Impact of Diverted Water on Hydrochemical Characteristics of Surface Water and Groundwater in the North China Low Plain: A Case Study of Nanpi County, Hebei Province (Postprint)

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Abstract

The North China Low Plain region exhibits substantial potential for grain production increase, yet it is also characterized by prominent conflicts between grain production and agricultural water resources. The conjunctive use of externally transferred water and shallow brackish groundwater constitutes an effective approach to addressing regional water resource issues, concurrently inducing alterations in the regional hydrological cycle and water environment. To elucidate the effects of external water transfer on the hydrochemical characteristics of surface water and groundwater in the North China Low Plain region, this study conducted investigations and seasonal sampling of surface water and groundwater in Nanpi County, Hebei Province, employing an integrated approach of hydrogeochemistry and hydrogen-oxygen ($ $2H, $ $18O) stable isotopes to examine the influence of external water transfer on surface water-groundwater interactions and their hydrochemical characteristics. The results demonstrate that from November to July of the subsequent year, surface water electrical conductivity (EC) and sodium adsorption ratio (SAR) increased, while $ $2H and $ $18O isotopes underwent progressive enrichment under evaporation effects; due to ion exchange and adsorption processes between surface water and surrounding soils, the hydrochemical type shifted toward saline water characterized by increased Na+, Cl−, and SO4ˆ2− concentrations and decreased HCO3− content. Water transfer modified the recharge relationship between surface water and shallow groundwater. From November to March of the subsequent year, shallow groundwater adjacent to ditches received direct recharge from external water transfer or irrigation, leading to reduced EC, shallower water table depths in March, with some sampling points plotting within the SAR-EC domain of the transferred water. Affected by water transfer, the hydrochemical types of shallow groundwater near ditches in March, including Na · Mg · Ca-Cl · SO4, Na ·

Mg-Cl • SO4 • HCO3, and Na • Mg-SO4 • Cl • HCO3, represent transitional facies between the November transferred water (Na • Mg • Ca-SO4 • HCO3 • Cl) and the shallow groundwater (Na • Mg-Cl • SO4). From March to July, shallow groundwater recharged ditch water, groundwater depths increased, and the hydrochemical types of shallow groundwater in July remained similar to those in March. Water transfer can seasonally improve the quality of ditch water and adjacent shallow groundwater, whereas it exerts no ameliorative effects on deep groundwater or pond water quality. Improvements in ditch water quality by water transfer are manifested during the transfer season, whereas amelioration of shallow groundwater quality exhibits a temporal lag; following water transfer in November 2014, shallow groundwater quality improved by March 2015. Therefore, implementing blended irrigation using transferred water, shallow groundwater, and pond water is of substantial significance for the rational development and utilization of regional saline and fresh water resources, reducing deep groundwater over-exploitation, and restoring groundwater levels.

Full Text

Introduction

The lowland area of the North China Plain possesses tremendous potential for grain yield increase, yet it is also a region where contradictions between grain production and agricultural water resources are particularly acute. The combined utilization of diverted water and shallow brackish groundwater represents one effective approach to addressing regional water resource challenges, though this will inevitably alter regional water cycling and the aquatic environment. To clarify the impacts of diverted water on the hydro-chemical characteristics of surface water and groundwater in the lowland areas of the North China Plain, this study conducted investigations and sampling of surface water and groundwater across different seasons following water diversion in Nanpi County, Hebei Province. Using an integrated approach of hydro-geochemical analysis and stable hydrogen-oxygen isotopes ($ $2H, $ $18O), we examined how diverted water influences the transformation between surface water and groundwater and affects their hydro-chemical characteristics.

