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Chapter 2

GROUNDWATER MANAGEMENT IN THE REGION OF LA PLATA, PROVINCE OF BUENOS AIRES, ARGENTINA

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ABSTRACT

The paper describes actions applied to the management of water resources in the region of La Plata (Buenos Aires Province, Argentina). The overexploitation of groundwater has modified the hydraulic conditions and, at the same time, has affected the hydrochemical characteristics by favoring contamination from human wastes. At present, the average exploited groundwater volume for human consumption is 73 hm^3/y and since a substantial increase of demand for water is predicted in

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future years, sustainable groundwater exploitation becomes essential. Rational management is necessary to reach a balance between water demands and groundwater conservation to avoid the extreme deterioration of water quality.

Keywords: groundwater management, Buenos Aires Province (Argentina), water balance, hydrologic modification

INTRODUCTION

Groundwater exploitation in La Plata started in 1885 to meet the needs of an increasing population. Through the years, the intense exploitation imposed a hydraulic regime characterized by depression cones in constant expansion that modified natural hydraulic gradients. The original flow direction of groundwater discharge towards the Rio de la Plata became altered, with a subsequent inversion of flow direction that caused salt water intrusion into the producing area.

As a result, in 1945 some exploitation wells had to be abandoned because of their increasing salinity. To compensate this loss and to keep pace with demand, in 1955 the drinking water supply was reinforced with fresh water from the Rio de la Plata, delivered to the city through a 9 km long pipe. At present, water supply is provided jointly from surface water and groundwater.

There is, however, a need for adopting reviewed techniques of groundwater management in agreement with the current demands. Problems derived from depletion of groundwater reserves tend to be solved with the increase, conservation and relocation of drinking water sources (Konikov and Kendy, 2005). However, such management policies have to be considered in a scenario of sustainable groundwater exploitation based on the quantification of the hydrological balance on a basin scale (Kalf and Wooley, 2005). Moreover, problems of water quality, pumping economy, ecological constraints and social and environmental effects of overexploitation should also be accounted for (Custodio, 2002).

This chapter aims to analyse the hydrological conditions in the region of La Plata, and recommends management methods for sustainable groundwater exploitation.

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STUDY AREA

The city of La Plata, located to the northeast of the Buenos Aires Province, was founded in 1882 (Figure 1). Urbanized, industrial and rural zones coexist in its area of influence. The population of La Plata is now over 687 000. There are about 1000 manufacturing industries related to food, metal, and automotive (Figure 2).

The city area spreads over the Arroyo del Gato (literally, Cat’s creek) basin with a drainage network altered with canals, rectifications, culverting, etc. The upper Arroyo del Gato basin has developed into a suburban zone with low population density where the primary economic activities are horticulture and floriculture, with a few industries. In the mid creek basin there is a significant increase in urbanization and population density, in addition to a larger number of industries, service activities and districts of precarious housing settled next to the stream. In the lower creek basin the watercourse crosses a low population density zone (Varela et al, 2002).

Geomorfologically, the study area is a typical flatland (topographic slope 0.1%) with its drainage basin developed between 0 and 25 meters above MWL (mean water level of the Rio de la Plata). The average discharge is 0.08 m^3/s. Two morphologic units (Figure 3) are clearly defined: the inland zone and the coastal plain (Fidalgo and Martinez, 1983). The interior zone extends between 5 and 25 m above MWL, where soils are well drained and infiltration processes predominate. The coastal plain is below 5 m above MWL and constitutes a zone of partial discharge of the groundwater system.

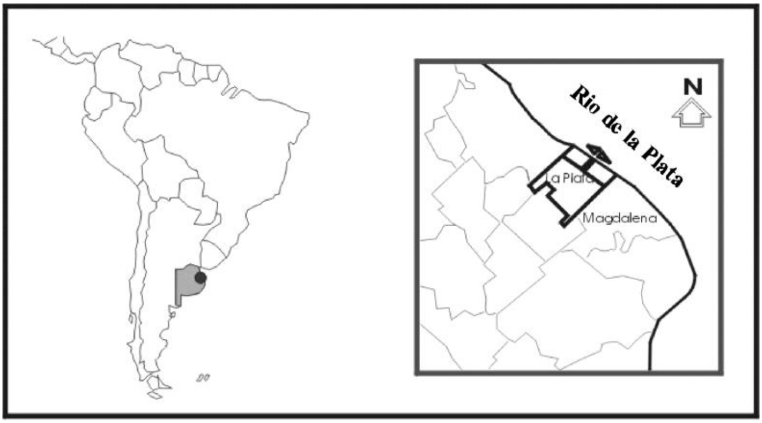

Figure 1. Study area.

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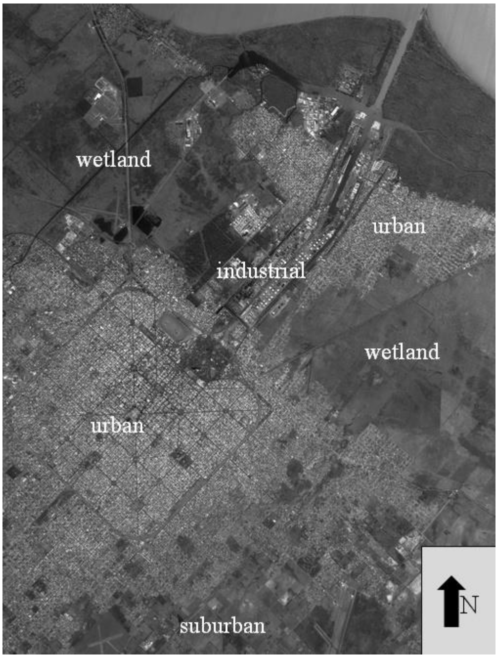

Figure 2. Land uses of the Arroyo del Gato Basin.

Figure 3. Morphologic units.

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GENERAL HYDROGEOLOGY

Hydrogeologically, there exist two units of practical importance: Puelches Formation (sands) and Pampeano Formation (loess, sand, silt and clays) (Figure 4). These units have alternating water producing sections separated by sediments of low permeability, all of them forming a multilayer aquifer. The upper aquifer known as Pampeano (Pampian) is composed of silts with subordinate sands and clays, with a thickness of around 50 m and a transmissivity of 200 m^2/d. The Pampeano includes the water table at a depth varying between 5 and 10 m under natural conditions. The Puelches sands underlie the Pampeano Fm and represent the most important aquifer in the northeast of the Province of Buenos Aires; they are composed of a sequence of fine to medium quartz sands with approximately 20 m in thickness and a transmissivity of 500 m^2/d (Auge, 1995, 2005). The regional recharge of the Pampeano is of meteoric origin, whereas the Puelche aquifer is indirectly recharged by the Pampeano through downward vertical filtration (Sala and Auge, 1973). Local groundwater discharges into the main streams, whereas regional groundwater discharges into the Rio de la Plata (Laurencena et al, 1999).

