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The impact caused by tap water recharge on groundwater quality

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ABSTRACT

Large-scale artificial recharge is planning for controlling subsidence in the fourth confined aquifer (A4) in Shanghai. However, it is unknown what negative impact would occur after the injection of tap water into A4. Based on collected material and data available in some sporadic experiments about tap water recharge to A2, A3, and A4 from the 1960s to the 1980s, this paper gave some evaluations on the changes of groundwater chemical characteristics, migration range of recharge water in single well and groups of wells. And various factors affecting groundwater quality during the artificial injection were discussed. The results showed that the physical and chemical composition of groundwater trended to that of recharge water, maximum influence distance of recharge water in single well in A2 was about 100 m in 20 years, and the maximum radius of groups of wells in A4 was about 1,000 m, while the range causing significant changes in groundwater quality was less than 1,000 m. This information will offer scientific basis for the large-scale artificial recharge in the near future.

Keywords: Artificial recharge; Tap water; The fourth confined aquifer; Land subsidence; Groundwater quality

1. Introduction

The aquifer system of Shanghai is formed from unconsolidated Quaternary sediments. The sediments are about 200–350 m thick, mainly composed of clay, sandy clay, and sand. From the top down, it could be divided into 12 layers: the phreatic aquifer (A0), the first aquitard (B1), the first confined aquifer (A1), the second aquitard (B2), the second confined aquifer (A2), the third aquitard (B3), the third confined aquifer (A3), the fourth aquitard (B4), the fourth confined aquifer (A4), the fifth aquitard (B5), the fifth confined aquifer (A5), and the sixth aquitard (Fig. 1) [1].

Before 1963, the second and third confined aquifer (A2 and A3) was the mainly developed layer for extraction in Shanghai. Because of excessive exploitation of groundwater, a regional groundwater

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depression had been formed. This lead to maximum settlement rate more than 110 mm/a [2] and serious disasters of land subsidence. In order to control land subsidence, Shanghai had taken plenty of measures to prevent the disasters, including reducing groundwater extraction, changing the layers of exploitation, and artificial recharge [3,4]. These measures made the groundwater level ascending gradually and gave significant control of land subsidence. Meanwhile, the fourth confined aquifer (A4) had become the mainly developed layer instead of A2 and A3. Consequently, A4 has been the major compressed layer since 1980s [5,6].

In order to lift the water level to alleviate subsidence in A4, a large-scale artificial recharge has been planned [7]. However, groundwater in A4 possesses a better quality than recharge water, which mainly comes from tap water. A question then arises: what impact would occur after the injection of tap water into A4.

Since the 1960s, a lot of organizations carried out the artificial recharge of groundwater studies. However, most of them focused on the quality and congestion problems in use of wastewater for artificial recharge [8–11] and few exampled the use of tap water for artificial recharge of groundwater. Based on collected material and data available in some sporadic experiments about tap water recharge to A2, A3, and A4 from the 1960s to the 1980s, this paper gave some evaluations on the variations in groundwater characteristics, migration range of recharge water and various factors affecting groundwater quality during the artificial injection, so as to offer scientific basis for the large-scale artificial recharge in the near future.

2. Variations in groundwater characteristics

2.1. Inorganic compounds

Seven injection wells (Yang164-1, Pu67-2, Pu91-2, Nan1-1, Yang156-1, Pu86-5, and Jing41-1) with a relative long-serial monitoring data were chosen to study the characteristics of groundwater quality before and after the tap water recharge.

The current groundwater had developed hundreds of thousands of years, and the total dissolved solids (TDS) is higher than surface water because of the dissolution of rocky components and minerals, as well as some water ions, such as Na^+, Ca^{2+}, Mg^{2+}, and Cl^-. When plenty of recharge water had been injected into the aquifer, concentrations of Na^+, Ca^{2+}, Mg^{2+}, and Cl^- would decrease, as same as the TDS. Consequently, the groundwater presented the trend of desalinization (Fig. 2).

