Water Research 91 (2016) 314–330

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Geostatistical analysis of tritium, groundwater age and other noble gas derived parameters in California

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ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
22 December 2015
Accepted 4 January 2016
Available online 8 January 2016

Keywords:
Groundwater
Water age
Geostatistics
Tritium
Noble gas

ABSTRACT

Key characteristics of California groundwater systems related to aquifer vulnerability, sustainability, recharge locations and mechanisms, and anthropogenic impact on recharge are revealed in a spatial geostatistical analysis of a unique data set of tritium, noble gases and other isotopic analyses unprecedented in size at nearly 4000 samples.

The correlation length of key groundwater residence time parameters varies between tens of kilometers (^{3}H; age) to the order of a hundred kilometers (^{4}He$_{ter}$; ^{14}C; ^{3}He$_{trit}$). The correlation length of parameters related to climate, topography and atmospheric processes is on the order of several hundred kilometers (recharge temperature; δ^{18}O). Young groundwater ages that highlight regional recharge areas are located in the eastern San Joaquin Valley, in the southern Santa Clara Valley Basin, in the upper LA basin and along unlined canals carrying Colorado River water, showing that much of the recent recharge in central and southern California is dominated by river recharge and managed aquifer recharge. Modern groundwater is found in wells with the top open intervals below 60 m depth in the southeastern San Joaquin Valley, Santa Clara Valley and Los Angeles basin, as the result of intensive pumping and/or managed aquifer recharge operations.

1. Introduction

Water is a limited resource in California. While some areas receive over 3000 mm of precipitation per year, a large proportion of the population is located in areas receiving less than 500 mm per year (Fig. 1b). Most precipitation falls in winter and a large proportion of precipitation falls as snow in the Sierra Nevada mountain range. Snowmelt contribution to rivers draining the Sierra Nevada causes peak discharge to occur in late spring. Reservoirs mitigate flood risk and store snowmelt, to be released gradually in summer. The groundwater system acts as a natural buffer for seasonal and inter-annual precipitation variability. Historically, groundwater has been exploited at a rate higher than the natural recharge rate, leading to depletion of fresh groundwater resources (Famiglietti et al., 2011). At present, groundwater recharge is enhanced by managed aquifer recharge (MAR), mainly in urban areas, to replenish overdrafted aquifers and utilize the storage capacity (Bouwer, 2002; Massmann and Sültenfuß, 2008). For optimal use and protection of groundwater, knowledge of the key characteristics of the groundwater system, such as recharge locations and mechanisms, groundwater flow patterns and subsurface residence times, are essential.

The Groundwater Ambient Monitoring and Assessment (GAMA) program (Belitz et al., 2010, 2003) aims to assess the quality and vulnerability of groundwater resources in California. A large proportion of the monitoring effort is dedicated to the collection and analysis of water quality samples (Deeds et al., 2012; Fram and Belitz, 2011a; Jurgens et al., 2009; Fram and Belitz, 2011b; Landon et al., 2011). Simultaneous collection and analysis of environmental tracers, including tritium, stable isotopes of the water molecule and dissolved noble gases and the helium isotope ratio, has allowed assemblage of an unprecedented database containing valuable information regarding key groundwater characteristics,

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http://dx.doi.org/10.1016/j.watres.2016.01.004
0043-1354/