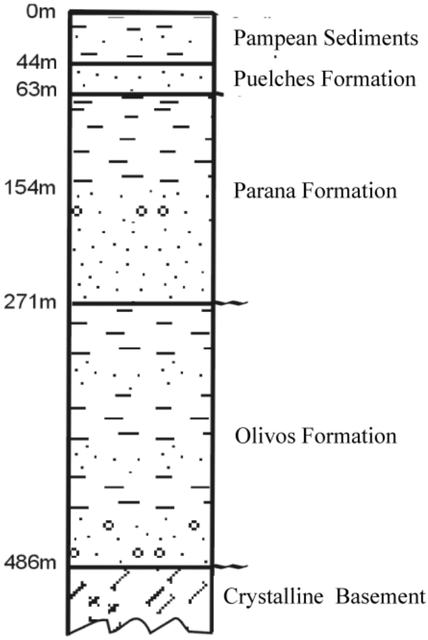

Figure 4. Stratigraphic column of the study area.

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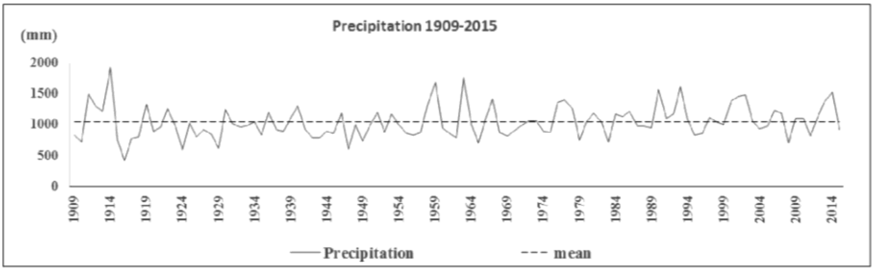

Figure 5. Typical annual precipitation of the La Plata (1909 – 2015). The dash line represents the mean precipitation.

HYDROLOGIC CHARACTERISTICS

The region is characterized by its climatic homogeneity. The annual precipitation shows alternating dry and humid periods (Figure 5). The annual mean temperature increased from 15.8ºC in 1988 to 16.8ºC in 2002. Background studies have shown that this increase was not due to the urbanization of the area.

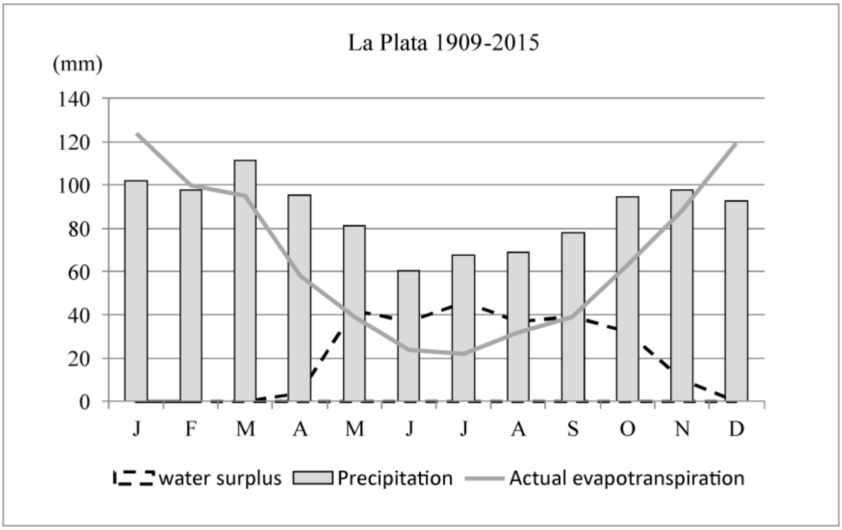

Figure 6. Water balance of La Plata (1909 – 2015).

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The mean annual precipitation from 1909 to 2015 was 1048 mm/y. The actual evapotranspiration, obtained from the water balance (Thornthwaite and Matter, 1955), is 783 mm/y. Fluvial drainage and infiltration reach 53 mm/y and 225 mm/y, respectively (Figure 6).

The natural hydrologic behavior was analyzed through the evaluation of the water balance in a neighboring river basin (Arroyo El Pescado) with similar hydrologic characteristics, but without the effect of human impact. The Arroyo El Pescado is effluent with respect to groundwater, and without intensive groundwater exploitation. The runoff for significant rainfall events (above 120 mm and five-day duration) varies between 1% and 60% of precipitation (Kruse et al. 2004). The analysis of the water table variations (1989-2000) shows clearly changes connected with meteorological oscillations. Recharge estimations in daily periods give values between 20% and 65% of rainfall above 150 mm and five-day duration, associated with important water excesses for dry prior conditions of the soil (Laurencena et al. 2002).

The phreatic water chemical composition of Arroyo El Pescado is sodium bicarbonates with salinities between 370 and 1600 mg/L, evolving to sodium chloride with 8,000 mg/L in the regional discharge zone (coastal plain). The surface water presents the same composition, with smaller salinity values varying between 400 mg/L in the upper creek basin to 950 mg/L in the coastal plain. The progressive increasing salinity, particularly of chloride contents, is noticeable downstream, which is an evidence of groundwater discharge into the stream (Gonzalez and Laurencena, 1988).

The Arroyo del Gato basin presents changes in natural water balance and the interrelation of surface water and groundwater. The existence of impervious zones (urban areas) diminishes the water availability to compensate the actual evapotranspiration, thereby causing an important increase in the excesses of the water balance, with the subsequent increase in volume and speed of runoff. It must be pointed out that the present stream regime is characterized by important floods of short duration (1 or 2 days), favored by drainage from the urban zone. The runoff in the urbanized area for storm events lasting 5 days and greater than 120 mm, oscillates between 23% and 90% of the precipitation. The smaller values correspond to dry conditions of preceding humidity, whereas the larger ones correspond to humid conditions. These magnitudes of runoff in the hydrologic balance allow deducing a decrease of excesses capable of infiltrating (Kruse et al. 2004).

Chemically, groundwater of the Arroyo del Gato basin is of similar major ionic characteristic to the Arroyo El Pescado. On the other hand, there is a

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marked increase in nitrate content reaching values higher than those recommended for human consumption; in many cases, more than 100 mg/L, forcing the abandonment of exploitation wells (Kruse et al. 2003). Surface water presents a high coloring and content of suspended substances, product of spills of human activities in the area (industrial effluents, sewer, etc.). The degree of contamination is verified by the high concentration of phosphorus (>0.25 mg/L of phosphates), organic substances and some pesticides. Since in this case there is a flow from the stream towards groundwater, the polluting agents can migrate towards the phreatic aquifer.

