

# ASSESSING THE RISKS OF DEEP INJECTION OF TREATED WASTEWATER INTO AN AQUIFER FOR STORAGE & RECLAMATION

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**Abstract:** Characterising behaviour of a particular liquid material injected into an aquifer is fraught with uncertainties and unknowns due to a multiplicity of factors. These include the sub-surface environment, the quality of the material to be injected, its behaviour during and after injection. Knowledge is required not only of the geological and chemical characteristics of the aquifer such as the profile of any existing native liquid material, but of the natural ecology of the soil into which product is to be injected and specific details of the composition of the liquid. Neither the soil nor the product for injection should be assumed to be inert or sterile. Some relationships between geological, chemical and microbiological constituents will occur if only through dint of close contact and the nature of these interactions needs understanding if, as in the instance of artificial injection, a change in existing natural conditions is involved.

Storage and reuse of wastewater for the growing metropolis of Sydney has been suggested as a way of capturing and reusing wastewater currently being disposed through ocean outfalls. The present paper examines some of the concerns in the deep injection of treated wastewater for reclamation-reuse purposes. This technology, termed aquifer storage and recovery (ASR) has already been tested in a 5-year experiment at the Andrews Farm site on the North Adelaide Plains of South Australia (Barry et al, 2002). The current paper in particular, focuses on three aspects of using ASR for water conservation purposes in the Sydney region. The approach is:

- (i) an overview of geological data on Sydney region comparing two hypothetical sites - the Bald Hill Claystone and the Botany Sands aquifer
- (ii) attention to issues of a hydrogeochemical and microbiological nature that could impact on groundwater in an aquifer if deep injection of wastewater is undertaken; and
- (iii) foreshadowing methods which could be used to learn more about microbial populations and behaviour in the aquifer after injection of treated wastewater.

## **Aquifer Sites in the Sydney Basin**

There has been interest in ASR for some years in government circles, at the Department of Sustainable Natural Resources, formerly the Department of Land and Water Conservation (DLWC) and Sydney Water. There has already been debate among academics about using ASR techniques for water conservation and recycling to service an increasing demand for water by the rapidly expanding urban metropolis of Sydney and the associated regions. Such initiatives have been successfully adopted in USA and more recently in Singapore for reuse projects.

In an attempt to lay the foundation to advance such a Project, researchers at the National Center for Groundwater Management at University of Technology, Sydney examined the suitability of the Sydney Metropolitan Area in the Sydney Geological Basin for receipt and storage. Pawelczyk (2002) provided an extensive and thorough examination of the geology and hydrology of the southern portion within these boundaries.

Using criteria identified by previous researchers (Corkery, 1978), Pawelczyk was able to reject a number of recognized stratigraphic sectors within the Sydney Basin (see Figure 1) as being unsuitable

for deep injection and storage of water. A variety of reasons were given ranging from the nature of the sediment, to closeness to known coal resources, to tendency towards grain suturing and/or quartz and clay cementation which would eliminate virtually all primary porosity, a necessary requirement for ASR (Pawelczyk, 2002).

Nevertheless, Pawelczyk identified two regions, Botany and Campbelltown which contained hydrogeologically suitable formations. The former contains the Botany Sands Aquifer while the latter includes the Bald Hill Claystone. The properties of the Botany Sands Aquifer are much better known than those of the Bald Hill Claystone.

From the available data, Pawelczyk concluded that it should be possible to exploit a portion of the 18300 hectare Botany Sands aquifer (total capacity approximately 170,000ML) for artificial aquifer storage and recovery (ASR). This suggestion however, was not without its problems.

### **Botany Basin Sands vs Bald Hill Claystone**

Three host lithologies for groundwater resources are evident in map notes accompanying the Hawkesbury-Nepean Catchment Groundwater Availability Map (Krumins, Bradd and McKribbin, 1998). Unconsolidated sediments, porous rocks and fractured rocks predominate.

Of these, unconsolidated sediments and porous rocks – sedimentary rocks of sandstone, sandy shale and shale which are inherently porous in nature - yield low salinity groundwater at varying levels but with low yields.

The Botany Sands aquifer favoured by Pawelczyk covers an area in the northern part of the Botany Basin. This area is constituted of unconsolidated sands, clays and peats. It is an unconfined aquifer and, according to DLWC (2000), the aquifer is currently the only significant source of groundwater within 45 kilometres of Sydney.