The results indicate that from November to July of the following year, evaporation increased the electrical conductivity (EC) and sodium adsorption ratio (SAR) of surface water while enriching $ $2H and $ 18Oisotopes.Exchangeandadsorptionbetweensurfacewater
},andSO_{4}$^{2-}$. Water diversion altered the recharge relationship between surface water and shallow groundwater. From November to March, shallow groundwater near diversion channels received direct recharge from diverted water or irrigation return flow, which decreased EC and raised the water table, with some sampling points falling within the SAR-EC range of the diverted water. Influenced by the diverted water, the hydrochemical types of shallow groundwater near channels in March were Na • Mg • Ca-Cl • SO_4, Na • Mg-Cl • SO_4 • HCO_3, and Na • Mg-SO_4 • Cl • HCO_3—transitional types between

the November diverted water ($Na \cdot Mg \cdot Ca\text{-}SO_4 \cdot HCO_3 \cdot Cl$) and shallow groundwater ($Na \cdot Mg\text{-}Cl \cdot SO_4$). From March to July, shallow groundwater recharged channel water, and the water table deepened. The hydrochemical type of shallow groundwater in July remained similar to that in March. Water diversion can seasonally improve water quality in regional channels and adjacent shallow groundwater, but has no improving effect on deep groundwater or pool water. The improvement in channel water quality occurs during the diversion season, while improvement in shallow groundwater exhibits a time lag—water quality improved in March 2015 following the November 2014 diversion. Therefore, mixed irrigation using diverted water, shallow groundwater, and pool water is significant for the rational development and utilization of regional brackish-fresh water resources, reducing deep groundwater exploitation, and restoring groundwater levels.

1.1 Study Area Overview

The study area is located in the transition zone between inland and coastal plains, belonging to the alluvial plain of the Yellow River and Haihe River [Figure 1: see original paper]. The region has a warm temperate semi-arid and semi-humid monsoon climate with abundant sunlight resources, an annual maximum temperature of 31°C, minimum of -19°C, $ $19°C accumulated temperature of 4,300°C, and average annual sunshine duration of 2,318 hours. Precipitation varies greatly both inter-annually and intra-annually, with a multi-year average (1954–2010) of 572.5 mm. Precipitation distribution is uneven within the year, with June–August rainfall accounting for approximately 73.6% of the annual total.

The region contains four aquifer groups [Figure 2: see original paper]. The first and second aquifer groups contain brackish and slightly saline water with low development and utilization rates. The third and fourth aquifer groups contain fresh water and serve as the primary water source for industrial and agricultural production. The area has a well-developed surface water system, including four major rivers (Grand Canal, Zhangwei New River, Xuanhui River, and Sigang New River), the Dalangdian reservoir, five diversion canals from Dalangdian (Canals No. 1–5), and major drainage ditches including Dalangdian Drainage, Xiaoquan Main Canal, and Ludong Ditch [Figure 1: see original paper]. Agricultural diverted water first enters the Xiaoquan Main Canal via the South Canal, then is distributed through four diversion canals from Dalangdian for irrigation. No secondary agricultural water diversion occurred in the study area between November 2014 and July 2015. During the sampling period, three irrigation events took place: November 2014 wheat irrigation using primarily deep groundwater and diverted water (fields near diversion channels used channel water while distant fields used deep groundwater), March wheat irrigation, and early July corn irrigation, both primarily using deep groundwater.

1.2 Sample Collection and Analysis

This study focused on surface water from the Dalangdian diversion canals and surrounding groundwater. Field investigations and water sampling were conducted in November 2014, March 2015, and July 2015 in the area north of Xuanhui River and west of Canal No. 4 [Figure 1: see original paper]. Samples included shallow groundwater, deep groundwater, channel water, and pool water. Shallow groundwater depth was measured in the field using a portable pH meter (pH/ORP/DO METER D-75, HORIBA Scientific, Japan) and electrical conductivity was measured with a conductivity meter (COND METER ES-71, HORIBA Scientific, Japan).

Groundwater samples were collected after pumping for approximately 3 minutes, then stored in sealed 50 mL and 100 mL plastic bottles at 4°C and analyzed within one week. Chemical and isotopic analyses were performed at the Key Laboratory of Agricultural Water Resources, Chinese Academy of Sciences. Cations (K^+, Ca^{2+}, Na^+, Mg^{2+}) and anions (Cl^-, $SO_4{}^{2-}$) were analyzed using ion chromatography (ICS-2100, Dionex, USA). $HCO_3{}^-$ was determined by double-indicator titration. All samples underwent anion-cation balance verification to ensure reliable error ranges within $±$5%. $ $2H and $ $18O were measured using a liquid water isotope analyzer (L2120-i Isotopic H2O; Picarro, USA) with VSMOW standards, achieving analytical precision of $±$0.5‰ for $ $2H and $±$0.2‰ for $ $18O.

