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Spatial variability of chloride deposition in a vegetated coastal area: Implications for groundwater recharge estimation

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SUMMARY

Knowledge of atmospheric chloride deposition is a prerequisite for applying the chloride mass balance (CMB) method for groundwater recharge estimation. Compared to bare areas, vegetated areas can significantly enhance chloride deposition rates as the vegetation canopy provides a large surface onto which water droplets and aerosols settle. Although generally acknowledged, this effect has often been ignored in practical applications of the CMB method. This paper studies the variability of chloride deposition in a coastal basin characterised by a heterogeneous vegetation cover, and the implications of this variability for groundwater recharge estimation using observation wells in the saturated zone. The study area is located on the Eyre Peninsula in South Australia. The theory of the CMB method for groundwater recharge estimation is revised in the context of highly spatially variable chloride deposition. A GIS-based approach is developed for mapping the chloride deposition accounting for distance from the coast, distribution of vegetation and edge effects; the latter implying a lower chloride deposition inside a vegetation stand than at the edge. In order to quantify the significance of one or several of these effects for recharge estimation, different chloride deposition maps and corresponding recharge estimates are derived. Compared with the reference scenario that accounts for all effects, neglecting the coastal effect results in a 33–36% higher average recharge estimate, whereas neglecting the vegetation effect results in a 17–22% lower average recharge estimate. The latter numbers are likely to represent a lower bound of the impact of neglecting the vegetation effect. A critical factor for accurate determination of the influence of vegetation appears to be the edge effect, albeit its importance is subject to significant uncertainty that warrants further monitoring.

1. Introduction

The chloride mass balance (CMB) method is the most widely used technique to estimate groundwater recharge in semi-arid and arid regions (Scanlon et al., 2006), and has been applied in many studies across the world (Anderson, 1945; Eriksson and Khunakasem, 1969; Allison and Hughes, 1978; Wood and Sanford, 1995; Sami and Hughes, 1996; Grismer et al., 2000; Lo Russo et al., 2003; Crosbie et al., 2010; Scanlon et al., 2010). The popularity of the CMB method arises from it being relatively simple and inexpensive (Edmunds and Gaye, 1994; Wood, 1999; Crosbie et al., 2010), and it is one of the few recharge estimation methods that can provide an estimate of low recharge rates (Scanlon et al., 2002).

The CMB is based on the principle that under steady-state, long-term conditions, with chloride being chemically inert, the mass flux of chloride into the unsaturated zone equals the mass flux out of the unsaturated zone by recharge to the groundwater. By measuring the chloride concentration at depth in the aquifer (as done in this study), and estimating the mass flux of chloride into the unsaturated zone, one can hence calculate the net recharge, i.e., the recharge to the water table less the amount extracted from the saturated zone by plant transpiration or direct evaporation (Crosbie et al., 2010). The mass flux of chloride into the unsaturated zone originates from atmospheric deposition at the land surface, in addition to potential fluxes arising from surface runoff into and out of the infiltration area. Application of the CMB thus requires knowledge of the atmospheric chloride deposition rate, amongst other fluxes. This is not straightforward. A range of processes controls the deposition, which commonly has a large spatial variability (Junge and Gustafson, 1957; Richter et al., 1983; Stuyfzand, 1993; Keywood et al., 1997; Gustafsson and Hallgren Larsson, 2000; Alcalá and Custodio, 2008; Guan et al., 2010). This variability makes the extrapolation of point measurements difficult, an issue that has often been recognised as the main

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source of uncertainty in the application of the CMB method (Edmunds and Gaye, 1994; Wood and Sanford, 1995; Scanlon et al., 2006; Crosbie et al., 2010; Alcalá and Custodio, 2014).

The ocean is commonly regarded as the primary source of atmospheric chloride (Eriksson, 1959; Gustafsson and Hallgren Larsson, 2000). Chloride is transported from the ocean to the continent and is deposited on the land surface and vegetation canopy via wet and dry deposition. Wet deposition occurs in the form of rain or snow, whereas dry deposition is due to the gravitational fallout of aerosols. Dry deposition also includes the deposition of water droplets (e.g., fog) and the absorption of gas on surfaces (Ulrich, 1983). Chloride deposition generally decreases with distance inland (Junge and Gustafson, 1957; Hutton, 1976; Gustafsson and Hallgren Larsson, 2000; Alcalá and Custodio, 2008), as the consequence of several processes that are likely co-occurring (Keywood et al., 1997). Firstly, the progressive vertical mixing in the troposphere and the removal of particles via deposition both produce lower chloride concentrations in raindrops and less effective dry deposition processes. Secondly, precipitation generally decreases inland, which reduces wet deposition. The chloride deposition gradient is strongest near the coast, which makes the assessment of chloride deposition particularly challenging in coastal areas (Alcalá and Custodio, 2008). In a coastal area of South Australia (<80 km from the coast), distance from the coast was shown to account for 70% of the observed total spatial variability in open-field bulk collectors (Guan et al., 2010). In such a setting, distance from the coast thus appears to be a relatively good, simple proxy for extrapolating chloride deposition measurements as a first-order approximation. Eriksson and Khunakasem (1969) used relationships between the rate of chloride deposition and distance from the coast, latitude and height above sea level to construct a chloride deposition map along the coast in Israel (<20 km from the coast), and subsequently derived recharge estimates using the CMB method. Stuyfzand (1993) showed the dependency of chloride deposition and groundwater chloride concentration on distance from the coast within the first few kilometres from the coast. Ordens et al. (2012) estimated chloride deposition as a function of distance from the coast in the same area as in this study (<10 km from the coast) with Hutton's formula (Hutton, 1976), and subsequently derived recharge estimates using the CMB.