GROUNDWATER EXPLOITATION

In the urban area the Puelche aquifer is overexploited, which has generated depression cones exceeding 70 km^2. Due to hydraulic interconnection between aquifers, this deepening of levels affects the water table.

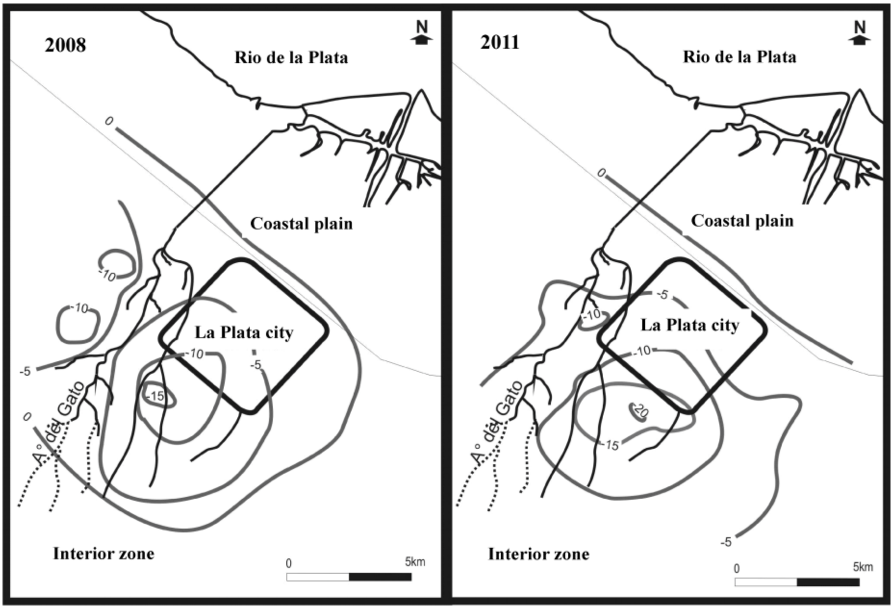

Figure 7. Piezometric map of La Plata. 2008 and 2011.

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At present, the development of relatively stable depression cones has produced a change in the natural hydraulic gradients of the water table, thereby modifying the natural interrelation between surface water and groundwater. This alteration becomes evident in the upper and mid creek basin where there is a clear influence of the watercourse on the water table (Figure 7). The average groundwater volume withdrawn for human consumption is 73 hm^3/y. The direct contribution of the aquifer is approximately 70% (51 hm^3/y) of the total exploited volume. The remaining 30% is supplied by infiltration of water seepage from gutters, water mains, sewer systems and urban irrigation. This means values on the order of 22 hm^3/y (314 mm/y) (Facultad de Ingeniería, 1994).

DISCUSSION AND CONCLUSION

The above factors show the complexity of the environmental hydrogeology problems and the fragility of the system to external agents. Remediation actions are to be carried out against past abuses that were both a direct consequence of the lack of a clear management policy on the use of natural resources, and the wrong belief that water resources were inexhaustible. To mitigate further economic losses and environmental damages, water management policies must be adopted. Policies have to be directed to conserving the resources, protecting the groundwater reserve and avoiding all possible source of contamination. The application of plans to reach a balance between the water demand and environmental protection is essential, and represents a fundamental base for a sustainable exploitation that will preserve freshwater reserves for future generations. Recommended actions include the exploitation of freshwater resources of rural areas, preventing their urbanization and development from potentially polluting activities.

At present, there is an overexploitation of the Puelche aquifer that has modified the natural hydraulic conditions, collaterally affecting the hydrochemical characteristics because of contamination from human wastes. A lack of sewer systems in some areas, as well as spills from water distribution networks favour accumulation and/or enrichment of polluting agents. Since a significant increase in the demand for water, particularly drinking water, is predicted in future years, it is essential to intensify groundwater assessment to get insight in water reserves, to protect recharge areas and delimit discharge zones. The suggested actions include:

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1. Concentrate most groundwater exploitation in rural areas such as the Arroyo El Pescado creek basin), limiting their urbanization and the development of potential polluting productive activities.
2. Groundwater exploitation should be aimed to satisfy drinking water demand.
3. Impose the use of surface water from the Rio de la Plata for all the water needs not requiring drinking properties.
4. Optimize groundwater volumes allocated for potable, industrial and irrigation uses and balance them with groundwater discharge and natural recharge.

Based on the vulnerability and risk of the resource, it is necessary to expand the sewer network in the urban zone, as well as to limit the use of herbicides, pesticides and fertilizers in the countryside. In addition, it is necessary to establish a monitoring network to control groundwater and its withdrawn volumes.

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Chapter 3

THE EVOLUTION AND CHARACTERISTICS OF NATURAL WATERS UNDER AN ARID CLIMATE IN NORTHERN XINJIANG (CENTRAL ASIA)

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ABSTRACT

This paper analyzed the physico-chemical characteristics of natural waters in a drainage system of northern Xinjiang (Central Asia) for an

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identification of the geological evolution and recharge mechanism of natural waters in an arid environment. The studied waters are different in mineralization but are typically carbonate rivers and alkaline in nature. No Cl-dominated water type occurs, indicating an early stage of water evolution. Regolith and geomorphological parameters controlling ground-surface temperature may play a large role in the water geological evolution. Three main morphological and hydrological units are reflected in water physico-chemistry. Climate influences the salinization of natural waters substantially. Direct recharge from seasonal snow and ice-melt water and infiltration of rain into the ground are significant recharge processes for natural waters, but recharge from potential deep groundwater may be less important. The enrichment of ions in lakes has been mainly caused by evaporation rather than through the quality of the recharged water.

Keywords: hydrogeochemistry, arid environment, recharge mechanism, climatic effect, Central Asia

1. INTRODUCTION

Water in the Earth system is not only one of the key components but also a major agent of the biogeochemical cycles that link the lithosphere, biosphere and atmosphere. In the central Asia, high mountains, particularly the Tibetan Plateau and Tianshan Ranges, function as barriers for atmospheric circulation and keep moisture from reaching an extensive region in western China, causing arid and hyperarid climatic conditions (Domros and Peng 1988; Sun et al. 2010). Fresh water in these regions is definitely a non-substitutable resource upon which humans and ecosystems depend. The arid land of northwestern China is significant repositories of information relating to hydrological evolution and climatic changes in central and eastern Asia. Northern Xinjiang in northwestern China, the geographical centre of the Asian Continent, is an extremely arid and ecologically weak region. An understanding of the source of natural waters in the northern Xinjiang watersheds is significant not only to policy makers for regional planning, but also to scientists interested in the hydrological cycles in an arid environment, and the climate change in Northern China and other arid regions of Asia.