2.1 Physicochemical Properties of Surface Water and Groundwater

presents statistical values of hydro-chemical parameters for surface water and groundwater in the study area. Regional surface water and groundwater are alkaline. pH showed minimal seasonal variation in deep groundwater and channel water, while average pH of shallow groundwater and pool water increased from November 2014 to July 2015. The pH variation pattern across water bodies was: November 2014—shallow groundwater (7.43) < pool water (8.24) < deep groundwater (8.25) < channel water (8.33); March 2015—shallow groundwater (7.57) < channel water (8.35) < deep groundwater (8.41) < pool water (8.54); July 2015—shallow groundwater (7.60) < deep groundwater (8.43) = channel water (8.43) < pool water (8.94).

EC values showed different seasonal patterns across water bodies. Deep groundwater had the lowest average EC with minimal seasonal variation (1,369-1,417 $\mathrm{S \cdot cm^{-1}}$). Shallow groundwater EC decreased from November 2014 to March 2015, then increased from March to July, with values in November 2014 and July 2015 being similar. Pool water EC showed opposite seasonal variation to shallow groundwater. Channel water EC increased continuously from November 2014 to July 2015, with an increase of 4,520 $\mathrm{S \cdot cm^{-1}}$. Specific seasonal patterns were: November 2014—deep groundwater (1,417 $\mathrm{S \cdot cm^{-1}}$) < channel water (1,623 $\mathrm{S \cdot cm^{-1}}$) < pool water (4,125 $\mathrm{S \cdot cm^{-1}}$) < shallow groundwater (4,173 $\mathrm{S \cdot cm^{-1}}$); March 2015—deep groundwater (1,403 $\mathrm{S \cdot cm^{-1}}$) < channel water (3,606 $\mathrm{S \cdot cm^{-1}}$) < shallow groundwater (3,863 $\mathrm{S \cdot cm^{-1}}$) < pool water (4,846 $\mathrm{S \cdot cm^{-1}}$); July 2015—deep groundwater (1,369 $\mathrm{S \cdot cm^{-1}}$) < shallow groundwater (4,167 $\mathrm{S \cdot cm^{-1}}$) < pool water (4,700 $\mathrm{S \cdot cm^{-1}}$) < channel water (6,143 $\mathrm{S \cdot cm^{-1}}$).

Considering local hydrogeological conditions and field investigations, the shallow groundwater depth in the lowland area is relatively shallow, facilitating rapid exchange between surface water and groundwater. The introduction of diverted water with lower EC into regional water cycling can reduce mineralization of regional surface water and shallow groundwater. Therefore, differences in EC values among water bodies across seasons can reveal their sources and recharge relationships.

Stable isotopes \$ \$2H and \$ \$18O serve as tracers for recharge relationships between different water bodies [15]. shows statistical characteristics of \$ \$2H and \$ \$18O values across seasons. Due to evaporation from surface water bodies, surface water \$ \$2H and \$ \$18O values are higher than groundwater and show seasonal trends, while groundwater isotope values varied little across seasons. The seasonal variation magnitude followed: pool water > channel water > shallow groundwater > deep groundwater.

2.2 Recharge Relationships Between Surface Water and Groundwater

As interconnected components of the same resource, surface water and groundwater mutually influence each other' s quantity and quality [16]. Clarifying their transformation relationship is crucial for regional water resource development and management. [Figure 3: see original paper] illustrates the \$ $2H-$ \$18O relationship for surface water and groundwater. Deep groundwater \$ \$2H and \$ \$18O values differed substantially from surface water and shallow groundwater. Xu [17], using Greenland ice core isotope data combined with local hydrogeological conditions and historical geography, concluded that deep groundwater in Cangzhou (well depth 300–450 m, \$ \$2H range -76‰ to -72‰, \$ \$18O range -10.7‰ to -10.1‰) was recharged by paleowater from the Late Pleistocene ice age, while shallow groundwater (well depth 10–50 m, \$ \$2H range -69‰ to -59‰, \$ \$18O range -9.6‰ to -8.2‰) was mainly recharged by Holocene Yellow River water. Chen [18] proposed isotopic ranges for shallow and deep groundwater in the North China Plain that correspond with this study' s values. Combined with hydrogeological conditions [Figure 2: see original paper], this confirms that deep and shallow groundwater have different origins and no hydraulic connection.

