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A field study of advanced municipal wastewater treatment technology for artificial groundwater recharge

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Abstract: Field studies were conducted to investigate the advanced treatment of the municipal secondary effluent and a subsequent artificial groundwater recharge at Gaobeidian Wastewater Treatment Plant, Beijing. To improve the secondary effluent quality, the combined process of powdered activated carbon adsorption, flocculation and rapid sand filtration was applied, which could remove about 40% dissolved organic carbon (DOC) and 70% adsorbable organic halogens. The results of liquid size exclusion chromatography indicate that in the adsorption unit the removed organic fraction was mainly low molecular weight compounds. The fractions removed by the flocculation unit were polysaccharides and high molecular weight compounds. The retention of water in summer in the open recharge basins resulted in a growth of algae. Consequently, DOC increased in the polysaccharide and high molecular weight humic substances fraction. The majority of the DOC removal during soil passage took place in the unsaturated area. A limited reduction of DOC was observed in the aquifer zone.

Keywords: artificial groundwater recharge; soil aquifer treatment; dissolved organic carbon

Introduction

Rapid urbanization and population growth are occurring in Beijing, the capital of China. The lack of water resources is emerging as a critical concern for the future development of the city. The available water volume per person in Beijing is now less than 300 m³/a. Groundwater is currently of critical shortage due to the significantly increasing usage. The serious overdraft resulted in a drop of the groundwater table in an area of 2200 km² in Beijing area (Wang, 2003; Fu *et al.*, 2000). To provide safe, reliable and sustainable sources of water, reuse of the secondary effluent is becoming an important mean in water management.

The Gaobeidian Wastewater Treatment Plant (WWTP) in Beijing processes about 9×10^5 m³/d of wastewater. This plant and other 7 wastewater treatment plants in Beijing are interested in the reuse of the secondary effluent as a stable and reliable water resource. Advanced treatment of secondary effluent combined with groundwater recharge system is increasingly being viewed as a valuable method to overcome the lack of natural water in many arid regions in the world (Ernst and Jekel, 1999; Wilson *et al.*, 1995; Shelef and Azov, 1996; Kanarek and Michail, 1996). This system might offer a good option for solving the water shortage problem in arid areas.

Biologically treated secondary effluent still contains residual refractory organic components, which can cause aesthetic and odour problems, as well as increase bacterial growth. Moreover, if the organic matter content is high, chlorine disinfection on the reclaimed water can result in the formation of mutagenic or carcinogenic compounds (Lindroos *et al.*, 2002). Dissolved organic carbon (DOC) and other

water parameters therefore must be reduced to acceptable levels before the reclaimed secondary effluent reaches the local groundwater aquifer. However, only parts of organic matters can be removed in the process of soil aquifer treatment (SAT) by surface infiltration through the vadose (unsaturated) zone and groundwater aquifer (saturated zone) in our former study (Yun *et al.*, 2000). Advanced treatment process is required to improve the secondary effluent quality before it is used for groundwater recharge. This study focused on fundamental processes for removing the residual organic compounds and investigating the removal mechanisms of different organic fractions in the selected different treatment units.

1 Materials and method

1.1 Description of the recharge basin

This study was carried out in the Gaobeidian WWTP, which includes activated sludge treatment with nitrification/denitrification. 200 m³/d secondary effluent was treated for groundwater recharge. In the recharge area, the soil in the upper 9.6 m (vadose zone) consists of sandy loams. The aquifer zone with a soil texture of sand and gravel is located in a depth from 9.6–17.5 m. There is a fine clay layer at the bottom of the aquifer zone at 17.5 m of depth. A LiCl tracer test indicated that it was almost impossible for the water in aquifer zone to percolate through this clay layer to the deeper aquifer. The porosity of the soil in vadose zone varies from 0.36 to 0.5 m. Table 1 lists the composition of the aquifer water. The concentration of dissolved organic matter of aquifer water is low. And the aquifer is suitable for groundwater recharge.

