supply condition

Huayan Water Company is in charge of water supply in Wuhu operating four drinking water treatment plants to provide a capacity of 720,000 m3/d. Among them, Liminlu Plant is one of the plants has 250,000 m3/d capacity that is indicated in Fig.5-18. Another main plant is Yangjiamen Plant loceated in the north of Wuhu with capacity of 350,000 m3/d. All the water sources for Wuhu City are along the Yangtze River while no groundwater usage.

5.4.2. Hydrogeology and water quality condition

Hydrology

The data from Datong monitoring station, 116km upstream to Wuhu, is used as hydrology condition for Wuhu City. According to data from 1950 to 2010, the average annual flow is 9.055*10^11 m3 but corresponded to rainfall. In flood season, from May to October, the flow amount is 71% of total flow amount. The information for 2015 is shown in Table 5-20.

Table 5-20 Hydrology information of Wuhu, flow and water level

Time	Water level (m)	Flow (m^3/s)
1.1	4.89	13200
2.1	4.78	11300
3.1	5.97	17000
4.1	6.76	19900
5.1	7.56	23100
6.1	10.65	38500
7.1	13.45	53200
8.1	11.79	43600
9.1	9.04	28800
10.1	9.57	31000
11.1	6.89	18900
12.1	9.33	29200

Table 5-21 Hydrology information of Wuhu, seasonal and annual variation

Time	January flow (m3/s)	August flow (m3/s)
2015	13200	43600
2014	12300	50800
2013	18200	39200
2012	12000	57800
2011	15400	30000

For the flow velocity, the velocity is influenced due to the Three Gorges Dam. According to the ADCP measurement, the average flow velocity is 1.46 m/s depended on the location of measurement point (Appendix E.1).

Hydrogeology

a). General circumstances

On the east side of the river, river bank is occupied by hills thus benchland is narrow or disappeared. The typical alluvial plain mainly consists of silty-fine sand, medium-coarse sand and sand gravel. From national level evaluation in 4.2, Wuhu is in potential area Yangtze River Delta and the general information also indicates the materials of soil are mainly sand and gravel.

Figure 5-20 Water intake point of Wuhu

b). Current treatment plant

Yangjiamen and Liminlu drinking water treatment plants are two majority plants using surface water. According to the field investigation information about water intake point in the river, no sand or gravel aquifer above 25.3 m appears (Appendix E.2) since the main material of the soil is clay, silty clay and a little bit farmland on the top.

Water quality

Table 5-22 Groundwater water quality results in Wuhu

水 质 分 析 成 果 表

Water quality analysis results

表3-8

位置 location	PH	总硬度 total hardness	总碱度 total alkalinity	游离二氧化碳 free CO2	侵蚀性二氧化碳 aggressive CO2	HCO_3^-	Ca^{2+}	Cl^-	SO_4^{2-}	水的类型 water type
7	6.9	169	120	43.4	10.6	261	78.7	99.5	3.79	C_{III}^{Ca}
10	6.8	160	139	62.8	21.6	302	70.9	58.3	2.98	C_{I}^{Ca}
70	6.8	180	170	61.4	9.31	371	76.9	56.4	4.85	C_{I}^{Ca}
29	7.0	343	292	125	45.2	636	150	44.6	1.44	C_{II}^{Ca}
36	7.1	288	400	65	18.2	871	123	41.1	5.76	C_{I}^{Ca}
水	7.5	86.0	86.6	12.1	4.71	188	43.4	32.8	2.98	C_{I}^{Ca}

The water quality for groundwater is shown in Table 5-22. According to the data, the groundwater tends to be neutral and all the parameters are in the range of no corrodibility.

There are 29 items are measured for source water quality in August (Appendix E.3) while two of them are beyond the Standard for Drinking Water Source (GB3838-2002).

Table 5-23 Exceeded contaminants in Wuhu water source

Item	Value	Standard
Total N (mg/l)	2.47	1.0
Fe	1.56	0.3

Because of the satisfied source water, the treatment process of Yangjiamen Plant is relatively simple as conventional treatment.

Figure 5-21 Conventional treatment processes in Yangjiamen Plant, Wuhu

After this series of processes, the water quality of drinking water is far more superior to the standard.

5.4.3. Criteria evaluation

Step 1 Basic criteria

- Water source

For Wuhu City, the Yangtze River is an ideal water source. The flow of the river is stable and sufficient.

- Hydrogeology

According to data and information for the existing water treatment plant, the soil conditions are not suitable for RBF because of clay layer, although for the whole river basin of the Yangtze River, the alluvial plain is probably suitable for RBF in general.

- Water quality

The water quality of the Yangtze River is general be on Level III in standard (GB3838-2002).

- Social

Regarding to social, the water demand of Wuhu City is not urgent currently. But the water company there has great interest on RBF.
The result of step 1 is shown in Table 5-24.

Table 5-24 Results of Wuhu site evaluation step 1

Step 1				
	Criteria	Reality	Qualified	Remark
Water source	Should be	The Yangtze River	√	
Water quality	Level III	Level II	√	GB3838-2002
Hydrogeology	Thickness > 10 m Connected K > 5 m/d	No aquifer	×	
Social	Water demand Land	No Yes	× √	

Although from national level evaluation and general information, Wuhu area probably has proper soil conditions, the specific information for Wuhu shows no suitable sand or gravel aquifer in tested soil (above 25.3 m). Therefore the site evaluation approach is stopped after step 1. The hydrogeology data is based on existed surface water treatment plant which may not consider groundwater conditions and be lack of underground information.
The best option for Wuhu can be first apply detailed and complete field investigations to detect the soil conditions. In case there is aquifer available nearby, the potential of applying RBF arises since on national level evaluation, this area is possible for RBF. Otherwise, long distance transport is an alternative solution as the example in Jiaxing.

5.4.4. New idea, Conclusions and Recommendations

New idea

For Wuhu City, the water supply is sufficient till now for the whole city so the demand is not pushing for RBF. But the policy is that every city which has more than 200,000 population and single water source is required to establish a backup emergency water source including groundwater, surface water or outside water transfer. So, a new idea for RBF development in China is backup emergency water source with advantages. For example reducing the water demand for RBF such as 20% of total water demand of one city thus the investment is reduced as well.

Conclusions

Wuhu City is not suitable currently to bring in RBF. On the one hand, the water supply in Wuhu is sufficient now thus no need to invest in a new treatment plant especially when the investment for RBF is relatively high. On the other hand, the location will decide the hydrogeological condition thus then judge whether it is suitable for RBF. Looking for a suitable location around Wuhu can be an alternative solution.

In Wuhu City, a new pattern to bring in RBF is proposed. It can be established as backup emergency water source. Under the leading of the policy from government, this is a potential for Chinese water market.

Recommendation

Make detailed investigations to the hydrogeological conditions in Wuhu area to find and evaluate the potential location since this area is possible for applying RBF from national level evaluation. This also can help to build backup emergency water source using RBF with proper location and capacity at this moment.

5.5. Deyang Site — Conjunctive System

5.5.1. Introduction to Deyang project and main purpose

Basic circumstances

Deyang City is located in the Sichuan Basin in southwest of China. After the earthquake in 2008, the reconstruction is under an extremely high speed. Meanwhile the population is increasing sharply from current 800,000. In such case, the water supply cannot fit the huge population. The Mianyuan River flows across the city and separates the city into two parts.

Figure 5-22 River location of Deyang

The annual average temperature is 15-17℃ and the annual rainfall amount is 900-950 mm decreasing from northwest to southeast.

Deyang water supply condition

Three main water sources are used for Deyang City. One is the Mianyuan River and another is water diversion from Dujiangyan. Besides, groundwater is used to be the main water source. But since recently, the groundwater level declines rapidly because of overexploitation. Thus a channel is built for water diversion from Dujiangyan. In this case, the water received from the channel is less dependent by Deyang City itself since it is demonstrated to be one of the 'Quality-induced water shortage' cities. The water demand now is around 140,000 m3/d but by 2020, urban population is expected to be increased to 1,000,000 and the water demand will be doubled to be 235,000 m3/d.

Because of the potential of earthquake, groundwater is more available for safe water supply. Thus, two exist well fields are going to be maintained. Artificial recharge with unavoidable RBF is introduced to Deyang City to keep the groundwater level stable.

5.5.2. Deyang project plan

Conjunctive water supply system

Conjunctive water supply system is proposed in Deyang case. It consists of the following components.

a) Recharge water source
b) Sedimentation basins
c) Dosage pond for chemical treatment
d) Constructed wetlands
e) Infiltration basins
f) Abstraction wells
g) Monitoring wells

The combination of components is shown in the figure below.

