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Spatial analysis of hydrogen and oxygen stable isotopes (“isoscapes”) in ground water and tap water across South Africa

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ABSTRACT

Stable isotopes in water (δ^2H and $\delta^{18}O$) are important indicators of hydrological and ecological pattern and process. δ^2H and $\delta^{18}O$ of water are incorporated into geological and biological systems in a predictable manner and have been used extensively as tracers in hydrological, ecological and forensic studies. Physical processes result in spatial variation of δ^2H, $\delta^{18}O$ in water across the landscape (so-called “isoscapes”) and provide the basis for hydrological, ecological, archaeological and forensic studies. Southern Africa is a globally important meeting point for ocean and climate systems, biological diversity and human societies, yet there is little information on the spatial variability of δ^2H and $\delta^{18}O$ in water across this important region. Here we present the first ground water and tap water isoscapes for southern Africa. We compare and contrast these two water resources, and consider how well global models of precipitation isotopes capture isotopic variation across South Africa. Ground water and tap water samples were collected from across South Africa, analysed for δ^2H and $\delta^{18}O$, and used to generate interpolated δ^2H, $\delta^{18}O$ and deuterium-excess ($d = \delta^2H - 8{*}\delta^{18}O$) isoscapes. We found coherent spatial structure in δ^2H, $\delta^{18}O$ and d of ground water and tap water that could be predicted by a geostatistical model based on simple environmental parameters (elevation, mean annual precipitation, precipitation minus potential evaporation, distance to coast and modeled isotope ratio of precipitation). This spatial structure resulted in considerable differences in isotopic composition of water in many of the major wildlife reserves in South Africa, indicating a good potential for wildlife forensics in this region. δ^2H and $\delta^{18}O$ of ground water, and to a lesser extent tap water, reflected the δ^2H and $\delta^{18}O$ of long-term weighted annual precipitation at the two GNIP stations in South Africa. However, large discrepancies between modelled isotopic composition of precipitation and our ground water and tap water isoscapes, particularly at higher elevations, highlighted uncertainty in the accuracy of modelled precipitation isoscapes for this region. Increased spatial sampling of precipitation, especially for high elevation regions, and temporal sampling of ground and tap water would considerably aid isotopic studies in this region.

1. Introduction

Stable isotopes in water (δ^2H and $\delta^{18}O$) are important indicators of hydrological and ecological pattern and process (Gat, 1996; West et al., 2006). The stable isotopic composition of water reveals information about the physical processes that lead to its formation and transport (Craig, 1961; Dansgaard, 1964; Gat, 1996). These physical processes result in spatial variation in δ^2H, $\delta^{18}O$ and deuterium-excess (defined as $d = \delta^2H - 8{*}\delta^{18}O$,) (Bowen and Revenaugh, 2003; Craig, 1961; Dansgaard, 1964). δ^2H and $\delta^{18}O$ of water are incorporated into geological and biological systems in a predictable manner (Ehleringer et al., 2008a; Killingley and Newman, 1982; Roden et al., 2000), allowing extensive use of δ^2H and $\delta^{18}O$ as tracers in hydrological, archaeological, ecological and forensic studies (Ehleringer et al., 2008b). Water isotopes have been used to trace the fate and origin of atmospheric moisture sources (Bowen et al., 2012; Burnett et al., 2004), partition evapotranspiration fluxes from the land surface (Williams et al., 2004; Yepez et al., 2003), trace moisture sources in terrestrial plants (Brienen et al., 2012; Hawkins et al., 2009; West et al., 2007), determine the dependence of vegetation on stream or ground water (Dawson and Ehleringer, 1991; Ehleringer and Dawson, 1992), identify the source of ground water recharge (Harvey and Sibray, 2001), identify region-or-origin on forensic materials (Bowen et al., 2005; Ehleringer et al., 2008b; Hobson, 1999), amongst many other applications.

Increasingly, the stable isotopic composition of water is being measured and modeled on a large and highly resolved spatial scale (Bowen et al., 2007; Wassenaar et al., 2009). These isotopic-landscapes, or “isoscapes” (West et al., 2010b), have considerable utility in that they allow the documentation and visualization of large-scale hydrological processes, on the regional, continental or global scale. A well-supported water isoscape allows interrogation of the hydrological

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processes causing the spatial pattern (e.g. seasonal rainfall patterns, precipitation/evapotranspiration ratios, catchment hydrology) (Bowen et al., 2011). It can also provide an isotopic base layer for the development of more complex biological isoscapes, such as leaf water (West et al., 2008), hair (Ehleringer et al., 2008a) and feathers (Cherel et al., 2000). Such isoscapes allow a statistical approach to determining the origin of materials (Neubauer and Shima, 2013). Spatial variation in stable isotopes has been used successfully in revealing patterns of animal migration (Rubenstein and Hobson, 2004) and forensic identification of a wide variety of materials (Ehleringer et al., 2008b).

Global monitoring of water isotopes commenced with the formation of the Global Network for Isotopes in Precipitation (GNIP) in 1961 (IAEA/WMO, 2006a). In many regions of the world, the GNIP dataset has sufficient temporal and spatial density to provide a good basis for spatial modeling (Bowen and Revenaugh, 2003). However, there are many regions where the station density is insufficient (e.g. Wassenaar et al., 2009). South Africa is such an example, where only two GNIP stations (Pretoria and Cape Town) exist in a country of over 1.2 million square kilometers. While good δ^2H and δ^{18}O datasets exist at these locations, there is relatively little data on how these isotopes vary spatially across South Africa. This lack of spatial data limits hydrological, archaeological, ecological and forensic studies in a region that is a globally important meeting point for ocean and climate systems, biological diversity and human societies, as well as under increasing pressure to optimize its scare water resources (New, 2002).