Table 1 Composition of the aquifer water at Gaobeidian WWTP, Beijing

DOC, mg/L	1.9	pH	7.3
COD, mg/L	6.46	AOX, µg/L	About zero
UV-254, m ⁻¹	4.85	P, mg/L	0.11
NH ₄ ⁺ -N, mg/L	0	NO ₃ ⁻ , mg/L	2.31

Note: AOX, adsorbable organic halogens

Several monitoring wells (MW) were located approximately 40 m to 90 m down gradient of the basins. A well (MW 1) was drilled directly below the recharge basin to observe the removal effect of the unsaturated zone. Fig.1 presents a simplified cross section of the recharge site. Well 4 (RW-4) was used as the recovery well and also as a monitoring well. After a period of operation, the recharged water can be pumped from Well 4 for further reuse. Three rectangular recharge basins were constructed. Two basins were 113 m², and another was 179 m². The original soil at upper 150 cm was removed and 20 cm fine sand was spread at the bottom of the basins in order to control the clogging layer. Plaster brick walls were built around the recharge basins.

From our experience, water levels lower than 20 cm would lead to the growth of grasses. The treated water was filled to the basins until 60 cm high. After the water level in basins declined by 5 cm, the treated water was re-filled again. The recharge basins were operated in a wet-dry cyclical pattern. The wet period lasted 6—8 d, and the dry period was 10—14 d. In

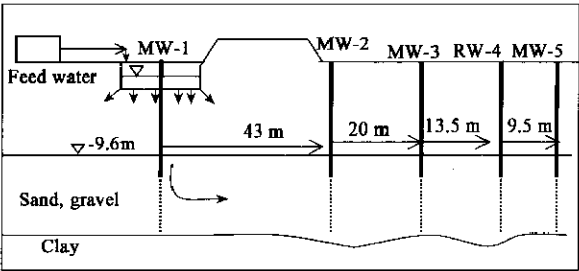


Fig.1 Cross section scheme of the groundwater recharge system in WWTP Gaobeidian (Beijing)

summer at the end of the wet period, the growth of green algae caused the decrease of the infiltration rate. During the drying period, algae died and were removed. Hydraulic permeability was re-established again in the recharge basins. And oxygen could diffuse into the sub-surface of the soil (Westerhoff and Pinney, 2000). In winter (from January to middle February) the recharge operation was ceased due to the low temperature and frozen period in Beijing.

1.2 Advanced treatment process

The experimental results in laboratory scale of our former study have shown that powdered activated carbon (PAC) adsorption, coagulation combined with sand filtration is an effective process to reduce the concentration of dissolved organic matters (Yun *et al.*, 2000). An advanced treatment process (Fig.2) was then set up.

Secondary effluent was treated firstly with

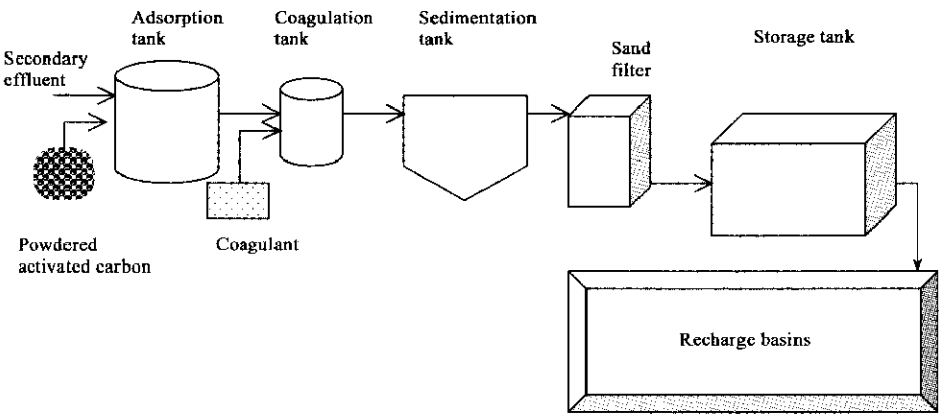


Fig.2 Flow diagram of the advanced treatment process

powdered activated carbon for 1 h in a tank (1.95 m high, 1.8 m inner diameter (ID)). The PAC dosage was 30 mg/L. Coagulation was applied with polyaluminum chloride (dosage 30 mg/L) for 20 min. The treated water flowed to sedimentation tank (3.7 m high, 3.6 m ID). After 2 h of sedimentation, the supernatant went to a sand filtration bed (1 m × 1 m × 1.8 m) with 1.2 m packed sand to remove residual particles to avoid clogging at the surface of the recharge basins. The filtrated water was kept in a storage tank and then transferred to recharge basins, which were only 50 m far away. Therefore the

investment of construction of pipes and the energy for the transportation of the water could be reduced to a low level.

