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Determining water quality requirements of coal seam gas produced water for sustainable irrigation

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ABSTRACT

Coal seam gas production in Australia generates large volumes of produced water that is generally high in total dissolved solids and has a high sodium absorption ratio (SAR) which may affect soil structure, hydraulic conductivity, and crop production if used untreated for irrigation. By coupling major ion soil chemistry and unsaturated flow and plant water uptake, this study incorporates effects of salt concentrations on soil hydraulic properties and on root water uptake for soils irrigated with produced water featuring different water qualities. Simulations provided detailed results regarding chemical indicators of soil and plant health, i.e. SAR, EC and sodium concentrations. Results from a base scenario indicated that the use of untreated produced water for irrigation would cause SAR and EC values to significantly exceed the soil quality guide values in Australia and New Zealand (ANZECC). The simulations provided further useful insights in the type of coupled processes that might occur, and what the potential impacts could be on soil hydrology and crop growth. Calculations showed that the use of untreated produced water resulted in a decrease in soil hydraulic conductivity due to clay swelling causing water stagnation, additional plant-water stress and a reduction in plant transpiration. In case the produced water was mixed with surface water in a 1:3 ratio prior to irrigation, the calculated soil SAR values were much lower and generally acceptable for sandy to sandy-loam soil. The use of reverse osmosis treated produced water yielded an acceptable salinity profile not exceeding guide values for SAR and EC; the plant water stress was limited as there was no additional salinity stress associated with the low level of salts. Results further illustrated that accounting for coupled geochemical, hydrological and plant water uptake processes resulted in more accurate water balance calculations compared to an approach where such interactions were not implemented. Coupling unsaturated flow modelling with major ion chemistry solute transport using HYDRUS provides quantitative evidence to determine suitable water quality requirements for sustainable irrigation using coal seam gas produced water.

1. Introduction

Production of coal seam gas in Australia requires depressurisation of the coal seam layers by extracting large volumes of groundwater. Reducing the hydrostatic pressure on the gas in the pores of coal seams allows gas to flow through natural and enhanced fracture networks to the gas production well (Moore, 2012). Water extraction rates in the main coal seam gas areas in Australia vary over time and geographically (QWC, 2012). Based on a 50-year time frame that is generally assumed for forecasting water production (DNRM, 2012), average water production rates range from 0.028 GL/year in the Clarence Moreton basin (New South Wales) (RPS, 2011) to 75–98 GL/year in the Surat Basin (Queensland) (QWC, 2012). By 2050, most Australian coal seam gas areas will have reached the end of their production stage (DNRM, 2012).

Treated coal seam gas water may be utilised for beneficial uses, including agriculture (irrigation and stock), urban uses (town water supply) and industrial uses (construction and processing). Assessment of the beneficial use of treated coal seam gas water for the Central Condamine Alluvium (Queensland) indicates the region has the capacity to deliver 854 GL (gigalitres), or around 35% of the historic depletion, by 2050 to irrigators and the Chinchilla Weir water supply scheme (DNRM, 2013). Other irrigation projects in

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Australia where produced water is used include large-scale forestry in Queensland's Bowen Basin and legume plantations (RPS, 2011). In the Bowen Basin, up to 8 ML/day of reverse osmosis (RO) treated produced water was used to irrigate 234 ha of pasture crop and an 800,000 tree timber plantation (Santos, 2009, 2010). Also in Queensland, 300 ha of oilseed-bearing legume tree (*Pongamia pinnata*) plantation are irrigated with RO treated produced water (Parsons, 2010).

Produced water is generally unsuitable for direct surface discharge or irrigation without any treatment or amendment (Stearns et al., 2005; Beletse et al., 2008; Nghiem et al., 2011). While sodium ions cause soil particles to disperse, particularly if the soils contain montmorillonite clays, most ions increase the aggregation of soil particles (Nghiem et al., 2011). Irrigation water with a high SAR[1] can lead to a decrease in infiltration and deterioration of the soil structure as the dispersed clay minerals, once dry, cause soils to become dense, cloddy and structureless, destroying natural particle aggregation. SAR values greater than 13 pose a risk to the soil ecosystem (Stearns et al., 2005), and even SAR values between 5 and 8 have been shown to cause irreversible plugging of soil pores and swelling (Mace and Amrhein, 2001). Traditional treatments to mitigate saline-sodic irrigation water can be used, such as for example the addition of gypsum and elemental sulphur (Vance et al., 2008; Šimůnek et al., 2006).