Most of the rivers in the northern Xinjiang drainage system originate from peripheral mountain glaciers and snow and drain areas of diverse geology and climatic conditions, with lower reaches in the desert environment. Geochemical studies of these waters are of considerable importance for a

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better understanding of the sources of the natural water resources and the influencing factors. At present, the Xinjiang province has become the focus of attention in China due to its rapidly increasing population and an evident climatic variation. Both of these factors consequently increase stress on regional water resources and environmental protection. Understanding the evolution and recharge mechanisms of natural water is a fundamental issue for both aquatic ecologists and water resource managers (Meyer et al. 1988; Kimbadi et al. 1999). Until now, except for a few studies about the chemical weathering and weathering flux in these regions (Zhu et al. 2011, 2012, 2013a, 2013b, 2015, 2016a, 2016b), little works were carried out in the northern Xinjiang drainage systems. Using the area of northern Xinjiang as an example, this paper provides insight into the physicochemistry of natural waters in arid environment. The geochemical evolution and recharge mechanisms of natural water and the climate effect in this region are emphatically discussed.

2. REGIONAL SETTING

The geographical location of the northern Xinjiang (China) ranges between 78° and 90°E and 42° and 50°N. It is approximately 603,000 km^2 in area and is bounded by the Tianshan Mountains to the south and the Altai Mountains to the north. Elevations increase from <500 m above sea level (asl) in the centre of the Zhungarer Basin to >3000 m asl in the south and north ranges (Figure 1c). The topography is generally flat in the centre plain and is rather cragged in the peripheral mountainous areas. The wide piedmonts and pediment plains are marked by the Gobi desert, grassland for herding and oasis areas with intensive agricultural activities. The land is controlled by an arid temperate continental climate. The mean annual air temperature is about 5°C, with a minimum of -10°C to -20°C in January and a maximum of 28°C to 33°C in August. The regional precipitation is derived mainly from westerlies, with a mean annual precipitation rate of 60-150 mm in the centre plain and 200-500 mm in the surrounding mountainous areas (Figure 1b). While the potential evapotranspiration is approximately 1000-3500 mm per year, it varies in aridity both seasonally and along the elevation gradient across northern Xinjiang, due to the distribution patterns of seasonal precipitation, temperature and relative humidity and the orientation of delivery of moisture by the westerlies.

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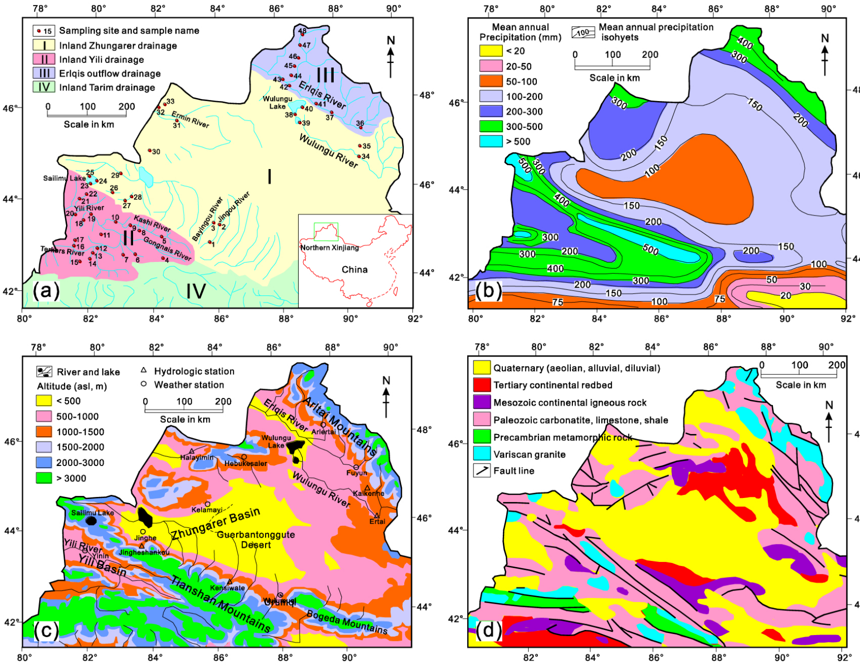

Figure 1. (a) Hydrological setting and sampling locations map, (b) mean annual precipitation isohyets distribution map, (c) topographical map and (d) lithological-distribution map of the northern Xinjiang (Central Asian) in China.

The northern Xinjiang drainage system includes three watersheds: the Zhungarer, the Yili and the Erlqis (Ma 2002) (Figure 1a). The Zhungarer and Yili watersheds are inland continental watersheds and the Erlqis watershed drains into the Arctic Ocean. Water resources in northern Xinjiang are mainly distributed in Yili (170.9 × 10^8 m^3), Arltai (129 × 10^8 m^3) and Tacheng districts (61.6 × 10^8 m^3) and the total volume of the surface water in northern Xinjiang is about 435.7 × 10^8 m^3. The temporal distribution of runoff in a year is extremely heterogeneous with 50-70% in summer, 10-20% both in spring and autumn, and less than 10% in winter. The uneven spatial-temporal distribution of water resources and dry climate environment determine the complete dependence of oasis agricultural activities on water. The Zhungarer Basin (379,000 km^2) is located at the central part of northern Xinjiang and is the geographic centre of the Asian Continent. The basin is a structural depression filled with unconsolidated Quaternary and Tertiary sediments as

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much as 500-1000 m in thickness (XETCAS et al. 1978), and is an extension of the Palaeozoic Kazakhstan block surrounded by Palaeozoic folded mountains. Aeolian deposits are widespread in this basin. The Gulbantonggute Sand Sea (48,800 km^2) is located in the central part of the basin. A large geographic distance from the surrounding oceans and the presence of the rain-shadow effect due to the surrounding orographic conditions is responsible for the arid climate of the Zhungarer Basin, which is necessary for the creation of the sand desert. Most rivers in the Yili watershed converged into the Yili River at their lower reaches. The Yili River is a large international river running from its sources in the northeast Borohoro Mountains and southeast Halik Mountains, both branches of the eastern Tianshan Mountains, and flowing eastward through the Yili basin into Kazakstan (Figure 1). It drains igneous and metamorphic Precambrian (An€) and Variscan (γ_4) granite, Carboniferous (C_1, C_{2+3}) carbonatite and limestone and Quaternary sediments (Ma 2002) (Figure 1d). The Yili River is about 430 km long inside the Yili watershed and contains three major tributaries in the catchment: the Kashi River in the northeast, the Gongnais River in the east and the Terkers River in the south and southeast. Much of the drainage areas of the tributaries are dominated by the sedimentary, mostly carbonate, lithologies (Figure 1d). The Erlqis watershed has headwaters in the southern slopes of the Arltai Mountains (Figure 1a). Rivers converge into the Erlqis River at their lower reaches, and the Erlqis River is also a large international river, flowing through Kazakstan northward through Russia and finally into the Arctic Ocean. The stem channel of the Erlqis River is about 500 km long inside the Erlqis watershed. The Buerjin River is one of the most important tributaries of the Erlqis River and is about 250 km long and originates in the glaciers of the Youyi Mountains (4373 m asl). The lithologic outcrops in the catchment are mainly the Devonian marine carbonate, clastite (D2, D2 + 3), and the igneous Variscan (γ_4) granite and Quaternary sediments (Ma 2002) (Figure 1d).

