Sustainability of groundwater abstraction structures in hard rock through MAR

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Abstract. Sustainibility of groundwater abstraction structures in hard rocks is a challenge due to erratic variations of the Transmissivity and Storativity within small distances. As the sustainability of the dugwells and borewells imparts confidence amongst farmers which in turn assures food security of the region, effective management of the aquifer is so vital. Successful implementation of Managed Aquifer Recharge (MAR) ensures the sustainability of the abstraction structures provided sincere exercise on the details of the source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use and selection of suitable artificial recharge structures based on the hydrogeological set up is carried out.

Introduction

Groundwater development and management is a major challenge because of the occurrence of heterogeneous and low yielding hard rocks. It's is no longer a case of locating water or identifying a site to dig a well/tube well but understanding the resource that feeds the well and reasons for depletion or deterioration of the resource. The expansion in irrigated area in India was possible because of the dramatic rise in the number of irrigation wells since 1970. In order to effectively manage groundwater resource, it is much important to know the quantum of resource, the hydrological relationships to recharge and discharge.

Groundwater has huge impact on the economy of the region and the livilihoods of the people around especially farmers. About 70 % of irrigated agriculture is by groundwater in India, the groundwater abstraction structures (Dugwell/Borewells) almost dictates the agricultural ouptut. Sustainibility of the abstraction structures in hard rocks is a challenge due to the complex hydrogeological setup. Sustainable groudwater abstraction sturctures in hardrocks imparts confidence to the farmers which in turn assures food security. Managed Aquifer Recharge thus enhances the recharge to the aquifer which in sustains the dugwells for a longer period.

Managed Aquifer Recharge in Hard rocks

Groundwater management is all about an integrated effort of understanding aquifers, managing demand and effectively implementing supply. Aquifer systems are different and so as the societies that depends upon them and uses them. Detailed aquifer mapping exercise is required in order to customize the broad regional Hydrogeological setting to local situations. Successful exercise of MAR in hard rocks requires the details on source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use. These components need to be quantified and put in the over context of natural recharge and discharge including abstraction so as to assess the impact to MAR in relation to the amount invested towards recharge structures. The knowledge on the stage of development of groundwater and the information on the variation of the aquifer parameters is must to select suitable recharge techniques.

The development of groundwater irrigation has not largely been policy driven as it has emerged out mostly through private activity (Fig.1). Free and low cost electricity has further encouraged groundwater development in the irrigation sector to a greater extent. The groundwater development in the 1950s was dominated by traditional dug wells extracting groundwater with depths generally not beyond 30 – 40 feet. During early 1970s, groundwater development was by dug-cum-bore-wells and the wells increased upto 100 feet and the wells were energized mostly by centrifugal pumps. The groundwater abstraction for irrigation phenomenally increased by late 1970's due to construction of more wells. On contrary, tanks became unusable for irrigation in many cases due to poor maintenance and this resulted in greater dependence on groundwater. With the advent of submersible pumps during mid 1980's the depth of wells increased to beyond 400 feet in many areas of the country and groundwater extraction increased rapidly since then mainly influenced by the subsidy made available on electricity. This led to rapid decline in the ground water level and to some extent deterioration in groundwater quality mostly in coastal areas.

Rapid changes have occurred in the past four decades in groundwater irrigation economy of the hard rock areas. The increased number of wells, the greater depth of the wells, failure of wells and higher cost per unit of water extracted, high density of wells per unit area and more irrigated area under commercial crops. MAR should address these sensitive issues in hard rocks for better irrigated agriculture by groundwater. The demand for water increased in line with the green revolution which has put greater focus on agriculture in order to increase food production. Groundwater abstraction for irrigation is totally governed by private as the farmers are the owners of the groundwater abstraction structures. Lack of surface waters invited the farmers to rely on groundwater. Groundwater from deep borewells paved way for reliable and equitable exploitation of water to sustain the crops. In this process, the yield of the dugwells and dug-cum-borewells declined drastically while investments in deep borewells increased manifold. MAR addresses these issues.

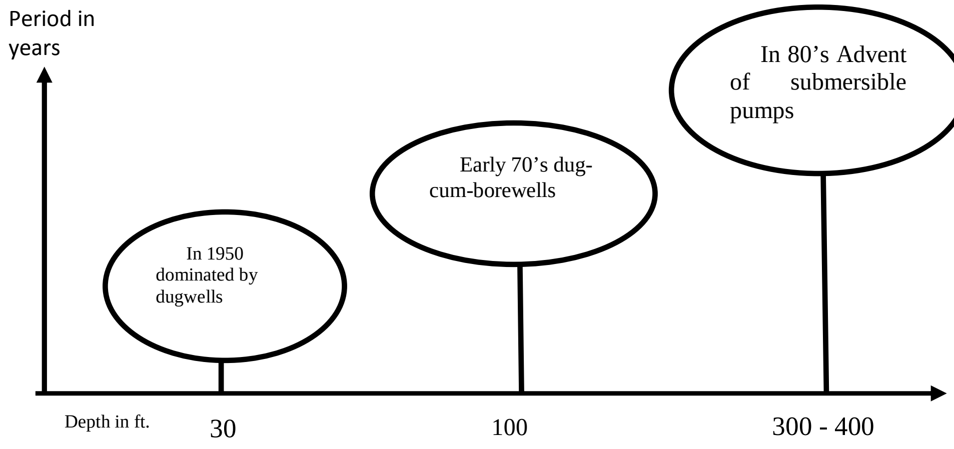

Fig.1 Stages of Groundwater development in Hard rock areas.

For efficient and successful MAR in hard rocks, it is necessary to understand the transmission capacity and the storage capacity of the aquifer. Aquifer parameters like Storativity (S) and Transmissivity (T) often show erratic variations within small distances in hardrock aquifers. The saturated portion of the mantle of the weathered rock overlying the hard fractured rock often makes a significant contribution to the yield of the wells. When a well in pumped in hard rocks in many cases, the drawdown in a pumping dugwell or borewell is often almost equal to the saturated thickness of the aquifer (Fig.2).

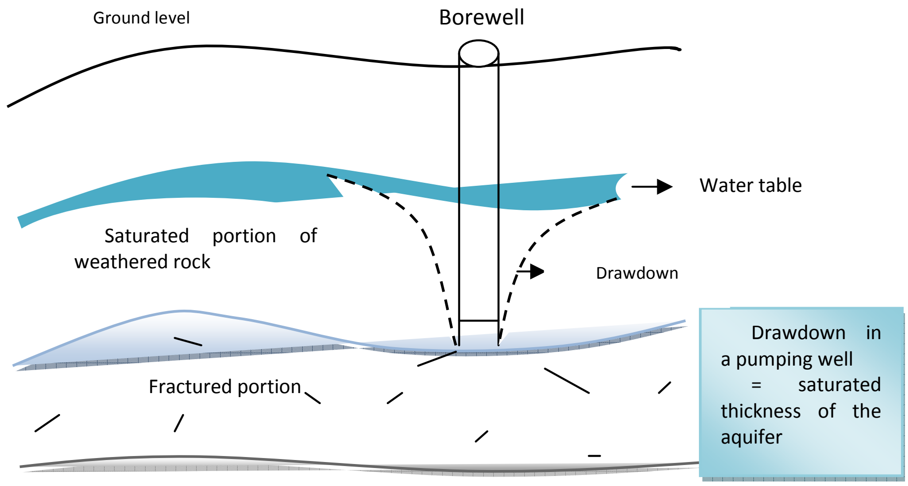

Fig.2. Schematic Sketch showing the drawdown in hardrocks

The recharge to groundwater takes place during the rainy season (monsoon) through direct infiltration into the weathered portion and also into the exposed portions of the network of the fissures and fractures. The ratio of rainfall recharge to rainfall in hardrock (Tamilnadu) ranges between 3 to 12 %. After monsoon, the recharged hard rock aquifer gradually loses its storage mainly due to abstraction and effluent drainage by streams and rivers. The annual recharge to the aquifer is thus a sizable part of the total storage of the aquifer and the whole system is sensitive to the availability of recharge during the rainy season. Artificial recharge structures like percolation ponds would be a source of sustained recharge to the aquifer even after the rainy season ceases.

The enhanced recharge facilitated by artificial recharge structures increases the pumping hours of the abstraction structures in a day. The continual recharge induced by the recharge structures enhances the pumping days. Numerous recharge structures are to be constructed for good results. The horizontal boreholes drilled radially outward from a dugwell (Fig.3), at various level below the water table do act as a recharge structure since it not only connects the fractures that increases the yield to the dugwell but would facilitate further recharge when the recharge structures like percolation pond or recharge shaft which in turn enhances the yield of the dugwell. In areas where vertical fractures, joints occur near to the dugwell, horizontal bores are more successful

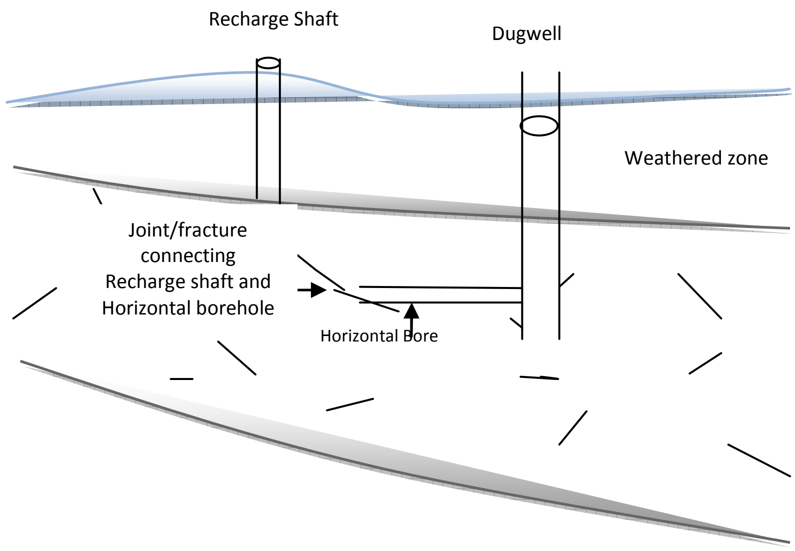

Fig.3. Sketch depicting the MAR structure

Summary

Sustainability of wells in hard rock regions through MAR- case studies by CGWB

The Central Ground Water Board has carried out Managed Aquifer Recharge in the hard rocks of Tamilnadu state. In the western ghats of Tamilnadu, even though the rainfall is substantially high, scarcity of water exists in the hard rock aquifer even during the post-monsoon season . The reason is attributed to moderate to steep gradient wherein the water at large quantity flows out to the low lying areas as surface runoff. The other important factor is the less residence time of groundwater within the hard rocks. The major concern of the farmers in these region is that the wells do not sustain for a longer hours in a day.

Gangavalli Block in salem district of Tamilnadu state area of 410 sq.km. This region has complex geological and hydrogeological environment. Charnockite and pyroxene granulite occur as bands trending NE-SW (Fig .4). The area receives rainfall during southwest (June – August) and northeast monsoons (October to December). The normal annual rainfall varies from about 800 mm to about 1600 mm. The mean daily maximum temperature varies from 19.2° C to 30.2°C.

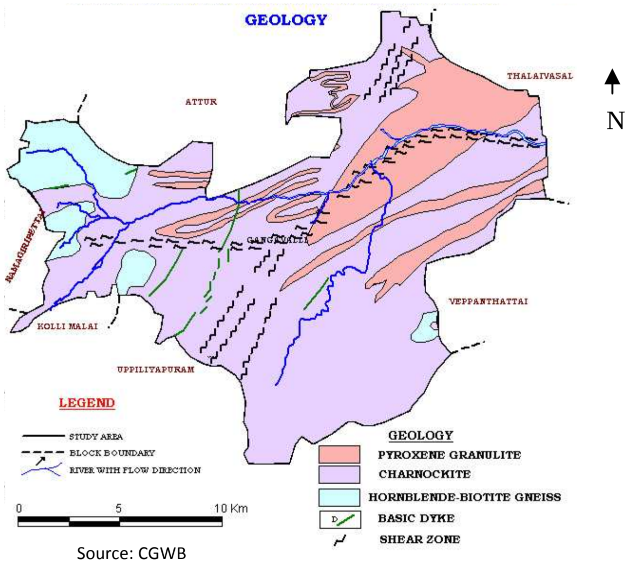

Fig.4. Geology of Ganagavalli region,Tamilnadu

The occurrence and movement of ground water are controlled by rainfall pattern, weathered thickness and fracture pattern, which in turn depends on physiography, climate, geology and structural features. The aquifer system can be considered as two layered aquifer system. (Weathered and deeper Joints/fractures).Ground water occurs under phreatic conditions in the weathered mantle and under unconfined to confined conditions in the deeper fracture zones. The thickness of weathered ranged between 1 and 28 m. Fracture down the depth of 42 to 57 meters yields exists. The dugwells are the major groundwater abstraction structures with the depth ranging from 10 to 30 m bgl. The yield of the dugwells ranged between 40 to 140 lpm and sustains for 60 to 90 minutes of pumping. The yields of dug wells are improved at favorable locations by construction of horizontal bores of 50 to 60 m in length. The rocks have wide transmissivity (1 to 250 m^2/day) and the specific capacity of the large diameter wells ranged between 60 and per meter drawdown.

The groundwater abstraction increased in early 90's due to the advent of numerous bore wells drilled by the farmers. This led to declining groundwater levels and reduction in yield of the dug wells. As per the groundwater resources estimation – 2004, the stage of groundwater development is 221% inferring that the groundwater extraction is twice than the annual replenishment. Artificial recharge was done to supplement the natural recharge to the groundwater so as to maintain the prevailing groundwater utilization and to prevent further impact on the crop yield. A total of 41 artificial recharge structures (check dam, check dam with recharge well, percolation pond, percolation pond with recharge well) were constructed under the central sector scheme during 2006 – 2008 (Subburaj A). In addition, desilting of the existing tanks was taken up to augment the storage capacity of the tanks so as to increase the recharge to the aquifer. The schematic representation (Fig.5) of the Gangavali region exhibiting the recharge structure is given as below;

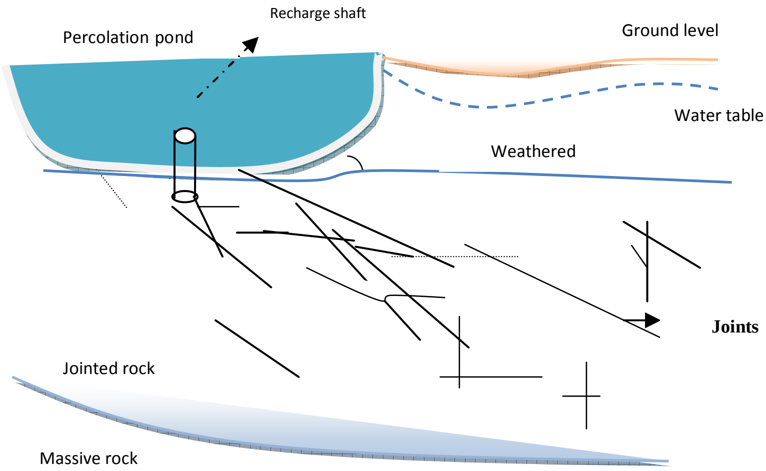

Fig.5.Schematic representation showing recharge structures in Ganagavalli region.

The tanks were expected to have three to five fillings annually depending upon the rainfall and the run off generated from the catchment. Only 50% of the water harvested in the tanks/ponds has been considered as water that could be recharged into groundwater system.