Existing data indicates that Bald Hill claystone and siltstone, predominantly composed of kaolinite (approx 75%) are the main geological features with quartz, haematite, siderite and goethite present in lesser proportions. Unlike the Botany area, the aquifer here is overlaid and confined potentially making it easier to conduct a focused study on the behaviour of groundwater over time and the impact of injected material.

Further: The Botany area is well settled with houses, units and some high rise residential occupying approximately 74% available above-ground area. An additional 12% is assigned to industry including industrial and agricultural chemical manufactures and petroleum related business.

In the past, the industry and manufacturing businesses were inclined to draw substantial amounts of groundwater from the Botany Sands aquifer beneath resulting in fluctuations in water table particularly with increased surface inflow during prolonged wet weather. These fluctuations in the water table have been monitored via a series of groundwater monitoring wells in the northern, southern and western regions of the Basin (Fish et al, 2000). As people have displaced industry in the Botany area over the past few years, industrial draw down of the underlying groundwater has been reduced considerably and the water balance in the aquifer beneath has stabilized.

### **Conditions in the Sub-Surface**

Conditions in an aquifer and the general environment deep in the sub-surface would affect the wastewater, organisms still present in it and any other suspended material. They, in turn will impact existing sub-surface conditions and biota. Changes that would be anticipated depend on:

- (i) Oxygen levels in the aquifer. Different species of microbes survive and reproduce under aerobic, anoxic and anaerobic conditions in an aquifer. And the deeper the aquifer, the lower the percentage of oxygen available for life.
- (ii) A carbon or organic carbon sources introduced as suspended or colloidal material with wastewater which can act as a food source for anaerobes as well as aerobes. Existing species in the aquifer which may or may not have been active prior to the introduction of wastewater may begin to reproduce and multiply.
- (iii) Temperature. While latitude of a site and geology are important, temperature in the soil, like oxygen, falls with depth from the surface. The presence of water can affect temperature as the water in soil can freeze thereby restricting movement and life.
- (iv) The existence of pores, cracks and fractures between soil particles can provide tiny pockets for air and water as well as a niche habitat for microbes as earlier discussed.
- (v) pH. Wastewater tends to have a higher pH than rain water (pH around 4.3) and other infiltrates which may percolate through the soil to reach the native groundwater.
- (vi) Research undertaken by Lovley and Goodwin (1988) and others suggest that there are discrete zones in the soil sub-surface where survival of a population is dependent as much on the availability of minerals in the soil, including pollutant residues and their chemistry

#### **Activity after Injection**

Conditions in the sub-surface and at the groundwater table, after injection of wastewater into a confined aquifer will show the impact of the injected liquor after a reasonably short period of time after allowing for mixing and settlement.

Using data from a typical wastewater treatment plant in the Sydney area (Table 1 Malabar STP), it could reasonably be presumed that coliform, enterococci and other species present in the discharge will face different and challenging conditions in the cold, low oxygen environment of a deep aquifer.

Unless break-point chlorination is practised - and this is not the case at Malabar STP - it could reasonably be presumed that many of these and other species would be present in the discharge effluent which would be injected into the aquifer. Competition for nutrients and carbon substrates between species such that one becomes dominant would distort the chemical and microbial balance achieved under normal pre-injection conditions. Changes of this nature would impact on water quality, potential for re-draw for reuse and possibly also technical issues associated with re-draw processes. Just to detail some of the other issues:

#### ***(a) Sorption Studies on Aquifer Sediments***

Sorption between a dissolved and particulate phase in aquifer systems is important for a wide range of organics, inorganics and metals. In the literature, organic carbon is recognized as the principal sorbent compartment for hydrophobic organic chemicals in aquatic systems. The partitioning potential of a chemical is characterized by its organic carbon partition coefficient.

Mineral surfaces contain oxide functional groups that give the surface a pH-dependent charge and that can be involved in electrostatic and ligand-exchange reactions. The mineral surfaces may contain pores of varying sizes. However, in many cases, the organic constituents of the sediment phase dominate sorption behaviour which can include both partitioning (absorption) and adsorption mechanisms. The dominant mechanism appears to depend on the source, composition and age of the organic matter, a heterogeneous mixture of natural material at various stages of degradation. Older, denser and more crystalline forms of organic matter include shale which can exhibit high sorption capacity. The sorption of non-polar, hydrophobic, organic compounds including residues of poly-aromatic hydrocarbons, phenols and industrial chemicals correlates well with the organic carbon content of the sediment.