In this study we present the first ground water and tap water isoscapes for southern Africa. We focused on ground water and municipal tap water as two key water resources that are readily measureable and integrate across a variety of disciplinary interests. Ground water is key water resource for vegetation, agriculture and human consumption in many of the more arid parts of the world. The isotopic composition of ground water approximates that of seasonally weighted long-term precipitation inputs, even in some of the most arid regions of the world (IAEA, 2007). As such, ground water may serve as a proxy for precipitation in areas of the world under-represented by GNIP stations (Wassenaar et al., 2009). Municipal tap water is a key deliverable for water resource management, representing the interface between human and hydrological systems, and has a direct effect on human geography and socio-economic development. Tap water has been shown to retain a similar isotopic composition to that of local precipitation (Bowen et al., 2007), although there is considerable potential for evaporative enrichment in surface-stored waters (e.g. reservoirs and dams). Thus, differences between the isotopic composition of ground water, tap water and modelled precipitation provides information on the coupling of water resources to precipitation source and can provide insight into resources that might be vulnerable to changes in climate or excessive exploitation (Bowen et al., 2007). Additionally, drinking water is incorporated into the tissues of consumers and provides an important forensic tracer of location (Ehleringer et al., 2008a; Hobson et al., 1999).

In the interpretation of our water isoscapes, we asked the following questions: 1) Is there a coherent spatial pattern in ground water and tap water isotopes across South Africa that can be geostatisically modeled? 2) What do differences between ground water and tap water isotopes reveal about drinking water resources? 3) Can ground water and tap water isoscapes be used as proxy for precipitation across South Africa? 4) What potential do these isoscapes have for the forensic tracing of wildlife?

2. Methods

2.1. Ground water sample collection

The ground water isotope data were obtained from the National Ground water Quality Monitoring Project (NGwQMP) run by the Department of Water Affairs, South Africa (http://www.dwaf.gov.za/Groundwater/NGQMP.aspx). Ground water samples were collected at 369 monitoring points around South Africa (Fig. 1) between April 2006 and September 2007.

2.2. Tap water sample collection

410 tap water samples were collected from around South Africa during the period April 2009 to December 2010 (Fig. 1). We used two techniques to gather samples. The first technique involved a return mail

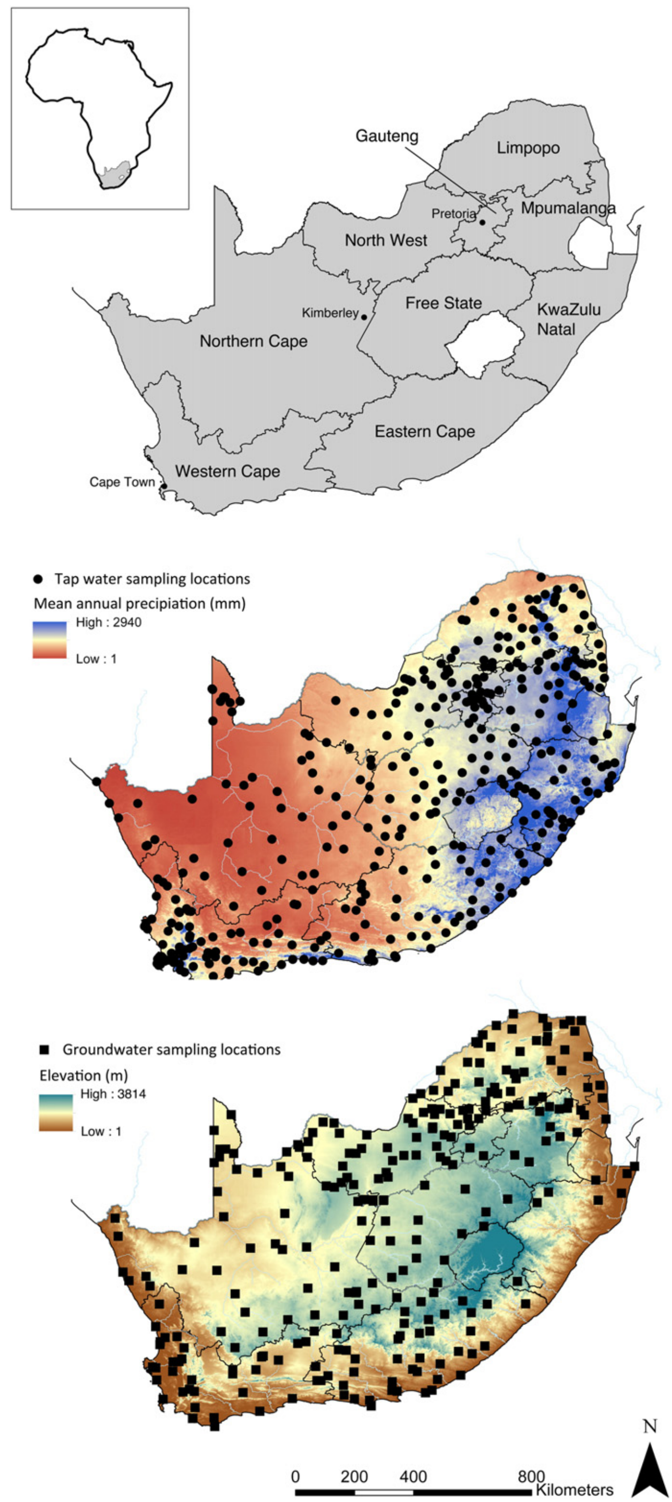

Fig. 1. The provinces of South Africa and sampling locations for tap water and ground water overlaid on mean annual precipitation (mm) and elevation (meters above sea level) respectively.