In surface water, HCO_3^- is one of the dominant anions as a result of dissolution of atmospheric CO_2. However, in rocky aquifer, there are lots of soluble carbonates, and groundwater would dissolve these carbonates during migration process, resulting in higher concentration of HCO_3^-. Thus, the injection would lower concentration of HCO_3^-. By contrast, concentration of SO_4^{2-} is a bit low, about 0–20 mg/L. This is due to lack of provenance substance in unconsolidated sediments. Therefore, recharge activities would rise up concentration of SO_4^{2-}, which come from tap water (Fig. 2).

Iron and manganese contents are unevenly distributed in Shanghai. However, results showed a general increase in iron and manganese contents after injection of tap water. The phenomenon could also been seen with lots of trace elements in groundwater,

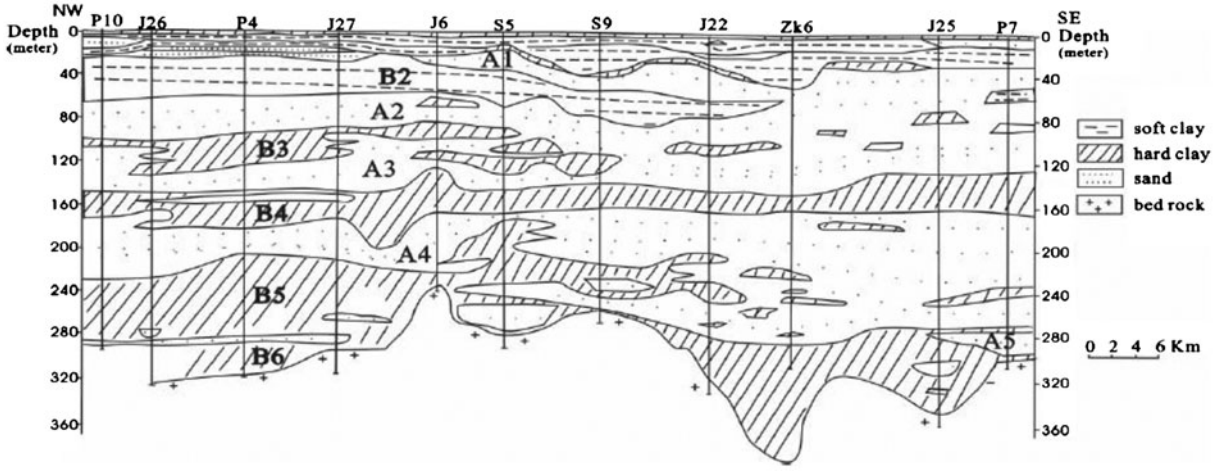

Fig. 1. Schematic stratigraphic section in Shanghai.