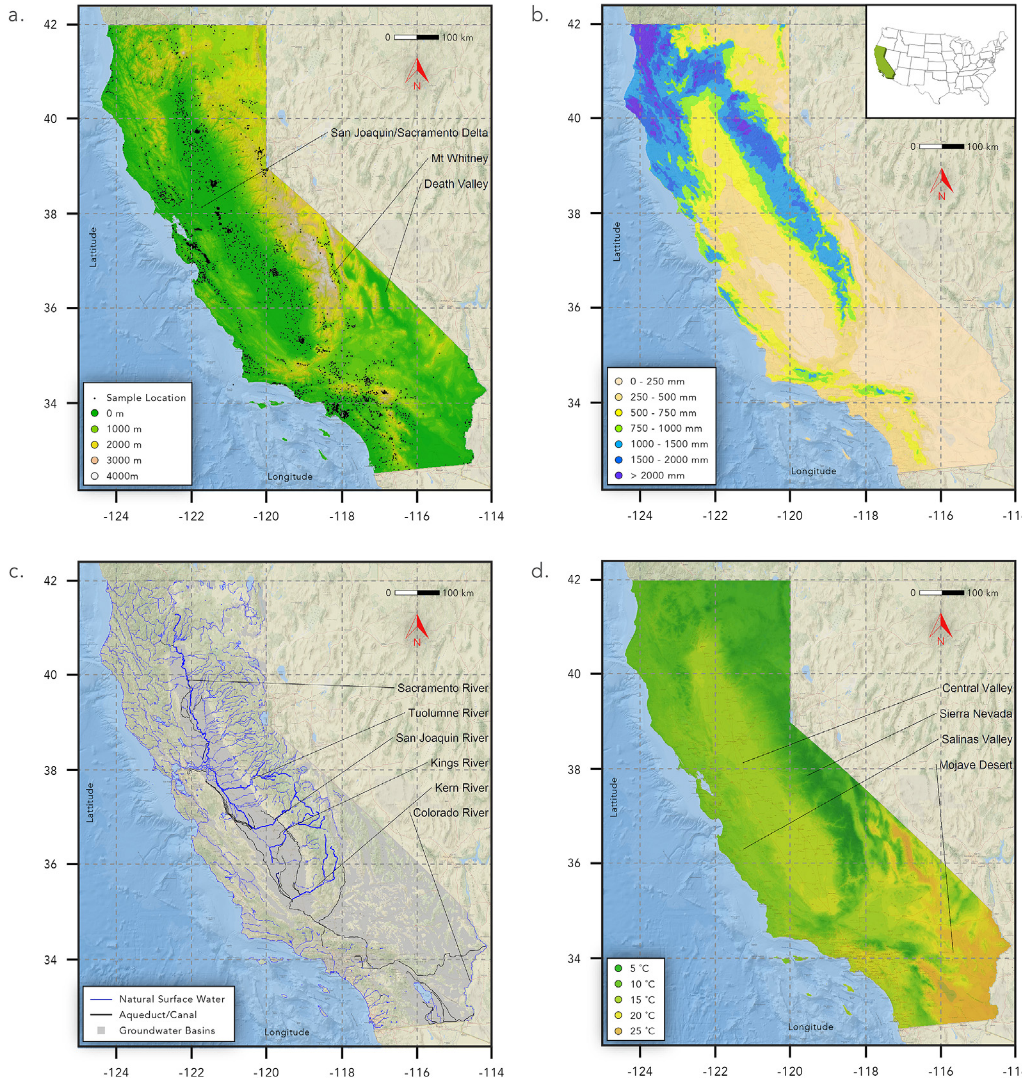

Fig. 1. Maps of elevation and sample locations (a), precipitation (b), hydrology (c) and mean annual air temperature (d) in California.

allowing assessment of contamination vulnerability and sustainability of groundwater abstraction.

Tritium is a tracer for modern groundwater that has recharged since the start of the nuclear era in 1945 (Nir, 1964; Vogel et al., 1974). Residence time distributions of groundwater and surface water have been derived by matching observed concentration time series to outflow concentrations of a mixing model, with the historical concentrations of tritium in precipitation as input (Stewart et al., 2010; Robert, 2004; Plummer et al., 2001; Izbicki et al., 2000; Michel, 1992; Rose, 2007; Kluge et al., 2010; Eastoe et al., 2011; Blavoux et al., 2013). When combined with the analysis of helium-3, the "$^3H/^3He$ age" of groundwater recharged after about 1950 can be calculated from the ratio of tritium and its decay product (Takaoka and Mizutani, 1987; Poreda et al., 1988; Schlosser et al., 1988). Accumulation of helium-4 in groundwater, from the decay of naturally occurring uranium and thorium, provides a qualitative age tracer over the 500 year to million year time scale (Solomon et al., 1996; Schlosser et al., 1989). Well water samples almost invariably comprise a mixture of different ages, which should be characterized by an age distribution, ideally derived from a number of different age tracers. References to "groundwater age" in this paper are limited to the (apparent) $^3H/^3He$ age, which represents the initial-tritium weighted mean age of the modern groundwater component. This is a useful metric of groundwater age for studying the vulnerability of groundwater and identifying areas of active recharge, despite the bias towards time periods of higher concentrations of tritium in recharging groundwater.

Dissolved noble gas concentrations in groundwater reflect the climatic and hydrological conditions at the time of recharge, such as temperature and water table fluctuations (Stute et al., 1992, 1995a; Aeschbach-Hertig et al., 2000a; Wilson and McNeill, 1997). Stable isotopes of the water molecule (represented by δ^2H and $\delta^{18}O$), vary spatially in precipitation in California due to continental and orographic effects, as illustrated by the variation in river water (serving as a proxy for precipitation) (Kendall and Coplen, 2001). Rivers generally maintain the signal of their source region (Dutton et al., 2005) and the stable isotope signature in groundwater acts as a fingerprint of the origin of precipitation if recharge occurs aerially or by river bank infiltration downstream of the source area. These analyses, taken together and interpreted in a physiographic context, allow us to address the following questions:

- Which aquifers contain modern groundwater, indicating areas of active recharge that are vulnerable to surface contamination?