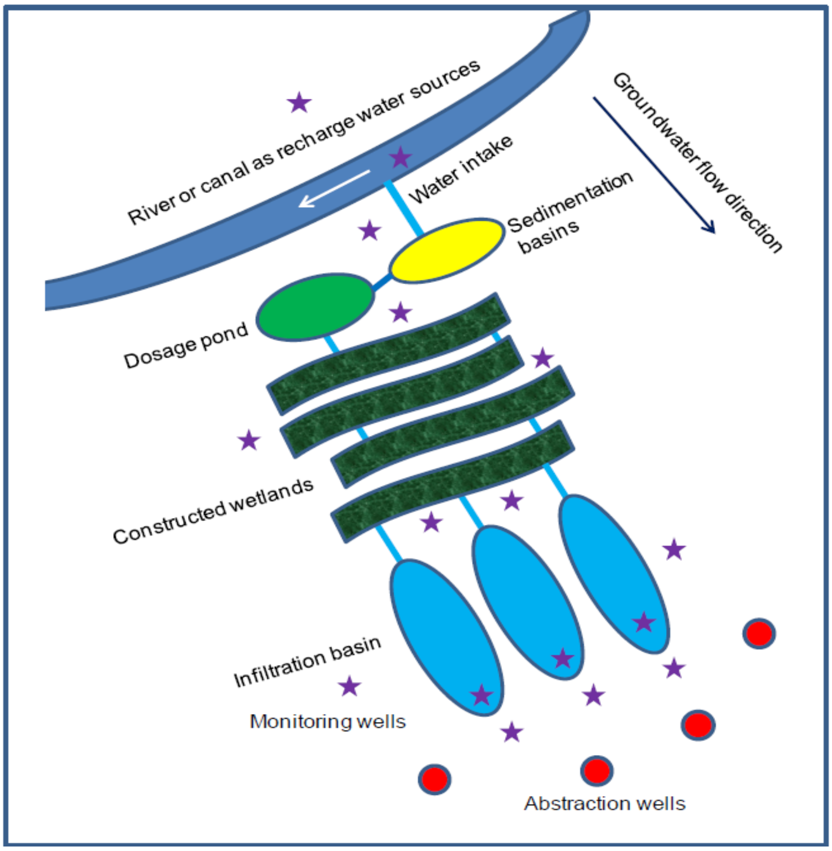


Figure 5-23 Conjunctive system in Deyang (Source: Zhou, 2013)

The main purposes of the successive water natural treatment processes are: 1) increase or recover the groundwater level as water bank, 2) support to water supply, 3) improving water quality through natural attenuation and removal of pathogen. At first, the source water is diverted into the sedimentation basin and then the nutrients and other chemicals are removed in construction wetlands. In the infiltration basin, the treated water is infiltrated into aquifer. In this process and also in the aquifer, the water is treated naturally as well. After sufficient retention, the water is abstracted again for drinking water production. At that time, the abstracted water is combined with filtrated water from the river (Zhou, 2013).

Pilot design in Deyang

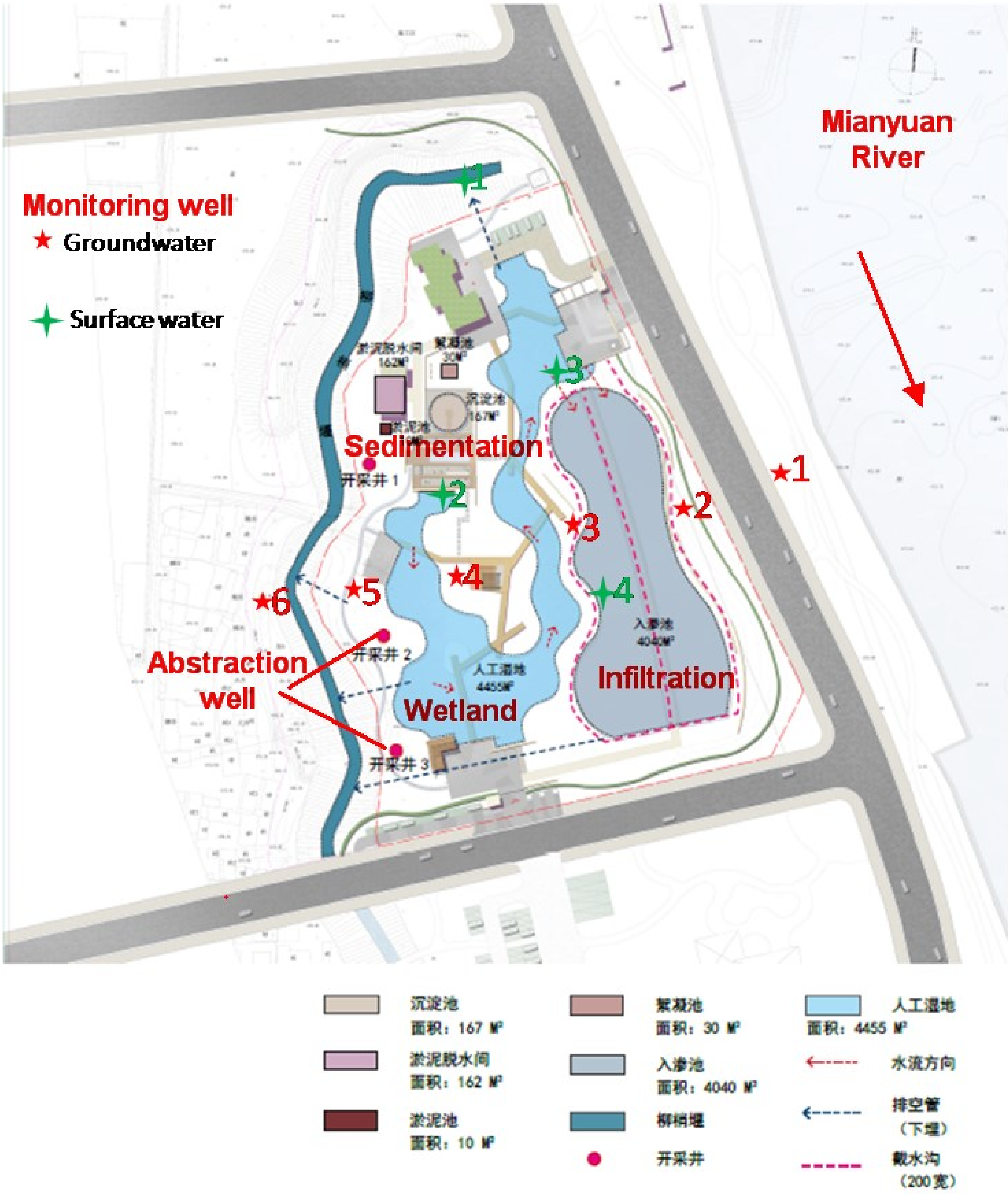


Figure 5-24 Pilot system sketch in Deyang

The pilot system is designed as a public natural park in 3 ha and on the river bank of Mianyuan River. For one ha land, the construction is for infiltration basin with capacity of

5,000 m3/d to recharge groundwater. One and half ha are constructed for wetland and the rest half ha land is for sedimentation basin. A well field will be located in this area for a capacity of 10,000 m3/d. Therefore, 50% of the abstracted water will be groundwater from local and RBF and 50% will be artificial recharge to guarantee the sustainable operation of the well field.

Expected results and up-scaling

The water quality for the Mianyuan River is sufficient for drinking water source in general but some items are beyond limitation for drinking water such as ammonia nitrogen, Fe, Mn, total N, total P and Bacteria. It is one typical type of polluted water in China which is called 'Quality-induced water shortage'. The expected water quality after abstraction is qualified to the standard for drinking water. Ammonia nitrogen and fecal contaminants are main issues to deal with. After the conjunctive system, the water quality is expected to fulfill Level III and release the pressure of post-treatment.

After experiment in pilot site, the first up-scaling is to build a full-scale system in Deyang City on a 50 ha land. Ten times of capacity is recommended to the full-scale site. The capacities are 50,000 m3/d for infiltration and 100,000 m3/d for abstraction. The share is still 50% and 50%. By then, the pilot and up-scaling systems will supply 45% of total domestic water demand of Deyang City in 2020 (Zhou, 2013).

5.5.3. Conclusions and recommendations

Conclusions

Strictly speaking, the Deyang site is not a case about RBF itself but it is an example to extend RBF development in China combined with artificial recharge and wetlands. To common problems like high ammonia nitrogen, wetland and RBF both have the capacity for removal. To cities like Deyang, the groundwater level is influenced by overexploitation, but surface water also faces pollution problems. Recently in China, many cities have chosen to build wetland near rivers to improve the water quality and to be public parks. And with the growing population, many cities also have to up-scale the water supply capacity. Conjunctive system is a new solution to provide safe and sustainable water supply.

Recommendations

Deyang site is still under construction and will be finished by the end of 2016. Further test and research are ongoing. At first, the efficiency of wetland which is a common issue for wetlands in China. And also the infiltration rate is another essential parameter in case it can meet the expected value. To analyze the effect of RBF or treatment by soil passage, the comparison between water quality before infiltration and after abstraction is also important. The use of computer model to analyze the groundwater changes and RBF share are included. During up-scaling, the experience from pilot is vital to full-scale and further to develop in the whole country.

5.6. Summary

Generally speaking, the results of investigations are satisfied although not all kinds of data and information could be collected. The influence factors are variable but finally the research questions can be answered.

Zhengzhou as a representative city in north of China where the water shortages are main problem is operating RBF for more than fifteen years and is still producing sufficient quality water for the city. Proper water source, soil passage and successful experience all indicate that RBF is effective to improve the water quality especially to turbidity, ammonia nitrogen and fecal contaminants. But due to the soil passage and combination of groundwater, the concentrations of iron and manganese not decreased too much and even sometimes increase. Monitoring of OMPs is usually absent. But meanwhile, problems are remaining in the operation and management like clogging of wells and depletion, possibly because of the design of the RBF system and the construction of wells. Outdated data and lack of information about peak situation are shortcomings in the evaluation.

Jiaxing as another representative 'Quality-induced water shortage' city and located in Taihu basin where water network is developed, but the hydrogeology condition is proven to be not suitable for RBF. MAR with deep well is an alternative solution in case the soil condition still present in deep ground. Otherwise, RBF coupled with long distance can be an option.

Wuhu is a representative city along the Yangtze River where plenty of surface water sources with satisfied quality and sufficient capacity make RBF no need to be developed in this area. Besides, according to the evaluation, the soil conditions are not suitable for Wuhu locally. If there are proper soil conditions nearby in Wuhu surroundings after detailed field investigation, the relative low operation and maintenance fee can become the main advantages for RBF to build as backup water source.

Deyang project has proposed a conjunctive system to apply natural water purification processes including wetland, artificial recharge and RBF. Using experience from Amsterdam, the conjunctive system may deal with polluted water source to produce cleaner drinking water for 'Quality-induced water shortage' cities

6

6. Conclusions and Recommendations

6.1. Conclusions for site evaluation approach

The main question *Will RBF help to water quality challenges in China?* can be answered now.

