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Assessing impact of irrigation water on groundwater recharge and quality in arid environment using CFCs, tritium and stable isotopes, in the Zhangye Basin, Northwest China

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SUMMARY

Environmental tracers CFCs, ^{18}O, ^{2}H and tritium were used to determine the natural groundwater recharge and the impact of irrigation activity on the groundwater system in the semi-arid Zhangye Basin of China. Groundwaters in the irrigated areas have been identified as mixtures containing fractions recharged in different periods of time. The CFC and ^{3}H data show that the oldest fraction in the groundwater was recharged before 1950, whereas the younger fractions were recharged in different periods of time since 1950. Stable isotope (^{18}O, ^{2}H), CFC and electrical conductivity data show that most of the samples can be regarded as binary mixtures with the river/irrigation water presents the younger fraction and the regional groundwater presents the older fraction. Binary mixing model is used to estimate the age and fraction of the younger component. Most of the younger fraction was recharged after 1980s, in response to the increasing irrigation activities. Compared to local precipitation surface water plays a major role in recharging the aquifer in the irrigated area. The irrigation activity had more impact on the aquifer under thin unsaturated zone (<10 m), due to short travel times and high amounts of recharge, whereas it had less impact on the aquifer under thick unsaturated zone (tens of meters). CFCs are useful in identifying regions of different impact of irrigation return flow. The positive correlation between nitrate and CFC data show that contaminants are transported to the saturated zone by irrigation water. This study shows that in this semi-arid basin due to strong evaporation of infiltrating surface water and regional groundwater, $\delta^{18}O$ and EC values, in contrast to CFCs, do not show simple relationship with NO_3^- concentration in groundwater. Combined with a proper mixing model, however, they can provide evidences that the CFCs found in groundwater were introduced by infiltrating irrigation return flow and, therefore, reveal that human activities can produce a much localized water circulation and influence groundwater vulnerability.

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1. Introduction

In densely populated arid and semi-arid regions, river water and groundwater are essential and scarce resources for life, agriculture and ecology. The assessment of renewability and vulnerability of the groundwater resources as well as the study of interaction of groundwater and river water is an important step to sustainable development in these regions.

In arid and semi-arid regions evaporation typically exceeds precipitation during most seasons, leading to practically negligible continuous recharge from the precipitation. In fact, this is the case in our study area, where precipitation amounts less than 200 mm per year, whereas pan evaporation is of the order of 2500–3500 mm per year. In arid regions, localized recharge is considered to be at least as significant as direct recharge (Stephens, 1994). However, the quantification of localized recharge caused by irrigation is rather complex owing to its heterogeneous character and spatial difference in hydrogeological conditions (e.g. thickness of unsaturated zone and lithology).

The Heihe River, the second largest inland river of Northwest China, flows through the Zhangye Basin, which has a population about 1.8 million. The expansion of agriculture in the middle reaches of the Heihe River in the past 30 years has resulted in a decrease of surface water supply, serious vegetation degradation, and desertification in the lower reaches of the Heihe River. Over 80% of the total river water in the basin is diverted from the main river course to irrigation canals (Gao, 1991; Chen et al., 2006). In

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order to meet the demands for water in the lower reaches of the Heihe River, particularly in the Ejina Basin, a total of 6–10 × 10^8 m^3 of the river water have been diverted annually from the middle to the lower reaches of the river since 2000 (Hao, 2001). Therefore, groundwater abstraction, which is concentrated in the Zhangye Basin for agricultural and industrial purposes, has been increasing gradually to compensate for the reduced river water supply.

Observations by Cao et al. (2002) show that in this irrigated region irrigation return has been a significant source of recharge. Quantitative estimation of irrigation return flow and residence times are vital for management of the groundwater resources and assessing vulnerability of aquifers to contamination (Böhlke and Denver, 1995; Manning et al., 2005; Moore et al., 2006; Osenbrück et al., 2006; Oster, 2006; Hinkle et al., 2007). However, no systematic age information was available prior to this study.

Chlorofluorocarbons (CFCs) have been used widely to provide information on groundwater residence times and mixing processes for waters up to 50 years old (e.g. Busenberg and Plummer, 1992; Dunkle et al., 1993; Cook and Solomon, 1995; Cook et al., 1995; Oster et al., 1996; Cook and Böhlke, 1999; Solomon and Cook, 2000; Plummer et al., 2001; IAEA, 2006; Kaown et al., 2009; Darling et al., 2010). Some studies have been carried out using CFCs to identify and quantify irrigation water in groundwater mixtures (Plummer et al., 2000; Horst et al., 2008).

At least two processes have to be considered for the CFC dating in agricultural areas: natural recharge and irrigation recharge under various hydrogeological environments (e.g. shallow and deep unsaturated zone). CFCs in water exchange with the atmosphere during irrigation, and if contaminated by other sources, the waters will contain elevated CFCs. Irrigation can be regarded as an anthropogenic recharge process overlapped on natural circulation process, and this may cause elevated CFC concentration relative to natural (or regional) groundwater. Irrigation water can be taken as an end-member of young component in a mixture of irrigation water and natural groundwater. CFCs can be used as indicators for identifying hydrogeological process in the following two environments: modern recharge from irrigation areas of shallow unsaturated zone with high CFC concentrations in groundwater; discharge from shallow unsaturated zone with low CFC concentrations.

