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Bayesian Belief Network analysis of soil salinity in a peri-urban agricultural field irrigated with recycled water

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ABSTRACT

Continuous use of recycled water (treated wastewater) over a long period of time may lead to the accumulation of salt in the rootzone soil. This is due to the relatively higher levels of salt content in the recycled water compared to surface water. In this study, an assessment framework is proposed to evaluate the level of salinity in recycled water that can have significant impact on the rootzone salinity when recycled water is used for irrigating peri-urban agricultural paddocks. The framework is constructed with a probabilistic expert system, more specifically, Bayesian Belief Network (BBN). The BBN model analyses the salt accumulation process with quantifying uncertainty associated with various variables related to this process. The proposed BBN was first developed and tested with the results from laboratory batch study and continuous column study conducted over 264 days. Later, a salt transport model HYDRUS 1D was used to quantify salt accumulation in the paddock over 20 years of study period, and the result was used to update the BBN to accommodate field condition. The salt transport modelling identified that in some year rootzone soil water electrical conductivity (EC_{SW} in dS/m) was more than twice of the maximum threshold of salinity tolerance. The BBN was used to quantify the uncertainty associated with the reduction of salinity in terms of electrical conductivity in recycled water (EC_{rw} in dS/m), which subsequently reduced the probability of exceeding the salt accumulation beyond the maximum threshold limit. It was found that, if EC_{rw} can be reduced by 13% (from 0.92 to 0.8 dS/m), there is around 49% probability that the EC_{SW} would be reduced by around 39% (from 6.5 dS/m to 4 dS/m), and will keep it within the threshold salinity limit of 3.0–5.0 dS/m 100% of the time. The study highlighted that any strategies that help in the reduction of salt in the recycled water will be beneficial in managing the soil salinity as a result of recycled water use for irrigating peri-urban agricultural field. The methodology presented in the study provides much needed knowledge for the development of robust and enlightened management strategies in relation to wastewater reuse.

1. Introduction

Recycling is one of the viable options to attain sustainable management of wastewater. The merits of recycled water is diverse which include reducing pressure on existing fresh water supplies, minimising effluent disposal to surface or coastal waters and provisioning constant volume of water than rainfall-dependant sources (Chen et al., 2012). The supply and use of recycled water may play an important role in enhancing urban water supplies in many water-scarce parts of industrialized countries because of its reduced treatment cost relative to seawater desalination and imported surface water. The technological improvement and economic affordability of wastewater treatment has made wastewater recycling a reality and broadened the most sustainable use of recycled water. One such reuse option includes application of recycled water in irrigation of agricultural land in peri-urban areas.

In Sydney, Australia, recycled water has been used for irrigation since 1960s. In 2011, Sydney Water supplied about 3.8 billion liters of recycled water for irrigating farms, sports fields, golf courses, parks, landscapes and racecourses and by 2015, it is expected that the recycling water will meet 12% of total water demand in greater Sydney (Sydney Water, 2013a). Thus the increasing use of recycled water, particularly for irrigating peri-urban agricultural fields, in the place of fresh water, is one of the important goals of the local and national governments to achieve sustainable management of water.

However, the downside of using recycled water, particularly for irrigation, is due to its contaminants. Particular contaminant that is of concern for this study is salts. Salinity is the concentration

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of soluble salts in water that are measured as total dissolved salts or electrical conductivity in soil solutions. From an environmental point of view, sodium and chloride are the two constituents of recycled water which are of most concern as they are more likely to remain as ions in soil solutions and contribute to the effects of salinity on plant growth (NRMMC-EPHC-AMC, 2006). In the conventional wastewater treatment process, the majority of mineral salts pass through the wastewater treatment system unaffected, unless reverse osmosis is used as one of the treatment processes (Aiello et al., 2007; Rebhun, 2004). As such, the recycled water contains elevated levels of salt (Rahman et al., 2015a), when the recycled water is used for irrigation, there is a potential risk of salt increase in the vadose zone.

The increase in salt concentration in the soil can adversely influence the amount of water a plant can uptake from the soil due to the osmotic effect. Several studies have reported increased salinity levels in soil due to the prolonged use of recycled water for irrigation (Adrover et al., 2012; Klay et al., 2010; Dikinya and Areola, 2010). Higher salt levels in the soil can adversely affect the soil potential for supporting plants and crops growth (Grewal and Maheshwari, 2013; Al-Hamaiedeh and Bino, 2010; Bernstein, 1975). Hence, it is important to control the salt accumulation in the soil, particularly in the rootzone, by controlling the salt levels in the irrigation water.

The Hawkesbury Water Reuse Scheme (HWRS), because of its long-term recycled water use for irrigation, has always been under the attention of the scientific community of the western Sydney region. While several risk assessment studies related to recycled water irrigation have been carried out (Aiken et al., 2010; Derry et al., 2006; Attwater et al., 2006), a limited number of studies have reported on the salt accumulation in the soil of HWRS paddocks that used recycled water for irrigation (Aiken, 2006; Rahman et al., 2015b). In addition, none of the previous studies, mentioned above, considered assessing the salt accumulation in a probabilistic manner. A probabilistic model involves a degree of variability and randomness, which is helpful in quantifying salt accumulation compared to a point value only. In this study, a novel methodology incorporating Bayesian Belief Network (BBN) is proposed to identify the level of treatment needed in recycled water that significantly influence the soil salinity and sodicity within the context of using recycled water for irrigation. Bayesian Belief Network was applied in this study because this method is capable of incorporating uncertainty of associated variables by using marginal probability distributions. The network provides graphical representation of key factors, which portrays a better understanding of the inter-dependent relationships between the factors of the decision process (Jensen and Nielsen, 2007).