The recharge structures had remarkable impact on the groundwater regime which was reflected by the sustainability of the dugwells and borewells even during lean periods. The dugwells that existed near to the recharge structures registered rise in water level. The dugwells existing at distance from the recharge structure though has not shown rise in water level, but the wells sustained for more days than earlier.

The wells either had longer duration of pumping or increase in number of pumping days. The impact on pumping hours of the dugwell before and after the MAR is given as figure.6. The pumping hours increased by 60 to 90 minutes in most of the dugwells existing within the benefit zone. The MAR in Gangavalli has inferred that the desilting of tank is most economical structure and recharge wells with percolation pond was much economical compared to the check dam. However, the checkdam was effective in preventing soil erosion and for regulation flow in the nalas. Also, for the sustainability of the abstraction structures, the number of fillings and its percolation is the controlling factor in many the structures. The recharge structures with short water retention period were more effective in enhancing the yield of the dugwells since the percolation rate was high. The maintenance of the recharge structures is vital for the continuous sustainability of the groundwater structures.

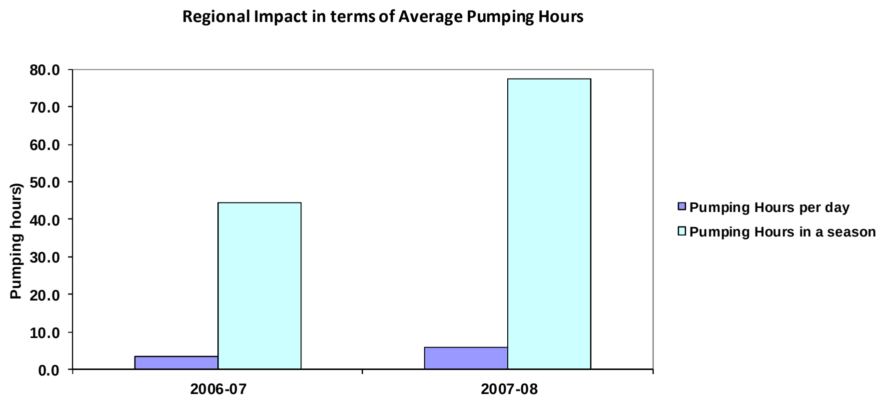

Fig.6. Impact on pumping hours due to MAR structures

Summary

Sustainability of the groundwater abstraction structures in hard rocks greatly depends on the replenishable groundwater recharge annually by rainfall and the erratic variations of the transmissivity and storativity within small distances. Successful implementation of Managed Aquifer Recharge (MAR) ensures the sustainability of the abstraction structures provided sincere exercise on the details on the source of water, availability of space in an aquifer to store the water and mechanisms to recover the water for beneficial use and selection of suitable artificial recharge structures based on the hydrogeological set up is carried out.

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Managed aquifer recharge with reclaimed water

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Abstract. In the current paper, the concept of managed aquifer recharge (MAR) with reclaimed water is introduced. The benefits as well as requirements of MAR are illustrated generally. In order to achieve the infiltration requirement as well as maintain a sustainable operation, pre-treatment for the purpose of water reclamation must be taken into consideration. Pre-treatment methods includings flocculation/filtration, dual membrane systems and chemical oxidation processes are presented generally covering the design parameters and application examples.

Introduction

Many countries and regions of the world are facing water scarcity and deterioration of groundwater quality caused by climate change and a continuous population growth especially in coastal areas. The acute or chronic water stress triggers the need for integrated water cycle management and the supplementation of the available freshwater resources. In this context, the exploitation of available surface or reclaimed water to promote the conservation or replenishment of groundwater levels *i.e.* through Managed Aquifer Recharge (MAR) has long been advocated (Bouwer, 2000). The main purposes of MAR schemes can be summarized as: to reduce, stop, or even reverse the decline of groundwater levels; to protect underground freshwater in coastal aquifer regions against saltwater intrusion; and to store water for future use (Abiye et al., 2009; Committee on Ground Water Recharge, 1994; Drewes, 2009; Furumai, 2008; Georgopoulou et al., 2001; Holländer et al., 2009; Li et al., 2006; Oron et al., 2007; Sheng, 2005). Municipal wastewater including storm water can be considered as an alternative water source if treated appropriately for the intended use. This is highlighted by the Urban Wastewater Treatment Directive (91/271/EEC) and by the Water Framework Directive (2000/60/EC) encouraging "reuse measures" and "artificial recharge" as supplementary measures that can be applied to reach the fixed environmental objectives for surface and groundwater bodies.

MAR usually evolves in response to local needs and hydrological conditions. Hence, there is an increasing variety of methods for MAR. Most commonly employed methods include bank filtration, soil aquifer treatment, infiltration ponds, etc (DAFF, 2010).

Bank filtration – extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovery (Bixio and Wintgens, 2006).

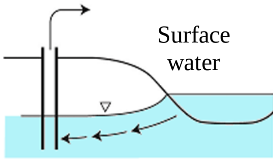

Fig.1 Scheme of bank filtration (DAFF, 2010; Dillon and Jimenez, 2008)

Soil aquifer treatment (SAT) – pre-treated infiltration water *e.g.*, surface water, storm water, or treated sewage effluent, is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the aquifer (Bixio and Wintgens, 2006).

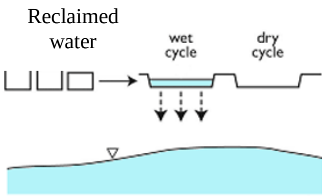

Fig. 2 Scheme of soil aquifer treatment (SAT) (DAFF, 2010)

Infiltration ponds – ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate (generally through an unsaturated zone) to the underlying unconfined aquifer (Bixio and Wintgens, 2006; Dillon and Jimenez, 2008).

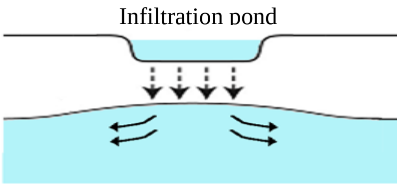

Fig. 3 Scheme of infiltration ponds (DAFF, 2010)

These methods take the advantage of the purification ability of primarily the unsaturated zone (also called vadose zone) in the soil-aquifer system and are capable to produce high quality abstracted groundwater. Main processes during soil-aquifer passage treatment are dispersion, filtration, biodegradation, sorption, and mixing with ambient groundwater (Høgh Jensen, 2001) . Mechanical filtration removes suspended solids, while a relatively high microbial activity can lead to mineralization or transformation of organics under aerobic conditions at the beginning of the infiltration flow path. Organic compounds can also sorb onto aquifer material to a certain extent depending on the properties of the compounds and solid material (Brady and Weil, 2002; Schwarzenbach et al., 2003; Worch et al., 2002). Microorganisms are adsorbed, strained out or die because of competition with other soil microorganisms. Nitrogen concentrations are reduced by denitrification meanwhile phosphate, fluoride and heavy metals are sorbed, precipitated or immobilized in the soil.

Examples of managed aquifer recharge projects

One of the most famous MAR practices for water reclamation purpose is the Shafdan project in Israel. WWTP effluent reclamation by SAT for agricultural irrigation has been practiced in the Dan Region, Israel, for half a century. The Dan Reclamation project (known by its Hebrew acronym Shafdan) is the largest wastewater treatment and reclamation project in Israel. It treats more than 140 million m^3 of WWTP effluent per year (approximately 0.4 Mm^3/d), serving a population of about two million, from the Greater Tel-Aviv area and produces high quality abstracted groundwater (Bixio and Wintgens, 2006; Mekorot, 2003; Pettenati et al., 2008).

In Shafdan, the effluent from the Dan Region WWTP is delivered into four recharge basins covering a total area of 80 ha as the infiltration water without further treatment. The effluent percolates vertically through 15 to 30 m of the unsaturated zone, and spreads horizontally through the aquifer. A series of recovery wells located 300 to 1,500 m from the recharging basins pump the recharge water from a depth of 100 to 200 m. The hydraulic loading to the basins varies between 80 and 150 m/yr, depending on the infiltration capacity of the basins (le Corre, 2009).

Table 1 General information of Shafdan SAT process

Test Site	ISRAEL, Shafdan, Negev
Source water	Secondary effluent
Pre-treatment method	-
Recharge method	Soil Aquifer Treatment (SAT)
Additional treatment	Intermediate chlorination
Recharge rate	339,000 m^3/d
Retention time (days)	180-360
Reuse purpose	Agriculture irrigation

The treatment efficiency of MAR at Shafdan in terms of basic water parameters and microorganisms is illustrated in Table 2. The long-term quality monitoring has shown that the system is performing with high reliability. Water recovered from the SAT system is of high quality and can be used for unrestricted agricultural irrigation (Bixio and Wintgens, 2006).

Table 2 Performance of MAR at Dan Region water reclamation scheme, Israel (Bixio and Wintgens, 2006; Mekorot, 2003)

Parameter	Unit	Before SAT	Well 1*	Well 2*	Well 3*	Well 4*	Removal %
TSS	mg/L	11	0	0	0	0	100
pH	-	7.41	7.3	7.4	7.3	7.4	-
Alkalinity	mg/L	268	275	290	300	293	-
BOD	mg/L	12	< 0.5	< 0.5	< 0.5	< 0.5	> 95
COD_f	mg/L	36	4.5	5	4	4.5-5.0	87.5
DOC	mg/L	12	1.5	0.8	1.2	1.1	90
UV254 absorbance	$cm^{-1}x10^3$	223	38	36	42	38	82.7`
Ammonia, as N	mg/L	6.53	0.2	< 0.02	< 0.02	< 0.02	> 99
Nitrate, as N	mg/L	1.0	2.64	6	6.5	6.75	
Nitrite, as N	mg/L	1.237	0.02	0.004	< 0.01	< 0.004	> 99
Phosphorous	mg/L	3.0	0.03	0.03	0.06	0.02	99
Total bacteria	No./mL	8.0E+05	454-455	2	22	7-8	3 log
Coliforms	MPN/100mL	4.1 E + 05	< 2	< 2	< 2	< 2	5 log
Faecal Coliforms	MPN/100mL	2.8E+05	< 2	< 2	< 2	< 2	4 log
Strept. Faecalis	MPN/100mL	9.0E+05	< 2	< 2	< 2	< 2	3-4 log

* Observation wells bored after the SAT.

Various MAR practices across the world using reclaimed water and/or storm water for infiltration were investigated in the RECLAIM WATER project (Reclaim Water, 2005). Table 3 gives an overview on the treatment technologies, recharge systems and end-uses relevant to the different case studies.

Table 3 Water reclamation schemes investigated in RECLAIM WATER (Le Corre et al., 2012).

Site location & capacity	Scheme description
Sabadell 30 km from Barcelona, Spain	Secondary treated wastewater effluent discharged into a river bed where it infiltrates and is recovered. The water is then disinfected (UV) and distributed for parks irrigation.
Nardò Salento Region, south of Bari, Italy	Secondary treated municipal effluent is transported to aquifer injection. Recharge acts as a salt intrusion barrier and resource is also used as drinking water source.
Shafdan Negev, Israel	Secondary wastewater from the Tel-Aviv area is recharged to an aquifer via a soil aquifer treatment (SAT) system. Recovered water is primarily used for irrigation but has accidental drinking water quality.
Gaobeidian Beijing, China	Tertiary effluent is used for aquifer recharge. Treatment is provided by coagulation, filtration and ozonation (in test) prior to infiltration and recharge.
Adelaide Salisbury, South Australia	Wetland treated urban stormwater injected into a brackish aquifer. Water recovered via separate recovery wells. Recovered water intended for drinking supplies, and until proven will be used for irrigation.

Torrele (Wulpen) Belgium	Tertiary treated municipal effluent is upgraded by Microfiltration and reverse osmosis, and then infiltrated via an infiltration pond to prevent salt intrusion and to recharge an aquifer used for drinking water production.
Mezquital Valley (State of Mexico)Mexico	Wastewater mixed with stormwater and surface water is discharged to an irrigated area of more than 76,000 ha. About 40 % of the irrigation water infiltrates into the aquifer. The water is recovered via separate wells and springs. 206 well systems, 31 springs, and 63 waterwheels are in operation. Recovered water is chlorinated and distributed for drinking water supply, industrial use, irrigation and other purposes (bathing, swimming, washing).
Atlantis (Cape Town) South Africa	Urban stormwater run-off, is collected via a series of detention basins and blended with secondary treated domestic wastewater and recharged up-gradient of the production well field for augmenting the water supply. The blend of natural groundwater and recharged water abstracted from the well field is used as potable water supply for the town of Atlantis.
NEWATER Singapore	NEWater is treated used water further purified using dual-membrane (microfiltration and reverse osmosis) and UV treatment. Four NEWATER factories are in operation supplementing Singapore's water supplies, part of the product water is use to augment drinking water reservoirs.

Removal of microorganisms was one of the most important parameters measured in the Reclaim Water project. Based on results presented in Table 4, the SAT in all selected locations exhibited high removal capacity. Intensive pre-treatment can ensure zero detection of total coliforms e.g. in Torrele, Belgium site. On the other hand, more than 99% removal was also achieved in the Mezquital, Mexico site where the mixture of raw wastewater and rain water was used as injectant.

Table 4 Total Coliforms (average values) measured in respectively the source, the injectant and the abstracted water selected sites in the Reclaim Water project (Le Corre et al., 2012).

Total Coliforms (CFU/100mL)			
Site	**Source**	**Injectant**	**Abstracted water**
Shafdan, (Israel)	9.8×10^5	9.8×10^5	4.0
Torreele (Belgium)	1.3×10^5	9.1×10^2	0
Gaobeidian (China)	6.0×10^2	7.0	1.0
Adelaide (Australia)	4.6×10^2	3.6×10	0
Mezquital (Mexico)	7.7×10^6	7.7×10^6	Well water 8.0 – 69 (depends on sample locations)

Organic trace pollutants in MAR schemes

In the last decade the occurrence and fate of organic pollutants (e.g. pesticides, pharmaceutical residues and industrial chemicals) in the aquatic requirements received growing attention. Particular in water reclamation these parameters are relevant as the compounds often pass conventional wastewater treatment plants. presents the observed concentrations of organic pollutants in the extracted groundwater from the observation well after the SAT at the Dan Region.

Table 5 Comparison of drinking water standards for specific organics and results obtained in Dan Region SAT observation well. The residence of the MAR at the observation well is approximately 12 months (Bixio and Wintgens, 2006; Mekorot, 2003).

Compounds [µg/L]	**Observation well**	**Drinking water std.**
Alachlor	< 0.1	20
Atrazine	0.1	2
Benzene	0.1	10
Benzopyrene	< 0.1	0.7
1,2 dichlorobenze	< 0.2	1000
1, 4 dichlorobenze	< 0.2	300
Carbon tetrachloride	< 0.2	5
Chlordane	< 0.1	2
Chloroform	< 1	100
DDT	< 0.1	2

Numerous studies have been carried out to characterise the occurrence and fate of various types of pollutants in MAR systems with a recent focus on wastewater originated trace organic contaminants. It is revealed that the subsurface soil-aquifer passage is only capable to attenuate a subset of trace organic compounds especially when reclaimed WWTP effluent was used for MAR.

