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Determining treatment requirements for turbid river water to avoid clogging of aquifer storage and recovery wells in siliceous alluvium

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ABSTRACT

The success of Aquifer Storage and Recovery (ASR) schemes relies on defining appropriate design and operational parameters in order to maintain high rates of recharge over the long term. The main contribution of this study was to define the water quality criteria and hence minimum pre-treatment requirements to allow sustained recharge at an acceptable rate in a medium-coarse sand aquifer. The source water was turbid, natural water from the River Darling, Australia. Three treatments were evaluated: bank filtration; coagulation and chlorine disinfection; and coagulation plus granular activated carbon and chlorine disinfection (GAC). Raw source water and the three treated waters were used in laboratory columns packed with aquifer material in replicate experiments in saturated conditions at constant temperature (19 °C) with light excluded for 37 days. Declines in hydraulic conductivity from a mean of 2.17 m/d occurred over the 37 days of the experiment. The GAC-treated water gave an 8% decline in hydraulic conductivity over the 16 cm length of columns, which was significantly different from the other three source waters, which had mean declines of 26–29%. Within the first 3 cm of column length, where most clogging occurred in each column, the mean hydraulic conductivity declined by 10% for GAC-treated water compared with 40–50% for the other source waters. There was very little difference between the columns until day 21, despite high turbidity (78 NTU) in the source water. Reducing turbidity by treatment was not sufficient to offset the reductions in hydraulic conductivity. Biological clogging was found to be most important as revealed by the accumulation of polysaccharides and bacterial numbers in columns when they were dissected and analysed at the end of the experiment. Further chemical clogging through precipitation of minerals was found not to occur within the laboratory columns, and dispersion of clay was also found to be negligible. Due to the low reduction in hydraulic conductivity, GAC-treated water quality was used to set pre-treatment targets for ASR injection of turbidity <0.6 NTU, membrane filtration index (MFI) < 2 s/L^2, biodegradable dissolved organic carbon (BDOC) < 0.2 mg/L, total nitrogen < 0.3 mg/L and residual chlorine > 0.2 mg/L.

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1. Introduction

Limited opportunities for further expansion of surface water or groundwater resources has necessitated new approaches to water management and supply such as Aquifer Storage and Recovery (ASR). Virtually all ASR operations experience some degree of clogging that can critically limit the quantity of water that is stored within the aquifer (Olsthoorn, 1982). Processes associated with ASR clogging include: irrecoverable accumulation of particulate matter that is present within the source water (Rinck-Pfeiffer et al., 2000; Pavelic et al., 2007); precipitation of minerals due to chemical or bacterial processes (Baveye et al., 1998); swelling or dispersion of reactive clays (Konikow et al., 2001); production of bacterial biomass growth due to nutrients present in the source water (Baveye et al., 1998; Rinck-Pfeiffer et al., 2000; Pavelic et al., 2007); and entrapment of gas through air entrainment, cavitations or biological processes.

The lack of reliable and efficient predefined water quality targets for injection into aquifers remains a source of uncertainty for the uptake of ASR (NRMMC–EPHC–NHMRC, 2009). This study was undertaken to evaluate the potential for clogging of injection wells in a proposed ASR scheme targeting the alluvial sand Calivil Formation aquifer with treated water from a turbid inland river. Column and batch studies were performed with aquifer material taken from the coarse grained sand aquifer, and source waters with different levels of pre-treatment. The aims of the 5-week column study were to determine:

- The potential for clogging of the ASR injection well;
- The principle causes of such clogging; and
- Water treatment targets prior to ASR injection to manage clogging.

2. Materials and methods

The experiment was designed to compare the potential for clogging using four qualities of water with varying degrees of treatment. The clogging potential was assessed by means of (1) a column study for physical, chemical and biological clogging evaluation, (2) a batch study for clay dispersion clogging evaluation, and (3) geochemical modelling for chemical clogging evaluation.

2.1. Source waters

Column studies were conducted with four different qualities of water:

- Untreated Darling River water collected from the Menindee town water supply offtake ("River")
- Bank filtration treated Darling River water collected from a specially drilled well (BHMAR 84-5) 110 m from the river bank; ("Bank") with treatment achieved during filtration through the sediments of the shallow Coonambidgal Formation.
- Menindee coagulation/flocculation treated Darling River water from the Menindee water treatment plant (treated with alum to meet the Australian Drinking Water Guidelines), additionally treated in the laboratory with added hypochlorite solution to maintain a disinfection residual >0.2 mg/L ("Town").
- Menindee coagulation/flocculation treated Darling River water as above, additionally treated in the laboratory with granular activated carbon (GAC) and hypochlorite solution to maintain a disinfection residual >0.2 mg/L ("GAC").

2.2. Sampling and preparation of aquifer materials

The target aquifer for ASR is the Calivil Formation that represents a fluvial Pliocene system. At the study site, the sands and gravels of the Calivil Formation ranges 5–45 m in thickness. The sediment is weakly consolidated, loose and friable in places, occasionally lithified in part by siliceous cement and intergranular mud. The semi-confined to confined Calivil Formation aquifer can be separated from unconfined aquifers in the shallow Coonambidgal and Menindee Formations by intervening silts and muds within the Blanchetown Clay or the upper part of the Calivil Formation itself. In turn, the Calivil Formation aquifer tends to be underlain by poorly permeable deposits (silts and muds) of the Renmark Group. Pumping tests performed in two production wells involving flow rates of 25 and 27.3 L/s, derived hydraulic conductivity estimates of 15 and 28 m/d respectively, corresponding to aquifer transmissivity values of 300 and 930 m^2/d.

Aquifer core material used in this study was taken from an intact core collected during drilling of an ASR investigation bore by a sonic vibracore rig. This technique uses audible frequency vibration rather than rotation to obtain uncontaminated and undisturbed continuous core samples. For the laboratory studies, an ASR target interval 'composite' sample was prepared from 18 sub-samples taken at 0.5 m intervals between 48.5 and 57.5 m of the intact core. This composite comprises medium to coarse quartz sand (69% 63 μm–2 mm; $d_{50} = 540$ μm) with minor fine silt, clay (5% < 63 μm) and gravel (26% > 2 mm). The sub-samples were dried in an oven at 45 °C, amalgamated and sieved to remove particles >2 mm. For all columns additional sieving was undertaken to remove the fraction <300 μm (7% w/w) for the final packing of the columns so as to minimise particle mobilisation effects in columns.

Repacked columns were used in order to allow replication of material properties of columns for direct comparison of the effect of water type. Removal of coarser fractions (>2 mm) was to avoid poor packing (low bulk density) of columns by attaining an acceptable column diameter to particle size ratio. Removal of the finer fraction was to overcome the problem of excessive initial decline in K/K_0 due to particle rearrangement in repacked columns that has not been observed in undisturbed sands and has a smaller effect in finer grained repacked media (Pavelic et al., 2011). That is, while it is recognised that removal of the finer fraction could potentially underestimate clogging of the native material, it is conceded that unless this material is excluded from samples from a high energy depositional environment, the results of column studies would be dominated by an artefact of packing, rather than by the effects of source water quality.

2.3. Aquifer material mineral and chemical analyses

Aquifer core samples were analysed for mineralogy using X-ray Diffraction (XRD) on the bulk sample (<2 mm) and on fine

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