3. METHODS

Field investigations were carried out on the whole region of northern Xinjiang during summer-autumn season in 2008. Chinese 1:50,000 scale topographic maps, a prismatic compass, a Thrommen altimeter and a Garmin GPS were used for orientation. All locations and elevations were recorded using GPS and topographic maps. Water samples were collected under natural flow conditions in one-liter polyethylene bottles from various parts of the Yili,

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Zhungarer, and Erlqis watersheds (Figure 1a), including river stems, stream channels, hill slopes, wells, lakes, ponds, man-made trenches and reservoirs. Taking into account that the tributaries reflect a much broader variety of geological, biological, and population patterns than do main stem rivers (Pawellek et al. 2002), it was of interest to sample tributary water to look for common features reflected in their hydrochemistry. Some pristine streams draining forested catchments were chosen in the Tianshan and the Arltai Mountains. All waters were surface-sampled except for well water extracted from pump shafts. Most water samples were colorless, but a few were yellow, gray or turbid in colour due to dissolved iron content or suspended solid particles. The colored river water samples primarily drained through the south and north piedmont areas of the Tianshan Mountains, with deep coves of loess and loess-like soil. Because no river and spring exist in the hinterland of the Gulbantonggute Desert, no surface water samples was collected for comparison from others in this work.

Water samples were filtered through a 0.45 μm Millipore membrane filters in the field and analyzed in the institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Analysis of water samples included total dissolved solids (TDS), pH, and ion concentrations. Ions were mainly measured with a DX600 Dionex ion-chromatography. Temperature (T), pH, and TDS were measured in situ using a portable Multi-Parameter Analyzer (Eijkelkamp 18.28). The water samples for cation analysis were acidified with hyper-pure HNO_3 below pH 4.5. Cations and anions were determined by ion chromatography (IC, Dionex 600) with deionized water (EC < 2.1 μS/cm) as the dilute base. The eluents used were 20 mmol/L MSA (methanesulfonic acid) at pH 4.5 and conductivity of approximately 400 μS/cm for cation analysis and 3.5 mmol/L Na_2CO_3, 1.0 mmol/L $NaHCO_3$ at pH 8.5 for anion analysis, respectively. One replicate for each sample was taken for ion analysis, and the instrument was recalibrated after every 5 samples. The alkalinity was measured with a Hach digital titrator using the Gran method (Wetzel and Likens 2000) within three days after sampling.

4. RESULTS

Major physio-chemical and chemical properties of the water samples studied are statically listed in Table 1. The data show that the natural water at various sites is different in terms of mineralization, with TDS ranging from 24.6 to 6200 mg/L, the mean being 580 mg/L. More than half of the

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investigated samples belong to fresh water (TDS < 1000 mg/L), and the remainder to brackish water (TDS 1-10 g/L). All natural water is alkaline, and pH values range from 7.0 to 9.81, with an average value of 7.87. In the Piper's diagram the natural waters are distributed in fields where alkaline earths exceed alkalis and strong acids and weak acids dominate partially in composition (Figure 2). There are four main water types: Ca-HCO_3, Ca-NDA (non-dominant anion), Ca-SO_4 and NDC-NDA (non-dominant cation) or Na-NDA. Ca-type water is most widely distributed in the study area. The Ca-HCO_3 and Ca-NDA types mainly occur in the montane areas and the low-pitched piedmont zones. The Ca-SO_4 and Na-SO_4 types are mostly distributed in the transition band between oasis and desert plain. Mg-type water merely occurs in the Sailimu Lake. There is no Cl-dominated water type that occurs in the study area (Figure 2).

Table 1. Statistical summary of the physical parameters and major ion concentrations determined in the study water samples (TH, total hardness; SAR, sodium adsorption ratio)

Parameter	Maximum	Minimum	Average	Median	10th	90th	SD
pH	9.81	7.00	-	7.85	7.33	8.24	0.47
Eh	-21.0	-187	-72.6	-72.5	-94.6	-41.8	27.6
EC (μs/cm)	5380	46.3	864	352	162	3426	1258
TDS (mg/L)	6200	24.6	580	186	86.1	1843	1071
Li^+ (mg/L)	0.13	nd	0.02	0.01	nd	0.04	0.02
Na^+ (mg/L)	1673	1.66	105	6.86	2.60	272	281
NH_4^+ (mg/L)	0.17	nd	0.02	nd	nd	0.03	0.04
K^+ (mg/L)	77.7	0.49	8.48	1.63	0.82	25.9	17.4
Mg^{2+} (mg/L)	190	0.63	27.2	6.49	2.44	81.8	49.5
Ca^{2+} (mg/L)	91.9	3.05	29.1	26.4	14.0	48.0	16.7
F^- (mg/L)	3.04	0.02	0.31	0.18	0.06	0.54	0.51
Cl^- (mg/L)	648	1.83	74.5	6.91	2.97	223	160
NO_3^- (mg/L)	36.5	nd	4.96	2.88	0.72	8.89	6.62
SO_4^{2-} (mg/L)	2655	2.52	205	45.3	9.01	682	437
HCO_3^- (mg/L)	799	9.76	117	69.4	29.7	283	142
TH (mg/L)	824	10.2	184	102	47.9	436	209
SAR	28.2	0.058	1.97	0.278	0.094	4.56	4.85