RBF can improve the source water quality in China. The major items controlled and monitored regularly in China now are TSS, nutrients, ions (including heavy metals), pesticides and fecal contaminants. Emerging items (e.g. EDCs, PhACS and DBPs) are more and more relevant with the development of economy and society. Meanwhile, conventional treatment processes are still applied to most of the plants aiming on removal of turbidity, color, suspended solids and bacteria. RBF not only has the function of conventional treatment but also other items can be tackled such as ammonia and emerging contaminants. Thus RBF can help to water quality challenges in China.
To apply RBF in China, a site evaluation approach was developed and tested on both national level and case studies. As discussed in section 4.3 and 5.2, the site evaluation approach can be used to evaluate candidate locations, although some modifications are still needed. For example, more proper criteria are needed on some items (e.g. ions and heavy metals) since not all the items in the criteria are suitable for China. A design model with rough cost estimates for RBF (and transport) systems has also been developed and can be used as first calculation to evaluate the feasibility of RBF in specific locations. The selection of factors such as the cost factor and other parameters needs more practical experience from China to make the model more accurate.

6.2. Conclusions for RBF in China

6.2.1. Meaning of RBF and future strategy

The development of a technique in China has to adapt to local conditions. Not only the objective facts, but also the way of doing things is important to follow. The situation is that the place of RBF is for all new-build plants, upscaling or reconstruction of plants and cities who have existing water supply infrastructure.

As the population is still growing and water quality is getting worse, RBF has large potential for China drinking water supply.
For sites that are currently using abstraction wells near the riverbank, the introduction of RBF can improve the performance of the current treatment, including the construction of well fields and also daily management when upscaling or reconstructing.

For cities where the surface water is polluted or frequently has shock loads, like 'Quality-reduced water shortage' cities, RBF can provide clean water source and resistance to shock loads.
For cities with stressful groundwater abstraction, RBF can relieve the depletion of groundwater to a certain degree.
As a pre-treatment, RBF can provide better water source, that will reduce the costs for post-treatment and give the potential for advanced treatment such as RO.
In addition, as a natural treatment technique, it is quite possible to combine RBF with other nature treatment such as wetlands and artificial recharge. Many cities now are constructing wetlands for water treatment or landscape which also can be an opportunity for RBF development.
To develop RBF in China especially in engineering applications, researchers and engineers who are experts on both theory and Chinese conditions are strongly needed. On the one side, the research about RBF is more than water quantity. More attention should be paid on the processes in soil passage and water quality variation in order to make RBF a sustainable technique for drinking water treatment than a way to obtain water. On the other side, besides theoretical research, the research findings can be used in engineering applications from pilot to full-scale. The combination of research and engineering should be more compact to ensure that the research is supporting the implementation of RBF in China.

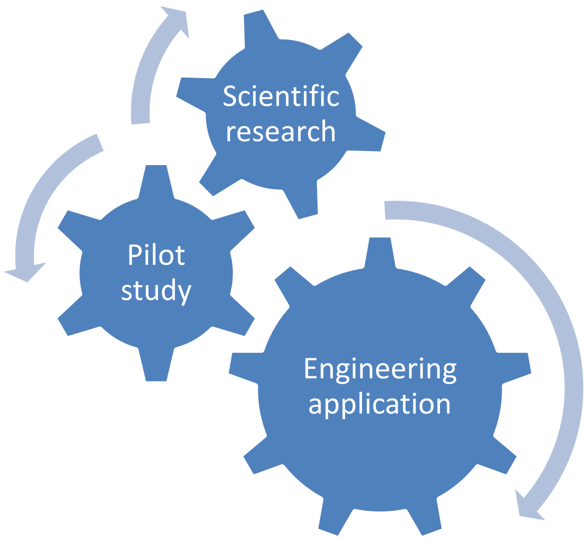


Figure 6-1 Combination of scientific research and engineering application

6.2.2. Difficulties for RBF in China

Still several difficulties remain when introducing RBF technique.
The most challenging and troublesome issue for site evaluation is data collection. During information and data collection, the data on peak situations is difficult to find as well as full seasonal and annual data. Although some of the data are now available to access, more effort is still needed on data collection. To solve this problem, improvement is needed on monitoring, statistics and documentation. For this, leadership of high-hierarchy

government and department is essential to make data collection more efficient.

Because of the feature of RBF that the design of RBF strongly depends on the actual situation of each site, detailed field investigation, pilot experiment, and trail operation are important to the performance of RBF and also are requiring long term preparation. It can be a difficulty since the project period is relatively shorter in China than in the Netherlands.

6.3. Recommendations

- Introduce RBF as an entire, scientific, systematic technique rather than a method only for obtaining source water.
- Research about RBF should focus more on its mechanisms in soil passage and pay more attention on water quality improvement processes.
- Relevant authorities from a high hierarchy should be involved to give more power on data and information collection for its comprehensiveness.
- The hydrogeological conditions are the most vital among all the criteria, therefore, careful and precise field investigations and data collection are extremely important to decide design parameters thus an effective RBF site.
- Advanced experience should be introduced to improve the design and performance of RBF sites.
- Compact interaction between the scientific research and engineering application.

6.4. Shortcomings Discussion

Shortcomings are pointed out for further research to be improved.

- Not enough specified literature reviews. For example, on soil condition aspects, the performance of different types of soil materials in RBF such as sand, gravel, clay and limestone (karst). Regarding water quality, studies on removal of OMPs and emerging contaminants should be enhanced with more and more attention paid to this topic in China.
- Costs estimation in China should be closely combined with Chinese conditions and specified cost estimations based on operating candidates in China should be done for future research.
- Outdated data for some sites especially on hydrogeology. The main information is from 1980 to 2000. This may influence the results. China Hydrogeological Map Atlas pressed by Chinese Academic of Geology Sciences in 1979 is used widely since it is the only public version. National Geological Archives of China (NGAC) established a Digital Library of NGAC recently (http://en.ngac.org.cn/) but the availability and utility of this system needs improvement. Similarly, several servers need certification to login which in reality is hard to achieve.
- Incomplete water quality data. In Zhengzhou site, the weekly, monthly or annual water quality data is relatively hard to collect compared to one day data in the regular situation. The monitoring items in Zhengzhou are regular and also simple. Comparatively speaking, situation in Jiaxing and Wuhu is superior to Zhengzhou about both variety of items and long term data.

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Appendices

A.1 Standard for Surface Water Environment Quality GB3838-2002

List 1 Standard Limit Values of Basic Items of Surface Water Environmental Quality Standard

Unit: mg/L

No.	Standard values Classifications Items	Classification I	Classification II	Classification III	Classification IV	Classification V
1	Water temperature (℃)	Range of water temperature change caused by artificial reasons: Average maximum temperature rise each week ≤1 Average maximum temperature drop each week≤2				
2	PH values (without dimensions)	6-9				
3	Dissolved oxygen ≥	Saturation factor 90% (or 7.5)	6	5	3	2
4	Hypermanganate index ≤	2	4	6	10	15
5	COD ≤	15	15	20	30	40
6	BOD5 ≤	3	3	4	6	10
7	NH3-N ≤	0.15	0.5	1.0	1.5	2.0
8	Total phosphorus (as measured by P)	0.02 (Lakes natural or man-made 0.01)	0.1 (Lakes natural or man-made 0.025)	0.2 (Lakes natural or man-made 0.05)	0.3 (Lakes natural or man-made 0.1)	0.4 (Lakes natural or man-made 0.2)
9	Total nitrogen (as measured by N) ≤	0.2	0.5	1.0	1.5	2.0
10	铜 Cu ≤	0.01	1.0	1.0	1.0	1.0
11	锌 Zn ≤	0.05	1.0	1.0	2.0	2.0
12	Fluoride (as measured by F⁻) ≤	1.0	1.0	1.0	1.5	1.5
13	Se ≤	0.01	0.01	0.01	0.02	0.02
14	As ≤	0.05	0.05	0.05	0.1	0.1
15	Hg ≤	0.00005	0.00005	0.0001	0.001	0.001
16	Cd ≤	0.001	0.005	0.005	0.005	0.01
17	Hexavalent chrome ≤	0.01	0.05	0.05	0.05	0.1
18	Pb ≤	0.01	0.01	0.05	0.05	0.1
19	Cyanide ≤	0.005	0.05	0.2	0.2	0.2
20	Volatile hydroxybenzene ≤	0.002	0.002	0.005	0.01	0.1
21	Petroleum ≤	0.05	0.05	0.05	0.5	1.0
22	Anionic surface-active agent ≤	0.2	0.2	0.2	0.3	0.3
23	Sulfide ≤	0.05	0.1	0.05	0.5	1.0
24	Coliform group (pieces/L) ≤	200	2000	10000	20000	40000

List 2 Standard Limit Values of Supplementary Items of Surface Water Resource for Concentrated Drinking Water Supply

Unit: mg/L

No.	Items	Standard Values
1	Vitriol (As measured by $SO4^{2-}$)	250
2	Chloride (As measured by Cl^{-})	250
3	Nitrate (As measured by N)	10
4	Fe	0.3
5	Mn	0.1

List 3 Standard Limit Values of Specified Items of Surface Water Resource for Concentrated Drinking Water Supply