Table 1 provides reporting data from Sydney Water monitoring of water quality of discharges from Malabar STP over a continuous three year period. It is clear from the levels of heavy metal residues - specifically cadmium, arsenic and mercury are well below levels required by its license. Suspended solids are much reduced from levels of influent material to the plant, but are the major "load" carried in the effluent. They are the principal source of carbon for microbial activity.

Levels of chlorine as free residual are low or insignificant. Hence the continued survival of a large population of viable coliform and enterococci bacteria which, under suitable conditions, could multiply to levels where they pose a risk to health. Whether the inhospitable anoxic, low temperature conditions arising from deep injection enable that to occur is among the unknowns at this stage.

#### ***(b) Selective Adsorption***

Ion exchange and adsorption to mineral surfaces may contribute significantly to the sorption of compounds having ionizable functional groups. In these instances, pH-dependent properties including cation-exchange capacity and solute speciation are important. Referring again to the data in Table 4, nitrate and nitrite are hardly detectable but ammonia is present at a range between 26-30mg/L, a level where it can serve as a source for anaerobes. Phenol, a source of hydroxyl ions, is present only at minimal levels. Levels of iron in 2001/02 average 5.6mg/L.

Recent studies of sorption of a range of naturally occurring metals on aquifer sediments has been conducted by the USGS Molecular Geochemistry and Nanoscience Group. Using sophisticated microscopy, the Group have shown that the bulk of uptake of metal ions occurs, not on the silicate grain surfaces but onto thin coatings of attached Fe-Al oxides and hydroxides.

The USGS work suggests that coatings in the nanomicrometer (*nm*) range appear to coat all surfaces of natural quartz grains as a general phenomena in a number of types of possible surface clusters and sorbed complexes of different size and orientation. These include hematite, zinc and other complexes which themselves will be attractive to other species including micro-organisms. The nature of these coatings whether muco-polysaccharide, humic or constituted of some thus far, other unidentified materials is still under investigation. Such bonding to humic substances, biofilm and mineral surfaces may be occurring through a combination and inter-balance of molecular, electrostatic and chemical processes. These latter issues are particularly important at the re-draw point and are discussed elsewhere in this paper.

#### ***(c) Niches and Microbial Habitats***

There are a wide variety of niches available in saturated sub-surface environments. Since soil grains are composed of particles of varying sizes (large pores >2 $\mu$ , small pores <0.2 $\mu$ , pores with open throats, pores with closed throats) and of differing composition and organic matter content, there are a wide variety of potential sub-surface niches for bacteria and other like material. Metabolic processes of microorganisms in aquifers can often shift geo-chemical equilibria as they garnish available free ions to catalyse biochemical pathways for growth.

Studies by Bennett, Hiebert and Rogers (2000) found that indigenous micro-organisms influence mineral weathering at both the macro- level - processes that disturb general groundwater chemistry and associated mineral-water equilibria - and at the micro- level where attached organisms influence mineral-water equilibria potentially releasing limiting trace nutrients from the dissolving mineral. For example, a micro-organism growing on a microcline grain would have a potential source of potassium, whereas a microorganism growing on a quartz grain would not.

Rogers (2002) demonstrated that microorganisms preferentially attach to surfaces that are nutritionally advantageous when those surfaces have similar electrostatic characteristics. A microorganism growing on an organic matter particle would have a source of solid carbon whereas one growing on a mineral grain would be limited to sources of dissolved or adsorbed organic carbon.

In nutrient limited environments, irreversible attachment of bacteria to silicate surfaces occurs predominantly to those surfaces from which limiting nutrients (such as P and Fe) can be leached. These findings confirm that the transport of bacteria through porous media may be controlled not only by surface charge and groundwater conditions but also by the mineral composition of the aquifer material as has been suspected. Accordingly small compositional changes in sediment mineralogy can have potentially significant impacts on which cells are transported and the speed of their movement.