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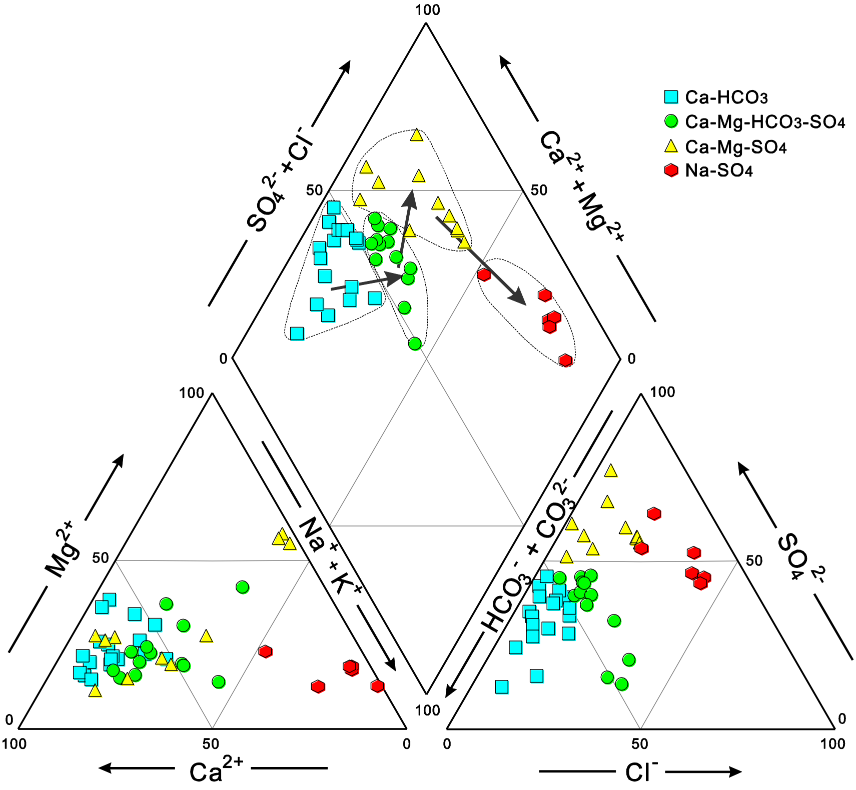

Figure 2. Piper plot of the study water samples.

5. DISCUSSION

5.1. Geochemical Evolution and Distribution

The natural waters in northern Xinjiang are similar to the majority of the large rivers on earth, which are typically carbonate rivers and alkaline in nature (Meybeck 1987). Compared with the upper ranges of typical values for major world rivers and the lower ranges for major pristine rivers (most common natural concentrations - MCNC) (Figure 3), such as the Amazon and Mackenzie (Meybeck and Helmer 1989; Meybeck 1996), the mean major-ion concentrations of the study waters are almost in excess of typical natural values of the major world rivers (Figure 3), except for Ca^{2+} and HCO_3^-. This suggests that the natural waters in northern Xinjiang fall close to the upper limit of concentrations in major world rivers, classified as “salted” by Meybeck (1996). Furthermore, the study waters are notably characterized by an enormous range over three orders of magnitude for concentrations and yields than that of global rivers (Figure 3). This indicates a definable spatial variation of water chemistry and quality in the study watersheds.

Cl-type water is usually one of the major water types in the desert environment in northern China, such as in the Taklamakan Desert (Zhang et al. 1995; Zhu and Yang 2007) and the Badain Jaran Desert (Yang and Williams 2003; Zhu and Yang 2010; Zhu et al. 2012). Cl-dominated water type does not exist in the study area (Figure 2), indicating that the natural waters in northern Xinjiang are still at the early stage of water evolution.

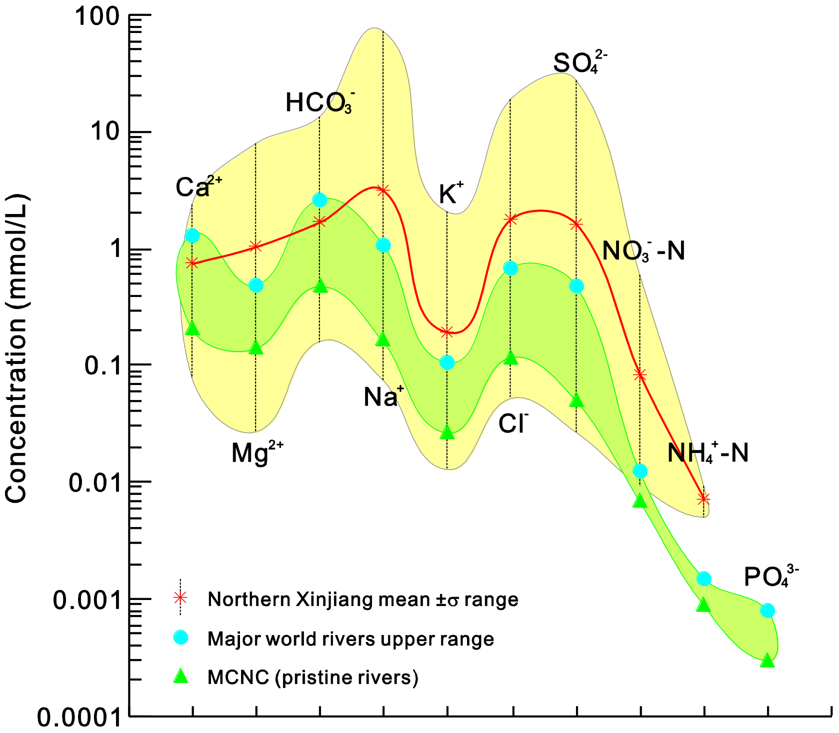

Figure 3. Typical ranges for major ions in the natural waters in northern Xinjiang. Also marked are the upper limits for these components in major world rivers and the median concentrations in pristine rivers (MCNC) (Meybeck and Helmer 1989; Meybeck 1996).

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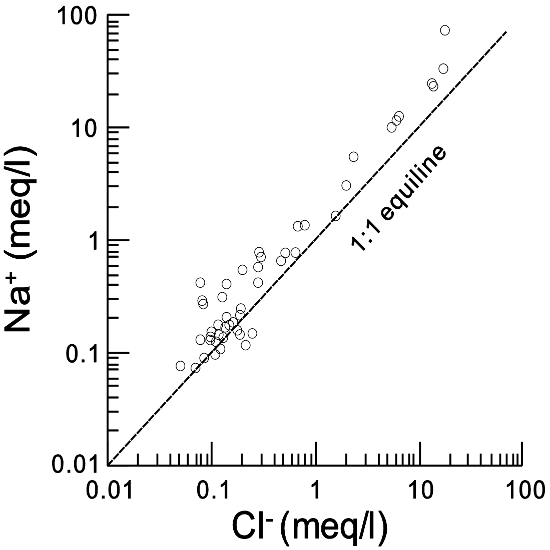

Figure 4. Scatter diagram of the concentrations of Na^+ vs. Cl^- of the study waters.