Unit: mg/L

No.	Items	Standard Values	No.	Items	Standard Values
1	Chloroform	0.06	41	Acrylamide	0.0005
2	Carbon tetrachloride	0.002	42	Acrylonitrile	0.1
3	Bromoform	0.1	43	Dibutyl phthalate	0.003
4	Methylene chloride	0.02	44	2-ethyl-hexyl ester phthalate	0.008
5	1,2- ethylene dichloride	0.03	45	Hydrazine hydrate	0.01
6	Epichlorohydrin	0.02	46	Tetra-ethyl lead	0.0001
7	Vinyl chloride	0.005	47	Pyridine	0.2
8	1,1- ethylene bichloride	0.03	48	Turpentine	0.2
9	1,2- ethylene bichloride	0.05	49	Picramic acid	0.5
10	Trichloroethylene	0.07	50	Butyl xanthic acid	0.005
11	Tetrachloroethylene	0.04	51	Active chlorine	0.01
12	Chlorbutadiene	0.002	52	D. D. T.	0.001
13	Hexachlorobutadiene	0.0006	53	Lindane	0.002
14	Styrene	0.02	54	Heptachlor eqoxide	0.0002
15	Formaldehyde	0.9	55	Parathion	0.003
16	Acetaldehyde	0.05	56	Methylic parathion	0.002
17	Acrolein	0.1	57	Malathion	0.05
18	Chloral	0.01	58	Rogor	0.08
19	Benzene	0.01	59	Dichlorvos	0.05
20	Toluene	0.7	60	Trichlorfon	0.05
21	Ethylbenzene	0.3	61	Demeton	0.03
22	Dimethylbenzene ①	0.5	62	Chlorthalonil	0.01
23	Cumene	0.25	63	Carbaryl	0.05
24	Chlorobenzene	0.3	64	Cypermethrin	0.02
25	1,2- dichlorobenzene	1.0	65	Fenamine	0.003
26	1,4- dichlorobenzene	0.3	66	Benzopyrene (a)	$2.8*10^{-6}$
27	Trichlorobenzene ②	0.02	67	Methyl mercury	$1.0*10^{-6}$
28	Tetrachlorobenzene ③	0.02	68	Polychlorinated biphenyl ⑥	$2.0*10^{-5}$
29	Hexachlorobenzene	0.05	69	Microcystin -LR	0.001
30	Nitrobenzene	0.017	70	Yellow phosphorus	0.003
31	Dinitrobenzene ④	0.5	71	Molybdenum	0.07
32	2,4- dinitrotoluene	0.0003	72	Cobalt	1.0
33	2,4, 6- trinitrotoluene	0.5	73	Beryllium	0.002
34	Nitro chlorobenzene ⑤	0.05	74	Boron	0.5
35	2,4- dinitro chloro benzene	0.5	75	Antimony	0.005
36	2,4- dichlorophenol	0.093	76	Nickel	0.02
37	2,4,6- trichlorophenol	0.2	77	Barium	0.7
38	Sodium pentachlorophenate	0.009	78	Vanadium	0.05
39	Anilin	0.1	79	Titanium	0.1
40	Benzidine	0.0002	80	Thallium	0.0001

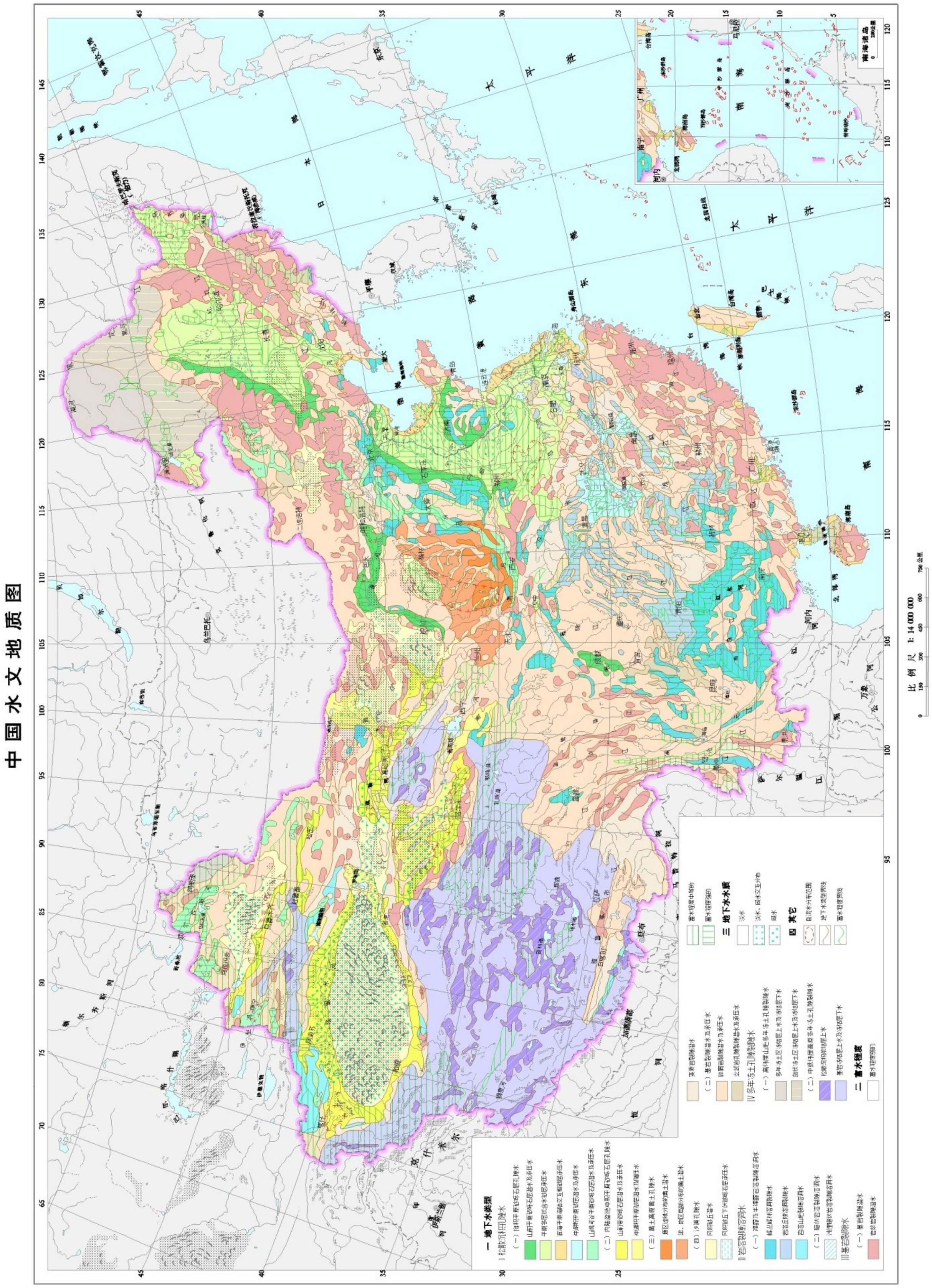
Note: ① Xylene: Including para xylene, meta xylene, and ortho xylene
② Trichlorobenzene: Including 1,2,3- trichlorobenzene, 1,2,4- trichlorobenzene , 1,3,5- trichlorobenzene
③ Tetrachlorobenzene: Including 1,2,3,4- tetrachlorobenzene, 1,2,3,5- tetrachlorobenzene, and 1,2,4,5-tetrachlorobenzene
④ Dinitrobenzene: Including para dinitrobenzene, meta nitro chlorobenzene, and ortho nitro chlorobenzene
⑤ Polychlorinated biphenyl: Including PCB-1016, PCB-1221, PCB-1232, PCB-1242, PCB-1248, PCB-1254, and PCB-1260

A.2 Standard for Groundwater Quality GB14848-93

No.	Item Standard value	Level Ⅰ	Level Ⅱ	Level Ⅲ	Level Ⅳ	Level Ⅴ
1	Chroma (degree)	≤5	≤5	≤15	≤25	>25
2	Odor and Taste	No	No	No	No	Yes
3	Turbidity (JTU)	≤3	≤3	≤3	≤10	>10
4	Visible Material	No	No	No	No	Yes
5	pH		6.5～8.5		5.5～6.5 8.5～9	<5.5，>9
6	TH (CaCO3) (mg/L)	≤150	≤300	≤450	≤550	>550
7	TDS (mg/L)	≤300	≤500	≤1000	≤2000	>2000
8	Sulfate (mg/L)	≤50	≤150	≤250	≤350	>350
9	Chloride (mg/L)	≤50	≤150	≤250	≤350	>350
10	Fe (mg/L)	≤0.1	≤0.2	≤0.3	≤1.5	>1.5
11	Mn (mg/L)	≤0.05	≤0.05	≤0.1	≤1.0	>1.0
12	Cu (mg/L)	≤0.01	≤0.05	≤1.0	≤1.5	>1.5
13	Zn (mg/L)	≤0.05	≤0.5	≤1.0	≤5.0	>5.0
14	Mo (mg/L)	≤0.001	≤0.01	≤0.1	≤0.5	>0.5
15	Co (mg/L)	≤0.005	≤0.05	≤0.05	≤1.0	>1.0
16	Volatile phenol (Phenol) (mg/L)	≤0.001	≤0.001	≤0.002	≤0.01	>0.01
17	Anion synthetic detergent (mg/L)	No	≤0.1	≤0.3	≤0.3	>0.3
18	Permanganate index (mg/L)	≤1.0	≤2.0	≤3.0	≤10	>10
19	Nitrate (N)(mg/L)	≤2.0	≤5.0	≤20	≤30	>30
20	Nitrite (N)(mg/L)	≤0.001	≤0.01	≤0.02	≤0.1	>0.1
21	Ammonia nitrogen (NH4) (mg/L)	≤0.02	≤0.02	≤0.2	≤0.5	>0.5
22	Fluoride (mg/L)	≤1.0	≤1.0	≤1.0	≤2.0	>2.0
23	Iodide (mg/L)	≤0.1	≤0.1	≤0.2	≤1.0	>1.0