By way of contrast: In environments rich in dissolved nutrients, colonization occurs predominantly on silicate surfaces with the greatest coulombic attraction for the cells. The ability of bacteria to attach and grow on nutrient-rich rocks and other sub-surface strata while leaving non-nutrient material barren, suggests the potential for preferential clogging of the most reactive mineral surfaces and flow paths. This has implications of a technical as well as hydrological nature, for deep injection of wastewater.

### **Discussion**

What are the implications which can be drawn for the injection of treated wastewater into a suitable, hypothetical aquifer?

The bacterial population present in groundwater in a deep aquifer is likely to be limited due to the low oxygen, poor levels of nutrients and temperature. Any species that does survive will not be numerous. Those most likely survive include *Clostridium spp.* which are endemic in soils and probably also varying numbers of *Legionella*, *Pseudomonas*, *Nitrobacter*, *Vibrio spp.* Other less numerous residents could include sulfate and iron III reducers such as *Desulfovibrio* and *Geobacter* respectively. The presence of hydrocarbon and organic carbon reducing agents will depend, in part on the level of organic soil carbon but also the level of contaminants.

An aquifer with relatively high silt and clay-peat content in the sub-surface would provide multiple sites and niches where microbes could congregate and scavenge available P, N and Fe which can be leached by any organisms present in the injected media. An environment dominated by silicates would be unlikely to host a comparable population of microbes except in those pores and spaces where grains of silt, peat or clay had become trapped. In both instances, final numbers and type of organism would depend on bio-available carbon, pH, suitable temperature and moisture conditions.

Bacterial adhesion of a species on particulate matter is influenced also by the electrostatic charge on mineral and bacterial surfaces, mineral surface roughness and surface alteration, glycocalyx formation, predation, and competition. In aquifers, resident bacteria will preferentially attach to these surfaces and/or to each other. Consequently, their movement through and within an aquifer tends to occur at a rate less than that of the flowing groundwater, leading to explanation of retardation mechanisms by a number of fairly sophisticated models.

The lack of knowledge on bacteria and viruses underlie the uncertainties about ASR and its associated health risks. Perhaps use of a spectrometer and of 16sr DNA sequencing analysis, which have identified a number of new species active under anaerobic conditions in wastewater treatment plants and in activated sludge systems, can prove equally useful in work in aquifers.

## **Caveats**

There are a number of caveats to the adoption of ASR as a tool for increased water reclamation and reuse. The first is cost. An ASR scheme needs to achieve at least equity with other scheme for using reclaimed water and to be equally safe and reliable to the consumer.

Finally, the risks - the impact of nutrients on soil and groundwater microflora and as these pertain to the health of those exposed to reclaimed water subsequent to ASR are valid concerns. These need to be properly and thorough identified and managed. As experience of the techniques involved, the engineering skills required and the processes for assessment of aquifers for suitability become more familiar, the politics of gaining regulatory approval will become less tortuous and the costs decline.

The growing and more ready acceptance of ASR in the USA and increasing use overseas such as in Singapore, has provided a model for Australia on how best to educate the community about these risks. Community attitudes & perceptions to reclaimed and recycled water take time to change and public education over a prolonged period is required. It is possible that with carefully prepared information on ASR, more ready acceptance of such schemes may occur.

Risks to health become a reality only if or when stored water is subsequently re-drawn for use either for irrigation (non-potable reuse) or for industrial purposes. Ideally reclamation will be undertaken from a second well remote from the original injection well. Such an arrangement minimizes the risk that material from wastewater injected through a first well, will not have been retained/sorbed in soil at or in its immediate vicinity and subsequently, dissolve or re-suspend in water being re-drawn after storage. Additional treatment possibly involving membrane filtration and/or reverse osmosis would provide a further assurance of safety to those inclined to question ASR.

At the point of withdrawal of stored product, the well-head provides entry point for oxygen which drives much aerobic bacterial activity on or near the upper soil surface. Stufzand (1998), Pyne (2002), Tsuchibashi, Asana & Sakaji (2002) and others have shown that the level of activity around the re-draw site can result in excessive proliferation of multiple species.

This is aided by concomitant presence of mucopolysaccharides, by-products of bacterial cell activity, natural organic matter and other breakdown products which can form a thick biomass or biofilm that frequently clogs the well. Since pathogens are among the bacteria and other protozoa and metazoa which are harboured in biofilm materials, there is increased risk of contamination of stored water being withdrawn through such affected junctures, with decline in quality of the resultant water and associated increased risk to human health, as evidenced in studies of water quality monitoring and turbidity readings.