1.3 Analysis methods

DOC was measured using a High TOC-5000 Low-Level Analyzer (Jena, Germany); AOX was measured by IDC-Analysystem AOX-3 (Jena, Germany); UV absorbency measurements at 254 nm were accomplished using a Shimadzu UV-3100 model UV-Vis-NIR recording Spectrophotometer (Shimadzu, Japan); Liquid size exclusion chromatography (TSK-50S column) was employed with on-line

organic carbon detection (LC-OCD) (DOC Labor, Karlsruhe, Germany) (Schumacher *et al.*, 2004).

2 Results and discussion

2.1 Advanced treatment

Table 2 lists the variances of organic matters and total P, N during the advanced treatment process. The DOC value (6.9 mg/L) of the secondary effluent (feed water) is relatively low. This is mainly due to the low content of humic substances in the drinking water of Beijing. The adsorption isotherm of the used powdered activated carbon on Gaobeidian WWTP secondary effluent showed a good sorption behaviour

for organic compounds in our study. When the applied dosage was 30 mg/L powdered activated carbon, the LC-OCD chromatographs indicated that the reduction of organic pollutants expressed by DOC was mainly in the low molecular range (Fig.3a). The removed 1 mg/L (14%) DOC could be ascribed to this fraction. On the contrary, high molecular fractions, such as, polysaccharides and humic substances remained stable. Their large size might hinder their entrance to the inside of the activated carbon, as well as the adsorption on the activated site. They cannot be effectively adsorbed by this activated carbon.

Polyaluminum chloride provoked a formation of

Table 2 Mean concentrations (min–max) in the samples of the advanced treatment process

	DOC, l/m	UV-254, m ⁻¹	AOX, µg/L	Total P, mg/L	Total N, mg/L
Feed water	6.9 (5.9–8.3)	12.1 (9.9–14.9)	44 (32–68)	1.65 (0.78–2.43)	28.8 (26–32)
After adsorption	5.9 (4.8–7.2)	10.6 (9.5–12.2)	12 (8–16)	1.59 (0.78–2.4)	28.5 (26–32)
After flocculation	3.9 (3.5–4.5)	6.6 (5.9–7.9)	12 (8–18)	0.4 (0.2–0.62)	27.1 (25–30)
Recharge basin	4.9 (3.6–5.8)	8.8 (6.2–10.1)	13 (8–15)	0.26 (0.03–0.44)	27.6 (25–29)

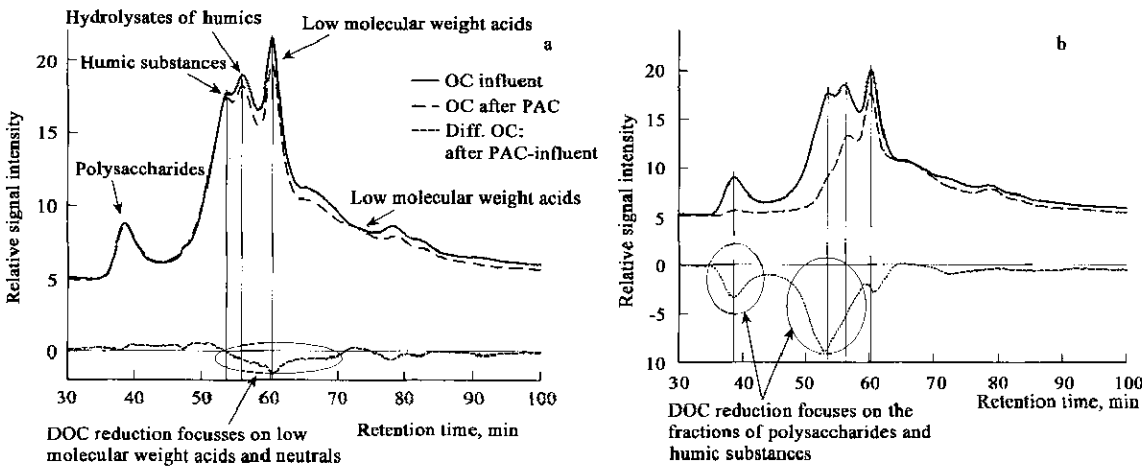


Fig.3 Comparison of LC-OCD chromatographs of samples from influent and effluent of powdered activated carbon-adsorption (a) and flocculation (b) OC, organic carbon