One of the most representative and systematic investigations about the occurrence of trace organic compounds in SAT is from the MAR applications in the city of Berlin in Germany. In Berlin, the groundwater based public water supply is strongly dependent on bank filtration and groundwater recharge. Nearly 70% of the 220 million m^3/year originate from these sources, ≈56% from bank filtration and ≈14% from groundwater recharge, with the remainder from natural groundwater recharge (Berliner Wasser Betriebe, 2003). At some bank filtration sites the surface water is strongly influenced by treated domestic WWTP effluent (e.g., 15-30% in Lake Tegel) (Ziegler et al., 2002). The bank filtration system is providing high-quality water, which is distributed without chlorination. Iopromide was detected at an average concentration of 151 ng/L in groundwater monitoring wells located at the Lake Tegel bank filtration site. Similar concentrations were also observed in the extracted groundwater at an artificial groundwater recharge basin receiving lake water. The antibiotic drug sulfamethoxazole was detected in the abstracted groundwater at the groundwater recharge site with an average concentration of 151 ng/L (Grünheid et al., 2005). Benzotriazole was found in abstracted groundwater from production wells located in Lake Tegel and Lake Wannsee bank filtration sites. Concentrations of benzotriazole ranged between 0.2 – 0.3 µg/L in the groundwater samples (Reemtsma et al., 2009). Phenazone-type analgesic pharmaceutical residues were also detected between 0.1 – 0.3 µg/L in abstracted groundwater from the Lake Wannsee bank filtration site in Berlin (Massmann et al., 2008). Other trace organic compounds such as bezafibrate, carbamazepine, clofibric acid, diclofenac and pimidone were detected in monitoring wells of shallow bank filtrates with concentrations ranging from 50 to 250 ng/L in Berlin (Heberer et al., 2004b; Massmann et al., 2004; Schittko et al., 2004). The occurrence of trace organic compounds in the SAT was also reported across the world. For example, nineteen pharmaceuticals including erythromycin, fluoxetine, and diphenhydramine were detected in soil samples which were irrigated with reclaimed water derived from urban wastewater in Colorado, USA (Kinney et al., 2006). In the south of France, trace organics, most frequently paracetamol, caffeine, and diclofenac, were detected in drinking water wells where recycled wastewater constitutes 20-30% of the drinking water (Rabiet et al., 2006). Partial removal of pharmaceuticals, including naproxen, ibuprofen, diclofenac, and propyphenazone, have been observed in laboratory and full-scale sand filtration, while other substances including carbamazepine, primidone, sulfamethoxazole, clarithrymycin, and erythromycin are inert to soil passage treatment (Nakada et al., 2008; Nakada et al., 2007).

Engineered pretreatment processes

The main objectives of reclaimed water pre-treatment prior to MAR are to protect the hydraulic capacity of the aquifer, to maintain the treatment ability of soil-aquifer system, ensure the quality of recovered water, and to prevent jeopardising of groundwater quality as well as adverse geochemical reactions. Contaminations with pathogens as well as inorganic and organic pollutants should be avoided in the recharge water. Nowadays, a wide range of water purification techniques are available and therefore the production of reclaimed water of any desired quality is technically feasible. According to the pre-treatment objectives the main quality aspects to be considered for municipal wastewater after centralized biological treatment are according to the report of the EU project Aquarec; Bixio and Wintgens, 2006:

- Bulk organics and macro nutrients (N and P)
- Salinity
- Organic micropollutants represent contamination due to their specific biologic activity
- Pathogens and viruses

- Toxic metals
- Soil clogging potential

Engineered treatment processes are normally designed to attenuate specific species or constituents with particular attributes within a defined range of source water flow rates and water quality characteristics. Therefore a series of treatments is usually required. Table 6 lists pre-treatments that have been used for aquifer recharge projects or research projects with a view to achieving the water quality requirements for effective aquifer treatment.

Table 6 Pre-treatments and their relative effectiveness for MAR with reclaimed water and storm water (Dillon et al., 2008)

Treatment	Reclaimed water	Storm water	Suspended solids removal	Labile organics removal
Roughing filter		Y	*	
Rapid sand filtration		Y	*	
Biofiltration		Y	***	**
Activated carbon filtration	Y	Y	*	***
Chemical coagulation and filtration		Y	**	*
Dissolved air flotation and filtration	Y		***	*
Membrane bioreactor	Y		***	*
Microfiltration		Y	***	
Reverse osmosis		Y	***	***
Activated sludge digestion	Y		*	**
Settling/aeration ponds	Y	Y	*	*
Wetland ponds		Y	**	*
Reedbeds		Y	**	*

Y = treatment has been widely applied for this type of source water. Treatment effectiveness: blank = ineffective. * = only partially effective. ** = moderately effective. *** = very effective

Conclusions

The paper generally demonstrates that well designed and operated MAR with reclaimed water can be used as a water stress mitigation option, but issues around site selection, pre-treatment, clogging prevention, geo-hydrchemistry, pollutant attenuation and appropriate post-treatment for a particular use have to be considered. Results from the EC FP6 research project RECLAIM WATER underline that managed groundwater recharge can be a save and reliable climate change adaptation method. Technologies and methods can be tailored to the different socio-economic contexts. In developing and emerging countries' context de-intensified natural systems, in particular MAR, can also provide a decent water quality at very low costs

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Towards Indian Water Quality Guidelines for Managed Aquifer Recharge (AusAID project)

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Abstract. The current extensive program of artificial recharge projects in India augment natural recharge thereby sustaining groundwater supplies for drinking water, agriculture, industry and for environmental protection. This paper describes the background and scope of a current AusAID project that aims to enhance groundwater quality protection wherever artificial recharge is undertaken through the development of guidance at national level. The project will help to ensure that recovered water is fit for all its planned uses. Recharge projects that follow this guidance and effectively manage both the quantity and quality of groundwater replenishment will be known as managed aquifer recharge (MAR) projects. Guidance will draw on recent Australian experience, but engagement with Indian experts and adaption based on Indian experience at selected demonstration projects will be needed to ensure these are relevant and useful.

Artificial Recharge in India

Much of India is monsoonal and has a very long intervening dry period. Water is at a premium in the dry season for drinking, stock and irrigation supplies. Monsoonal rains are heavy, eroding top soil, and flooding turbid streams. Much of the terrain has low relief, unsuited to dams, and there is only minor storage capacity in its hard rock aquifers. As a result, Indians have become highly inventive in detaining water close to where if falls as rain, in order to increase soil moisture and recharge both alluvial and hard rock aquifers as a buffer against the oncoming dry (Chadha, 2002).

Farmers and city dwellers and National and State Governments understand what is needed and the potency of stored water for social and economic resilience. A national plan for artificial recharge was produced by the Central Ground Water Board (CGWB 2005) which has invested in developing recharge projects in all states where there has been a need, generally working in partnership with State and Local governments and non-government organizations towards achievement of the plan. This has been accelerated in recent years by a range of on-ground works to recharge groundwater implemented at village scale throughout India as a part of the government's Mahatma Gandhi National Rural Employment Guarantee Act 2005 (NREGA) to enhance livelihood opportunities while developing a durable asset base. Of the A$8.6B committed in 2010/11 a large proportion (estimated at 70%) was invested in construction of small-scale structures to conserve water via soil and aquifers. Since 2008, a dug well rehabilitation program has supported farmers in cleaning out wells that had run dry due to aquifer overdraft, and recharging them with available sources of surface water. About 4.5 million wells are intended to be recharged in this program, albeit in the current absence of water quality guidance for groundwater replenishment. In urban areas of some states, new houses are required to recharge their roof runoff to sumps and wells so as to contribute to groundwater supplies and not to urban stormwater. In Gujarat there is even a greenhouse gas abatement program that provides carbon credits to industries that recycle water, including stormwater and their groundwater pumping is metered to ascertain the credits.

The uptake of recharge enhancement has been phenomenally successful in volumetric terms and has supported much agricultural production and many communities that otherwise would not be sustainable Government of India (2010b) and Table 1). However to date water quality aspects have tended to be subjugated and there are opportunities to enhance existing guidance documents; the Indian Guidelines for Artificial Recharge (CGWB 2000) and Manual for Artificial Recharge of Groundwater (CGWB 2007), to take more specific account of groundwater quality protection. When both water quantity and quality are effectively managed the term “managed aquifer recharge” may be applied. India is beginning to make huge strides in the development of water resources management policies, which may include account of the groundwater replenishment and its role in sustaining supplies from aquifers.

Managed Aquifer Recharge in Australia

In contrast, Australia, is slow in taking up managed aquifer recharge, and these advances have been stimulated by the Commonwealth Government. The Water Smart Australia (A$2B) program of the National Water Commission, supplemented by the Stormwater Harvesting Fund (A$200M) has helped local government and water utilities in urban areas to recycle water sewage and stormwater, and a proportion of this has been stored in aquifers. In Adelaide stormwater storage in confined aquifers will account for $20Mm^3$/yr by 2014 and is planned to reach $60Mm^3$/yr by 2050. The rural areas have been almost untouched by managed aquifer recharge since pioneering work in the Burdekin Delta that since the mid 1970s has resulted in $40Mm^3$ annual recharge in a successful effort to prevent aquifer salinisation and protect crops. One exception is the Fortescue Metals mine water management project where reinjection of 20 Mm^3/yr groundwater is being undertaken in the North West of Australia to sustain aquatic ecosystems otherwise impacted by dewatering and also to create reserves of water for future mineral processing. Even so the accumulated groundwater replenishment from all Australian projects is less than 2% of India’s.

Table 1. A profile of managed aquifer recharge in India and Australia

Country	India	Australia
Estimated quantity of recharge enhancement (Mm^3/yr)	>4,000*	80 #
Potential quantity of recharge enhancement (Mm^3/yr)	36,200*	500 #
Guidance on hydraulics and design of recharge enhancement	CGWB (2000, 2007)	ongoing research on clogging and recovery efficiency
Water allocation policies for groundwater and MAR	in progress. Government of India Draft Water Act (2012)	uptake at State level in progress following Waterlines#38 (Ward and Dillon 2011)
Water Quality Guidance for Managed Aquifer Recharge	to be developed	NWQMS #24 (NRMMC-EPHC-NHMRC 2009)

* derived from CGWB (2005) # Parsons *et al* (2012)

The Raising National Water Standards Program under the National Water Initiative, overseen by the National Water Commission was used to develop Guidelines for Managed Aquifer Recharge (NRMMC-EPHC-NHMRC 2009) to protect health and the environment. This is now an integral part of the National Water Quality Management Strategy series of documents. Accompanying this was a compendium of example risk assessments for nine demonstration projects produced according to the Guidelines (Page *et al* 2010). Groundwater quality protection is now accounted for explicitly in the formation of new recharge projects and in re-evaluating historical practices. Australia was the first country to adopt risk-based guidelines for managed aquifer recharge, just as it has for water recycling and drinking water supplies. These all follow the same principles adopted internationally in the World Health Organisation’s Water Safety Plans (WHO 2010).

Much work has been done to evaluate the consequences of introducing a new source of recharge water into an aquifer already in geochemical equilibrium (eg. Vanderzalm *et al* 2009) and to study the fate of species introduced into an aquifer (eg. Dillon and Toze 2005). Kazner *et al* (2012) also studied the combination of engineered pre-treatments with aquifer treatment processes for producing safe water supplies in a number of case studies.

A framework for water resources policies accounting for MAR has also been developed in consultation with states (Ward and Dillon 2011). This allows account of entitlements to harvest, recharge, recover and use water. Giving a tradeable entitlement to recover, related to the volume and quality of water recharged, protects the benefits of those who recharge aquifers. This framework has now been adopted in two states and there are plans in other states to also adopt these.

Hence Australia has much to learn from India on project mobilisation and implementation at small to medium scale and it is likely that India can benefit from the water quality perspective that Australia now brings to protecting health and the environment under the National Water Quality Management Strategy. AusAID is assisting in this process. It is expected that closer ties between these two countries under science linkages programs will yield significant mutual benefit in the field of replenishing aquifers to secure safe water supplies.

Are Australian MAR Guidelines Useful for India?

A fuller description of the Australian Guidelines for Managed aquifer Recharge is given in a companion paper by Page and Dillon (2012). The application of Australian MAR Guidelines to various MAR projects in other countries, including developing countries, was tested and the utility and constraints in applying them was reported in more detail by Dillon *et al* (2010b). The guidelines were applied to case studies in China (2), India (2), Jordan, South Africa and the United States of America by researchers or water utility managers actively involved in those projects. Indian sites were a dug well recharge scheme in Gujarat, India (Jain 2010); and a check dam (percolation tank) at Kodangipalayam in Tamil Nadu, India (Gale *et al* 2006; Dillon *et al* 2009).

Those applying these guidelines for the first time reported that they found the entry level assessment (Stage 1) easy. The assessment did not reveal any issues that the proponents had not already considered, nor did it fail to address any issues that the proponents had considered. Several proponents reported that the entry level assessment and the maximal risk assessment provided check lists that they thought would be useful for assessing future projects. No proponents recorded any difficulty in undertaking the entry level assessment, which is in keeping with the objective in developing the guidelines to provide a very simple starting point based on minimal information.

However, completing the maximal risk assessment (Stage 2) revealed that all project reviewers had difficulty in assessing risks to human health, particularly from pathogens that were likely to be present in source water for recharge. There were several reasons for this. Firstly, there is a lack of data on the viral content of source waters originating from streams, urban stormwater or water reclamation plants. In every case, viruses were the most critical of the microbial pathogens.

Furthermore, proponents generally did not feel confident in their ability to perform a reliable quantitative microbial risk assessment, or in making conservative assumptions about source water quality.

Possibly because all the sites had hydrogeological investigations data available, the level of uncertainty in the fate of recharged water was relatively well defined, with the exception of recharge to the karstic or fractured rock aquifers. Factors affecting the relevance of the guidelines were predicted to be:

1. the ability to establish accepted environmental values for an aquifer and hence water quality requirements for aquifer protection
2. variability of source water quality and the capability to measure water quality parameters important for risk assessment (including human pathogens and micropollutants)
3. ability to acquire information on aquifer hydraulic and geochemical properties
4. ability to measure attenuation rates in the soil-aquifer system for the hazards of highest concern
5. reliability of power supplies, preventive measures and controls
6. ability to invest in monitoring and reporting

Development of MAR guidelines for India

Clearly it is important that guidelines are pragmatic and easy to use. Preliminary results suggest that the Stage 1 of the Australian MAR Guidelines could find immediate and useful applications in India, however more widespread testing would be useful, and adaptations made where necessary. Simplification of Stage 2 risk assessments will be required that can protect human health and the environment but reduce the associated investigations and analysis costs. It is likely that use of surrogate and indicator organisms that are much more easily and cheaply measured than rotavirus, C*ryptosporidium* and *Campylobacter* (the reference pathogens in the Australian Guidelines, Page *et al* 2012) could provide a useful pathway forward as has been applied elsewhere in the world (Drewes 2008, Schijven *et al* 1998; Schijven and Hassanizadeh 2000). Similarly these could also be applied for organic chemicals, along with a reconnaissance in the catchment for pesticide and herbicide use, industries likely to use hazardous chemicals, and for presence of sewage and indicators of sewage organic chemical constituents in India.

Salinity, nutrients and inorganic chemicals from source water or aquifer origin will still need to be assessed. In addition to meeting water quality targets required for the recovered water use, nutrients can act as a stimulant to microbiological activity. This can lead to clogging of infiltration wells and basins and can alter the reduction-oxidation potential of the aquifer and hence influence the geochemistry and microbiology of the aquifer, thereby changing the rates of contaminant attenuation or pathogen inactivation. A basic decision tree to determine the likelihood of arsenic release (Figure 1) could be used directly or with adaptation to suit information likely to be available in India.