24	Cyanide (mg/L)	≤0.001	≤0.01	≤0.05	≤0.1	>0.1
25	Hg (mg/L)	≤0.00005	≤0.0005	≤0.001	≤0.001	>0.001
26	As (mg/L)	≤0.005	≤0.01	≤0.05	≤0.05	>0.05
27	Se (mg/L)	≤0.01	≤0.01	≤0.01	≤0.1	>0.1
28	Cd (mg/L)	≤0.0001	≤0.001	≤0.01	≤0.01	>0.01
29	$Cr6^{+}$(mg/L)	≤0.005	≤0.01	≤0.05	≤0.1	>0.1
30	Pb (mg/L)	≤0.005	≤0.01	≤0.05	≤0.1	>0.1
31	Be (mg/L)	≤0.00002	≤0.0001	≤0.0002	≤0.001	>0.001
32	Ba (mg/L)	≤0.01	≤0.1	≤1.0	≤4.0	>4.0
33	Ni (mg/L)	≤0.005	≤0.05	≤0.05	≤0.1	>0.1
34	DDD (μg/L)	No	≤0.005	≤1.0	≤1.0	>1.0
35	BHC (μg/L)	≤0.005	≤0.05	≤5.0	≤5.0	>5.0
36	Total coliform group (1/L)	≤3.0	≤3.0	≤3.0	≤100	>100
37	Total bacteria count (1/L)	≤100	≤100	≤100	≤1000	>1000
38	Total radioactivity σ (Bq/L)	≤0.1	≤0.1	≤0.1	>0.1	>0.1
39	Total radioactivity β (Bq/L)	≤0.1	≤1.0	≤1.0	>1.0	>1.0

B China Hydrogeological Map (Chinese version)



C.1 Well Test Results of Zhengzhou Site

Weel test results
Aquifer

Materials Start level (m)Thickness (m)Total thickness (m)

北郊水源地测井资料计算部分钻孔参数一览表 表4—6—7

Gravel medium/coarse sand
Fine sand

Medium sand
Coarse/medium sand

Medium/fine sand

Medium/coarse sand
Fine/medium sand

孔号	含水层						备注
	岩性	层顶底板埋深(m)	层厚(m)	K(m/d)	总厚度	T(m²/d)	
TG—1	含砾中粗砂	16.2—25.2	9.0	22.9	41.8	1008	凌庄滩地
	细砂	25.2—28.2	3.0	15.0			
	含砾中粗砂	28.2—58.2	29.8	25.4			
TG—5	含砾中粗砂	13.6—39.8	26.2	39.3	35.0	1212	花园口京水
	中砂	45.0—53.8	8.8	20.7			
TG—2	粗中砂	14.4—45.6	31.2	25.1	51.4	1211	花园口石桥村
	粗中砂	49.8—64	14.2	24.1			
	中细砂	65.8—71.8	6.0	14.3			
TG—7	中细砂	14.8—46.4	31.6	25.1	41.4	1142	姚桥乡黄岗庙
	含砾中粗砂	50.8—60.6	9.8	35.6			
T—11	含砾中粗砂	20.0—43.0	23.0	33.9	36.4	1069	省民政学校
	中砂	46.2—59.6	13.4	21.6			
ZS—1	中砂	8.0—37.2	29.2	18.2	29.2	531	花园口京洼村
ZS—2	中砂	13.3—17.2	3.9	20.9	19.8	552	姚桥乡花沟王
	中粗砂	18.3—29.0	10.7	35.6			
	细中砂	30.6—35.8	5.2	17.2			
ZS—3	中细砂	10.9—25.0	14.1	6.7	52.4	685	姚桥乡小贺庄
	中砂	25.0—43.7	18.7	21.9			
	细砂	46.4—50.8	4.4	6.9			
	中砂	50.8—57.8	7.0	14.6			
	细砂	57.8—66.0	8.2	5.9			
ZS—4	中细砂	8.3—32.0	23.7	16.0	51.2	835	中牟、刘集、关帝庙
	中粗砂	33.0—47.0	14.0	22.3			
	细粉砂	49.1—52.6	3.5	2.3			
	中细砂	52.6—62.6	10.0	13.6			
ZC—5	中砂	11.8—34.0	22.2	18.2	39.1	600	刘集大吴
	细砂	38.8—55.7	16.9	11.6			
ZD—5	中砂	18.6—50.2	31.6	22.4	45.4	1044	来潼寨滩地
	细中砂	53.4—59.0	5.6	17.6			
	含砾中粗砂	60.6—68.8	8.2	29.0			
ZG—3	粗中砂	21.2—71.0	49.8	25.3	49.8	1260	来潼寨滩地

C.2 Field Investigation for Beijiao Water Source Area, Surface Water Quality

Surface Water Quality

the Yellow River (13 samples)

Range Average Unit

Total hardness, Free CO2, Soluble SiO2, COD, Minoralization, Sand content, Oxidate, Phenol

地表河渠水化学成份统计表 表 7—1—3 单位:mg/1

项目	黄河(12 个样)		贾鲁河(5 个样)		索须河(2 个样)		东风渠(3 个样)		石沟(2 个样)		魏河
	范围值	平均值	范围值	平均值							
K^+	3.17—5.0	3.94	12—30.8	16.56	4.35—9.65	7.0	4.36—8.5	7.02	5.36—3.68	4.52	20.0
Na^+	57.0—95.0	79.6	142.0—230.0	184.6	58.75—98.5	78.63	97.5—110.0	103.17	94.5—98.5	96.5	243.0
Ca^{2+}	43.49—64.33	54.78	63.33—152.5	96.23	60.52—91.78	79.51	60.72—75.75	68.67	68.74—63.33	66.04	95.99
Mg^{2+}	20.19—31.13	23.87	28.09—34.26	31.2	26.39—33.44	29.92	27.36—33.32	30.63	40.74—31.74	36.24	27.58
Fe^{3+}	0 未—0.04		〈0.01—0.26	0.09	未—0.02		未		0.02		
Fe^{2+}	未—0.04		〈0.002—0.04	0.014	未—0.028		〈0.02—0.024		〈0.02—0.048		0.016
Al^{3+}	〈0.01		〈0.01				〈0.01				0.01
NH_4^+	0.04—1.36	0.21	1.0—50.0	21.56	0.08—31.0	15.54	0.06—50.0	22.53	未—0.07		80.0
Cl^-	52.82—99.26	79.08	146.41—376.12	239.07	51.76—93.94	72.85	96.07—151.78	117.93	70.19—93.94	82.07	279.35
SO_4^{2-}	84.05—185.88	133612	9.6—86.93	56.87	157.54—194.52	176.03	62.92—153.70	107.27	57.16—172.91	115.04	121.04
HCO_3^-	173.3—246.52	192.77	366.12—671.22	534.54	237.37—350.86	294.12	244.69—475.96	363.48	201.37—485.11	343.24	686.48
CO_3^{2-}	0.0	0.0	0.0	0.0	0.0—3.0	1.5	0.0		0.0—6.0	3.0	0.0
NO_3^-	2—16.45	9.82	〈0.01—20.62	4.25	8.0—37.01	22651	0.2—37.84	15.35	0.7—7.18	3.94	1.6
NO_2^-	未—0.060		〈0.002—0.004	0.0024	0.0028—0.73	0.37	未—1.6		〈0.002—0.012		〈0.002
F^-	0.6—1.02	0.76	0.2—0.9	0.64	0.8—0.8	0.8	0.6—0.8	0.71	0.42—0.80	0.61	0.6
Br^-	〈0.02—0.12		〈0.002								
I^-	〈0.01—〈0.05		〈0.01—0.05								
PO_4^{3-}	未—0.20	0.044			未—0.32		未—3.8		未—0.02		
总硬度	193.5—288.49	243.4	273.5—521.5	367.7	288.73—337.53		286.39—317.54	297.54	339.58—288.73	314.16	353.0
游离 CO_2	1.99—7.95	4.31	7.95—256.33	94.98			63.59				180.82
可溶性 SiO_2	6.0—14.0	8.29	10.0—38.0	22.2	3.0—18.0		3.0—20.0	13.0	6.0—12.0	9.0	18.0
耗氧量	1.36—4.49	2.79	9.4—101.5	49.16	3.51—5.55		3.67—3561	20.46	2645—4.93	3.69	97.6
PH	7.3—7.85	7.57	6.85	7.17	7.2—7.7	7.45	7.1—7.3	7.22	7.3—7.8	7.55	7.2
矿化度	379.35—578.83	493.78	656.05—1206.33	940.62	496.19—581.86	539.03	579.9—749.04	669.84	584.88—592.11	588.5	1230.44
含砂量	0.396—25.7	12.26	0.041								
氧化物	0.003—0.004	0.0035									
酚	0.005—0.006	0.0055									
Hg^{2+}	0.0001—0.0002	0.00015									
Mn^{2+}	1.0—1.16	1.08									
Cr^{3+}	〈0.002		〈0.002								
Se^{4+}	0.004										
Cd^{2+}	〈0.001										
Cu^{2+}	〈0.001—0.001										
Pb^{2+}	〈0.001										
Zn^{2+}	〈0.005—0.009										
As^{3+}	0.009—0.017										

C.3 Water Quality Report of Government Office of the Yellow River

续附表1　黄河流域省界水体及重点河段水质状况一览表

序号	河名	站名	断面位置	流量 (m³/s)	本月水质 1)	上月水质 1)	与上月相比较	水质目标 2)	超标项目	备注
33	黄河	三门峡公路桥	河南省三门峡市		Ⅲ	Ⅲ	→	Ⅲ		三门峡市水源地
34	黄河	三门峡	河南省三门峡市	760	Ⅲ	Ⅲ	→	Ⅲ		
35	黄河	南村	河南省渑池县		Ⅱ	Ⅱ	→	Ⅲ		山西 河南 →河南省界
36	黄河	沙沃	河南省济源市		Ⅱ	Ⅱ	→	Ⅲ		
3[illegible]	[illegible]	[illegible]浪底	[illegible]	32[illegible]	[illegible]	Ⅱ	→	Ⅲ		
38	黄河	花园口	河南省郑州市	308	Ⅱ	Ⅱ	→	Ⅲ	铁	郑州市水源地
39	黄[illegible]	[illegible]	[illegible]省开封市	[illegible]	[illegible]	[illegible]	[illegible]	Ⅲ	铁	[illegible]
40	黄河	高村	山东省东明县	307	Ⅱ	Ⅱ	→	Ⅲ		河南→山东省界 濮阳市水源地
41	黄河	孙口	山东省梁山县	314	Ⅱ	Ⅱ	→	Ⅲ		河南 山东 →山东省界
42	黄河	艾山	山东省东阿县	288	Ⅱ	Ⅱ	→	Ⅲ		
43	黄河	泺口	山东省济南市	253	Ⅱ	Ⅱ	→	Ⅲ		济南市水源地
44	黄河	滨州	山东省滨州市		Ⅲ	Ⅱ	↓	Ⅲ		滨州市水源地
45	黄河	利津	山东省利津县	174	Ⅱ	Ⅱ	→	Ⅲ		干流入海把口站 东营市水源地
46	白河	唐克	四川省若尔盖县					Ⅲ		四川入黄省界
47	黑河	大水	甘肃省玛曲县					Ⅲ		四川→甘肃省界
48	大夏河	折桥	甘肃省临夏县	12.4	Ⅳ	Ⅲ	↓	Ⅲ	氨氮	
49	洮河	红旗	甘肃省临洮县	67.9	Ⅲ	Ⅳ	↑	Ⅲ		

the Yellow River
in Zhengzhou
Water quality this month
Exceed standard: Fe
Huayuankou station
Flow m3/s
Water quality last month
Drinking water source for Zhengzhou