Unlike deep groundwater, shallow groundwater isotopes overlap with some surface water values, indicating close hydraulic exchange. Intense evaporation enriches surface water isotopes, and recharge from isotopically enriched surface water to shallow groundwater makes shallow groundwater isotopes relatively enriched, approaching some surface water values. Meanwhile, some surface water isotopes are substantially higher than groundwater, demonstrating evaporation characteristics. Shallow groundwater near pools shows isotopic values similar to pool water ($ $2H range -48.9‰ to -46.8‰, $ $18O range -5.9‰ to -5.6‰) but higher than other shallow groundwater, confirming recharge from pool water to adjacent shallow groundwater (S20).

While isotopic relationships prove close hydraulic connection between surface water and shallow groundwater [15], they cannot demonstrate seasonal recharge direction. Seasonal variation in shallow groundwater depth provides an important indicator of recharge relationships [20]. [Figure 4: see original paper] shows shallow groundwater depths at selected sampling points. Except for S16, groundwater depth decreased from November 2014 to March 2015, then increased from March to July. Groundwater depth also showed spatial variation related to distance from channels. Under direct channel recharge and irrigation return flow, shallow groundwater depth near channels fluctuated significantly; with increasing distance, channel water influence decreased and depth fluctuation diminished. Precipitation was minimal between November 2014 and March 2015, yet shallow groundwater depth decreased [Figure 4: see original paper], contrary to previous hydrogeological monitoring data showing continuous decline during this period [17]. This indicates that shallow groundwater depth decrease resulted from direct recharge by diverted water and irrigation return flow. From March to July 2015, as channel water volume decreased, shallow groundwater recharged channel water, causing depth increase. The continuous decline at S16 was related to seasonal industrial wastewater discharge, which directly entered shallow groundwater through hidden pipes; cessation of discharge and shallow groundwater flow diffusion caused continuous water level decline.

In summary, from November 2014 to March 2015, diverted water directly or through irrigation recharged shallow groundwater near channels; from March to July 2015, shallow groundwater near channels recharged channel water. Shallow groundwater far from channels was less affected and is not discussed here.

2.3 Effects of Water Diversion on Regional Hydro-chemical Characteristics

Previous studies show that mixing of diverted water with groundwater can improve groundwater quality [21], while groundwater flow interactions with the surrounding environment alter hydro-chemical characteristics [22]. Since pool water does not receive diverted water and most pools are distant from channels, pool water represents unaffected surface water. Diverted water directly enters channels, so channel water, especially at diversion starting points, represents diverted water chemistry. The time lag in surface water recharge to groundwater means November 2014 shallow groundwater represents pre-recharge conditions. Due to chemical differences between diverted and regional water, diversion affects water chemistry in receiving areas. Since diverted water exists only in channels, this discussion focuses on channel and shallow groundwater chemistry. Piper diagrams were used to analyze chemical characteristic changes.