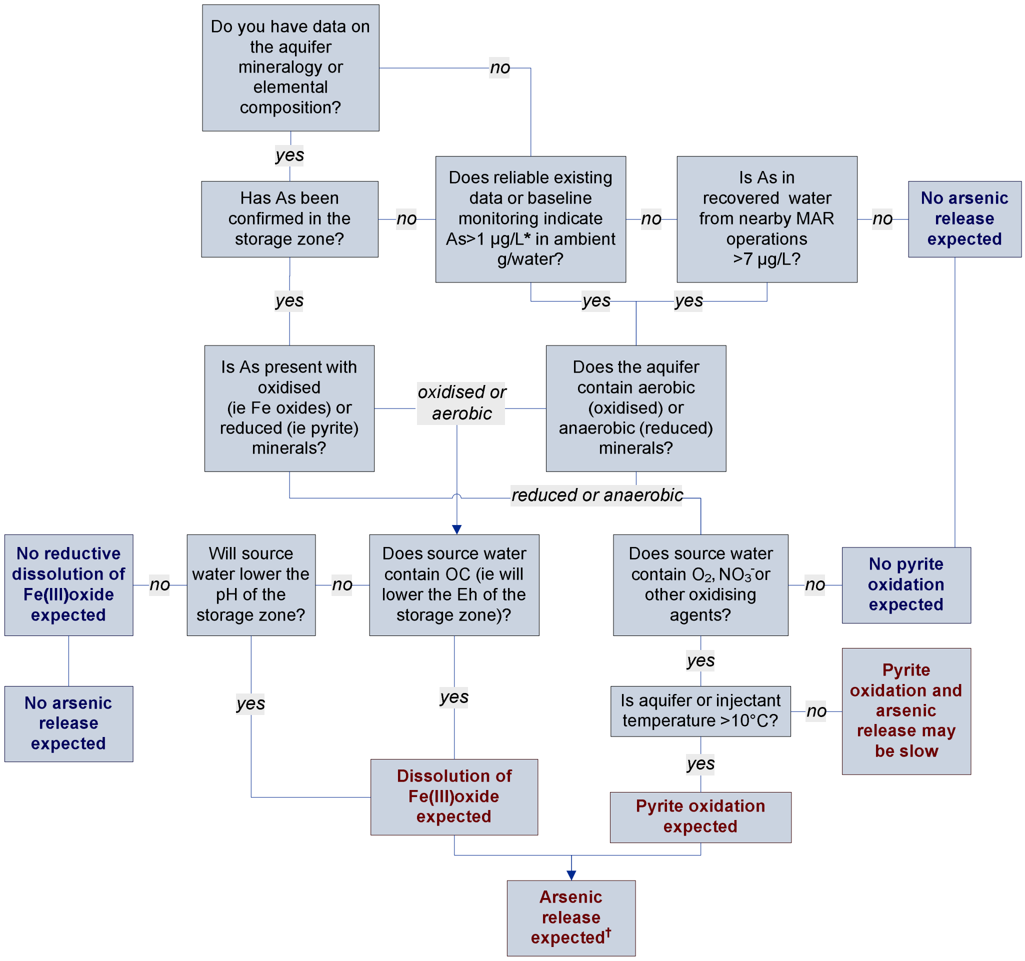

Fig 1. Decision tree for identifying arsenic mobilisation in aquifer storage and recovery

*Arsenic (As) concentrations should be reported to 1 µg/L. †Other trace metals may be released concurrently.

Turbidity and particulates also require some consideration, in order to mitigate the potential for clogging of recharge facilities, and also for their role in assisting migration of pathogens in aquifers (Šimůnek *et al*. 2005; Wall *et al*. 2008). Radionuclides are unlikely to exceed drinking water guidelines from MAR operations unless they are already present in native groundwater at unacceptable concentrations.

Due to extensive areas of fractured rock aquifers, contaminant migration in fractures does need to be taken into account, especially as travel times along fractures can be very fast in comparison with equivalent primary porosity media. This reduces the amount of time for inactivation of pathogens in transit from a recharge location to any well in the vicinity used as a drinking water supply. Hence water supply wells in proximity to recharge sources need to be protected using simplified approaches such as buffer distances, and safety verified by monitoring of appropriate indicator organisms.

CGWB is giving consideration to the possibility of including a chapter on water quality to update the Indian Guidelines for Artificial Recharge (CGWB 2000) or Manual for Artificial Recharge of Groundwater (CGWB 2007). Demonstration sites are needed where information is available to help with development and testing of this chapter. An AusAID project entitled '*Guidance on water quality in managed aquifer recharge (MAR)*' will provide support for this task.

Success of MAR operations is important and for the immediate future, it is suggested that monitoring for water quality be undertaken at a number of case studies sites and used to form an evidence-based approach to determining circumstances where it is possible with less effort in investigations to reliably protect health and the environment commensurate with local standards (as proposed by Anderson *et al* 2000).

Conclusions

Managed aquifer recharge in India is crucial to the sustainability of many groundwater supplies. A science-based approach to assure protection of public health and the environment is warranted when establishing new managed aquifer recharge operations, and to evaluate the safety of existing artificial recharge operations, especially for those in close proximity to drinking water supply wells. As a general principle, MAR should not be used to experiment with public health, but with adequate safeguards it may provide a low cost means of protecting the safety of drinking water. Central Ground Water Board is considering developing a chapter on water quality issues for updating the current Indian Guidelines for Artificial Recharge. Such a chapter could incorporate some of the fundamentals of the current Australian Guidelines for Managed Aquifer Recharge, after ground-truthing by monitoring at some selected Indian managed aquifer recharge sites.

Australian MAR Guidelines allow for logical and efficient stage-wise development of projects commensurate with risks, account for water quality changes in aquifers, provide for water quality and pressure effects in aquifers and connected ecosystems, address greenhouse gas emissions and allow for monitoring to inform continuous improvement in their application. Test applications of the Australian Guidelines on several sites including two in India suggest that the qualitative first stage is likely to be useful and corresponds with the undocumented approaches by existing project proponents. However the quantitative second stage of these Guidelines is currently impractical in India because it relies on quantitative analyses of water quality, including for pathogens and trace organic chemicals, which are unlikely to be available at Indian sites.

Hence it is proposed that the Indian Guidelines take better account of costs of investigations and incorporate more information on surrogates and indicators for pathogenic microorganisms and organic chemicals in order to reduce the costs of investigations and analyses. There would also be value in obtaining improved characterization of water quality of classes of source water used in India with a view to providing an initial estimate of the log removals required for pathogens and trace organics (and their surrogates) within the aquifer before recovery. Greater reliance will need to be placed on published experimental data, interpreting its relevance via aquifer environmental conditions. It is intended that a simplified version of the guidelines be produced, especially if this can be correlated with the Australian Guidelines by examining more data for several selected sites.

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Pre-treatment and post-treatment for MAR systems

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Abstract. Pre-treatment and post-treatment are integral parts of the managed aquifer recharge (MAR) systems to facilitate the enhanced functioning of these systems and to ensure that the extracted waters subsequently meet the water quality requirements for intended applications. Depending upon the source water quality, type of MAR system used and its operation, and local water quality guidelines or standards, the type of the pre-treatment and post-treatment system requirements vary considerably. Sedimentation, filtration and disinfection are some of the common pre-treatment systems applied for MAR systems. Commonly used post-treatment for MAR systems include disinfection, aeration-rapid sand filtration, ozonation-activated carbon filtration and membrane filtration aiming at removal of the contaminants present in the source water that were not sufficiently removed during MAR and new contaminants that are introduced during the soil passage.

Introduction

Natural treatment systems namely bank filtration (BF), artificial recharge and recovery (ARR) and soil aquifer treatment (SAT) are managed aquifer recharge (MAR) systems that are robust, reliable, capable of removing multiple contaminants and are sustainable (Ray 2008; Dillon 2005; Amy and Drewes 2007). In addition to replenishing groundwater aquifers, depending upon the quality of the water source used for recharge (river or lake water, stormwater, wastewater treatment plant effluents) and local hydrogeological conditions, these MAR systems can serve at least as a pre-treatment or sometimes even as a total treatment system (Schütz, 2008; Sharma *et al*., 2012). Comprehensive analysis of the source water quality as well as quality of the water currently present in the aquifer to be recharged must be done prior to design of MAR system. Very often the "treated water" from the MAR systems may not meet the required local water quality guidelines or standards for intended use and thus require additional post-treatment. Furthermore, some contaminants present in the source water may pollute the aquifer or influence the performance of MAR systems and therefore, often pre-treatment of source water is done before the recharge. Pre-treatment and post-treatment thus form an integral part of the MAR systems. Depending up on the raw water quality, local hydrogeological conditions, process conditions applied and intended use of the extracted water, a MAR system can have pre-treatment or post-treatment or both. Figure 1 shows a schematic of MAR system components from water quality and treatment perspectives.

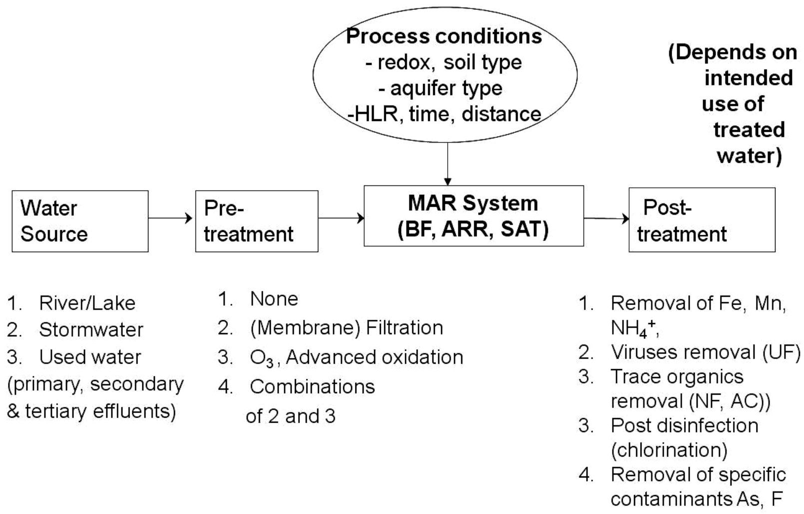

Fig.1. MAR system components from water quality perspectives

Need for pre-treatment and post-treatment

The following are some of the main reasons to employ pre-treatment and post-treatment in MAR systems aiming at water and wastewater treatment and reuse.

i) Some contaminants present in source water may seriously affect the performance of a MAR system (e.g. clogging or contamination of the soil layer and aquifer) and reduce its efficiency for removal of certain contaminants

ii) Some contaminants in source water are not removed or only partially removed by MAR systems (e.g. bulk organics, nutrients and organic micropollutants)

iii) Some new contaminants may be introduced during the MAR due to local hydrogeological conditions (e.g. iron, manganese, ammonium, arsenic, fluoride, colour, nitrate, natural organic matter etc.)

iv) Some treatment may be needed to meet local water quality guidelines and standards for artificial recharge and intended reuse of the reclaimed water

v) Additional treatment may be required to ensure “multiple barrier treatment system” in the context of deteriorating quality of source waters, increasing water demand, emerging contaminants and climatic change

Pre-treatment for MAR systems

Pre-treatment refers to removing some of the critical contaminants in source water to enhance the performance of subsequent MAR systems. Pre-treatment may be required to avoid clogging and contamination of the aquifers, and to enhance the removal efficiency of different contaminants during soil passage. Sedimentation, filtration (roughing or rapid sand), and disinfection are some of the common pre-treatment applied for MAR systems. Some pre-treatment filters also incorporate additional layer of adsorbents for the removal of heavy metals or other specific contaminants from source water before recharge. Furthermore, some water supply companies apply comprehensive water treatment employing advanced processes before using this water for infiltration (van der Hoek, 2000; Balke and Zhu, 2008)

Where river or lake water of low turbidity is diverted to infiltration basins for enhancing irrigation supplies, no treatment may be necessary. Dillon *et al.* (2009) reported that constructed wetlands may be suitable as pre-treatment when urban stormwater is being used to recharge a brackish limestone aquifer with recovery of water for irrigation without any requirement for post-treatment. Furthermore, they mentioned that microfiltration (MF) and granular activated carbon (GAC) filtration were needed at an artificial storage and recovery (ASR) site with a very fine-grained aquifer to prevent clogging of the well and that this requirement was more stringent than those to protect groundwater quality and for recovered water to be fit for use. On the other hand, when wastewater treatment plant effluent is used for recharge aiming at indirect potable reuse, there is need for high degree of pre-treatment before recharge. Again, the pre-treatment requirements may vary depending upon whether surface infiltration (basins), vadose zone wells or direct injection wells are employed for MAR. Table 1 summarizes the main water quality concerns and commonly used pre-treatment options for different types of source water used for MAR.

Often some type of pre-treatment is applied before the wastewater treatment plant effluent is applied for aquifer recharge or treatment using SAT. The objective of the pre-treatment is to improve removal efficiencies for different contaminants, increase run time and to reduce clogging (Sharma *et al*., 2011). Pre-treatment operations and processes can include fine screening, primary treatment, lagoons or ponds, constructed wetlands, biological treatment, membranes, and disinfection. Primary sedimentation or the equivalent is the minimum recommended pre-treatment for all SAT systems. This level of treatment reduces wear on the distribution system, prevents unmanageable soil clogging, reduces the potential for nuisance conditions, and allows the potential for maximum nitrogen removal. For small systems, a short-detention-time pond is recommended. Long-detention-time facultative or aerobic ponds are not recommended because of their propensity to produce high concentrations of algae. The algae produced in stabilization ponds will reduce infiltration rates significantly (NAP, 1994).

Table 1. Main water quality concerns and pre-treatment options for different types of water used for MAR

Source water	Main water quality concern for MAR	Pre-treatment options
Rainwater (from roofs)	Suspended solids, turbidity (fines)	Sedimentation, sand filtration
Urban runoff	Suspended solids, turbidity, nutrients, heavy metals	Sedimentation, sand filtration, adsorption, constructed wetlands
River water	Suspended solids, turbidity, bulk organic matter, colour, pathogens	Sedimentation, sand filtration, coagulation, adsorption, disinfection
Wastewater treatment plant effluents	Depends on the degree of wastewater treatment (pathogens, suspended solids, nutrients, bulk organic matter, colour, organic micropollutants)	Depends largely on the MAR method employed (Sedimentation, sand filtration, coagulation, adsorption, disinfection, constructed wetlands, membrane filtration, advanced oxidation and their combinations)

The following are some examples of different pre-treatment processes applied before MAR of different types of water:

(i) India: Artificial recharge of the groundwater using the rainwater from the roofs or stormwater (urban runoff) is a common practice in India. The commonly used common pre-treatment systems before recharge of rainwater or stormwater (urban runoff) include sedimentation tanks (desilting basins), sand filters, wrapped PVC pipes and metallic filters (CGWB, 2007; Hollander *et al*., 2009). Very often these pre-treatment units are constructed as a part of recharge structures.

(ii) Salisbury (Australia): In stormwater reuse system of City of Salisbury Australia, stormwater from Parafield and Ayafield catchments are pre-treated in storage tanks (for settling of fine sediments) and constructed wetland (for filtration, aerobic degradation, phytoremediation and volatilization) before artificial recharge (direct injection for ASTR) (Rinck-Pfeiffer *et al*., 2010).

(iii) Amsterdam (The Netherlands): The Leiduin water treatment plant is one of the two plants of Waternet (Amsterdam Water Supply Company) supplying water to the city of Amsterdam, The Netherlands. The raw water from Lekkanaal (a man-made side branch of the Rhine River) is pretreated at Nieuwegein and transported via pipelines for a distance of about 50 km to dune areas near the Leiduin water treatment plant. The standard pre-treatment process employed at the Nieuwegein pre-treatment plant is coagulation (with ferric chloride), sedimentation, rapid sand filtration, and pH correction with caustic soda. After pretreatment, the water is transported to the nearby dune area for infiltration. The system consists of 40 infiltration ditches with a total length of 24.6 km and an average width of 35 m. The dune area used by Waternet is about 36 km^2, of which 10 km^2 is taken up by actual infiltration areas (van der Hoek, 2000; Tielemans, 2007).