The large variation in Ca^{2+} and Na^+ concentrations in the natural water samples from the study area (Table 1 and Figure 2) may theoretically reflect local mineralogical changes in the sediments and in the carbon dioxide produced by biological processes in their surface layers. However, biogenic weathering might not be a key factor, because the natural water here is alkaline in general. The CO_2 reactions in the natural water are possibly not very active at many sites because of alkaline conditions and limited vegetation on the surface. The heterogeneity of the ionic compositions (Figure 2) may also be caused by local variations in the mineralogy of the natural water reservoir and geochemical processes occurring in the aquifer. Principally, the amount of sodium rises as the chloride content increases in the investigated samples (Figure 4), supporting the view that geochemical processes play a role in the chemistry of natural water. Referring to the Na/Cl ratios, part of samples (mostly from mountainous areas) with lower TDS lie very close to the 1:1 ratio line (Figure 4), indicating that sulphate and other salts are relatively abundant in the natural water with higher TDS (mainly under fluvial-plains and desert environments). The regolith and geomorphological parameters controlling ground-surface temperature may play a large role in rock weathering regime and so in the water chemistry, because solution of lithological components is controlled to a large extent by the ground temperature in a periglacial landscape and its surrounding areas (Beylich et al.

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2004). Such as in areas of shade, cold ground and thin regolith, the TDS of natural water (surface water and shallow groundwater) is low, whereas the TDS is high in areas exposed to intensive radiation. Data from the artic-oceanic drainage basin of northern Sweden (Latnjavagge) show that water chemistry may vary considerably in a small area with very homogeneous lithology but great slope segments. The regolith in northern Xinjiang area varies in thickness from less than a meter to more than 5 m between upper and lower slope segments.

The water samples from the oasis areas in the Zhungarer basin where the community administrations are located show much higher TDS than samples from more pristine areas. This is probably caused by two processes: (1) direct pollution reflecting increased population and agricultural density and (2) re-seepage of wastewater. It appears that the wastewater can infiltrate into the natural water systems quickly, because the irrigation and housing, and therefore waste and dung depot, are very close and easy to the aquifer due to the close hydrological conditions with low topography in the basin. Compared with the nitrate contents (0.5-7.7 mg/L) in the surface waters, groundwater samples in the Zhungarer watershed have clearly higher concentrations of nitrate (22-37 mg/L). The high concentration of nitrate in these samples is probably related to the decomposition process of untreated waste. In fact, the nitrate concentration is quite high in the majority of the ground water samples from the entire study area. In the arid and desert environment, both humans and their animals depend on the groundwater (wells) to live. Therefore human influence is quite strong around the wells and the dung depot is often located not far from the wells. This may be the reason for the high concentration of nitrate in the water samples. There is no wastewater treatment system in this region yet. In the interests of the health of local residents it is necessary to add sewage treatment.

5.2. Recharge Mechanisms of the Natural Waters

The possible mechanisms for natural water (especially river and shallow groundwater) recharge in the areas of the northern Xinjiang are: (a) direct infiltration of rain into the ground; (b) direct recharge from seasonal snow and ice-melt water; (3) recharge from potential deep groundwater. The first two processes are thought to be significant, but the third may be much less important, because the northern Xinjiang watersheds form a various ranges in a desert landscape. Based on the tectonic structure of mountain-basin couples,

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it is concluded that the recharge of the shallow groundwater is mainly through infiltration of seasonal snow and ice-melt water derived from mountain areas and local precipitation that infiltrates downwards quite quickly owing to the loose nature of the regolith. Due to the large temporal and spatial variability of rainfall, infiltration is related to the amount of precipitation of each event. From dried channels in the fields one can assume that there may be ephemeral streams and ponds in the study area when it rains. As a result, the overall recharge process is quite heterogeneous. The clear difference in ion concentrations suggests that the hydraulic relationship between various sampling sites is weak.

For the areas of fluvial plain in the Zhungarer, we consider that the precipitation directly onto the rivers, lakes and reservoirs plays a minor role in the recharge today, because the amount of precipitation is much smaller than the evaporation occurring on the water surface. Field observations indicate that all rivers in these areas were recharged mainly by mountain stream water and partially by groundwater at present time. Owing to the isolated geomorphological basin structures, it is unlikely that the recharge mechanisms might have fundamentally changed in the past. The large range in chemical composition of water samples suggests not only the heterogeneity of the recharge conditions in the study areas, but also a possible mixing with enriched waters that could be in different aquifers. However, the input from other regions (via surface runoff or groundwater inflow) seems to be rather insignificant in the local water cycle. Besides, a large proportion of rain is maybe added to the shallow groundwater system because of rapid infiltration in the loose and sandy sediments. Observations and interviews with local residents suggest that the water from the shallow aquifer can meet the water demand of inhabitants with traditional life styles and adequate livestock grazing in the desert environment of northern Xinjiang.

The highest TDS concentrations were observed at some lake depressions (such as the Salimu Lake) around the central Zhungarer watershed. From field observation, it is assumed that the Salimu Lakes are mainly recharged by glacier/snow waters, because it is located in a highland depression surrounded by high mountains and there is surficial inflow but no outflow. The major ions in the lake are Mg^{2+} for cations and SO_4^{2-} for anions. At present, Salimu is one of the largest lakes in northern Xinjiang and has relatively high TDS (1850 mg/L). Compared with the chemistry of other lake samples, the proportions of sodium and chloride are much lower in the Salimu lake water. From a global point of view, the dominant ions in most saline lakes are Na^+ and Cl^-, and occasionally in some less saline lakes, Na^+ and HCO_3^-/CO_3^{2-} (e.g., Day 1993).

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It is reasonable to believe that the brines of these lakes were formed by long and intensive evaporation, because Na^+ and Cl^- are often associated with evaporites. We can exclude the halite origin for the Salimu Lake. However, Mg^{2+} and SO_4^{2-} are also often associated with evaporites. Dissolution of sulphates (such as gypsum and anhydrite) may be an important source here. In general, major ions in saline waters were derived from the catchment or the substratum (e.g., Kilham 1990). However, atmospheric precipitation should not be ignored as a potentially significant source of ions (Eriksson 1985) in the water of the study area because of frequent dews and rimes. In many large saline lakes of northern China and Mongolia, Cl^-, SO_4^{2-} and HCO_3^- are almost equally predominant anions, while Na^+ and K^+ are strongly dominant cations. The salts of these lakes were thought to have originated from high evaporation and soil salinization (Egorov 1993). The salinity of the Chinese lakes increases westwards, consistent with the trend of increasing aridity. Both natural climatic changes and irrigation activities have caused decadal variations in the salinity in these lakes. From limnological analysis of different world regions, it was concluded that large, deep, saline lakes often contain alkaline, sodium rich waters with considerable chloride, sulphate, and carbonate plus bicarbonate (Melack 1983). The chemistry of lakes in the northern Xinjiang drainage basins is, to a considerable extent, consistent with those of large lakes. Also, from this point of view, it appears that the enrichment of the ions in the lakes has been mainly caused by evaporation, rather than through the quality of the recharged water.