C.4 Real Time Monitoring Data of Shiyuan Treatment Plant

Water Quality Analysis Report

Unit Standard Intake After
GB3838-2002 Sedimentation

郑州市自来水总公司柿园水厂水质分析报表

2012年 4月 16日　　取水时间： 4·11　　郑水统字技术06表

	类别	项目	单位	地面水二类水体质量标准	黄河进口	邙山沉沙池	东站出口	暗渠进口			
Turbidity	物理检验	浑浊度	NTU		114	8.31	13.4	10.6			
Temperature		温度	℃		10.9	13℃	12.3	13			
Chroma		色度	度		15(高)	15	15	15			
		嗅和味			土霉3	土霉3藻腥2	土霉3藻腥2	土霉3藻腥2			
		肉眼可见物									
	化学检验	pH值		6.5~8.5	8.17	8.20	8.18	8.21			
E-conductivity		电导率	us/cm		1034	1009	1008	1016			
		UV_{254}			0.028	0.023	0.031	0.025			
Alkalinity		总碱度	mg/L		204.3	201.8	206.8	196.7			
Chloride		氯化物	mg/L	≤250	107.9	104.0	106.1	101.6			
Total hardness		总硬度	mg/L		290.4	231.5	319.8	312.0			
		钙	mg/L								
		镁	mg/L								
Total Fe		总铁	mg/L	≤0.3	1.66	0.23	0.25	0.25			
Aluminum		铝	mg/L		0.058	0.017	0.022	0.020			
Ammonia nitrogen		氨氮	mg/L	≤0.5	1.18	0.75	0.84	0.65			
Nitrite nitrogen		亚硝酸盐氮	mg/L	≤0.1	0.057	0.059	0.065	0.067			
Nitrate nitrogen		硝酸盐氮	mg/L	≤10	3.33	2.87	3.25	3.21			
		COD_{Mn}	mg/L	≤4	3.02	3.10	3.02	3.18			
		COD_{Cr}	mg/L								
		BOD_5	mg/L								
Mn		锰	mg/L	≤0.1	0.47	0.09	0.09	0.12			
		余氯	mg/L								
		氟化物	mg/L	≤1.0							
		六价铬	mg/L	≤0.05							
		氰化物	mg/L	≤0.05							
		酚	mg/L	≤0.002							
		~~砷~~ 嗅阈值	~~mg/L~~	~~≤0.05~~	12.9	13.8	13.8	13.8			
DO		溶解氧	mg/L	≥6	9.88	11.1	10.3	10.3			
Sulfate		硫酸盐	mg/L	≤250	163.1	167.8	172.1	169.8			
Total phosphorus		总磷	mg/L	≤0.1	0.07	0.04	0.04	<0.04			
Alga 10^4/L	微生物检验	藻类	万个/L		74	164	76	95			
E-Coli		总大肠菌群	MPN/100mL	≤10000	2300	230	230	230			
Hear resistant E-Coli		粪大肠菌群	CFU/100mL		200	50	190	168			
Bacteria		细菌总数	CFU/mL		650	250	720	760			

主任： 郭海燕　　制表： 王燕娟　　审核： 安文

C.5 Shallow Groundwater Chemical Components Analysis in Zhengzhou

Shallow Groundwater Chemical Components Analysis

浅层地下水化学成分统计表　单位 mg/l　表 7—1—1

Items 项目	Range 范围值	Average 平均值	Items 项目	Range 范围值	Average 平均值
K^+	0.5—4.3	2.32	Hg^{2+}	<0.001—0.0003	
Na^+	40.3—115.4	55.3	Mn^{2+}	<0.01—0.14	
Ca^{2+}	45.1—181.6	110.9	Cr^{6+}	<0.001—<0.002	
Mg^{2+}	13.7—64.4	32.7	Se^{4+}	<0.0001	
Fe^{3+}	0.02—1.04	0.30	Cd^{2+}	<0.001	
Fe^{2+}	<0.002—0.12		Cu^{2+}	<0.001	
Al^{3+}	<0.01		Pb^{2+}	<0.001—0.001	
NH_4^+	<0.01—0.8	0.17	Zn^{2+}	0.022—0.059	0.034
Cl^-	12.8—199.9	73.3	As^{3+}	<0.002—0.017	
SO_4^{2-}	1.9—173.9	64.02	Mo^{5+}	0.006—0.007	0.0065
HCO_3^-	166.6—705.4	486.7	Co^{2+}	<0.001	
NO_3^-	<0.01—13.03	2.44	Sr^{2+}	0.64—0.77	0.71
NO_2^-	未—0.008		Li^+	0.01—0.007	0.0085
F^-	0.26—1.10	0.62	B_a^{2+}	0.3—<1.0	
Br^-	<0.01—0.08		Ag^+	<0.001	
I^-	<0.01—0.1		H_2SiO_3	18.2	
PO_4^{3-}	0.08—0.28	0.14	Soluable SO2 可溶性 SiO_2	13.0—22.0	16.43
HBO_2	0.26		Cyanide 氰化物	<0.001—0.005	
Total hardness 总硬度	169.2—615.0	413.9	Phenol 酚	<0.002	
Free CO2 游离 CO_2	6.95—29.81	19.8	总 α(Bq/l	0.11—0.19	0.15
COD 耗氧量	0.36—2.77	1.01	总 β(Bq/l	0.076—0.086	0.081
Sand content 含砂量 kg/m^3	0—0.41	226 Ra (Bq/l)	0.0064—0.0082	0.0073	
Total bacteria 细菌总数 个/ml	<1—17	PH 值	7.0—7.8	7.38	
E-Coli 大肠杆菌 个/l	<3	矿化度	282.5—959.0	596.7	

C.6 Medium-deep Groundwater Chemical Components Analysis in Zhengzhou

Medium-deep groundwater chemical components analysis

Items | Wells | Items | Wells

中深层地下水化学成分统计表　　　表 7—1—4　单位 mg/l

项　目	Ti5	TG4	TG8	项　目	TG5	TG4	TG8
K^+	2.25	7.0	0.7	Hg^{2+}		<0.0001	<0.0001
Na^+	75.0	155.0	125.0	Mn^{2+}		0.01	0.04
Ca^{2+}	60.52	70.94	53.71	Cr^{6+}		<0.001	<0.001
Mg^{2+}	25.66	56.66	56.06	Se^{4+}		<0.0001	0.0001
Fe^{3+}	0.16	0.6	6.32	Cd^{2+}		<0.001	<0.001
Fe^{2+}	0.04	<0.002	<0.002	Cu^{2+}		<0.001	<0.001
Al^{3+}		<0.01	<0.01	Pb^{2+}		<0.01	0.01
NH_4^+	0.2	<0.01	<0.01	Zn^{2+}		0.013	0.035
Cl^-	18.08	76.57	130.10	As^{3+}		<0.002	<0.002
SO_4^{2-}	25.94	278.57	187.32	Mo^{5+}		0.002	0.005
HCO_3^-	461.92	472.9	335.61	Co^{2+}		<0.001	<0.001
NO_3^-	2.80	<0.01	0.40	Sr^{2+}		1.3	1.4
NO_2^-	0.008	<0.002	0.048	Li^+		0.04	0.041
F^-	0.60	0.76	0.60	Ag^+		<0.001	
Br^-		0.08	0.28	H_2SiO_3		32.5	
I^-		<0.01	<0.01	可溶性 SiO_2 (Soluable SiO2)	20.0		12.0
PO_4^{3-}	0.08			氰化物 (Cyanide)		<0.001	0.002
HBO_2		0.29	0.23	酚 (Phenol)		<0.002	0.002
(Total hardness) 总硬度	256.39	410.0	364.5	总 α(Bq/l)		0.36	
(Free CO2) 游离 CO_2		25.71	15.9	总 β(Bq/l)		0.088	
(COD) 耗氧量	0.23	0.12	0.35	^{226}Ra(Bq/l)		0.0047	
PH 值	7.3	7.25	7.35	含砂量 Kg/m^3 (Sand content)		0.002	
(Mineralization) 矿化度	462.29	1144.1	734.7				