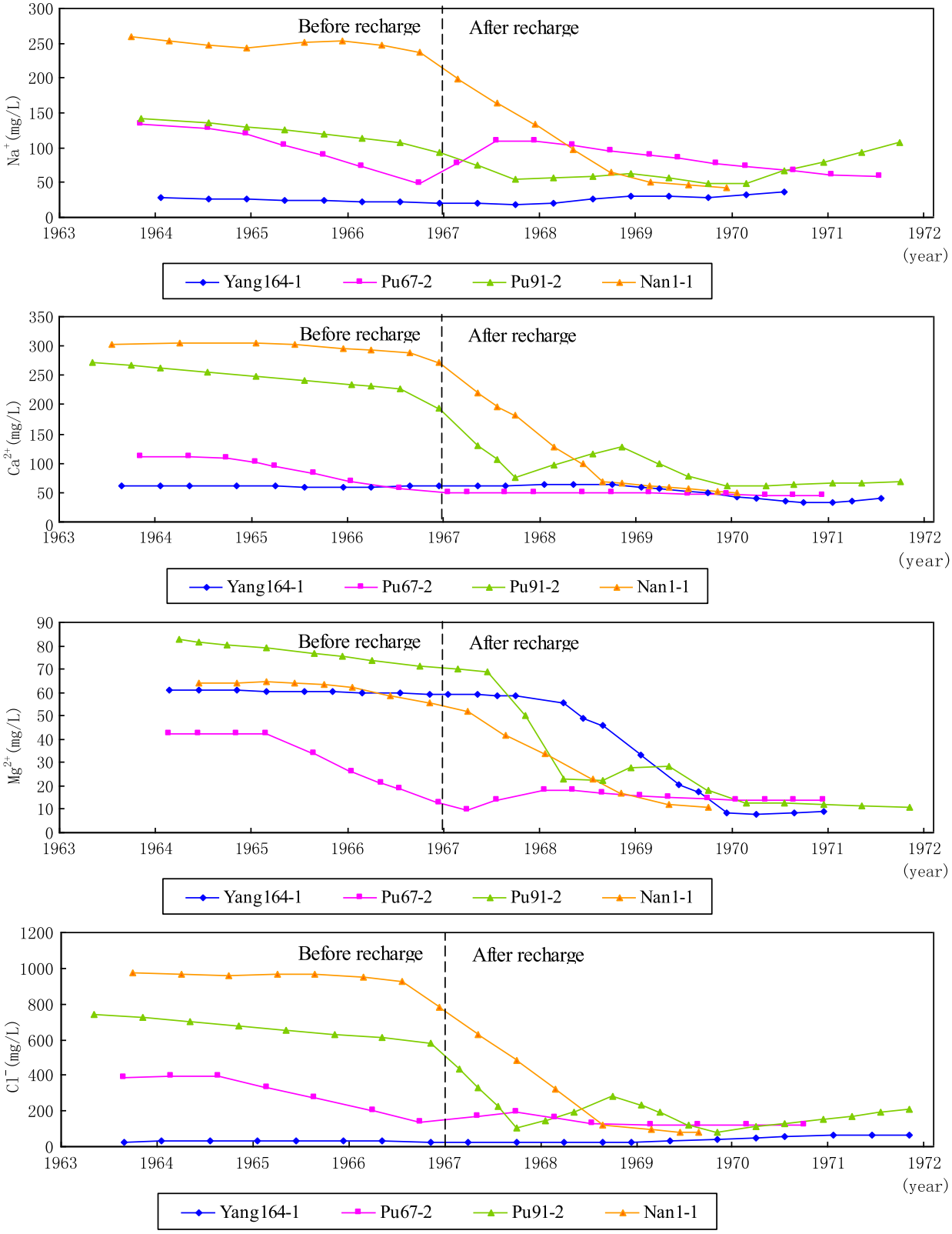

Fig. 2. Variations of the major ions concentration in groundwater of some recharge wells.