In this paper, CFCs, together with tritium, stable isotopes (^{18}O and ^{2}H), as well as electrical conductivity measurements, are used to identify and quantify irrigation water recharge in groundwater mixtures from a shallow sand aquifer in the Zhangye Basin. The objective of the study is to assess the impact of irrigation water on groundwater recharge and quality, in particular, in an arid region where evaporation exceeds precipitation through out the year to provide a better understanding of the aquifer system for improvement of river basin management.

2. Description of study area

The Zhangye Basin is a northwest-trending basin about 180 km long and 35–60 km wide (Fig. 1). The plain slopes generally northwestward from an altitude of about 1700 m above sea level (masl) in the southeast to about 1300 masl in the northwest and is flat relative to the surrounding mountains, where altitudes range from 2000 to 5000 masl in the Qilian Mountains to the west and 1600–3000 masl in the Helishan–Longshoushan Mountains to the east. The entire basin is drained by the Heihe River and its tributaries. The river originates from the upper mountain area and is sourced by rain, melt water from snow and glaciers, which accounts for 80–90% of the surface and ground water of the river-basins in the Heihe Catchment, with only 10–20% from local lateral inflow (Zhang et al., 2004).

Yingluoxia (the Yingluoxia Gorge) and Zhengyixia (the Zhengyixia Gorge) divide the drainage area of the Heihe River into upper, middle and lower reaches, with the Zhangye Basin located in the middle reaches. River water inflow at Yingluoxia was about 1.6 × 10^9 m^3/a, and outflow at Zhengyixia has been less than 1 × 10^9 m^3/a since 1985.

The mean annual air temperature in this basin is about 7.6 °C. The climate is semiarid. The mean annual precipitation ranges from 50 mm to 150 mm and the mean pan evaporation rate is about 2000–2200 mm/year (Gao 1991). Most surface flow and recharge to groundwater originate as precipitation in the Qilian Mountains, the catchment area, with a mean annual temperature of 3–4 °C, mean annual precipitation of 200–500 mm (Wang and Cheng, 1999). Glaciers cover approximately 421 km^2 above 4500 masl (Chen, 2002).

The Zhangye Basin consists of alluvial fans and floodplain downgradient of the distal fan-front. The alluvial fan consists of coarse-grained gravel and sand with a thickness up to 1000 m, and the floodplain consists of silty sand with a thickness of 50–200 m (Fan, 1991; Chen, 1997) (Fig. 2). From the southeast to northwest of the basin, grain size of the sands decreases from coarse to fine, and the aquifer varies from a single-layer to dual- or multiple layers. The water table depth ranges from 50 to 170 m in the southwest, 10–50 m in the middle, and 1–5 m in the northeast near the riverbank and in the lower part of the floodplain. Ground water flow is generally from southwest to northeast, with a hydraulic gradient of about 0.6–0.8% in the southeast, which decreases to 0.3% in the northwest in the Quaternary Porous Aquifer. Hydraulic conductivity values for the porous aquifer range from 5 to 45 m/day.

Regionally, water in the Zhangye Basin moves from the Qilian Mountain front to the river valley (Fig. 1). The Heihe River with its tributaries and extensive canals are the major source of recharge to the Zhangye Basin Aquifer. Given that the mean annual recharge from the river and its tributaries to the basin aquifer remains constant, the amount of recharge to the aquifer will depend on the amount of water used for irrigation.

Irrigation is mainly located between Zhangye–Linze–Gaotai close to the western bank of the river, where the unsaturated zone thickness ranges from several to tens of meters and the river water is relatively abundant. At this particular reach, the system has close interaction between groundwater and surface (irrigation) water. The irrigation water recharge had resulted in a rising groundwater level in the Linze–Gaotai river valley plain since the 1990s (Yang and Wang, 2005).

3. Methods

A total of 59 wells from the Zhangye Basin were sampled in October 2002, June/July 2003, March 2004, July 2004, and September 2004. Sampling locations are shown in Fig. 1. Groundwaters were taken from wells for public supply and water level monitoring wells, and most of the wells are housed in solidly built pumping stations or in chambers with a concrete floor and roof. Water table is in a wide range from a few meters to 170 m, and water depth in wells is in the similar range as the water table (Table 1 and Fig. 3).

Fig. 2 indicates that it is almost a single aquifer in the front fan area that consists mainly of middle to coarse-grained sand with pebble. Samples collected from deep wells do not necessarily mean that they consist of mixtures of multilayered water, though certain degree of mixing may occur. During sampling, the information of the well structure and depth of submersible pump was collected, so that it can be used to infer the collected water samples whether it is from a single aquifer or multi-aquifer.

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