C.7 Filtrated Water Source and Production Water Quality Analysis in Zhengzhou

Process Quality Control Analysis Report

Source water　After filtration　Production

East aeration　West aeration

郑州自来水投资控股有限公司水质监测中心　东周水厂　化验室

工艺质量控制点分析报表

2016 年　1 月 19 日　　星期　二　　郑水统字水质02表

	项目 \ 类别			原水 东曝气池 (East aeration)	原水 西曝气池 (West aeration)	滤后水 (After filtration)	出厂水 (Production)
Turbidity	浑浊度(NTU)	9:00		2.58	2.82	0.11	0.07
		15:00		1.62	1.31	/	0.08
Chroma	色 度（色）	9:00		<5	<5	<5	<5
Oder and Smell	臭和味（嗅和味）	9:00		无	无	无	无
Visible substances	肉眼可见物	9:00		微粒悬浮物	微粒悬浮物	无	无
Temperature	水　温(℃)	9:00		16	16	/	16
	pH	9:00		7.66	7.69	7.68	7.60
Ammonia nitrogen	氨氮(以N计)　(mg/L)	9:00		0.04	0.07	<0.02	<0.02
CODMn	耗氧量(高锰酸盐指数)(mg/L)	9:00		1.45	1.37	1.17	1.01
Fe	铁(mg/L)	9:00		0.67	0.76	<0.05	<0.05
Mn	锰(mg/L)	9:00		0.21	0.19	<0.05	<0.05
Residual Chlorine	余　氯　(mg/L)	9:00	立即	/	/	/	0.40
			10分钟	/	/	/	0.40
		15:00	立即	/	/	/	0.40
			10分钟	/	/	/	0.40
Total bacteria court	菌落总数（CFU/mL）	9:00		0	0	/	0
Total E-coli	总大肠菌群（CFU/100mL）	9:00		未检出	未检出	/	未检出
Heat resistant E-coli	耐热大肠菌群（CFU/100mL）	9:00		未检出	未检出	/	未检出
	备注			· No detected			

制表：白雪　　　　审核：佛建莉

D.1 Removal Efficiency of Wetland in Jiaxing

	项目	数值	水样名称 (Name)	平均值 (mg/L) (Average)	平均去除率 (Removal efficiency)	均值所属类别(参考 GB383 -2002 地表水限值) (Standard)
Turbidity	浊度 (NTU)	运行至今 Since beginning	进水 In	31.9	10.0%	参考指标
			出水Out	25.6		
		2014 年 1-2 月	进水	23.7	32.6%	
			出水	14.7		
		2015 年 1-2 月	进水	29.6	13.4%	
			出水	24.3		
Ammonia nitrogen	氨氮 (mg/L)	运行至今	进水	1.49	45.4%	Ⅳ类 Level IV
			出水	0.89		Ⅲ类
		2014 年 1-2 月	进水	2.71	26.3%	劣Ⅴ类 Less Level V
			出水	1.99		Ⅴ类
		2015 年 1-2 月	进水	2.83	13.8%	劣Ⅴ类
			出水	2.25		劣Ⅴ类
COD	耗氧量 (mg/L)	运行至今	进水	6.40	8.6%	Ⅳ类
			出水	5.81		Ⅲ类
		2014 年 1-2 月	进水	6.69	9.5%	Ⅳ类
			出水	6.00		Ⅲ类
		2015 年 1-2 月	进水	5.71	3.9%	Ⅲ类
			出水	5.47		Ⅲ类
DO	溶解氧 (mg/L)	运行至今	进水	7.0	-0.7%	Ⅱ类
			出水	7.1		Ⅱ类
		2014 年 1-2 月	进水	9.0	-5.6%	Ⅰ类
			出水	9.4		Ⅰ类
		2015 年 1-2 月	进水	9.2	-16.0%	Ⅰ类
			出水	10.7		Ⅰ类
Fe	铁 (mg/L)	运行至今	进水	1.34	6.0%	饮用水源水补充项目，≤0. mg/L 为合格 <0.3 mg/l Qualified
			出水	1.11		
		2014 年 1-2 月	进水	1.05	36.4%	
			出水	0.62		
		2015 年 1-2 月	进水	1.13	9.0%	
			出水	0.98		
Mn	锰 (mg/L)	运行至今	进水	0.29	27.4%	饮用水源水补充项目，≤0. mg/L 为合格 <0.1 mg/l Qualified
			出水	0.21		
		2014 年 1-2 月	进水	0.29	29.6%	
			出水	0.20		
		2015 年 1-2 月	进水	0.22	18.8%	
			出水	0.18		
Total P	总磷 (mg/L)	运行至今	进水	0.18	27.0%	Ⅲ类
			出水	0.13		Ⅲ类
		2014 年 1-2 月	进水	0.15	-3.3%	Ⅲ类
			出水	0.16		Ⅲ类
		2015 年 1-2 月	进水	0.11	23.8%	Ⅲ类
			出水	0.08		Ⅱ类
Total N	总氮 (mg/L)	运行至今	进水	4.48	21.6%	劣Ⅴ类
			出水	3.53		劣Ⅴ类
		2014 年 1-2 月	进水	6.47	18.7%	劣Ⅴ类
			出水	5.26		劣Ⅴ类
		2015 年 1-2 月	进水	5.98	9.5%	劣Ⅴ类
			出水	5.41		劣Ⅴ类

项目	数值	水样名称 (Name)	平均值 (mg/L) (Average)	平均去除率 (Removal efficiency)	均值所属类别(参考 GB383 -2002 地表水限值) (Standard)
浊度 (NTU)	运行至今	进水	32.9	8.2%	参考指标
		出水	27.9		
	2014 年 8 月	进水	34.8	17.3%	
		出水	28.8		
	2015 年 7 月	进水	33.3	-11.7%	
		出水	36.0		
	2015 年 8 月	进水	36.0	6.0%	
		出水	33.7		
氨氮 (mg/L)	运行至今	进水	1.39	43.7%	Ⅳ类
		出水	0.84		Ⅲ类
	2014 年 8 月	进水	0.74	81.7%	Ⅲ类
		出水	0.11		Ⅰ类
	2015 年 7 月	进水	0.53	54.8%	Ⅲ类
		出水	0.21		Ⅱ类
	2015 年 8 月	进水	0.21	33.6%	Ⅱ类
		出水	0.12		Ⅰ类
耗氧量 (mg/L)	运行至今	进水	6.36	8.0%	Ⅳ类
		出水	5.81		Ⅲ类
	2014 年 8 月	进水	6.16	9.0%	Ⅳ类
		出水	5.61		Ⅲ类
	2015 年 7 月	进水	6.04	1.6%	Ⅳ类
		出水	5.91		Ⅲ类
	2015 年 8 月	进水	4.77	9.4%	Ⅲ类
		出水	4.32		Ⅲ类
溶解氧 (mg/L)	运行至今	进水	6.9	-1.2%	Ⅱ类
		出水	7.1		Ⅱ类
	2014 年 8 月	进水	5.4	21.6%	Ⅲ类
		出水	4.2		Ⅳ类
	2015 年 7 月	进水	5.9	-0.9%	Ⅲ类
		出水	6.0		Ⅲ类
	2015 年 8 月	进水	5.4	10.4%	Ⅲ类
		出水	4.8		Ⅳ类
铁 (mg/L)	运行至今	进水	1.38	3.7%	饮用水源水补充项目，≤0.3 mg/L 为合格
		出水	1.21		
	2014 年 8 月	进水	1.56	12.3%	
		出水	1.37		
	2015 年 7 月	进水	1.38	-17.3%	
		出水	1.58		
	2015 年 8 月	进水	1.50	-4.9%	
		出水	1.57		
锰 (mg/L)	运行至今	进水	0.29	22.9%	饮用水源水补充项目，≤0.1 mg/L 为合格
		出水	0.23		
	2014 年 8 月	进水	0.32	21.0%	
		出水	0.25		
	2015 年 7 月	进水	0.27	15.0%	
		出水	0.24		
	2015 年 8 月	进水	0.25	10.4%	
		出水	0.22		
总磷 (mg/L)	运行至今	进水	0.19	26.2%	Ⅲ类
		出水	0.13		Ⅲ类
	2014 年 8 月	进水	0.22	36.4%	Ⅳ类
		出水	0.14		Ⅲ类
	2015 年 7 月	进水	0.14	28.6%	Ⅲ类
		出水	0.10		Ⅱ类
	2015 年 8 月	进水	0.16	22.7%	Ⅲ类
		出水	0.12		Ⅲ类
总氮 (mg/L)	运行至今	进水	4.41	18.9%	劣Ⅴ类
		出水	3.59		劣Ⅴ类
	2014 年 8 月	进水	2.51	26.3%	劣Ⅴ类
		出水	1.85		Ⅴ类
	2015 年 7 月	进水	3.41	7.0%	劣Ⅴ类
		出水	3.17		劣Ⅴ类
	2015 年 8 月	进水	2.98	11.5%	劣Ⅴ类
		出水	2.68		劣Ⅴ类