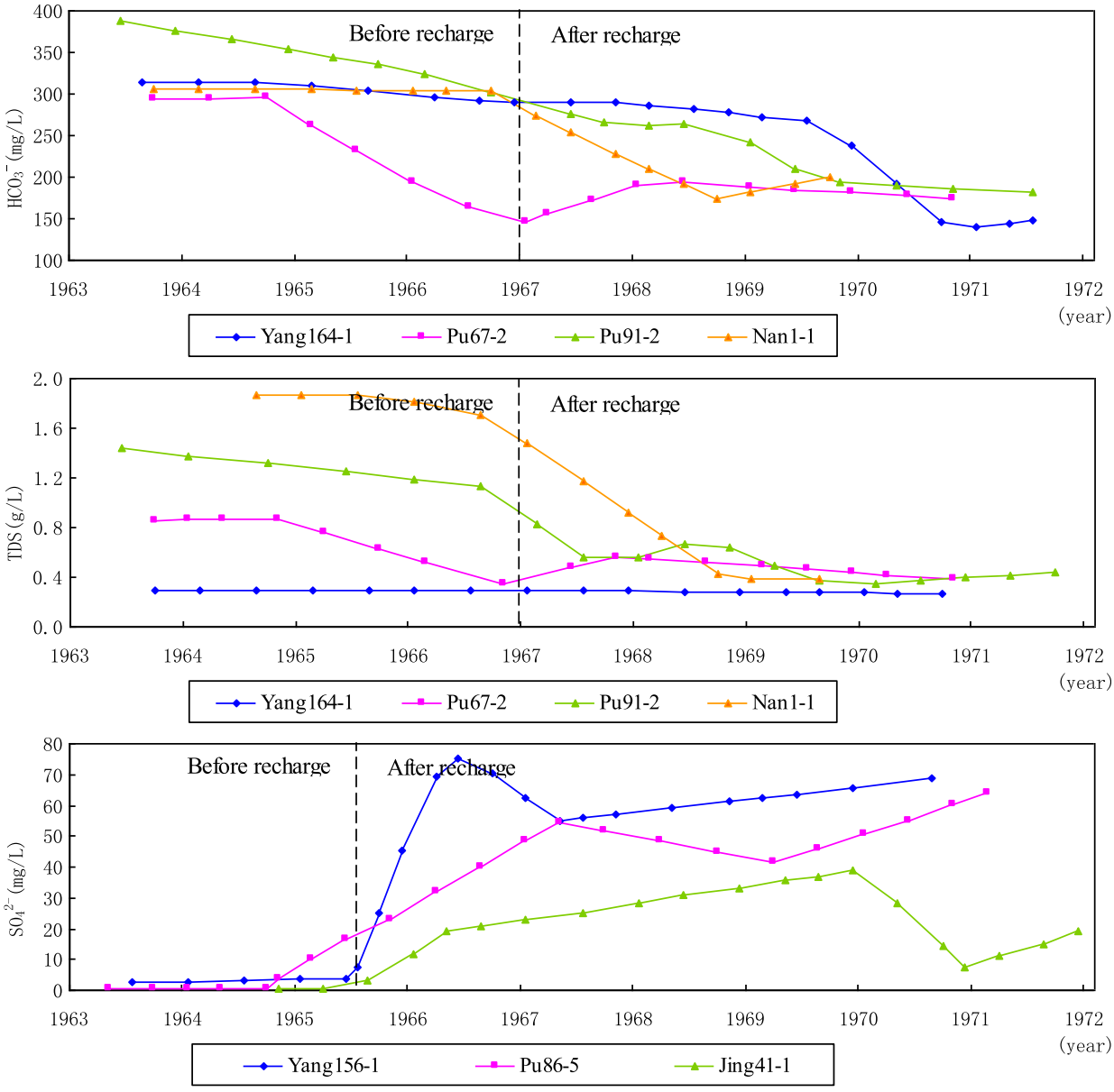

Fig. 2. (*Continued*)

such as copper, zinc, lead, cadmium, mercury, and chromium, but arsenic was an exception. This was because of the high concentration of arsenic existing in some areas and recharge water made the dilution of arsenic when mixing with groundwater.

2.2. Organic compounds

With respect to organic compounds, recharge water brought plenty of organic contaminants into the aquifer, which gives rise to higher figure of chemical oxygen demand (COD). The COD of original groundwater was generally 0.4–2.5 mg/L; however, COD rose up to 1.0–4.5 mg/L after recharging. Table 1 illustrated the average value of COD before and after the recharge in A2, A3, and A4.

Due to the entrophication pollution in surface water, nitrogenous compounds in groundwater were focused particularly. NH_4^+, NO_2^- and NO_3^-, were selected as monitoring markers. Mostly, the main form of nitrogenous compounds in groundwater was

Table 1
The average value before and after recharge

Components	A2		A3		A4	
	Before recharge	After recharge	Before recharge	After recharge	Before recharge	After recharge
NH_4^+ (mg/L)	2.01	1.74	2.07	1.43	0.53	1.32
NO_2^- (mg/L)	0.003	1.54	0.013	1.20	0.007	1.30
NO_3^- (mg/L)	0.006	0.69	0	0.80	0.113	1.78
COD (mg/L)	2.06	3.29	1.35	3.54	0.79	4.05

NH_4^+, while NO_2^- and NO_3^- were in low content. But after recharge, content of NO_2^- increased significantly about ten times, while NO_3^- increased slightly. However, NH_4^+ showed different trends in different confine aquifers. Contents of NH_4^+ in original A2 and A3 were higher than tap water, while A4 had lower content. So After tap water recharge, NH_4^+ went up in A4 and down in A2 and A3. Table 1 gave the average values of nitrogenous compounds and COD in A2, A3, and A4. Nevertheless, the increase in due to NO_2^- not only from tap water recharge, but also from the reduction of nitrate compounds.