5.3. Response to Climate

The regional distribution pattern of chemical water types (Figure 2) reveals that a transitional trend exists between natural waters in the northern Xinjiang drainage basins. Water types are generally transformed from Ca-HCO_3 to Ca-Mg-HCO_3 to Ca-Mg-SO_4 and to Na-SO_4. This trend is spatially accompanied by the altitude variation of landscapes in the order of mountains, pediments, piedmont plains and desert plains. It indicates a potential control of a vertical zonality of temperature and relevant geological effects on the natural water evolution. Besides this trend, another kind of zonal distribution of hydrogeochemistry also exists in the northern Xinjiang drainage basins. For example, the relatively wet zones, with AMP > 200 mm in three watersheds, consist of the Ca-HCO_3, Ca-NDA and NDC-NDA types. In the relatively dry zones, with AMP < 200 mm, however, the Ca-SO_4 and Na-SO_4 types

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predominate. The Ca-HCO_3-dominated chemistry of river water in the relatively wet zones couples well with regional carbonate lithological distributions (Figures 1d). It confirms that rock weathering and the regional lithologic distributions have a major effect on the evolution of river chemistry in the wet zones. The precipitation processes can accelerate the rock weathering processes (White and Blum 1995). The water types in dry zones tend to be relatively uniform. Because the lithological distributions are not homogeneous, evaporation processes, which can result in the selective precipitation of solute fraction ($CaCO_3$) and subsequent changes in water chemistry as water moves downstream in the relatively arid zones (Gibbs 1970; Kilham 1990; Feller 2005), could be responsible for the accumulation and evolution of sodium and sulphate salts. It indicates a major effect of climate rather than geology on the evolution of water chemistry in dry zones.

The strong relationship between the annual mean summer precipitations (AMP) in northern Xinjiang and the altitudes of the sampling sites in this study can be well expressed as $AMP = 0.14 \times altitude + 101.3$ ($r = 0.88$, $p < 0.005$). The total dissolved solids in most samples decreased in concentration with the increasing altitude (Figure 5). It indicates a potential influence of precipitation on dissolved materials in the water. The fact that rock types are not distributed according to the altitude (Figure 1c, d) implies that topography and temperature, in addition to rock type and weathering, affects water chemistry indirectly by influencing AMP/evaporation processes.

In the central parts of the study watersheds, evaporation probably influences the salinization of surface and ground water substantially, because the TDS value of river water clearly varies along their channel courses, such as the Erlqis, Wulungu, Jingou, Gongnais and Yili rivers (Figure 5). The river waters in the middle reaches of the Jingou, Gongnais and Wulungu have TDS values of 90, 95 and 321 mg/L, respectively, and gradually change to higher values of 112, 147 and 2000 mg/L after flowing about 70, 100 and 300 km downward, respectively. The Jingou, Gongnais and Wulungu rivers have few tributaries over their water courses (Figure 1a), so the waters flowing along the lengths of these courses do not mix extensively with water from different tributary sources. In addition, the seasonal changes of discharge and sources cannot be the reasons for the variation in the dissolved solid concentrations for one-day-collected samples from a single river. Accordingly, the increase of TDS from upper reaches toward lower reaches in these rivers can be interpreted in terms of evaporation and dissolution of soil salts along their river courses. Due to the relatively fixed channel course at present, the dissolution of soil salts alone river bed maybe does not vary greatly. So if

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evaporation processes cause the change of concentration of dissolved material during water flow, given no change in the flow speed of ~5 km/h, it is intense enough in these drainage basins that runoff can decrease by one-third to one-fifth during one day.

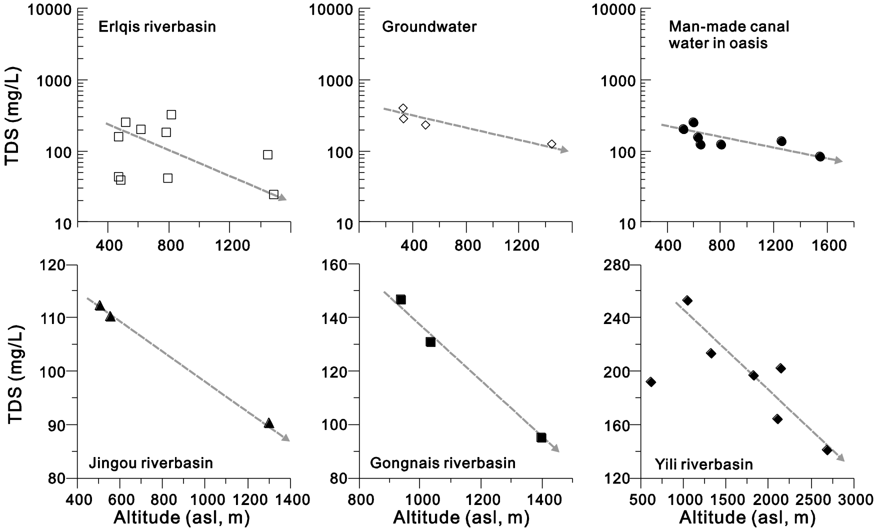

Figure 5. TDS vs. altitude (m, asl) of the study water samples.

CONCLUSION

The physico-chemical characteristics of the natural waters in northern Xinjiang drainage system, as well as the climatic, geological and topographical context where they flow and reside, allowed the identification of fluvial geological evolution and recharge mechanism of the natural water resources in arid environment. The natural water at various sites in the study area is different in terms of mineralization and is similar to the majority of the large rivers on Earth in general, which are typically carbonate rivers and alkaline in nature. However, there is no Cl-dominated water type that occurs in the study area, indicating that the natural waters in northern Xinjiang are still at the early stage of water evolution. The regolith and geomorphological parameters controlling ground-surface temperature may play a large role in water chemistry and its evolution. Evaporation influences the salinization of natural water substantially. The high concentration of nitrate in oasis water is probably

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related to the decomposition process of untreated waste. Direct recharge from seasonal snow and ice-melt water and infiltration of rain into the ground are thought to be significant recharge processes for natural water in the study area, but recharge from potential deep groundwater may be much less important. The chemistry of lakes is to a considerable extent consistent with those of large lakes in the world but the enrichment of the ions in the lakes has been mainly caused by evaporation, rather than through the quality of the recharged water. Two kinds of zonal distribution of water types exist in the northern Xinjiang drainage basins. It confirms that temperature-and-precipitation-dependent geological weathering and lithologic distributions have a major effect on the evolution of water evolution in the wet zones and a major effect of climate (evaporation) rather than geology on the water evolution in dry zones.

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