D.2 Surface Water Source Quality Analysis in Jiaxing

28 regular items analysis report

水 源 水 水 质 常 规 28项 检 测 数 据

	No.	Name	Standard	January	Guanjinggang DWTP	August	Guanjinggang DWTP	Unit
	序号	样品名称 项目	GB 3838-2002II 类水限值	石臼漾原水	贯泾港原水	石臼漾原水	贯泾港原水	单 位
PH	1	pH值	6—9	7.76	7.60	8.09	7.58	—
DO	2	溶解氧	≥6	6.14	5.58	4.2	3.1	mg/L
Permanganate index	3	高锰酸盐指数	4	4.73	5.59	4.66	4.23	mg/L
COD	4	化学需氧量（COD）	15	15	18	20	10	mg/L
BOD5	5	五日生化需氧量（BOD_5）	3	2.80	3.10	3.75	<2	mg/L
Ammonia nitrogen	6	氨氮（NH_3-N）	0.5	0.94	1.54	0.15	0.19	mg/L
Total P	7	总磷（以P计）	0.1	0.06	0.10	0.12	0.14	mg/L
Total N	8	总氮（以N计）	0.5	3.72	5.35	2.91	2.89	mg/L
Cu	9	铜	1.0	<0.1	<0.1	<0.1	<0.1	mg/L
Zn	10	锌	1.0	<0.1	<0.1	<0.1	<0.1	mg/L
Flouride	11	氟化物（以F^-计）	1.0	0.61	0.68	0.39	0.45	mg/L
Se	12	硒	0.01	<0.002	<0.002	<0.002	<0.002	mg/L
As	13	砷	0.05	<0.002	<0.002	<0.002	<0.002	mg/L
Hg	14	汞	0.00005	<0.0001	<0.0001	<0.0001	<0.0001	mg/L
Cd	15	镉	0.005	<0.0004	<0.0004	<0.0004	<0.0004	mg/L
Cr	16	铬(六价)	0.05	<0.004	<0.004	<0.004	<0.004	mg/L
Pb	17	铅	0.01	<0.004	<0.004	0.007	<0.004	mg/L
cyanide	18	氰化物	0.05	<0.002	<0.002	<0.002	<0.002	mg/L
volatile phenol	19	挥发酚	0.002	<0.002	<0.002	<0.002	<0.002	mg/L
Petrolume	20	石油类	0.05	<0.05	<0.05	<0.05	<0.05	mg/L
LAS	21	阴离子表面活性剂	0.2	<0.05	<0.05	<0.05	<0.05	mg/L
sulfide	22	硫化物	0.1	<0.02	0.034	<0.02	<0.02	mg/L
Heat resistant E-Coli	23	粪大肠菌群	2000	330	790	1700	5400	个/L
Sulfate	24	硫酸盐（以SO_4^{2-}计）	250	70.1	113.5	32.0	40.8	mg/L
Chloride	25	氯化物（以Cl^-计）	250	61.4	73.0	17.0	22.6	mg/L
Nitrate	26	硝酸盐（以N计）	10	2.14	3.54	1.40	1.70	mg/L
Fe	27	铁	0.3	0.72	0.49	0.29	0.76	mg/L
Mn	28	锰	0.1	0.129	0.140	0.104	0.050	mg/L
	备注	GB 3838-2002II 类水域功能：适用于集中式生活饮用水地表水源地一级集中式生活饮用水地表水源地一级保护区						

E.1 Flow Velocity Analysis of the Yangtze River

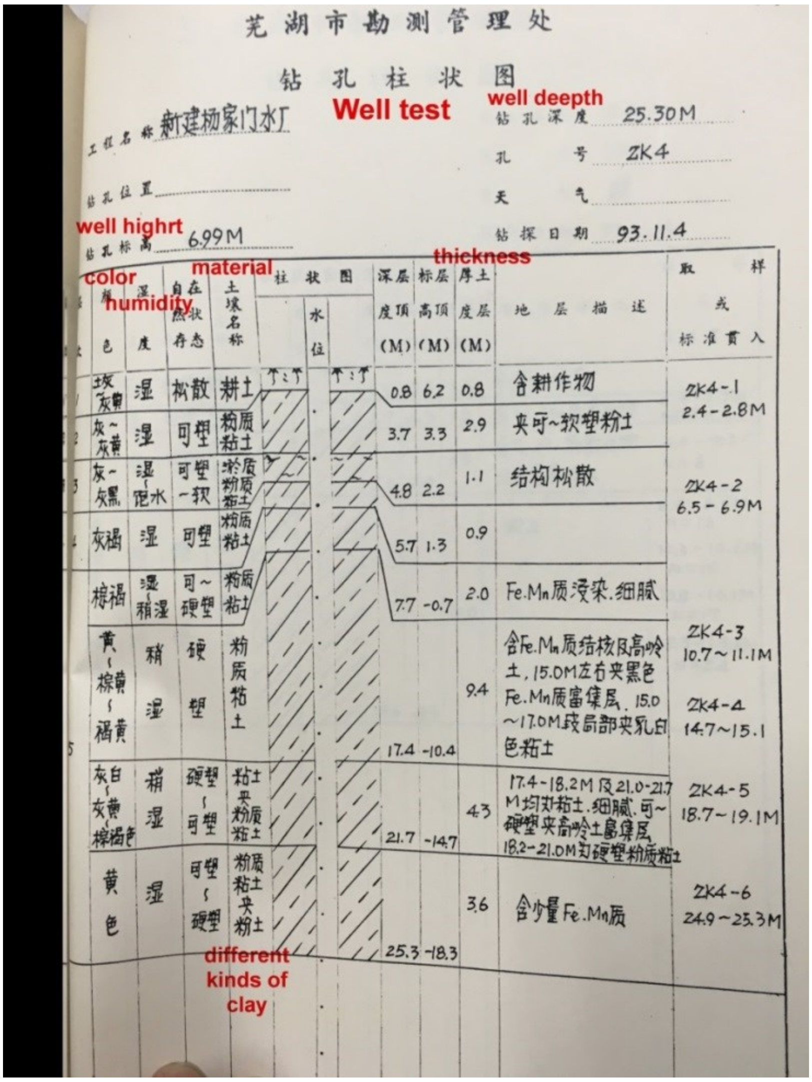
Water Velocity Analysis Report

ADCP 水文测验测点流速流向成果表

断面名称：YJM
平面系统：1954年北京坐标系
测验时间：2012年6月9日
高程系统：1985国家高程基准

垂线编号 (No.)	施测时间（时：分）(Time)	垂线最大水深 (M) (Deepth)	流速 (m/s) 相对水深 0.0	0.2	0.4	0.6	0.8	1.0	垂线平均 (Average)	流向 (°) 相对水深 0.0	0.2	0.4	0.6	0.8	1.0	垂线平均 (Average)
Y1	9:42	13.2	0.620	0.669	0.686	0.734	0.649	0.452	0.654	341.65	341.96	336.93	335.68	339.29	336.23	338.54
Y2	9:41	17.9	0.834	0.904	0.836	0.810	0.742	0.489	0.789	338.12	329.71	324.68	329.99	336.25	332.00	330.96
Y3	9:39	23.9	2.268	2.181	2.082	1.933	1.792	1.372	1.961	349.70	349.84	348.93	350.25	351.60	350.74	350.10
Y4	9:37	21.9	2.307	2.202	2.148	2.003	1.780	1.285	1.982	352.65	353.81	353.83	356.19	357.96	7.06	355.76
Y5	9:35	22.3	2.240	2.063	1.941	1.785	1.357	0.767	1.730	350.24	351.05	351.26	350.44	352.46	351.82	351.12
Y6	9:33	16.4	2.092	1.997	1.923	1.840	1.794	1.433	1.863	352.15	352.80	351.34	352.51	356.19	355.75	353.25
Y7	9:32	18.6	1.998	1.949	1.854	1.748	1.545	1.227	1.741	355.66	355.29	356.19	355.56	359.24	357.15	356.41
Y8	9:30	20.1	1.825	1.794	1.669	1.639	1.456	1.065	1.600	355.14	356.70	358.62	0.06	1.73	0.24	358.76
Y9	9:29	23.9	1.559	1.546	1.492	1.385	1.239	0.832	1.371	355.42	355.36	357.82	355.98	354.75	351.26	355.67
Y10	9:27	27.9	1.101	1.010	1.001	0.901	0.833	0.601	0.919	358.88	356.28	356.13	355.49	353.23	355.03	355.77

E.2 Well Tests Report of Wuhu Site



E.3 Surface Water Source Quality Analysis in Liminlu Plant, Wuhu

Water Quality Analysis Report
Liminlu plant source water

Items UnitStandardValueQualify Items UnitStandardValueQualify

表 3-13 安徽省城市供水水质监测网芜湖监测站

全分析检测报告

送检日期：2012. 08. 13 依据标准：GB3838-2002

样品名称：利民路水厂水源水 报告编号：Q120801-03

Label	项 目	单位	标准值（Ⅱ类）	检验值	评价	项 目	单位	标准值（Ⅱ类）	检验值	评价	Label
Temperature	水温	℃		26. 6	合格	镉	mg/L	≤0. 005	<0. 0020	合格	Cd
	pH		6～9	7. 70	合格	铬(六价)	mg/L	≤0. 05	<0. 004	合格	Cr
DO	溶解氧	mg/L	≥6	6. 8	合格	铅	mg/L	≤0. 01	<0. 0050	合格	Pb
CODMn	高锰酸盐指数	mg/L	≤4	3. 1	合格	氰化物	mg/L	≤0. 05	<0. 007	合格	cyanide
CODCr	化学需氧量（以 COD_{cr} 计）	mg/L	≤15	<10. 0	合格	挥发酚	mg/L	≤0. 002	<0. 002	合格	Volatile Phenol
BOD5	五日生化需氧量（BOD_5）	mg/L	≤3	2. 1	合格	石油类	mg/L	≤0. 05	<0. 05	合格	Petroleum
Ammonia nitrogen	氨氮（NH_3-N 计）	mg/L	≤0. 5	0. 35	合格	阴离子表面活性剂	mg/L	≤0. 2	<0. 05	合格	Anionic Syrfactant
Total P	总磷(以 P 计)	mg/L	≤0. 1	0. 07	合格	硫化物	mg/L	≤0. 1	0. 12	不合格	Sulfide Not qualified
Not qualified Total N	总氮(以 N 计)	mg/L	≤0. 5	2. 47	不合格	粪大肠菌群	个/L	≤2000	50	合格	Heat resistant E-Coli
Cu	铜	mg/L	≤1. 0	<0. 050	合格	硫酸盐（以 SO_4^{2-} 计）	mg/L	≤250	34	合格	Sulfate
Zn	锌	mg/L	≤1. 0	<0. 050	合格	氯化物(以 Cl^- 计)	mg/L	≤250	12	合格	Chloride
Fluoride	氟化物(以 F^- 计)	mg/L	≤1. 0	0. 36	合格	硝酸盐	mg/L	≤10	2. 97	合格	Nitrate
Se	硒	mg/L	≤0. 01	<0. 00002	合格	铁	mg/L	≤0. 3	1. 56	不合格	Fe Not qualified
As	砷	mg/L	≤0. 05	<0. 00002	合格	锰	mg/L	≤0. 1	<0. 050	合格	Mn
Hg	汞	mg/L	≤0. 00005	<0. 00001	合格						