flocs, which enclosed the spiked powdered activated carbon from the water. Sedimentation and rapid sand filtration finally removed the flocs and the activated carbon together. The chromatographs of the samples before and after the flocculation (Fig.3b) show that the polysaccharide fraction has been removed almost completely. Other substances with high molecular weight (humic substances) have also been removed to a great extent. Polysaccharides and high molecular weight fractions accounted for a large proportion of the DOC in this secondary effluent. Their removal played an important role in the reduction of DOC in flocculation unit, which was about 2 mg/L (29%).

By treatment with powdered activated carbon, the level of AOX could be reduced by 70% (Table 2). Investigations concerning AOX-blank values of the employed powdered activated carbon showed that the

activated carbon was free of organic halogens. There was no additional AOX removal by flocculation. Powdered activated carbon is an effective unit to remove AOX. Drewes also reported that PAC could reduce the AOX concentration by 40% from the advanced effluent of WWTP Berlin-Ruhleben Germany (Drewes and Jekel, 1998). Activated carbon adsorption exhibited no significant sorption of total P and N, while flocculation led to a removal rate of total P over 70%. The use of powdered activated carbon adsorption (460 USD/t) and polyaluminum chloride (121 USD/t) flocculation removed about 40% of DOC in the secondary effluent. The estimated costs of adsorption material and chemical reagent (powdered activated carbon and polyaluminum chloride) for the advanced treatment would be 0.018 USD/m³.

2.2 Disinfection

Disinfection with sodium hypochlorite (NaClO) solution was investigated before the treated water flowed into the recharge basins. The total bacteria, total coliform, disinfection by-products, AOX were detected. When the dosage of chlorine was 6–8 mg/L, a good disinfection effect, total bacterial less than 10 CFU/ml and total coliform less than 20 CFU/L, could be obtained in the treated water. However, AOX increased obviously with the increasing dosage of chlorine. This implies a significant formation potential of disinfection byproducts in this water. Many of the compounds represented by AOX are persistence of biodegradation in the groundwater or surface water, and their potential risk effects on human health are still under investigation. Moreover, the experiences of using bank filtration or surface water for groundwater recharge in Middle Europe showed that there was a reliable elimination of pathogenic bacteria, viruses and parasites in the subsurface (Schmidt, 1996). Therefore, chlorination process before groundwater recharge was not recommended in this investigation.

2.3 Soil aquifer treatment

There was intense algae growth in summer in the recharge basins. Due to the release of dissolved organic carbon by algae activity, the concentration of DOC has increased by about 1 mg/L. That was 4.9 mg/L. In the LC-OCD chromatograph in Fig.4, it is obvious that this increase of DOC resulted from the formation of polysaccharides and other organics eluting in the fraction of the humic substances. The generated fresh humics and polysaccharides are expected to be readily biodegradable.

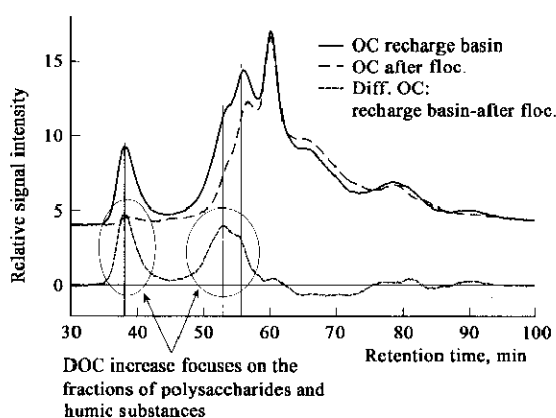


Fig.4 Comparison of LC-OCD chromatographs of samples taken from the flocculation effluent and the recharge basin