3. Migration range of recharge water

In order to study the migration impact of artificial groundwater recharge, tracer experiments were designed, under conditions of single-well recharge and groups of well recharge.

3.1. Single-well recharge

The chosen single well should satisfy the conditions, both far away from other recharge wells and less interference factors. For this consideration, a single well located in Pudong District was selected and recharge started at 1967. After five years, five observation wells were set away from the well 14.0 m (H1), 24.7 m (H2), 36.3 m (H3), 59.2 m (H4), and 68.1 m (H5), respectively (Fig. 3). And in the five years, a total of 250,000 m^3 of tap water were recharged into A2 from the recharge well, as well as groundwater extraction of 24,000 m^3.

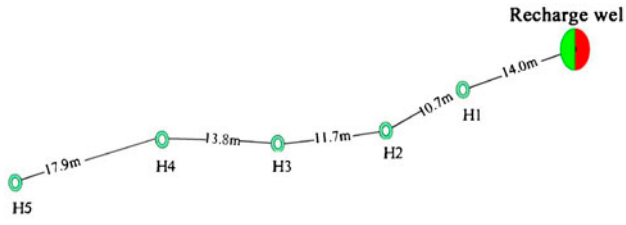

Fig. 3. Distribution of observation wells for single-well recharge in A2.

According to monitoring results, chloride content was about 490 mg/L at the well site, much higher than the content of recharge water, while content of SO_4^{2-} was zero. The main form of chloride was Cl^-, which was chemically stable and had strong migration capability. So Cl^- was considered for the ideal tracer. In contrast to recharge water, groundwater had almost zero content of SO_4^{2-}, which could give better indication of recharge water migration. Therefore, this study selected Cl^- and SO_4^{2-} as tracer substances.

In one extraction–recharge cycling year, extraction stage mainly was in summer, and recharge stage was in winter. And continuous monitoring from each observation well was carried out since 1972. Within 1980, water quality changed significantly. In the furthest observation well H5 (Fig. 4), content of Cl^- showed distinct changes, while SO_4^{2-} was in condition of occasionally positive detection, mostly in recharge stage. From above results, a preliminary conclusion could be inferred: the recharge water had spread to H5 well, and its maximum radius of influence was greater than or equal to 68.1 m. Within the next few years, content of Cl^- continued to fluctuate from extraction stage to recharge stage, while frequency of positive detection for SO_4^{2-} become higher and higher, and its content was also rising. Five years later, SO_4^{2-} continued to be positive detected instead of intermittent detection. Even in extraction stage, the groundwater in H5 could not be restored to the original groundwater status, which showed that the minimum radius of influence was greater than 68.1 m. If at this rate projections, the impact distance of tap water was about 110 m in the condition of maintaining the same recharge activities 20 years. Taking into account the possible attenuation with radius increase, the estimated maximum distance of recharge water was about 100 m.