Studies have been undertaken to assess the feasibility of using sodium-rich produced water for salt-tolerant crop production (Johnston et al., 2008; Vance et al., 2008; Beletse et al., 2008). Vance et al. (2008) used saline-sodic coal seam gas produced water with an SAR between 17 and 57 for irrigating grasslands and hayfields in the Powder River Basin, Wyoming. For the use of produced water to be effective, the method further required applications of gypsum and elemental S to provide calcium ions and an acidified soil environment to promote calcite dissolution. Further field studies in Wyoming with bioenergy feedstock species indicated that produced water can be used for short-period (2 years) irrigation of such crops (Burkhardt et al., 2015). However, the study also concluded that prolonged use of untreated produced water for irrigation would likely have deleterious long-term effects on the soil and plants unless the water was treated or diluted with good-quality water.

Water produced during the depressurisation phase of coal seam gas mining in Waterberg district, South Africa, is highly saline and dominated by sodium bicarbonate. With careful management, Beletse et al. (2008) determined that coal seam gas irrigation water with SAR values of 85 could be used to grow certain crops, but additions of gypsum and organic matter to the soil were necessary to counteract infiltration problems that arose due to the excessive sodium that had accumulated in the soil.

Investigations of soil and vegetation recovery in British Columbia document the natural recovery of salt-affected plots (Leskiw et al., 2012), with natural attenuation from above normal rainfall in the first few years after the salt deposition being effective in removing salts from the root zone and subsoil. These results, however, were obtained for a humid climate; it is expected that natural attenuation under arid or semi-arid climates would be much less effective. Bright and Addison (2002a,b) developed standardised guidelines to assist spill response and soil remediation in northern British Colombia at sites where salt-containing produced water is released as part of oil and gas exploration and extraction activities. Generic soil quality standards for human health, aquatic life, and soil ecological functioning, as manifested through soil invertebrate and plant responses, were developed for salt ions. Whilst the impairment of metabolic functioning of soil microbes is recognised as playing a major role in nutrient cycling and other processes important to terrestrial ecosystems, there is insufficient data available to define a threshold for salt ions; instead, a microbial functional impairment standard is used that is developed from nutrient and energy cycling data.

In Australia, the Queensland Department of Environment and Heritage Protection (DEHP) recommends the minimum standards for using produced water for irrigation purposes. The guidelines indicate that the electrical conductivity (EC) should be less than 950 μS/cm or 0.95 dS/m (95th percentile over a one-year period), and the SAR should be less than 6 for heavy soils and less than 12 for light soils (95th percentile over a one-year period) (DEHP, 2014). Another potential issue when produced water is used for irrigation is the relatively high boron content. If not removed, boron can be damaging to some flora. The boron ANZECC guide value for long-term irrigation (up to 100 years) is 0.5 mg/L.

In Australia and New Zealand, the minimum quality of irrigation water is defined in The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC, 2000). Plant salt tolerances and recommended trigger values for metals and metalloids in irrigation water are also provided in ANZECC (2000). For instance, for different soil types, permissible levels of chloride, sodium, and SAR have been defined (Table 1).

To support the sustainable management of soil and landscapes under irrigated agriculture, Biggs et al. (2012) developed a framework to assess the salinity risk associated with the use of coal seam gas water for irrigation in the Queensland Murray-Darling Basin. Biggs et al. (2012) identified the description of the unsaturated zone as the key knowledge and data gap when conducting salinity risk assessments. In particular, studies are needed about (i) critical soil attributes (porosity, initial soil water content, substrate hydraulic conductivity) to depths below the "root zone", (ii) the extent of the root zone for different crops, and (iii) the quantification of lateral flow processes. Biggs et al. (2012) further highlighted the need to better define critical thresholds for agronomic and degradation purposes (e.g. acceptable root zone salinity) across landscapes, improve process understanding such as the fate of excess water (lateral flow or drainage), and deeper soil/regolith processes and properties.

The current study endeavours to address those knowledge gaps that relate to better process understanding (e.g., critical soil properties, critical thresholds) using the unique features of the HYDRUS-1D simulator that are relevant for salinity risk assessment (Jacques et al., 2013a; Šimůnek et al., 2006, 2016). To this end, this study simulates coupled processes of variably saturated water flow, plant water uptake and coupled transport of multiple major ions in soils irrigated with produced water of different water qualities. Through this process coupling, we explicitly include critical soil processes required for salinity risk assessment associated with coal seam gas produced water in the analysis. Simulations of the movement of multiple ions in a vegetated soil profile under irrigation are based on the major ion chemistry module UnsatChem (Šimůnek and Suarez, 1994) implemented in the finite element code HYDRUS-1D (Šimůnek et al., 2008).

2. Materials and methods

2.1. Soil hydrological model

Simulation of variably saturated flow in soil requires a mathematical relationship between (i) the soil water content (θ) and the soil pressure head (h), i.e. the soil water retention curve $\theta(h)$, and (ii) either the water content or the pressure head and the unsaturated hydraulic conductivity $K(\theta)$ and $K(h)$, respectively. We applied the

[1] Sodium adsorption ratio $(SAR) = [Na^+]/\{([Ca^{2+}] + [Mg^{2+}])/2\}^{1/2}$ where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are in meq/L.