These final issues further build argument supporting the need for studies of microbial as well as chemical risks to health to determine the safety of deep injection of treated wastewater as a means for water reclamation and reuse. They also point the direction for future work.

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**Table 1: Total chemical concentrations in effluent and receiving waters at Malabar STP site**

Source: ESD Report 2002, Sydney Water

Analyte	Reporting year	Number		Units	Observed		Total Load Concn (kg)	Receiving
		of observes	% Detectn		Median Concn	Max Concn		Water Median Concn
aluminium	1999/2000	2	100	□g/L	570	600	108882.87	1.071429
	2000/01	2	100	□g/L	415	529	81083.87	0.780075
	2001/02	2	100	□g/L	760	1110	152733	1.428571
ammonia	199/2000	12	100	mg/L	26.8	30.5	5095957.37	0.05037594
	2000/01	12	100	mg/L	28	32.5	4609108.41	0.052632
	2001/02	12	100	mg/L	26.6	31.1	4470225.36	0.05
arsenic	1999/2000	2	100	□g/L	2	2	381.46	0.03759398
	2000/01	2	100	□g/L	2.5	3	483.72	0.04699
	2001/02	2	100	□g/L	3	3	584.75	0.005639
chlorine as free residual	1999/2000	2	50	mg/L	<0.01	<0.50	no value	<0.000018796
	2000/01	2	50	mg/L	<0.01	<0.50	no value	<0.000019
	2001/02	2	50	mg/L	<0.01	<0.50	no value	<0.000019
cadmium	1999/2000	2	100	□g/L	0.85	no value	160.17	0.001597744
	2000/01	2	100	□g/L	0.4	no value	74.53	0.000752
	2001/02	2	100	□g/L	0.75	no value	153.51	0.00141
copper	199/2000	12	100	□g/L	66	111	13710.36	0.1240602
	2000/01	12	100	□g/L	55	82	10236.05	0.103383
	2001/02	12	100	□g/L	59	124	12464.11	0.110902
cyanide	1999/2000	2	100	mg/L	0.0865	0.148	16828.9	0.00016259
	2000/01	2	100	mg/L	0.1535	0.179	27690.59	0.000289
	2001/02	2	100	mg/L	0.043	0.072	8895.47	0.000081
iron	1999/2000	2	100	□g/L	8250	9100	1568797.38	15.50752
	2000/01	2	100	□g/L	5400	6500	966875.38	10.15038
	2001/02	2	100	□g/L	5600	5700	1056950.19	10.52632
mercury	1999/2000	2	100	□g/L	0.2	0.3	37.59	0.00037594
	2000/01	2	50	□g/L	<0.100	0.2		<0.000188
	2001/02	2	100	□g/L	0.25	0.3	48.44	0.00047
nitrate	1999/2000	12	75	mg/L	0.02	0.13	6785.96	<0.00001879699
	2000/01	12	41.67	mg/L	<0.010	0.35	no value	<0.000019
	2001/02	12	8.33	mg/L	<0.010	0.01	no value	<0.000019
nitrite	1999/2000	12	50	mg/L	<0.010	0.02	1731.82	<0.0001879699
	2000/01	12	41.57	mg/L	<0.010	0.46	no value	<0.000019
	2001/02	12	50	mg/L	<0.010	0.02	no value	<0.000019
phenol	1999/2000	2	50	□g/L	<1.000	9	no value	<0.001879699
	2000/01	2	100	□g/L	7.5	12	1236.8	0.01409
	2001/02	2	50	□g/L	<1.000	6	no value	<0.001880
suspended solids	1999/2000	365	100	mg/L	125	196	23881964	0.2368421
	2000/01	365	100	mg/L	125	204	22817149	0.236842
	2001/02	365	100	mg/L	130	212	24621716	0.244361
zinc	1999/2000	2	100	□g/L	112.5	133	21343.17	0.2114662
	2000/01	2	100	□g/L	68	68	12706.54	0.12782
	2001/02	2	100	□g/L	129.5	172	25551.71	0.243421

**Figure 1: Malabar STP Process Flow Diagram with Monitoring and Discharge Points**