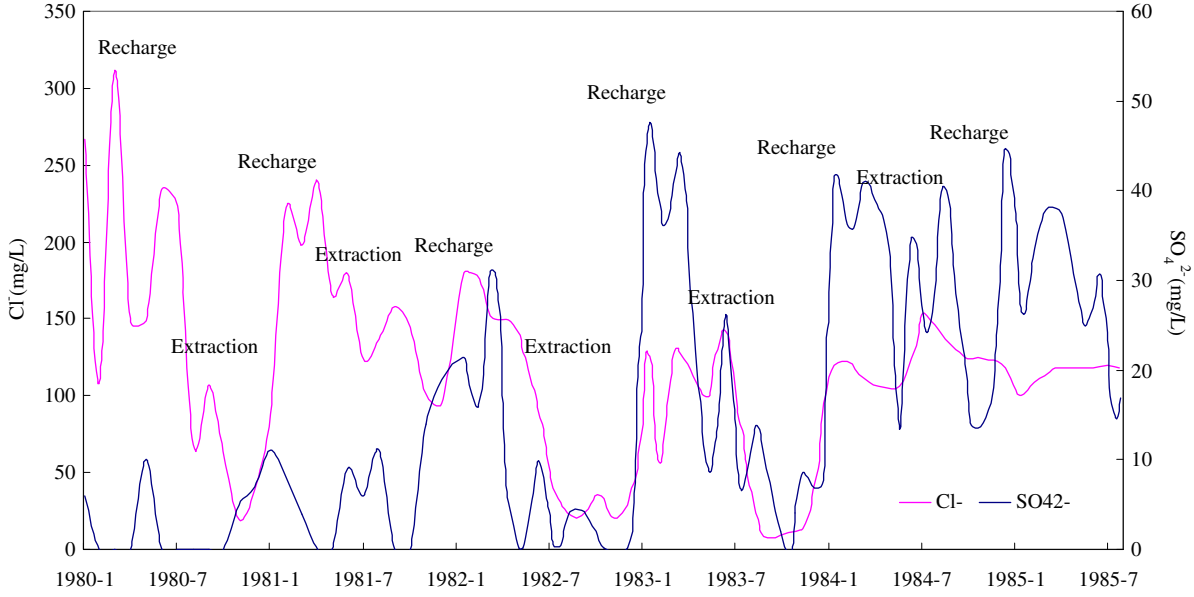

Fig. 4. Changes of Cl^- and SO_4^{2-} concentration in H5.

3.2. Groups of well recharge

The selected recharge area included eight artificial wells, and two observation wells were equipped. The distances from the area center were 500 m (W1) and 1,000 m (W2), respectively. Isotope tritium and Cl^- were selected as monitoring tracers. Tritium is a stable isotope, and the concentration in groundwater is less than 2 TU. These features endow tritium with a good tracer of groundwater irrigation. For Cl^-, it has stable chemical property and strong migration ability, which gave a good choice for a tracer.

The monitoring results from 1979 to 1982 showed that W1 begun to detect the existence of tritium continuously six months later. The concentration was 6.5–17.0 TU, lower than recharge wells. W2 begun to detect tritium intermittently 12 months later, and the concentration was 2.9–8.7 TU, lower than recharge wells and W1. At the same time, the concentration monitoring of Cl^- presented that W1 gave approximate synchronous but slightly lagging trends with recharge wells, indicating that W1 had been significantly affected by recharge water. Meanwhile, the concentration of Cl^- in W2 did not change significantly, remaining the background level (Fig. 5).

The finding of tritium in W2 made known that a part of recharge water had spread to the W2 nearby, but the steady concentration of Cl^- in W2 showed that there was no significant change in groundwater quality. Based on analysis described previously, some patterns could be drawn that the recharge maximum radius of many wells was about 1,000 m, but the range causing significant changes in groundwater quality was less than 1,000 m.

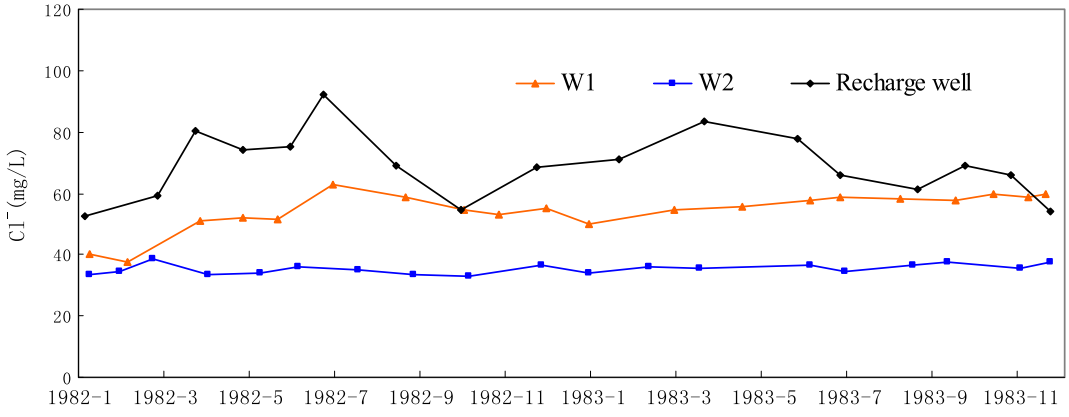

Fig. 5. Changes of Cl^- concentration in groups of wells.