In this study, the DOC concentration decreased from 4.9 mg/L in the recharge basins to 2.3 mg/L in the monitoring Well 1 (Fig.5), which was just underneath the recharge basins. It indicated that the most proportion of the organic matter was removed already in the unsaturated layer when the water passed down through the vadose zone (0–9.6 m). Similar

findings have been reported in other study on the artificial recharge that organic matter was removed in the uppermost soil layer (Drewes and Fox, 1999a; Frycklund, 1995). The removal of DOC fractions was the results of microbial degradation, physical and chemical adsorption and mechanical filtration by soil particles. Drewes and Fox (1999b) have confirmed with field measurements that biodegradation is the dominant removal process for DOC during soil aquifer treatment. Fig.5a demonstrated how DOC varied with distance at monitoring wells down gradient of the infiltration basins. The average DOC concentrations varied between 2.1 and 1.9 mg/L in the monitoring wells located 43 m to about 90 m. These values were only slightly lower than the DOC value in monitoring Well 1 and almost the same to the DOC of the background. It exhibits that the removal rate of organic matter was relatively small after the artificially recharged water reached the aquifer zone.

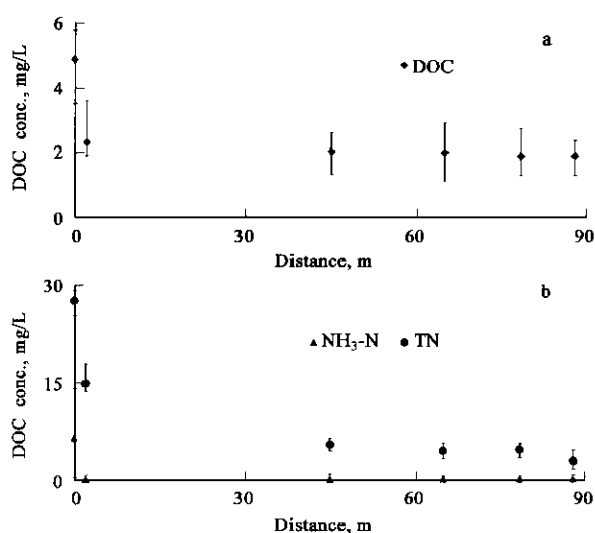


Fig.5 DOC (a), total N and $\text{NH}_4^+\text{-N}$ (b) concentration in aquifer at distances of 0–90 m from the infiltration basins

The removal of total N and $\text{NH}_4^+\text{-N}$ had a similar behaviour in comparison to DOC. An obvious proportion of N and $\text{NH}_4^+\text{-N}$ was removed during the infiltration process in the vadose zone (Fig.5b). $\text{NO}_3^-\text{-N}$ was the main existing form of total N in recharge basins, and it was almost the only existing form after the infiltrated water reached the aquifer. Almost all $\text{NH}_4^+\text{-N}$ was oxidized to $\text{NO}_3^-\text{-N}$ in the uppermost soil layer (at the bottom of the recharge basins). The concentration of $\text{NH}_4^+\text{-N}$ in different monitoring wells showed no obvious difference. They were between 0.2–0.21 mg/L. $\text{NO}_3^-\text{-N}$ can be transformed to N_2 under anoxic conditions. The dissolved oxygen was almost consumed for biodegradation of organic matters by aerobic microorganisms at the bottom of basins and the vadose zone. There was very limited dissolved oxygen

in the aquifer, and an anoxic condition existed in the aquifer. This and the dilution with aquifer water may account for the reduction of NO_3^- -N between monitoring Wells 1 and 2.

The mean concentration of total phosphate in the monitoring Well 1 was 0.08 mg/L. And the detected values in monitoring Wells 2, 3, 4 and 5 were all less than 0.1 mg/L. Other values like AOX and UV-254 declined slightly as the down gradient distance increased.

3 Conclusions

An artificial groundwater recharge with the advanced treatment of secondary effluent was investigated in this study. The results showed that the selected advanced process and soil aquifer treatment was able to reduce the organic substances greatly. The LC-OCD chromatographs proved that powdered activated carbon adsorbed low molecular range of DOC, while flocculation could reduce polysaccharides and high molecular range DOC. The retention of the treated water in open recharge basins will result in an increase of organic matters, mainly were polysaccharides and high molecular fraction of the humic substances. During SAT, part organic matters were removed in the unsaturated zone, while the reduction rate of DOC was limited in aquifer layer. In reclaimed water from Well 4, a desired concentration of $\text{DOC} < 3$ mg/L, $\text{AOX} < 20$ $\mu\text{g/L}$ and low content of P, NO_3^- -N could be achieved.

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