(iv) Wulpen (Belgium): The water reclamation plant of Wulpen/Torreele water plant in Belgium, operating since July 2002, reuses municipal wastewater effluent to produce 2,500,000 m^3/year of infiltration water (after treatment with ultrafiltration, reverse osmosis and UV) for an artificial groundwater recharge in St-Andre dune water catchments. The recharged water is recaptured from wells located a distance of 35 to 120 m infiltration ponds after a minimum residence time of 40 days in the dune aquifer and then further treated for drinking water supply (van Houtte and Verbauwhede, 2005).

(v) California (USA): Groundwater Replenishment System (GWRS) in Orange County, California is the world's largest wastewater purification or reclamation system for indirect potable reuse. At this state of the art facility, the secondary effluent is further polished employing microfiltration, reverse osmosis and advanced oxidation (UV/H_2O_2) treatment before using it to recharge the aquifer and to create salt water intrusion barriers (GWRS, 2010).

Post-treatment for MAR systems

Post-treatment refers to upgrading the quality of the "treated water" produced by different MAR systems so that it meets the water quality requirements for different applications. Requirements for post-treatment of "product water" from MAR systems vary from simple disinfection to complete full-scale treatment depending upon on the quality of the source water used for natural treatment (recharge), type, design and operation of MAR system utilized, process conditions applied and applicable water quality guidelines or standards for intended use (Sharma and Amy, 2010).

In general, two main water treatment requirements after MAR systems include (i) removal of contaminants like bulk organics, nutrients and organic micropollutants that are not removed or only partially removed by natural treatment systems like BF, ARR and SAT and (ii) removal of contaminants like iron, manganese, arsenic, fluoride or color that are introduced into the water in different layers of aquifer during the soil passage due to changes in redox conditions, ion-exchange and dissolution of the minerals.

Generally, conventional water treatment (coagulation, rapid sand filtration, ozonation, activated carbon filtration and disinfection) or advanced treatment (membrane filtration, advanced oxidation) or their combinations are applied as post-treatment. Very often designs of these post-treatment systems are site specific. Commonly, used post-treatment methods include (i) disinfection/chlorination to ensure microbial safety and disinfectant residual in the water distribution system, (ii) aeration/chemical oxidation-rapid sand filtration to remove common groundwater contaminants like iron, manganese and ammonium, (ii) ozonation for oxidation of bulk organics and organic micropollutants, (iv) activated carbon filtration (with or without pre-ozonation) to remove the organic micropollutants and colour/taste and odour present in the water, (v) softening and pH correction to remove the hardness and to ensure that there is no scaling or corrosion of water distribution system. Table 2 presents the main water quality concerns for water extracted from a MAR system and commonly applied post-treatment methods.

Post-treatment of water from natural treatment systems will be more crucial in the future to ensure safe water supply in the context of increasing water demand, deteriorating source water quality, emerging contaminants and climate variability. With the proper design of the MAR systems for a given water quality and hydrogeological condition and with the provision of appropriate pre-treatment where applicable, the requirements for post-treatment (including energy and chemicals) can be minimized. Therefore, it is important that pre-treatments and post-treatments are considered from the planning, design and implementation of MAR systems as this has direct consequence on the overall cost of water treatment and on the long-term sustainability of applying MAR systems for water and wastewater treatment and reuse.

Table 2. Common water quality concerns for water from MAR systems and post-treatment options

Water quality concern	**Pre-treatment options**
Pathogens	Disinfection (Chlorination, ozonation, UV disinfection)
Iron, Manganese, Ammonium	Aeration/chemical oxidation - rapid sand filtration
Fluoride, Arsenic	Coagulation - sedimentation, rapid sand filtration, adsorption-based processes using specific adsorbents
Nitrate	Ion-exchange, biological-denitrification, membrane filtration
Hardness	Chemical softening, ion-exchange, membrane filtration
Organic micropollutants	Ozonation, activated carbon filtration, advanced oxidation, membrane filtration
Salinity (from brackish groundwaters)	Membrane filtration (reverse osmosis)

The following are some examples of different post-treatment process applied after the ARR and SAT of different types of water:

(i) India: Limited information is available on the post-treatment of water obtained from MAR systems utilized for municipal or industrial (re)use in India. Majority of the rainwater MAR systems in India do not employ any specific post-treatment for reuse of the extracted water for irrigation purposes. Disinfection (often chlorination) is applied as the only treatment, if water from the MAR system is used for drinking purposes. Presence of iron, manganese in groundwater is a common in water quality problem in India, for which normally aeration/chemical oxidation followed by rapid sand filtration is applied. Some groundwaters in India have elevated concentration of arsenic and fluoride for which coagulation-sedimentation-filtration or adsorption-based processes using specific adsorbents are employed as treatment at household or community level.

(ii) Berlin (Germany): After bank filtration and artificial recharge, only aeration and rapid sand filtration is employed at Berlin Waterworks to increase oxygen concentration and to remove iron and manganese present in the extracted water. This water is then distributed to the consumers without disinfection (Grunheid *et al*., 2005).

(iii) Amsterdam (The Netherlands): After the average residence time of about 100 days (ranging from 60–400 days) in the dunes, the infiltrated water is abstracted through the drains and collected in an open basin. This ARR water then is further treated at the Leiduin water treatment plant by employing cascade aeration, rapid sand filtration, ozonation, pellet softening, two-stage biological activated carbon filtration, and slow sand filtration to achieve drinking water. No final disinfection is applied before supplying the water to the city of Amsterdam (van der Hoek, 2000; Tielemans, 2007).

(iv) Israel: The Dan Region Project, the largest wastewater reclamation and reuse scheme in Israel, employs SAT for further polishing of secondary/tertiary effluent, which is then used for irrigation. MEKOROT, the national water company of Israel, is conducting pilot studies on alternative hybrid SAT system employing sand filter and ultrafiltration as pre-treatment and nanofiltration as post-treatment for SAT in order to increase infiltration rates and removal efficiencies for different contaminants (Ideolovitch *et al*., 2003; Aharoni *et al*. 2011).

(v) Colorado (USA): The Prairie Waters Project of the City of Aurora uses an innovative natural purification process (combination of bank filtration and artificial recharge) to perform initial treatment of water from the South Platte River. After the natural purification process, water is piped 54.7 km south using a 1.5 m pipeline to the Aurora Reservoir Water Purification Facility.

The new treatment facility uses multiple treatment processes that include chemical softening (to reduce hardness, iron, manganese, and scaling potential), advanced oxidation using ultraviolet (UV) light and hydrogen peroxide (to inactivate pathogens and oxidize remaining trace organics), rapid sand filtration (to remove remaining particles and pathogens), and activated carbon adsorption (to adsorb remaining trace organics and improve taste) (Ingvoldstad, 2007).

Summary and Conclusions

MAR systems like BF, ARR and SAT are robust and have high potential to improve the quality of different types of source waters during soil passage. These systems often require some pre-treatment and/or post-treatment to avoid detrimental effect on the aquifer system, improve their removal efficiencies, and to meet the water quality guidelines or standards for intended applications. Type of the pre- or post-treatment system that should be used together with a MAR system depends on its design and operation, source water quality, size of the recharge system, process conditions applied as well as treated water quality requirements. Some of the common pre-treatment methods include sedimentation and filtration while disinfection, aeration/chemical oxidation followed by rapid sand filtration, activated carbon filtration with or without ozonation, advanced oxidation as well as membrane filtration systems have been applied for post-treatment. Proper design of a MAR system with appropriate pre-treatment will reduce the need for extensive post-treatment and make the MAR technology more cost-effective and offer a sustainable solution for integrated water resources management.

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MAR risk assessment and water quality considerations

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How to establish a MAR project using a risk assessment framework

Potential proponents need to know first whether they have the five essential elements (Stage 1 assessment) of a MAR project outlined below before proceeding further. If the project looks potentially viable at this first stage, the Australian MAR Guidelines (EPHC, 2008) lead proponents through the investigations (Stage 2) and commissioning trials (Stage 3) to an operational project (Stage 4).

Stage 1 - Five essential ingredients

The five critical elements for a successful MAR project are:

- a sufficient demand for recovered water
- an adequate source of water for recharge
- a suitable aquifer in which to store and recover the water
- sufficient land to harvest and treat water
- capability to effectively manage a project

Demand: The volumetric demand for recovered water (within an economic scale) or a clearly defined environmental benefit of recharge is essential for MAR. The purposes for which water will be recovered also need to be defined (Figure 1). Generally this will provide the revenue stream to pay for the water supply cost elements of the project. In urban areas demand for stormwater detention for mitigating floods, improving coastal or receiving water quality and enhancing urban amenity and land value may also contribute revenue streams for MAR projects. For reclaimed water projects the decline in discharge of treated effluent to sea may provide a motivation for investment in MAR.

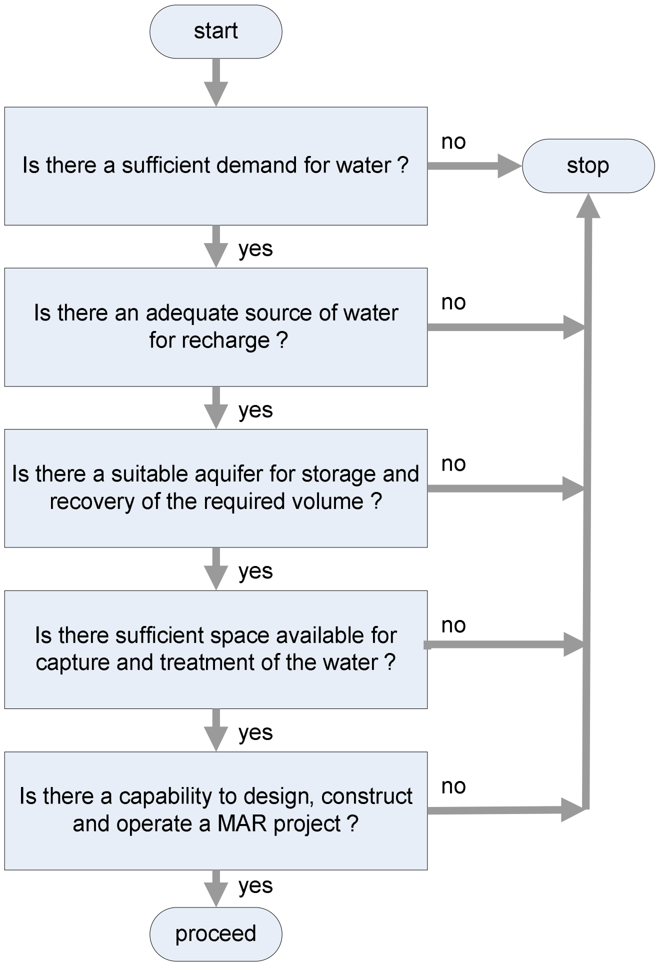

Fig.1. A checklist for considering whether to undertake a managed aquifer recharge project.

Source: Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand with sufficient excesses to build up a buffer storage to meet reliability and quality requirements. In an over-allocated catchment it is unlikely that an entitlement to surface water would be available.

Stormwater and reclaimed water are usually abundant resources in urban areas but require treatment and storage before reuse. The availability of stormwater or reclaimed water to make useful contributions to city water supplies is not a constraint. The primary limitation to stormwater harvesting and use is the ability to store the water from runoff events for subsequent use as drinking water supplies or as irrigation, industrial supplies or other non-drinking uses. MAR can provide an economic means of storing water in urban areas.

Sewage effluent requires extensive treatment before placement in either dams or aquifers prior to reuse. Aquifers have advantages with respect to ongoing passive treatment of the water and allowing longer assured residence times before recovery for drinking.

Aquifer: A suitable aquifer is critical for MAR. It needs to have an adequate rate of recharge, sufficient storage capacity and be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred so that mixing with fresh recharge water should still allow recovered water to be fit for use.

Local hydrogeological knowledge is needed to identify the presence of aquifers and their suitability for MAR. Basic stratigraphic and hydrogeological information existing wells can serve as valuable background information before drilling new wells and can be used to determine potential sites for MAR. Hydrogeological reports generally provide some indication of the level of knowledge of the local aquifers and their degree of uniformity. Aquifer properties vary spatially so it is not generally reliable to extrapolate from one site to predict viability or performance at a nearby site.

At any given location there may be several aquifers stacked on top of each other interleaved with low permeability layers. This allows choice of one or more with the most favourable characteristics for water storage. Depending on their degree of inter-connection, it may be possible to store water of different qualities in different aquifers at the same location.

Detention Storage: There should be open space, or dams, wetlands, ponds or basins to detain sufficient water without causing flood damage to enable the target volume of recharge to be achieved. Similarly there needs to be space available for whatever treatment process, if any, is subsequently determined to be required. In established urban areas space for capture can be a major impediment to stormwater water harvesting and ASR wells are commonly used to avoid land requirements of infiltration systems. For recycled water from a sewage treatment plant generally no additional detention storage will be required at the recharge facility.

Management capability: Hydrogeological and geotechnical knowledge, as well as knowledge on water storage and treatment design, water quality management, water sensitive urban design, hydrology and modelling, monitoring and reporting are all required to meet governance requirements. Such expertise will be required from Stage 2 and a growing number of consultants are experienced in investigations and design of MAR projects.

Identify the degree of difficulty

Appendix 1 gives an example of a checklist to understand the degree of difficulty associated with a conceived project. This serves as a guide to the amount of effort required in project investigations and commissioning trials in order to manage human health and environmental risks in accordance with the relevant water quality management guideline (for example, National Water Quality Management Strategy). This consists of 13 questions with commentary on information required to answer and the consequences of the answer on the need for further information during the investigation stage (Stage 2).

The questions address the water quality of the source water in relation to environmental values of the aquifer, of intended uses of recovered water, potential for clogging and potential for mineral reactions. They ask about groundwater quality in relation to recovered water uses, and whether groundwater needs to be protected for drinking supplies or high conservation ecological values, or is highly saline. They also ask whether there are nearby groundwater users or ecosystems, is the aquifer confined or artesian, fractured or cavernous, are if there similar projects with similar source water in the same aquifer and whether the proponent or his consultant or intended operator has experience with MAR or water quality management.

Costs of MAR investigations and trials are not trivial and having completed this checklist the proponent should know whether their proposed project has a low or high degree of difficulty and the types of information which will be of most value in the investigation stage. Because of the costs of these investigations it is normal to first seek assurance that at least the core approvals for MAR are likely to be obtained, before investing in such investigations.

Approvals required

Approvals that may be needed for a MAR project to proceed include:

- an entitlement to a share of the source water, such as stormwater, reclaimed water or other source, taking account of environmental flows and other users of the source water
- a permit to construct wells for investigations, ASR or recovery
- planning approval for a water impoundment, covering geotechnical safety, amenity, insect and pest nuisance and danger of drowning
- a declaration of environmental values of an aquifer, accounting for ambient groundwater quality and current uses
- approval to recharge water to an aquifer, to protect an aquifer's environmental values, prevent excessive changes in the hydraulic head, and to protect human health and the environment as a result of the recovery of stored water for intended uses.
- an entitlement to a share of the aquifer storage space, recognising that this is finite, and may be smaller than the harvestable volume of source water

- an entitlement to recover water from an aquifer, possibly as a proportion of the cumulative recharge that may depend on the degree to which the aquifer is over-exploited and will take account of other groundwater users and water bankers so as not to cause them adverse impacts

- transfer of water entitlement, endowing the recharger with an ability to transfer their entitlement to a third party, subject to hydrogeological constraints and not into locations where piezometric heads are already depressed

- a permit for the use of recovered water, to ensure that usage conforms with catchment management plans and that the water quality is fit for intended uses

Next steps

Assuming that the entry level assessment (Stage 1) indicates that the project is apparently viable, the degree of difficulty does not deter the proponent, and the regulator has not identified other impediments, the next stage is to undertake investigations on source water, pre-treatment methods and the aquifer to determine if the project will demonstrably protect human health and the environment, notably the aquifer.