[Figure 5: see original paper] presents Piper diagrams for surface water and groundwater across seasons. Diverted water chemistry showed seasonal variation. Channel water chemistry changed along flow paths: input points (C1, C9, C10) showed $Na \cdot Mg \cdot Ca\text{-}SO_4 \cdot HCO_3 \cdot Cl$ type, while endpoints (C4, C5, C6, C7) showed $Na \cdot Mg\text{-}SO_4 \cdot Cl$ type [FIGURE:5a arrow direction]. Shallow groundwater chemistry was complex with large seasonal variation. In November 2014, different sampling points showed large differences [Figure 5a: see original paper]. Influenced by diverted water recharge, shallow groundwater near channels in March 2015 clustered in Region 1 of [Figure 5b: see original paper], with types $Na \cdot Mg \cdot Ca\text{-}Cl \cdot SO_4$, $Na \cdot Mg\text{-}Cl \cdot SO_4 \cdot HCO_3$, and $Na \cdot Mg\text{-}SO_4 \cdot Cl \cdot HCO_3$—transitional types between shallow groundwater ($Na \cdot Mg\text{-}Cl \cdot SO_4$) and diverted water ($Na \cdot Mg \cdot Ca\text{-}SO_4 \cdot HCO_3 \cdot Cl$). This demonstrates that diverted water significantly improved water quality in shallow groundwater near channels from November 2014 to March 2015. From March to July, without diverted water recharge, shallow groundwater chemistry changed little. From November 2014 to July 2015, evaporation and soil interactions transformed surface water chemistry toward saline water with increased Na^+, Cl^-, and ${SO_4}^{2-}$ and decreased ${HCO_3}^-$ [FIGURE:5c arrow direction]. Different arrows in [Figure 5c: see original paper] show inconsistent water quality changes at different sampling points, proving that channel water quality changes are closely related to surrounding environments.

Besides water transformation, hydrochemical evolution is influenced by hydrodynamic conditions [23]. Formation of groundwater chemistry in different hydrodynamic zones relates primarily to dissolution of carbonate, sulfate, and silicate minerals and evaporation-concentration processes. Gibbs diagrams qualitatively assess impacts of rock weathering, atmospheric precipitation, and evaporation-concentration on groundwater chemistry, classifying water into precipitation-controlled, weathering-controlled, and evaporation/crystallization-controlled types [24]. In Gibbs diagrams, the x-axis represents cation ratio $Na^+/(Na^+ + Ca^{2+})$ or anion ratio $Cl^-/(Cl^- + {HCO_3}^-)$, while the y-axis represents total dissolved solids.

[Figure 6: see original paper] shows Gibbs diagrams for surface water and groundwater. All sampling points fell in the range where $Na^+/(Na^+ + Ca^{2+}) > 0.5$, indicating Na^+-dominated cations and evaporation-concentration influence. Some points fell where $Cl^-/(Cl^- + {HCO_3}^-) < 0.5$, indicating ${HCO_3}^-$-dominated anions and rock weathering influence; others fell where $Cl^-/(Cl^- + {HCO_3}^-) > 0.5$, indicating Cl^--dominated anions and combined rock weathering and evaporation-concentration influence. Inconsistent control between cations and anions primarily relates to ion exchange-adsorption between water and soil. Large amounts of Na^+ in water exchange-adsorb Ca^{2+} and Mg^{2+} from clay minerals through the reaction [23,25]:

$$4Na^+ + Ca–X_2 + Mg–X_2 \rightarrow 4Na–X_2 + Ca^{2+} + Mg^{2+}$$

where X represents clay minerals.

All deep groundwater sampling points fell where $Cl^-/(Cl^-+HCO_3^-) < 0.5$ [Figure 6b: see original paper], with ions primarily from rock weathering. November 2014 channel water also fell in this range, with chemistry primarily influenced by rock weathering in the water source area and flow path environment. From November 2014 to July 2015, channel and pool water showed increasing TDS and $Cl^-/(Cl^-+HCO_3^-)$ and $Na^+/(Na^++Ca^{2+})$ ratios, indicating evaporation-concentration and ion exchange-adsorption. From November 2014 to March 2015, some shallow groundwater points shifted from evaporation-concentration to rock weathering zones, confirming diverted water recharge. From March to July, the opposite shift occurred, proving evaporation was the main influence. Higher TDS in shallow groundwater than surface water also reflects evaporation-concentration during surface water recharge to groundwater.

