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Research papers

Multivariate indications between environment and ground water recharge in a sedimentary drainage basin in northwestern China

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ABSTRACT

A paucity of studies on the interaction between environment and ground water recharge severely restricts the ability of people to assess future water resources under changing environment. In this study, an effort to explore the relationship between the arid environment and ground water recharge was carried out using multivariate statistical techniques in a sedimentary drainage basin (the Jungar) in northwestern China. Hierarchical cluster analysis (HCA) and principal components analysis (PCA) were performed based on hydrogeochemical data to assess the ground water recharge and its governing factors. Observation of the HCA and PCA analytical results revealed a division of seven clusters (C1 to C7) and three principal components (PC1 to PC3), which explained 59.6%, 16.6% and 10.9% of the variance, respectively, and thus, accounted for the majority of the total variance in the original dataset. Based on these Q-mode HCA clusters and R-mode PAC scores, dominant environmental processes influencing recharge regimes were identified, i.e., geogenic, geomorphoclimatic, and anthropogenic, which separated the recharge regimes into four zones (Zone I to Zone IV). Zones I and II (C4 + C1) were associated to "elevated hydroclimate degree" coupled to "low salinity". Zone III (C2 + C3) was associated to "moderately elevated salinity" and evidently "elevated contamination" but coupled to "low hydroclimate degree". Zone IV (C5 + C6 + C7) was associated mainly to "elevated salinity" coupled to "low or inverse hydroclimate degree". It revealed that the geogenic processes are more significant (60%) than the geomorphoclimatic (17%) and anthropogenic (11%) processes. As a result, the overall recharge process is rather heterogeneous and is strongly environment dominated in the Jungar drainage system. Compared with other watersheds in arid environment, a distinctive feature of the Jungar waters is that they are affected by a combination of natural and non-natural events, rather than following a steady and continuous geological evolution. These will continue to influence the recharge regime of the Jungar for a long time due to its steady tectonics and arid climate. However, changing rainfall, but not snow, is becoming the key factor driving changes in ground water resources in this drainage system, as results of the decades of warming and humidification in northwestern China.

1. Introduction

Ground water is an almost ubiquitous source of generally high-quality fresh water. These characteristics promote its widespread development, which can be scaled and localized to demand, obviating the need for substantial infrastructure (Giordano, 2009). In various environments, natural ground water discharges sustain baseflow to rivers, lakes and wetlands during periods of low or no rainfall. Despite these vital contributions to human welfare and aquatic ecosystems, a paucity of studies on the relationship between environment and ground water recharge severely restricted the ability of the Intergovernmental Panel on Climate Change (IPCC) to assess interactions between ground water and environmental change in its assessment reports (Arnell et al., 2003; Kundzewicz et al., 2007).

Environmental conditions influence ground water systems both directly through replenishment by recharge and indirectly through changes in ground water use (Drever and Hurcomb, 1986; Menzel and Burger, 2002; Giordano, 2009; Taylor et al., 2013a). The long-term effects of environment on ground water, such as climate forcing, largely independent of human activities, can be detected from palaeohydrological evidence from regional aquifer systems in semi-arid and arid parts of the world (Scanlon et al., 2006). For example, much of the ground water flowing in large sedimentary

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aquifers of northern China (Alashan Plateau), southern Africa (Kalahari sands), North Africa (Nubian sandstone aquifer system), Australia (Great Artesian basin) and the central United States (High Plains aquifer), was recharged by precipitation thousands of years ago (De Vries et al., 2000; Lehmann et al., 2003; Edmunds et al., 2003; McMahon et al., 2004; Gates et al., 2008). Environmental tracers records in unsaturated soil profiles within these basins indicate that little ($\leq$5 mm/yr) or no recharge has since taken place (Scanlon et al., 2006); which is the case across many of other basins in arid environment. These records also suggest that the recharge occurred under cooler climates ($\geq$5 °C cooler) before and occasionally during Late Pleistocene glaciation, with further local additions during the Early Holocene (>5000 years BP).

In the modern era, however, to establish links between the environment and ground water is complicated by human activities. Natural replenishment of ground water occurs from both diffuse rain-fed recharge and focused recharge via leakage from various sources and is highly dependent on prevailing climate as well as on land cover and underlying geology. Ground water that was recharged during cooler, wetter climates of the Late Pleistocene and Early Holocene is commonly referred to as 'fossil ground water'. By contrast, modern, transient ground water system is recharge-flux dominated rather than storage dominated like in fossil aquifers (Foster and Loucks, 2006).