Stage 1 was a rapid qualitative assessment but Stage 2 is quantitative, using existing information supplemented by site-specific investigations that were foreshadowed in Stage 1. Information to confirm that the project is operating as intended will not be available until commissioning of a pilot project, or the full-scale project after it is constructed. A staged approach (Figure 2) to project development helps avoid wasting time and money, and can improve the design of the project by tailoring it to the aquifer. It also allows investment appropriate to the MAR project in relation to alternative or complementary projects.

Stage 2 investigations enable risks to be assessed and the preventative measures by which they can be managed to be indentified. This requires information describing the source water quality, infrastructure and proposed operations of the project, and characterisation of the hydrogeology to demonstrate that all hazards have been addressed with sufficient supporting information for a management plan. Where further information is needed, a pilot project might be required.

At this point the risks of success will be better defined and a decision would be made on whether to invest in constructing the MAR project or in alternative water supplies. Such a decision would account for the full range of costs and benefits of all projects.

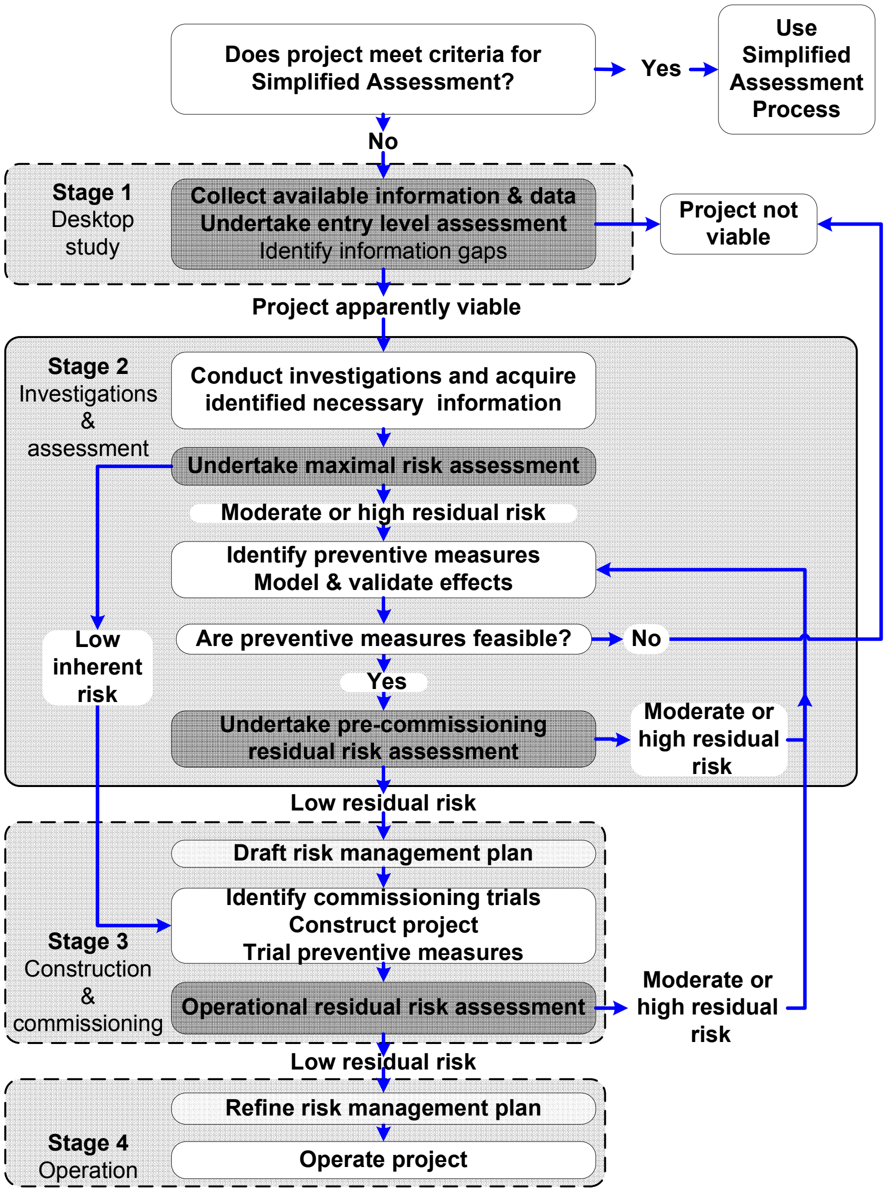

Fig.2. Risk assessment stages in managed aquifer recharge project development

For many MAR projects the level of some risks cannot be known before implementation, accompanied by suitable monitoring. Known as commissioning trials, Stage 3 monitoring provides a basis for ongoing operation of the MAR scheme. It also provides for the development of management plans for the ongoing operation of the project, Stage 4, which will require ongoing monitoring to ensure that risks to human health and environmental health are controlled.

A risk assessment framework for health and environmental protection

The risk management framework for MAR operations comprises 12 elements (Figure 3) that fall into four main categories:

- commitment to responsible use and management of recycled water

- MAR system analysis and management, such as risk assessment and a series of preventative measures
- supporting requirements, such as employee training, community involvement, research and development, validation, and documentation and reporting systems; and
- review, including evaluation and audit processes.

All 12 elements need to be implemented for the risk management approach to be successful.

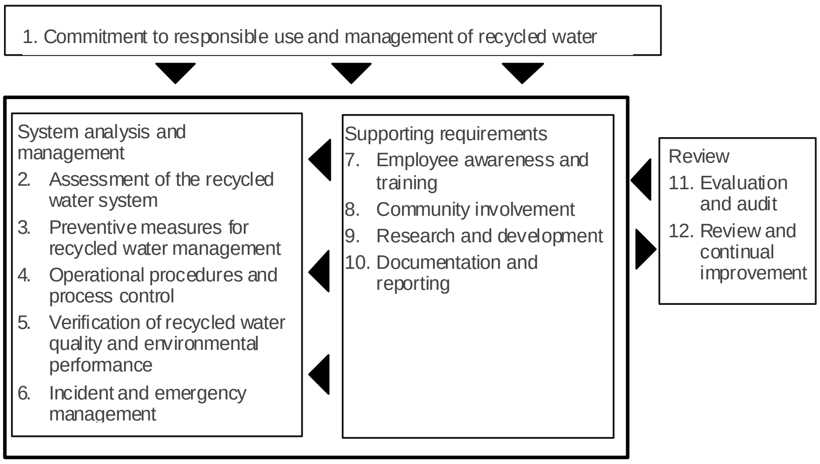

Fig.3. Elements of the framework for managing water quality and use (EPHC, 2008).

This approach aims to protect the environmental values of all intended uses of recovered water and of the aquifer beyond a transient attenuation zone, and to prevent adverse impacts. This is done by assessing potential hazards and the risks associated with each, and identifying preventive measures to manage the risks.

A simplistic view that treating water to near drinking standards before recharge will protect the aquifer and recovered water is incorrect. For example chlorination, to remove pathogens that would sustainably be removed in the aquifer, can result in water recovered from some aquifers containing excessive chloroform. In some locations, drinking water injected into potable aquifers has resulted in excessive arsenic concentrations on recovery due to reactions with pyrite containing arsenic. Source water that has been desalinated to a high purity dissolves more minerals within the aquifer than water that has been less treated.

Hence a scientific approach is recommended that takes account of three ways that aquifers interact with recharged water:

1. Sustainable hazard removal - allowing for attenuation during passage through soil and aquifer within an attenuation zone (Figure 14), (eg pathogen inactivation, biodegradation of some trace organics, a limited amount of nutrient assimilation)

2. Ineffective hazard removal –- these hazards need to be removed prior to recharge because they are either unremoved (eg salinity) or removal is unsustainable (eg adsorption of any metals and organics that are not subsequently biodegraded, or excessive nutrients or suspended solids)

3. New hazards introduced by aquifer interaction (eg metal mobilization, hydrogen sulphide, salinity, sodicity, hardness, or radionuclides) - there is a need to change the quality of recharge water to avoid these (eg change acidity-alkalinity, reduction-oxidation status or reduce nutrients)

The response of an aquifer to any water quality hazard depends on specific conditions within the aquifer including temperature, presence of oxygen, nitrate, organic carbon and other nutrients and minerals, and prior exposure to the hazard.

The zone of aquifer in which water quality may be measurably affected by MAR may be larger than the attenuation zone, but in this outer domain the water quality should continuously satisfy the initial environmental values of the aquifer The effects of MAR operations on hydraulic heads (pressures) may be measurable over a much larger area, especially in confined aquifers, and may extend several kilometres. If the aquifer is originally too saline for the uses of recovered water, a storage zone can be identified that contains water which when recovered is fit for its intended use (Figure 4).

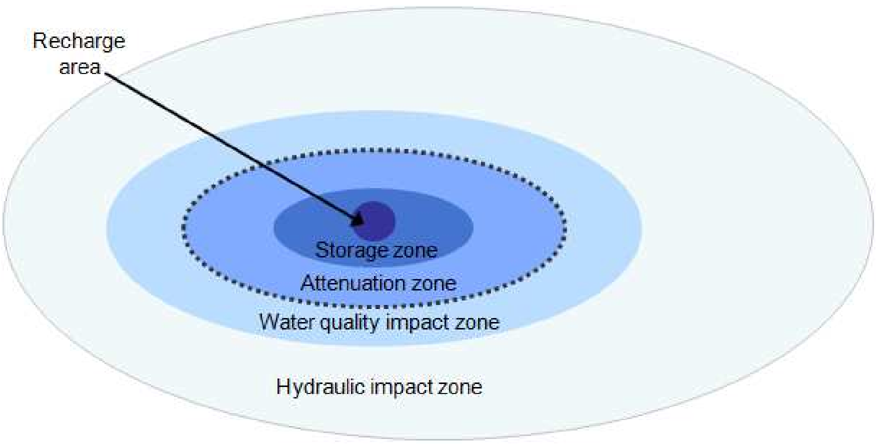

Fig.4. Schematic showing zones of influence of a MAR operation.

The dotted line in Figure 4 marks the outer boundary of the attenuation zone. This represents the maximum separation distance between the MAR recharge structure and well(s) for verification monitoring to ensure that the ambient groundwater quality is protected. As the attenuation zone defines sustainable attenuation only, on cessation of the MAR operation this will shrink and disappear as ultimately the whole aquifer will meet all its initial environmental values.

Water quality considerations

Applying the system analysis and management components (Elements 2–6) of the framework for water quality management to MAR reveals a number of water quality hazards (Table 1). Hazards to human health or the environment may originate from:

- the source water for recharge
- native groundwater
- aquifer minerals reacting with recharge water
- byproducts of treatment processes or maintenance practices.

Table 1. Summary of key water quality hazards in source water, groundwater and aquifer materials for MAR projects, with examples of specific hazards and preventive methods.

Hazard	Origin[a]	Examples	Preventive measures
Pathogens	S, (G)	Viruses	Adequate aquifer residence time
Inorganic chemicals	G, A, S	Arsenic	Control Eh during recharge (avoid mobilisation)
Salinity and sodicity	G, (S)	Salinity	Increase volume of freshwater recharged
Nutrients	S, (G)	Nitrogen	Pretreat water (eg activated sludge)
Organic chemicals	S, (G)	Pesticides	Exclude prone sub-catchments
Turbidity and particulates	S, (G)	Suspended solids	Pretreat water (eg wetland)
Radionuclides	G, A, (S)	Alpha-radiation	Aquifer selection (avoidance)

A = aquifer minerals, G = groundwater, S = source water for recharge

[a] Brackets show possible secondary source; Eh = a measure of redox potential, the propensity for oxidation and reduction reactions.

These key hazards impact on:

- the aquifer beyond the attenuation zone (and hence other groundwater users and groundwater dependent ecosystems)

- the uses of recovered water

- situations where the byproducts of MAR water treatments and operations are reused or discharged (see Table 2).

Table 2. Examples of hazardous byproducts of managed aquifer recharge operations.

General hazard	Example of specific hazards
Water treatment byproducts	Any process with reject water (eg reverse osmosis) or byproduct (eg coagulation, filtration, backwash water) may produce water with elevated concentrations of suspended solids, pathogens, inorganic chemicals, nutrients, salinity and organic chemicals
Purge water	Suspended solids, pathogens, metals, nutrients and organics in recharge water may be concentrated in water purged from an aquifer storage and recovery well during maintenance
Basin scrapings	Pathogens, metals, nutrients and organics in recharge water may be concentrated in scrapings produced by infiltration basin maintenance. If they meet quality criteria, scrapings may be reused in agriculture as a component in soil conditioner

Note: The waste management hierarchy should be invoked in the priority order of: avoid, reduce, reuse, recycle, treat and dispose.

Proponents developing a MAR project should engage specialist consultants to identify and quantify health, environmental (eg hydrogeological and geotechnical) and management risks. The next step is to develop preventive measures to mitigate risks and appropriate monitoring methods to assess each hazard, including critical control points where applicable. Hazard preventive measures may include one or more of the following barriers:

- source water selection
- recharge control system (eg recharge shut down if the monitored indicator variable is outside critical control limits)
- aquifer selection
- project location (away from sensitive groundwater-dependent ecosystems or end uses)
- treatment of recharge water to remove hazards or precursor(s) to their formation or occurrence
- adequate detention time for passive treatment within the aquifer
- treatment of recovered water before distribution to end uses
- incident response plans, including feedback from real-time monitoring.

In many MAR operations, multiple barriers may be needed, so that if any one barrier fails, human health and the environment will still be protected. Table 3 summarises preventive measures, many of which apply to more than one hazard. Depending on the particular project, other critical control points and preventive measures may be more appropriate. Education and training are important components of implementing and maintaining prevention measures.

Table 3. Summary of preventive measures and critical control points for MAR.

Preventive measures	Description	Critical control point
Exclusion barriers — preventing entry		
Hazard source control	Selection or management of water sources before recharge (eg catchment, recycled water, roof runoff, stormwater)	No
Intake levels	Exclusion of floating hazards by maintaining intake levels below the water surface	No
Exclusion of water that does not meet critical limits	Continuous monitoring of indicator variable, to provide feedback to divert water flow or stop recharge when critical limit is exceeded	Possibly: depends on the hazard, associated risk prevented and monitoring system
Exclusion barriers — removing hazards		
Residence time in the soil or aquifer	Attenuation of all human pathogens and selected organic chemicals	Yes: system needs to provide required residence time. Recovery rate is restricted to ensure adequate time between recharge and recovery
Travel distance in aquifer	Travel distance (between recharge and recovery) chosen to provide a minimum residence time under the range of operating conditions	No: component of system design
Treatment processes	Concentration of specific hazards decreased before recharge or on recovery	Possibly: at the point of recharge and/or recovery; depends on the hazard and effect on the specific environmental endpoint
Preventive measures to manage risks in commissioning and validation monitoring (Stage 3)		
Operate early warning feedback system	Monitor near-recharge wells for early warning of treatment effectiveness and to allow corrective actions to be implemented	Yes: detection exceeding critical limit trigger corrective action
Recover recharged water and re-treat	Recover contaminated water to prevent exposure	No: however, volume to be recovered would be reduced by use of an early warning system
Prevent distribution of recovered water to unacceptable end uses	If recovered water does not meet water quality requirements for intended uses, stop recovery (to allow longer residence time), divert to acceptable uses or re-treat	Possibly: surrogate parameter correlated with water quality concern may be used

Preventive measures	Description	Critical control point
Post-treatment of recovered water	Treat recovered water to remove identified hazards	Yes: direct or surrogate parameters exceeding critical limit trigger corrective action
Reduce rate of recharge or recovery	Modify flow rates to increase residence times, reduce pressure gradients across thin aquitards, or reduce MAR-induced flow and level variations	No: subject to validation monitoring

Pathogens

In confined aquifers, sources of enteric pathogens (ie intestinal pathogens) are limited to those present in the recharge source water. However, in unconfined aquifers, other sources of such pathogens may exist. Potential water sources for managed aquifer recharge (eg wastewater, greywater, stormwater) can contain a wide range of enteric pathogens that pose a risk to human health.