Vegetation canopies can significantly enhance chloride deposition compared with an open field by efficiently capturing droplets and aerosols from the atmosphere (Ulrich, 1983). When the captured chloride is flushed during rainfall events, it reaches the land surface and can infiltrate into the soil. Depending on vegetation type, canopy structure, height, age, density, distance from the forest edge, distance from the coast and meteorological conditions the presence of vegetation can result in an increase of the atmospheric chloride deposition ranging between 20% and 2200% (Parker, 1983; Ulrich, 1983; Beier and Gundersen, 1989; Lindberg et al., 1990; Peters, 1991; Granat and Hällgren, 1992; Stuyfzand, 1993; Neary and Gizyn, 1994; Crockford et al., 1996; Moreno et al., 2001; Erisman and Draaijers, 2003; Kauffman et al., 2003; Herrmann et al., 2006; Małek and Astel, 2008; Brecciaroli et al., 2012; Deng et al., 2013). While this effect has been fully recognised and studied in the fields of atmospheric science and forestry, it has not often been accounted for in the CMB method for groundwater recharge estimation. But because the recharge estimates depend linearly on the chloride deposition rate, neglecting the vegetation effect can imply a very significant underestimation of the recharge in areas where a significant proportion of the land is covered by vegetation. For example, Eriksson and Khunakasem (1969) estimated an average 30% increase of chloride deposition due to vegetation and applied it uniformly over the study area, thus implying a 30% increase of the recharge estimates compared with estimates that would neglect this effect. Deng et al. (2013) also demonstrated the significance of the effect of vegetation for the CMB method by discussing a number of examples where neglecting the enhancement due to vegetation would imply an underestimation of up to 100% of the recharge.

While the significance of the effect of vegetation for the CMB method has been demonstrated in previous works, difficulties arise when the vegetation cover is heterogeneous and the CMB method is applied using observation wells in the saturated zone. In that case, the capture zone of the observation wells must be known, and a detailed chloride deposition map must be available. These aspects have not been covered jointly in previous works. In this paper the results of a field study on the spatial variability of the chloride deposition in a naturally vegetated area are presented, and the implications for CMB-based groundwater recharge estimation are quantified. The studied basin is a coastal area, where distance from the coast also strongly controls the chloride deposition variability. Two fundamental questions are addressed: (i) what is a possible strategy to account for the effects of vegetation and distance from the coast in the CMB in an area featuring a heterogeneous vegetation cover; and (ii) how significant are the different processes involved, i.e., how wrong can the recharge estimates be if they are neglected? In this context it is meaningful to revise the theory developed by Eriksson and Khunakasem (1969) for groundwater recharge estimation using the CMB. This theory neglected the effects of dispersion (defined as the combination of molecular diffusion and mechanical dispersion). Dispersion implies that the chloride measured in an observation well originates from a certain two-dimensional area, and not from a line, as was assumed in Eriksson and Khunakasem (1969). If the spatial variability of the chloride deposition is high, estimating the average chloride deposition over a two-dimensional area instead of over a line may yield significant differences in the recharge estimates.

The paper extends previous recharge studies of the coastal Uley South Basin, Eyre Peninsula, South Australia (Ordens et al., 2012, 2014). This basin, important for its groundwater resource (Werner et al., 2011), is representative of many coastal settings in which atmospheric chloride deposition may be a function of both vegetation and distance from the coast. It features a heterogeneous vegetation cover, which makes the assessment of the overall effect of vegetation on chloride deposition challenging. Previous work in the area relied on open-field chloride deposition estimates to apply the CMB method for groundwater recharge estimation, as commonly practiced (Ordens et al., 2012). However, Ordens et al. (2012) highlighted that neglecting the influence of vegetation on chloride deposition was an area of significant uncertainty in their results. This paper complements the previous work with new chloride deposition data. A methodology for mapping the chloride deposition over the entire basin using GIS techniques is presented, and the effects of the spatial variability of the atmospheric chloride deposition on recharge estimates are quantified.

2. Study area

The Uley South Basin (34°47′S, 135°32′E) is a topographically closed coastal area in the southern part of Eyre Peninsula, South Australia, facing the ocean on the south-west side (Fig. 1a). It covers an area of 129 km^2, extending 18 km along the coast and 7 km inland on average. The elevation is characterised by coastal cliffs ranging from 100 to more than 140 m AHD (Australian Height Datum), and by a gentle decrease inland, down to less than 10 m AHD in the centre of the basin. The climate of Uley South is semi-arid, characterised by cold and wet winters, and hot and dry summers (Harrington et al., 2006). The long-term average rainfall for the period 1897–2013 at Big Swamp monitoring station,