Between environment and ground water recharge, climate and land cover largely determine precipitation and evapotranspiration, whereas the underlying soil and geology dictate whether a water surplus (precipitation minus evapotranspiration) can be transmitted and stored in the subsurface (Giordano, 2009; Doll, 2009). Modelled estimates of diffuse recharge globally (Doll and Fiedler, 2008; Wada et al., 2010) range from 13,000 to 15,000 km^3/yr, equivalent to $\sim$30% of the world's renewable freshwater resources (Doll, 2009) or a mean per capita groundwater recharge of 2100 to 2500 m^3/yr. These estimates represent potential recharge fluxes as they are based on a water surplus rather than measured contributions to aquifers. Furthermore, these modelled global recharge fluxes do not include focused recharge, which, in semi-arid and arid environments, can be substantial (Scanlon et al., 2006; Favreau et al., 2009).

High mountains in central Asia, 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 environments (Domros and Peng, 1988; Sun et al., 2010). These regions receive low and variable annual rainfall (<500 mm/yr in winter seasons and <200 mm/yr in summer seasons), and are characterized by potential evapotranspiration that is far greater that the precipitation (ratio of annual mean precipitation (AMP) to mean potential evapotranspiration <0.5; UNEP, 1992). Natural water resources in these regions are generally scarce and highly uncertain. Fresh water is definitely a limited and indispensable resource upon which humans and ecosystems depend. The water availability is very much a function of the local geology and climate (Zhu et al., 2012a). Understanding of the relationship between environment and recharge of ground waters, as well as the role of various environmental components on assessing potential impacts of natural or anthropogenic perturbations on ground water, is of great significance not only to policy makers for regional planning, but also to scientists interested in hydrological cycles in arid environments over the world (Meyer et al., 1988; Mast et al., 1990; George et al., 1997; Arnell, 1999; Kimbadi et al., 1999; Cramer and Hobbs, 2002; Hagg et al., 2007; Jolly et al., 2008; Dragon and Gorski, 2015).

The Jungar drainage system in northwestern China is the geographical centre of the Asian Continent, which can be regarded as a significant repository of information relating to the hydrological evolution and environmental changes in Central Asia. At present, with the increased demand for natural water resulting from fast demographic growth, accelerated urbanization, economic and agricultural activity diversification, natural water resources in this arid region are relatively low, compared to demand. Water resource becomes overexploited in some places as its natural recharge by rainwater does not succeed in maintaining the hydrologic balance. The imbalance between water demand and resources induces the degradation of the water quality. In such a case, relationships between environment and the water recharge sources are a key to understand the hydrodynamic and physicochemical conditions of the natural water. Until now, however, little work focusing on these questions has been done in this arid drainage system.

It should be kept in mind that virgin aquatic conditions may significantly differ from managed conditions in arid environment, because natural water recharge is not a fixed number, but may vary with the boundary conditions of the recharge system (Seiler and Gat, 2007). Conventional methods such as water balance and hydraulic methods sometimes fail in determining natural water recharge in extreme environments (arid, semi-arid, or cold) (Drever, 1997), because of missing knowledge and the lack of reliable data on various characteristics such as the catchment extent, input/output, the hysteretic hydraulic functions, the transient hydraulic conditions, in-homogeneities, and on transfer functions to overcome scale problems (Seiler and Gat, 2007). Under such conditions, tracer methods offer a valuable support for natural water studies.

As rivers carry the imprints of chemical erosion on the continental and local scales in the forms of dissolved materials, geochemical methods have been applied widely to examine the spatial variability in the water's characteristics and better understand the functioning of hydrosystems (e.g., Garrels and MacKenzie, 1967; Caritat and Saether, 1997; Pilla et al., 2006; Zhu and Yang, 2007; Stadler et al., 2010; Zhu et al., 2011, 2016), as they are basically an independent method from hydraulics on filter flow and, therefore, enable to complement hydraulic methods on evaluating natural water recharge or mixing of waters of different origins. In this integrated hydrosystem, multiple factors and multivariate analysis become necessary. The statistical modeling techniques provide an effective tool for the integration of different hydrogeological and hydrochemical information worldwide (Guler et al., 2002; Cloutier et al., 2008; Masetti et al., 2008; Chaudhuri et al., 2012; Chaudhuri and Ale, 2014a). In particular, this application exploits the exploratory power of multiple techniques in identifying single factors and their combinations that influence composition and evolution of ground water. Due to their simplicity, these methods have wide applicability in any parts of the world that are fraught with similar water resources problems (Chaudhuri and Ale, 2014b).

For example, Steinhorst and Williams (1985) used multivariate statistical analysis of water chemistry data in two field studies to identify groundwater sources. Usunoff and Guzman-Guzman (1989) demonstrated the usefulness of the approach in hydrogeochemical investigations when considering the geological and hydrogeological knowledge of the aquifer. Melloul and Collin (1992) used principal components analysis (PCA) to supplement classical geochemical methods such as Scholler and Piper diagrams and successfully identified major water groups and factors affecting groundwater quality in an aquifer. Schot and van der Wal (1992) and Cloutier et al. (2008) applied principal components and clusters analysis to hydrochemical data to show the regional impact of human activities on groundwater composition. In the study of Farnham et al. (2003), the application of multivariate statistical analysis to trace element chemistry of groundwater helped identify rock-water interaction processes and groundwater redox