Public health and environmental risks associated with pathogens in relation to managed aquifer recharge are identical to those described in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

Fate and behaviour of pathogens in MAR

Pathogen survival in groundwater is affected by physical, chemical, and biological processes (Toze and Hanna 2002, Gordon and Toze 2003). The inactivation of pathogens in aquifers highlights their potential use as robust treatment barriers in the multi barrier approach. Pathogen presence and survival in aquifers is highly variable and is influenced by a variety of factors, including:

- pathogen type
- recharge water source type
- temperature
- redox state and oxygen concentrations
- activity of indigenous groundwater microorganisms
- aquifer geochemistry.

Further information on the effects of these parameters on pathogen survival in aquifers is given by Dillon and Toze (2005) and NRC (2008). Although all of these parameters (either independently or collectively) may influence pathogen survival, different pathogens can also vary in their environmental stability (eg between different locations), depending on local groundwater conditions. Enteric viruses are generally accepted to be the most resistant to decay (ie have the highest potential for survival); followed by protozoa and then bacteria.

Little is known about the fate of helminths during MAR. In Australia (except for the tropical northern regions), helminths pose minimal risk. They can be controlled by suitable pretreatment, and are effectively removed from water by simple treatment systems such coagulation, flocculation and sedimentation in stabilisation ponds (Jimenez 2003). Even if a helminth egg was able to pass through treatment systems, their small size (40–90 µm) means that simple filtration processes in more consolidated and sand aquifers would be likely to remove them.

Managed aquifer recharge projects relying on aquifer treatment to remove pathogens before recovery for drinking water supplies will always require validation. The efficiency of pathogen removal depends on site-specific conditions; uncertainties can be resolved by monitoring to validate attenuation rates. In terms of log removals, aquifers are conceptually much like other natural and engineered water treatment processes for pathogens (NRMMC–EPHC–AHMC 2006). Log-removals in aquifers are primarily related to the residence time of the recharge water, the redox state of the aquifer and the temperature; they are typically expressed in terms of the number of days required for a 1-log reduction in pathogen numbers.

As a rule of thumb, the most reliable assessment of pathogen attenuation at a given site is measurement of pathogen survival in situ using inoculated diffusion chambers. Due to temporal variations in pathogen numbers in source water, detecting no pathogens in groundwater samples sheds little light on the aquifer's actual pathogen inactivation rate. Relevant laboratory-derived attenuation data must be obtained at a temperature and redox status relevant to the aquifer, using chambers inoculated with microorganisms from the aquifer.

As validation data from MAR sites accumulates, greater precision in estimating pathogen attenuation rates in aquifers is expected. Verification monitoring involves attempting to detect microbial indicators and targeted enteric viruses in the recovered water. This is done by monthly sampling of observation wells within the attenuation zone and of the recovered water.

Secondary treated effluent does not appear to affect the numbers of indigenous pathogens in an aquifer. Laboratory evaluation of the effect of secondary treated effluent on the abundance of indigenous opportunistic pathogens in aquifer material did not result in any significant difference in comparison with controls (S. Toze CSIRO Land and Water, pers comm, 2007).

Recent studies (Reed 2007, Reed et al 2007) have documented the changes in native microbial populations near the Bolivar (South Australia) reclaimed water ASR trial and the Floreat Park (Western Australia) reclaimed water infiltration galleries. These studies confirmed trends in populations related to proximity to nutrient-rich recharge water and changes in redox status. In distal water, where water quality indicated presence of reclaimed water, microbial community populations, biodiversity and activity were unchanged. Although the evidence is not conclusive, it suggests that MAR is unlikely to stimulate recovery of higher numbers of indigenous opportunistic pathogens (eg Pseudomonas, Aeromonas) than would be recovered by pumping native groundwater.

Management of pathogens via MAR

Preventive measures to reduce the risk of pathogenic hazards and achieve performance targets include:

- source control (eg catchment management for stormwater sources)
- removing pathogens using treatment processes (eg engineered or natural treatment processes to achieve the required log removal rate of the reference pathogens)
- reducing exposure through preventive measures on-site (eg controlling public access during irrigation with recovered water).

These three measures are described in Sections 3.4.1–3.4.3 and Appendix 3 of the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

The concept of tolerable risk is central to the management of enteric pathogens via managed aquifer recharge. These guidelines adopt a tolerable risk of 10^{-6} disability adjusted life years (DALYs) per person per year (NRMMC–EPHC–AHMC 2006).

Given the potentially large numbers of pathogenic hazards in source waters, three reference pathogens — rotavirus, Cryptosporidium and Campylobacter — have been selected to represent viral, protozoan and bacterial hazards respectively. For a detailed description of DALYs, and the calculation of microbial health-based performance targets for the reference pathogens, refer to Appendix 2 of the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006). The unique feature of MAR is the consideration of the aquifer's effects on pathogens.

Inorganic chemicals

This section is applicable to the major ions (calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate, bromide and fluoride); metals (aluminium, cadmium, chromium, copper, iron, manganese, nickel, lead, strontium and zinc); metalloids (arsenic, boron and silicon); and gases (hydrogen sulfide and methane). Nitrogen and phosphorus are discussed separately below.

Unlike pathogens, there is insufficient information on chemical parameters to support DALYs. Tolerable risk is therefore defined in terms of guideline concentrations (ANZECC and ARMCANZ 2000; NHMRC–NRMMC 2004; WHO 2006; EPHC–NHMRC–NRMMC 2008a).

The key inorganic hazards resulting from aquifer storage are:

- increased arsenic, iron, manganese, trace species or hydrogen sulfide, producing recovered concentrations in excess of the beneficial use guideline value
- increased iron in recovered water, which impacts on water supply infrastructure (eg irrigation)
- changes to major ion chemistry alter the sodicity or nutrient balance of the recovered water, affecting its suitability for potential uses (eg irrigation).

When elevated metal concentrations exceeding the beneficial use guideline value occur in backwash water from injection wells, or in the initial water recovered from an aquifer storage and recovery well, care should be taken in the treatment, use and disposal of this waste stream.

Sources and fate of inorganic chemicals in MAR

The chemistry of water stored in an aquifer during MAR is affected by chemical reactions, driven by the aquifer's conditions (eg pH, redox state, minerals, organic matter, microbial activity). Reactions can occur between the source water and the native groundwater, and between the source water and the aquifer material. This can change water quality and aquifer permeability. The key risks related to subsurface reactions are described below.

Arsenic increase

Mobilisation of arsenic from the aquifer sediments can occur when pyrite in the storage zone is oxidised, or iron (III) oxides are dissolved (see decision tree in Appendix 3). This is a key issue for confined target zones in which reduced minerals are present, despite starting with source water at acceptable arsenic concentrations (Arthur et al 2003), and may lead to concentrations of arsenic greater than the drinking water guideline value.

Iron increase

Release of iron from the sediments in the storage zone occurs mainly when organic matter in the source water reacts with iron (III) oxyhydroxides and oxides (ie goethite, hematite). It can also occur from pyrite oxidation or by changing the pH of the storage zone (see decision tree in Appendix 3). Iron release is generally an aesthetic water quality concern, potentially causing an elevated colour; but, it can also contribute to aquifer clogging. Iron increases can be associated with the release of other hazards such as arsenic and radium.

Manganese increase

Dissolution of manganese from manganese oxides and oxyhydroxides in the sediments occurs by reaction with organic matter in the source water, or by changing the pH of the storage zone (Ibison et al 1994). Like iron, manganese may contribute to the colour of the recovered water.

Trace ion increase

The ion species affected include: aluminium, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, fluoride, iron, lead, manganese, molybdenum, nickel, vanadium, uranium and zinc. All of these can cause health or environmental concerns. Increases in trace constituents frequently coincide with an increase in iron, manganese or arsenic.

Mechanisms for trace ion release include:

- oxidation of sulfide minerals, such as pyrite, due to presence as trace elements within the mineral (similar to arsenic, although arsenic is generally more mobile than cations)
- iron (III) oxide dissolution under changing pH or Eh, as these surfaces often contain adsorbed trace species
- exchange or displacement from the solid surface by another species (eg cation exchange)
- mineral equilibrium, when water in the storage zone is not in equilibrium with the dominant mineral phases
- dissolution of mineral phases or accumulated particulates under changing pH or Eh.

Hydrogen sulfide increase

Hydrogen sulfide gas is produced when organic matter, introduced to an anoxic storage zone, reacts with dissolved sulphate. In the sequence of microbial-mediated redox reactions, iron mobilisation is likely to precede the production of hydrogen sulfide. Hydrogen sulfide contributes an aesthetic hazard by imparting taste and odour to the recovered water.

Changes to major ion composition

Mixing of the source water with saline groundwater, or ion exchange between the source water and the solid phase exchange sites, can significantly affect the contribution of sodium, calcium and magnesium. This is an important consideration if the recovered water is to be used for irrigation, because it can alter the risk of soil sodicity.

Excessive dissolution of carbonate minerals can:

- lead to injection well and aquitard stability concerns
- increase production of sand in recovered water
- extend preferential flow paths, which may reduce the residence time available for hazard attenuation.

Carbonate mineral dissolution may also expose reactive surfaces such as sulfide minerals, and increase the potential for release of metal and metalloid species.

The source water used in a MAR scheme is unlikely to be in equilibrium with the minerals present in the storage zone. As a result, some dissolution of minerals will occur when the source water comes into contact with minerals in the aquifer. The degree of dissolution depends on the solubility of the mineral in the given conditions (eg pH, temperature, pressure, ionic strength, contact time). Mineral equilibrium can also be altered during subsurface storage by other reaction processes; for example, barium can be released by the dissolution of barite (BaSO4) in aquifer sediments, after dissolved sulfate concentrations have been reduced by bacterial sulfate reduction (Zhou and Li 1992).

Carbonate minerals can be a major influence on the quality of water recovered, because carbonate dissolution is a rapid reaction. In contrast, silicate dissolution is a very slow buffering reaction between pH 6 and 8 (Appelo and Postma 1999), and has minimal impact on water quality over the timescale of a managed aquifer recharge scheme. Dissolution of carbonate minerals will increase aquifer permeability, and the impact on the stability of injection wells and the aquitard must be considered.

Mineral dissolution can increase the salinity and hardness of the water available for recovery, and also increase minor constituents such as barium or fluoride (fluorite dissolution). Solubility controls may limit the dissolved concentration of some hazards, such as barium (barite solubility), phosphate (apatite solubility) or iron (iron oxyhydroxides or oxides), but mineral precipitation can lead to clogging concerns. The tendency for mineral dissolution or precipitation can be examined through the saturation index of a solution.

The redox state within the storage zone alters the inorganic chemistry of the recovered water. Redox reactions in MAR will often be induced by addition of source water that contains oxygen to an anoxic aquifer, or by addition of organic matter to an aquifer. Redox zones, and the resulting water quality, can vary spatially and temporally during a managed aquifer recharge operation. A highly reactive zone often develops near the point of injection or infiltration, resulting in water quality that differs from the bulk of the stored water. For example, if source water high in organic matter is used, the reactive zone can become anaerobic. This can lead to dissolution of iron (either present in the aquifer sediments or accumulated around the injection well from filtration of particulate matter in the source water) or in situ generation of hydrogen sulfide.

Changes in redox conditions and water quality can also occur:

- over time under different flow rates (eg injection or infiltration versus storage)
- where degree of saturation changes (eg wetting and drying cycles in soil aquifer treatment)
- in flow reversal during recovery in an aquifer storage and recovery operation.

Sorption to clay minerals, organic matter or iron oxide surfaces can act as an attenuation mechanism for trace metals and metalloids. However, sorption is not permanent. It can be reversed by preferential sorption of another species, or by pH–Eh-dependent changes in the surface properties that alter the number of available sorption sites. In addition, the sorption capacity of an aquifer may be limited, delaying breakthrough of the hazard to a downstream monitoring or recovery location.

Mixing is an important influence on the quality of recovered water, if the native groundwater is brackish or contains hazards that exceed target values for the specific beneficial use. Mixing of two waters can produce a solution that is more aggressive toward the aquifer minerals (Runnels 1969). If an inorganic constituent in the groundwater exceeds water quality targets, dilution may not be sufficient to ensure water quality targets are met if additional processes, such as mineral dissolution, release that species from the aquifer sediments. The effect of mixing should be considered in relation to salinity targets or operational constraints.

Metals in source water are largely in particulate form, and thus will accumulate in the subsurface, close to the point of entry (ie well face or basin floor). Accumulated metals may be removed permanently from the system by operational maintenance, such as well redevelopment or basin scraping. Some in situ dissolution may occur, producing a localised increase in soluble metal concentration. This is most likely to affect the first water recovered from an aquifer storage and recovery well.

Management of inorganic chemicals

Source control may include limiting the contribution from hazardous activities (eg catchment management, trade waste discharge agreements), and diversion of flow outside water quality criteria (eg pH, conductivity).

Pretreatment measures include:

- source water treatments (eg filtration, coagulation, flocculation)
- pH adjustment (eg prevention of manganese release from sediments) (Ibison et al 1994)
- redox control to limit reaction within the aquifer (eg limiting organic carbon in source water, deoxygenating to prevent arsenic release).

Residual risk assessment management of inorganic chemicals within the aquifer requires validation of the conceptual understanding of geochemical processes and of the preventive measures necessary to manage the human health and environmental risks. Validation monitoring (Stage 3) is necessary because the presence of trace amounts of some minerals can cause problems. Drill core and groundwater samples collected in Stage 2 cannot be relied on to detect all minerals present in the aquifer that recharged water will come into contact with.

Upon recovery and (where necessary) for high-value use, the major ions contributing to salinity can be removed. This can be achieved by post-recovery treatments such as aeration and filtration, or other techniques (individually or in combination) including oxidation, precipitation, coagulation, sorption, ion exchange, lime softening and filtration (NHMRC–NRMMC 2004).

Salinity and sodicity

The public health and environmental risks associated with salinity and sodicity (the abundance of sodium relative to calcium and magnesium) in relation to MAR include:

- salinity values exceeding the beneficial use value for total dissolved salts or sodium content
- osmotic effects on plant health and yields, due to irrigation with saline water
- rising watertables, due to leaching requirements to remove excessive salinity
- sodicity-related decline in structure of agricultural soils
- salinity effects on infrastructure and other assets (eg excessive corrosion or scaling in pipes, fittings and appliances; salt damp in stone and masonry structures).