Bayesian Belief Networks have been used successfully to better understand and model different environmental problems, which includes decision making on maintaining ecological health of river, framework to maintain sustainability of coastal lake-catchment system, assessing sources of salinity in coastal aquifer, and assessment and management of integrated water resources (Chan et al., 2012; Ticehurst et al., 2007; Ghabayen et al., 2006; Giordano et al., 2015; de Santa Olalla et al., 2005; Batchelor and Cain, 1999; Saravanan, 2010). In case of recycled water, a concurrent study was conducted by Rahman et al. (2015a) for controlling sources to reduce salinity in sports field irrigated with recycled water. However, the application of Bayesian Belief Network for managing salinity issues associated with the use of recycled water for peri-urban agricultural irrigation needs more attention. Therefore, the proposed decision support system (assessment framework) incorporating Bayesian Belief Network is a novel technique. The main objectives of the present study are (i) to use a probabilistic method, viz., Bayesian Belief Network, to evaluate the risk of salinity hazard associated with the use of recycled water for peri-urban agricultural irrigation; and (ii) to identify the level of treatment needed to reduce salinity in recycled water for salt accumulation in the soil by recycled water irrigation over 20 years.

2. Case study area

The Hawkesbury Water Reuse Scheme is situated within the Hawkesbury Campus of the Western Sydney University in Richmond NSW, approximately 80 km northwest of Sydney (Fig. 1). The Hawkesbury Water Reuse Scheme has been built upon partnerships between the University and Sydney Water Corporation (SWC), Richmond TAFE, Hawkesbury City Council, and Clean-Up Australia (Booth et al., 2003). The scheme consists of Richmond, Blacktown, Londonderry and Clarendon paddocks. The D21 paddock (S 33°37.478′ E 150°45.706′) is under Blacktown paddock and had irrigation history since 1989. However, the irrigation in this paddock was ceased in 2008. The soil sample from this paddock was collected on 2012. Soil samples were collected from the paddock between the depths 0 and 0.2 m, using open pit method. The texture of the soil was determined (NCST, 2009) as loamy sand comprising of 88.1% sand, 6.0% silt and 5.9% clay. Bulk density (in field condition) and saturated electrical conductivity (EC_e) was determined as 1500 kg/m^3 and 0.375 dS/m, respectively. The soluble cations were determined as 1.17, 0.288, 1.51, and 0.56 mmol(c)/L for Na^+, Ca^{2+}, Mg^{2+}, and K^+, respectively; the Sodium Adsorption Ratio (SAR) was determined as 1.234. The hydraulic parameters (van Genuchten et al., 1991) including residual water content (θ_r), saturated water content (θ_s), shape parameters (α and n) and saturated hydraulic conductivity (K_s) were 0.041 m^3/m^3, 0.497 m^3/m^3, 0.006, 2.572, and 298.26 cm/day, respectively (the soil water characteristics curve was evaluated by pressure plate method according to ASTM (2002)). The HWRS receives recycled water from Sydney Water's Richmond STP, which is first collected in a Receiving Pond, and then pumped up into the first University storage, the Effluent Turkey Nest Dam (capacity 93 ML) (Booth et al., 2003). Up to late 2005 the supply from this STP was essentially secondary, involving a trickling filter (TF) process with pond stabilisation. However, in 2005 Sydney water carried out extensive alterations to the STP, replacing the old TF process by intermittently decanted aerated lagoon (IDAL) process with tertiary treatment involving sand filtration and chlorination/dechlorination (Aiken et al., 2010). The electrical conductivity of the recycled water was measured between 0.81 and 0.84 dS/m.

3. BBN model

In this research Bayesian Belief Network is used as a basis for assessment framework. The BBN works effectively in a situation where partial information is known and incoming data has a probability distribution (Valiente et al., 2012). The network diagram is a representation of cause and effect of an event or variable via graphical representation. In this paper, the network diagram is considered for different variables instead of events. The BBN is based on Bayes' theorem, which is given by (Bolstad, 2004):

$$P(A|B) = P(A)\left[\frac{P(B|A)}{P(B)}\right] \quad (1)$$

Bayes' theorem shown in Eq. (1) provides a method for updating evidence based beliefs about a variable A given the information about another variable$B$. For this reason $P(A)$is generally called the *prior* probability of A, whereas $P(A|B)$is called the *posterior* probability of Agiven B; the probability of $P(B|A)$is called the likelihood of Bgiven A(Jensen and Nielsen, 2007).

The BBN is based on the ideas that the parameters are considered random variables having a number of *states*. The set of states associated with variables $A$and $B$of Eq. (1) can be denoted by $A = a_1, a_2, \ldots\ldots, a_n$ and $B = b_1, b_2, \ldots\ldots, b_n$. The