4. Analysis on impact factors of groundwater quality

4.1. Recharge water quality

The quality of recharge water not only affected the groundwater chemical types around the recharge wells, but also controlled the evolution direction of groundwater qualities [12–15]. The conditions of recharge water quality affect groundwater quality directly, which was displayed in Section 2.1.

4.2. Extraction–recharge conditions

The impact of extraction–recharge conditions on groundwater quality were caused by the following factors: extraction–recharge ratio, extraction–recharge equilibrium, extraction–recharge disequilibrium, and recharge process and time.

Extraction–recharge ratio refers to the ratio between water quantities of extraction and recharge in an extraction–recharge cycling year. Because of the difference of extraction–recharge ratios, the quantity and residence time of residues water changed underground. And it would cost a certain time to complete the physical, physical–chemical and biochemical reaction between mixing of recharge water and groundwater, which gave a great impact on the quality of groundwater.

Extraction–recharge equilibrium refers to the equality condition between extraction quantity and artificial recharge quantity during an extraction–recharge cycling year. Under such conditions, the chemical components with higher concentrations in groundwater would descend due to the dilution of recharge water, and certain components that inherently do not exit in groundwater would gradually ascend due to the bringing of recharge water.

Extraction–recharge disequilibrium refers to the inequality condition of the extraction quantity less than artificial recharge quantity during an extraction–recharge cycling year. There would be a lot of recharge residues in the aquifer every year and affect the groundwater quality and chemical environment, making the groundwater quality changes toward the direction of recharge water quality.

In addition, recharge process and recharging time also affected the groundwater quality. Tube wells had been used in the artificial recharge in Shanghai, and it need to keep the tubes sealed during recharge. The seal conditions affected the recharge results and groundwater quality around recharge wells. Under the unsealed conditions, the recharge water would bring air into recharge wells and mix them together in aquifer, which would block the groundwater flow in sandy pores. Furthermore, the dissolved oxygen in the mixture would change the redox conditions around the wells, and Fe^{2+} would be oxidized to Fe^{3+}, leading to enrichment of Fe element around the wells. This also would block the recharge tubes.

Recharge time was one of the important factors which greatly affected groundwater quality. Under the conditions of extraction–recharge disequilibrium, the longer recharge time and bigger differences between groundwater and recharge water, the more trend toward to recharge water quality characteristics. In wells with short recharge time, there were less recharge residues. The dominant action was mechanical mixing, and diffusion mixing had not yet been formed. The mixed water was in an intermediate quality between groundwater and recharge water.

4.3. Physical and chemical effects

The groundwater quality is also controlled by physical and chemical factors such as temperature changes and water-rock interaction, occurring in recharging water process.

The groundwater temperatures in A2, A3, and A4 varied from 20 to 25°C, while recharge water temperatures are not the same with groundwater temperatures. There is amount of dissolved oxygen in recharge water, which is inversely proportional to the temperature. The higher the temperature, the lower the amount of dissolved oxygen. So the dissolved oxygen concentration was higher in winter than in summer. Due to high concentration of low-valence Fe and Mn in groundwater, there would be more oxidation from Fe^{2+} to Fe^{3+}, easily leading to more $Fe(OH)_3$ precipitation.

For possible water–rock interaction, there are lots of carbonate substances in the aquifers, as calcite, dolomite et al. After the artificial recharge, the water–rock equilibrium would be destroyed because of dissolved CO_2 in recharge water. This would make some carbonate dissolved in aquifer, resulting in higher measured concentrations of Ca^{2+}, Mg^{2+}, HCO_3^- than theoretical calculation, as well as the total hardness test results.

4.4. Biochemistry

Dissolved oxygen and nutrients desired by bacterial in groundwater, such as organic and inorganic C and N, could be intruded with recharge water. Under appropriate temperature and pH conditions, they would provide favorable conditions for the growth and development of micro-organisms. From our studies, the activities of micro-organisms are higher in

recharge wells than non-recharge ones. And in recharge wells, the main micro-organisms types are iron bacteria, row thiooxidans, sulfate-reducing bacteria, and denitrification thiobacillus. The biochemical activities would increase the concentration of Fe, Mn, NO_2^-, and H_2S, while corrosion and block phenomenon of well pipe would occur.