2.4 Effects of Water Diversion on Regional Groundwater Quality

Water diversion alters water cycling relationships and causes water quality changes in receiving areas [13]. To evaluate irrigation water quality impacts, the relationship between sodium adsorption ratio (SAR) and EC was used for water classification [26]. [Figure 7: see original paper] shows irrigation water quality classification diagrams. In November 2014, channel water fell into three categories: diverted water at diversion starting points in the C3-S1 region [FIGURE:7a Region 1]; diverted water at channel endpoints in C3-S2 and C4-S2 regions [FIGURE:7a Region 2]; and unaffected channel water in C4-S3 and C4-S4 regions [FIGURE:7a Region 3]. During flow, diverted water showed increasing EC and SAR trends, shifting from Region 1 to 2, indicating quality deterioration.

Under continuous evaporation and channel exchange-adsorption, March 2015 channel water showed higher EC and SAR than November 2014, with some points reaching the unaffected Region 3. Influenced by June rainfall and evaporation, July 2015 channel water showed characteristics closely related to surrounding environments. Rainfall improved quality in some channel water points, which fell in C4-S2 and C4-S3 regions.

[Figure 7b: see original paper] shows seasonal pool water quality classification. Under evaporation, pool water SAR and EC increased from November 2014 to March 2015. From March to July 2015, different sampling points showed varying patterns due to local environments. P3 and P5 showed little EC change but increased SAR, demonstrating exchange-adsorption characteristics. P6 showed increased SAR but decreased EC due to leakage recharge from deep groundwater irrigation. P4 and P7 showed both increased SAR and EC, proving evaporation and exchange-adsorption were dominant factors.

[Figure 7c: see original paper] shows seasonal shallow groundwater quality classification. Affected by hidden pipe discharge, S16 groundwater fell in the deep groundwater region [FIGURE:7c Region 1] with low EC. Shallow groundwater near channels fell in C3-S1 and C3-S2 regions, matching diverted water distribution during diversion periods, proving diverted water significantly improved adjacent groundwater quality [FIGURE:7c Region 2]. However, this improvement was temporary, with high salinization risk during other seasons. [Figure 7d: see original paper] shows deep groundwater quality classification, revealing minimal seasonal variation and confirming that diverted water has no effect on deep groundwater quality.

Water diversion changed surface water-groundwater transformation and irrigation water quality in the North China Plain lowland area. From November 2014 to July 2015, evaporation caused increasing EC and SAR in surface water (channel and pool water) and isotopic enrichment. Exchange-adsorption with surrounding soils increased Na^+, Cl^-, and SO_4^{2-}, continuously degrading surface water quality. From November 2014 to March 2015 following diversion, shallow groundwater near channels received direct or irrigation recharge from diverted water, resulting in shallower water tables and reduced EC increase. From March to July 2015, as channel water decreased, shallow groundwater recharged channel water. No hydraulic connection exists between shallow and deep groundwater. Under mixing of channel and shallow groundwater, March 2015 shallow groundwater near channels showed transitional hydrochemical types ($Na \cdot Mg \cdot Ca\text{-}Cl \cdot SO_4$, $Na \cdot Mg\text{-}Cl \cdot SO_4 \cdot HCO_3$, $Na \cdot Mg\text{-}SO_4 \cdot Cl \cdot HCO_3$) between diverted water ($Na \cdot Mg \cdot Ca\text{-}SO_4 \cdot HCO_3 \cdot Cl$) and shallow groundwater ($Na \cdot Mg\text{-}Cl \cdot SO_4$), with SAR-EC ranges matching November 2014 diverted water.

Diverted water represents high-quality freshwater suitable for direct irrigation and can temporarily improve channel water quality, which rapidly degrades after diversion ends, becoming unsuitable for irrigation by March. Channel water deterioration during flow results from Na-Ca exchange-adsorption, placing endpoint water quality at the margin of irrigation usability. Regional pool water and shallow groundwater carry high salinization risk and are unsuitable for direct irrigation. Deep groundwater irrigation also poses significant soil sodification risk. Therefore, mixed irrigation using diverted water, shallow groundwater, and pool water represents an effective measure for comprehensive agricultural water resource utilization and deep groundwater exploitation reduction to restore water levels. This study enhances understanding of surface water-groundwater transformation and hydro-chemical changes under inter-basin water diversion conditions, providing theoretical support for rational agricultural water management and ensuring grain production in the North China Plain lowland area following the South-to-North Water Diversion Project.

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