5. Conclusion

The artificial recharge water quality condition would greatly impact the groundwater quality. Therefore, quality control of recharge water is the primary step to avoid groundwater pollution in recharge wells. After recharge, concentration of NH_4^+ and NO_2^- in groundwater of A4 showed a large increase, which lowered the usability of groundwater. So the concentration of nitrogenous compounds should be paid great attention to in recharge water.

Make sure that the recharge tubes would be sealed well and take regular pump returning to avoid blockage in wells. Furthermore, attentions should be paid to wellhead protection to guard against industrial micro-organisms and other organisms.

In order to control the impact of micro-organisms on groundwater quality, recharge water should be degassed before injection. And raise the extraction–recharge ratio as far as possible under the premise that land subsidence has been controlled effectively.

References

[1] S.J. Ye, Y.Q. Xue, J.C. Wu, Z.X. Wei, Q.F. Li, A regional land subsidence model embodying complex deformation characteristics, Proceedings of Eight EISOLS, Mexico, 399 (2010) 76–81.

[2] L.K. Wu, Y.F. Sun, Discussion on Shanghai land subsidence and control, Acta Geol. Sin. 2 (1973) 109–120.

[3] Z.S. Chen, Z.C. Luo, Q. Li, Analysis of cause of land subsidence in Shanghai, J. Geod. Geodyn. S1 (2009) 94–98.

[4] J.B. Liu, Y.P. Zhang, J.Z. Wu, Evaluation of groundwater-environmental capacity and its application on land subsidence controlling in Shanghai, Shanghai Geol. 4 (2010) 24–28.

[5] S.L. Gong, The microscopic characteristics of Shanghai soft clay and its effect on soil mass deformation and land subsidence, J. Eng. Geol. 4 (2002) 42–48.

[6] S.L. Gong, P.C. Li, J.H. Wu, X.G. Li, Analysis of groundwater seepage field and stratum stress field of land subsidence in Shanghai, J. Liaoning Technol. Univ. (Nat. Sci. Ed.) S1 (2009) 236–239.

[7] H.M. Wang, Study on risk evaluation and control schemes of land subsidence in Shanghai city, Shanghai Geol. 4 (2010) 13–17.

[8] H. Bouwer, Issues in artificial recharge, Water Sci. Technol. 33 (1996) 381–390.

[9] P. Tsourlos, G. Vargemezis, K. Voudouris, T. Spachos, A. Stampolidis, Monitoring recycled water injection into a confined aquifer in Sindos (Thessaloniki) using electrical resistivity tomography (ERT): Installation and preliminary results, Proceedings of the 11th International Congress, Athens, XXXVII (2007) 580–592.

[10] K.P. Tsagarakis, G.E. Dialynas, A.N. Angelakis, Water resources management in Crete (Greece) including water recycling and reuse and proposed quality criteria, Agric. Water Manage. 66 (2004) 35–47.

[11] K. Voudouris, P. Diamantopoulou, G. Giannatos, P. Zannis, Groundwater recharge via deep boreholes in Patras industrial area aquifer system (NW Peloponnesus, Greece), Bull. Eng. Geol. Environ. 65 (2006) 297–308.

[12] X.Q. Du, X.Y. Ye, Y. Lu, B.M. Chi, B. Steffen, Y.S. Yang, Advances in clogging research of artificial recharge, Adv. Earth Sci. 9 (2009) 973–980.

[13] K. Seki, T. Miyazaki, A mathematical model for biological clogging of uniform porous media, Water Resour. Res. 37 (2001) 2995–2999.

[14] A. Vandenbohede, E. Houtteb, L. Lebbea, Water quality changes in the dunes of the western belgian coastal plain due to artificial recharge of tertiary treated waste water, Appl. Geochem. 24 (2009) 370–382.

[15] G.J. Zhang, D.G. Yang, P.X. Wei, Impact of reusing recharge to shallow groundwater on groundwater in Anyang, Water Resour. Prot. 26 (2010) 38–40.