The mixing of recharge water and ambient groundwater in MAR will cause the salinity of recovered water to differ from that of the recharge water. In general, the salinity of ambient groundwater within aquifers targeted for managed aquifer recharge should be similar to or higher than the source water (in keeping with the principles outlined in the Groundwater Protection Guidelines, ANZECC-ARMCANZ 1995). Therefore, native groundwater will represent an additional source of salinity (and sodicity) in recovered water. The environmental risks of salinity and sodicity and their effects on soil structure and agricultural production are discussed in the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006).

Sources of salt in MAR

All source waters for MAR contain natural salinity levels, derived from inorganic salts, minor amounts of dissolved organic matter and small colloidal material. The inorganic constituents of source waters may be characterised by measures such as conductivity, total dissolved salts and sodicity. Typically, the salinity of roof runoff is lower than stormwater runoff. Stormwater runoff, in turn, has lower salinity than water recycled from sewage effluent. This is because the enrichment or addition of salts from natural or anthropogenic processes in water transported through a rural or urban catchment increases its salinity levels.

Salinity levels in groundwater range from fresh to highly saline. Infiltration of shallow saline groundwater into leaky sewers can substantially increase the salinity and sodicity of sewage effluent, rendering it unfit for recycling via managed aquifer recharge unless it is treated or blended.

Management of salinity and sodicity

Management controls include preventive measures such as:

- catchment water quality management and source control (to minimise salt export and remove or mitigate point sources of salinity, where viable)
- source water selection
- site selection to target aquifers that minimise risk
- pretreatment or post-treatment (desalination)
- shandying of recovered water with alternative, lower salinity sources (shandying is the addition of one water source to another).

Nutrients: nitrogen, phosphorus and organic carbon

This section discusses nitrogen and phosphorus — recognised as environmental hazards for water recycling (NRMMC–EPHC–AHMC 2006) — and organic carbon, an important nutrient in relation to microbial processes in the subsurface.

Nitrogen and phosphorus are identified as key environmental hazards due to their potential for causing nutrient imbalance in irrigation water, soil eutrophication and toxic effects on terrestrial biota (NRMMC–EPHC–AHMC 2006). While subsurface storage is likely to reduce nutrient concentrations, the overall nutrient balance of the recovered water still needs to be considered in relation to its beneficial use. Nutrients (predominantly organic matter) in the source water will stimulate microbial activity in the subsurface. In turn, this alters the concentration of inorganic and organic chemicals in the water and affects aquifer permeability.

Sources and fate of nutrients in MAR

The level and variability of nutrient loads in source waters is largely affected by pretreatment measures. Recycled water potentially contains high nutrient loads that may vary with seasonal effects on microbial treatment processes. Nutrient concentrations in stormwater are generally likely to be lower than in recycled water, but will vary with catchment type (eg industrial areas).

Removing organic carbon and nitrogen is a passive water quality treatment provided by MAR operations (Dillon and Toze 2005). Organic matter can be removed by biodegradation, microbial assimilation, filtration, sorption or precipitation. Biodegradation occurs through redox processes that influence the mobility of inorganic chemicals and the fate of organic chemicals. Colloidal organic matter can also facilitate the transport of other chemical hazards. The amount of organic matter removed by biodegradation depends on its character; the easily biodegradable portion can be removed within days of introduction to the subsurface, while less reactive material may degrade over a longer time (Fox et al 2001). Reactive organic matter present in the sediments may also be degraded. Microbial assimilation occurs when the nutrient rich source water is introduced to the subsurface, leading to the development of a biofilm near the point of entry (ie well face or basin floor). The biofilm forms a reactive zone that can have distinct redox chemistry from the rest of the storage zone, and is largely responsible for subsurface water quality treatment. Filtration of particulate organic carbon provides an additional energy source to sustain microbial activity, and can produce soluble degradation byproducts.

Nitrogen can exist in various forms in source waters, including organic nitrogen (predominantly proteins), ammonium, nitrate, nitrite and gaseous nitrogen. The dominant nitrogen species in recycled water are organic nitrogen, ammonium and nitrate. The fate of nitrogen depends on its form and the redox conditions encountered. Under aerobic conditions, nitrification will convert ammonium to nitrate; under anaerobic conditions, ammonium can be adsorbed to mineral surfaces by ion exchange until the exchange capacity is exceeded. Nitrate can be removed by reduction to nitrogen gas (denitrification) or ammonium. In the unsaturated zone, some partitioning of ammonium to gaseous ammonia and loss through volatilisation at the air–water interface may occur.

Management of nutrients

Source control may include limiting the contribution from hazardous activities, and diverting flow when water quality indicators (eg colour and turbidity) exceed pretreatment or discharge criteria.

Pretreatment measures include:

- inline filtration on source water delivery infrastructure (for particulate organic carbon)
- biofiltration
- passive treatment through wetlands.

The effectiveness of natural treatments systems such as wetlands for nutrient removal depends on their maintenance. Monitoring is necessary to assist with managing wetland treatment systems.

Removal of subsurface organic carbon and nitrogen relies on treatment through redox processes (eg Soil Aquifer Treatment; Fox et al 2001; Amy and Drewes 2007). Validation would need to be supported by evidence of declining concentrations and physiochemical conditions. Phosphorus removal would also need evidence of declining concentrations, supported by mineralogy (iron, aluminium oxides) or mineral saturation calculations. Organic carbon can be recovered from recovered water by granular activated carbon and membrane filtration, if necessary, for high-valued use (NHMRC and NRMMC 2004). Biological clogging of recharge wells and infiltration basins and galleries should also be considered.

Organic chemicals

This section discusses trace organic compounds (often referred to as micropollutants) including:

- pesticides
- hydrocarbons
- polycyclic aromatic hydrocarbons (PAHs)
- emerging chemicals of concern
- endocrine disrupting chemicals
- personal care products

- pharmaceuticals
- flame retardants.

Trace organic compounds are predominantly anthropogenic in origin (eg PAHs are a combustion product of carbon fuels); however, some may be naturally occurring (eg algal toxins).

Organic chemicals can pose health risks (NHMRC–NRMMC 2004) and environmental risks (NRMMC–EPHC–AHMC 2006). There are numerous emerging chemicals — for example, endocrine disrupting chemicals, pharmaceuticals and personal-care products, and some disinfection byproducts (eg N-nitrosodimethylamine, NDMA) (NRMMC–EPHC–AHMC 2006). If an established water quality guideline value does not exist for a specific chemical, EPHC–NHMRC–NRMMC (2008a) provides methods for determining guideline values for any chemical with respect to drinking water uses; it also provides guidance on dealing with mixtures of chemicals.

Environmental toxicity testing may be required to provide additional information on the impacts of MAR projects on sensitive environments. Guidance on environmental toxicity testing is provided in Chapter 3 of Aquatic ecosystems of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000a).

Sources and fate of organic chemicals in MAR

Determining the presence of organic chemicals in source waters, and carrying out the associated risk assessment can be difficult, due to intermittent loadings and analytical detection capabilities for these substances. However, the origin of the source water should allow the likelihood and nature of organic chemical presence to be estimated. The effort taken to characterise organic constituents of source water must be proportionate to the risk posed to public health and the environment.

In general, subsurface storage provides a treatment step for organic chemicals (Dillon and Toze 2005). However, formation and attenuation of trihalomethanes (a group of disinfection byproducts) has been reported during storage (Pavelic et al 2005, 2006b). The potential for disinfection byproduct formation can be lowered by reducing the amount of organic matter in the source water, or altering the disinfection regime to reduce residual chlorine (Jimenez 2003).

Subsurface removal of organic chemicals can occur through volatilisation (in the unsaturated zone) and biodegradation (in the unsaturated and saturated zones). Degradation rates vary with pH, temperature, redox state and the presence of cosubstrates such as dissolved organic carbon. Sorption will also retard organic chemical movement, but the sorption removal capacity may be limited. However, sorption does provide additional residence time for degradation to occur. No allowance should be made for attenuation in the aquifer due to sorption alone for chemicals that do not degrade under the redox conditions and temperature relevant to the aquifer's storage zone.

The availability of environmental fate data for organic chemicals varies considerably. The fate of hazards such as benzene, for example, is reasonably well documented (Howard 1991); but there may be little information on emerging chemicals of concern. It is critical to ensure that existing environmental fate data was determined in a similar physiochemical environment to that expected in the MAR scheme under consideration. In the absence of relevant field data, laboratory studies can predict the fate of the hazard under the expected conditions (Oliver et al 1996, Ying et al 2003).

If the storage zone is an unconfined aquifer, organic chemicals may be present from point sources (eg industrial activities) and diffuse sources (eg pesticide use). Mixing between the source and native groundwater may therefore affect the recovered water quality.

Management of organic chemicals

Source control may include limiting the contribution from hazardous activities to trade waste or stormwater discharge, and improving hazard management for high risk activities in order to reduce source concentrations or prevent against shock loadings from spills.

Pretreatment and post-treatment measures include biofiltration, passive treatment through wetlands and advanced tertiary treatment, such as membrane filtration.

Reliance on attenuation of organic chemicals in the aquifer requires validation of the reduced concentration with time and distance, supported by details of the residence time in the aquifer and its physicochemical and redox conditions.

Indicators may be selected for monitoring to focus effort on species that will give the most sensitive indicator of effective system performance (Drewes et al 2008).

Turbidity and particulates

The public health and environmental risks associated with turbidity in relation to managed aquifer recharge include:

- recovered water having turbidity in excess of drinking water guidelines (where drinking is an intended end use) which if not removed, can impact on pumps and irrigation infrastructure

- reduced disinfection performance, leading to increased risk from microbial pathogens
- increased risk of transporting a range of contaminants that can sorb to particles
  - heavy metals
  - phosphorus
  - various organics
  - microbial pathogens
- discharge of backwash water during redevelopment (backwashing) of injection wells, impacting on the stormwater catchment downstream.

Sources of turbidity in MAR

All source waters for managed aquifer recharge contain natural levels of particulates — measured as turbidity or suspended solids — derived from inorganic silt, clay-sized particulates and organic matter. Stormwater runoff usually contains highly variable turbidity levels, as a result of factors related to climate, catchment geomorphology, and land use and management. Secondary or tertiary treated sewage effluent typically contains lower concentrations of particulates, and a higher organic content, than stormwater. Roof runoff is typically low in particulate matter, but can be high due to deposition of vegetation debris or poor management. Groundwater turbidity levels are generally low, but can be high in wells that are inappropriately designed or inadequately developed.

Managed aquifer recharge practices can generate particulate hazards as a result of mineral dissolution and particle remobilisation within the soil or aquifer, and through the standard practice of backwashing injection wells to maintain recharge rates.

Management of turbidity

Turbidity management controls include preventive measures such as:

- source selection
- catchment water quality management and source control to
- minimise particulate export
- remove or mitigate point sources of turbidity (where viable)
- pretreatment or post-treatment before recharge through
- settling tanks
- wetlands
- coagulation
- filtration.

Radionuclides

Radioactive materials (eg uranium, thorium, potassium-40) occur naturally in the environment, and risk of human exposure to radiation is predominantly from natural sources. Additional exposure can occur through anthropogenic activities such as medical (radiopharmaceuticals) and industrial use of radioactive materials.

The main radionuclide concern is recovery of water posing a risk to human health by ingestion of drinking water or foods via crop irrigation, stock watering, or food chain accumulation (radium and radon), or inhalation of gas released from the water supply (radon).

Radioactivity is measured in becquerel (Bq), where 1 Bq= 1 disintegration per second. Health considerations are based on the effective dose of radiation, measured in sievert (Sv), which takes into account the equivalent dose received by all tissues or organs, weighted to account for their different sensitivities to radiation. The acceptable radiation dose via the ingestion of water should be <1 mSv/year (NHMRC–NRMMC 2004). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 from the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004).

Sources of radionuclides in MAR

Recycled water or stormwater may contain radionuclides if they receive water from medical and industrial uses. Groundwater may contain naturally occurring radium and radon isotopes (radium 226, radium 228 and radon 222). Mining activities may also concentrate naturally occurring radionuclides (eg processing mineral sands, producing phosphate fertiliser).

The major source of radionuclides in MAR will usually be from the interaction of stored water with the aquifer matrix during aquifer storage. Native groundwater radioactivity is a useful indicator of the minimum level of radiation in the recovered water. Natural concentrations of radionuclides vary considerably, and depend on the properties of the aquifer, which are (Dillon and Toze 2005):

- geology
- porosity
- grain size
- redox state
- major ion chemistry.

In general, high radionuclide concentrations are found in granitic fractured rock (crystalline) aquifers and near rich organic coal deposits (Herczeg and Dighton 1998). Leaching of uranium from carbonate aquifers has also been reported (Williams et al 2002).

Radon concentrations in recovered water and the native groundwater before managed aquifer recharge will be similar, because equilibrium between radon in the aquifer material and the source water is reached in less than three weeks (Dillon and Toze 2005).

Iron or manganese oxyhydroxides can adsorb substantial amounts of radium. Thus radium concentrations can increase through a MAR scheme if oxidation of organic matter leads to dissolution of these iron or manganese oxyhydroxide surfaces. Radium concentrations can also increase through the dissolution of radium-bearing minerals such as phosphates (Dillon and Toze 2005).

Management of radionuclides

The radioactivity of native groundwater in the storage zone can be screened by measuring gross alpha and beta activity (excluding potassium-40), followed by analysis of individual radionuclides, if the gross alpha or beta exceeds the target value (NHMRC–NRMMC 2004).

If the target aquifer is a potential source of radium, geochemical modelling is warranted to evaluate the potential for additional release through mineral dissolution or oxidation of organic rich deposits. Modelling would also define acceptable values for pH, oxygen, nitrate and organic carbon within the source water, to minimise the potential for geochemical reactions that could release radium during aquifer storage.

Potential pretreatment and post-treatment includes aeration for radon-222, and lime softening, ion exchange or reverse osmosis for radium-226 and radium-228 (NHMRC–NRMMC 2004).

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APPENDIX 1

Entry-level risk assessment —degree of difficulty

	Information required for assessment	Questions and indicators of degree of difficulty
1	**Source water quality with respect to groundwater environmental values**	
	• Where multiple samples are available, the highest concentration of each analyte should be used in the evaluation; unless there is justification that events resulting in those values will be prevented when the MAR project is established • Alternatively, in the absence of water quality data from actual source water, data may be used from existing similar MAR projects using the same type of source water and recharging the same aquifer • In the absence of either data source above, generic data from AGWR guidelines may be used: • for stormwater; the Phase 2 guidelines (EPHC–NHMRC–NRMMCb, in progress) gives generic data on concentrations of selected hazards in stormwater from roof catchments (Table 5.1) and urban catchments (Table 5.2). In the absence of other information, use 95 percentile data • for reclaimed water; maximum concentrations detected in secondary treated sewage may be used as a starting point and the Phase 1 guidelines (NRMMC–EPHC–AHMC 2006) gives generic data (Table 4.10). These data range from sewage that has been treated in water reclamation plants (min value) to raw secondary treated effluent (max value) • Assessment of quality variability and factors affecting quality are deferred to the maximal risk assessment	Q1. Does source water meet the water quality requirements for the environmental value of ambient groundwater? (Note: environmental values of water are listed in Table A1.1 along with a reference to water quality criteria for each) If Yes — low risk of pollution is expected. This is a necessary condition, but not a sufficient condition for low risk. If **No** — high maximal risk is likely. Expect Stage 2 investigations to assess preventive measures to reduce risk of groundwater contamination beyond attenuation zone (and size of attenuation zone).

	Information required for assessment	Questions and indicators of degree of difficulty
2	**Source water quality with respect to recovered water end use environmental values**	
	• If the source water does not meet the water quality requirements for the environmental values of intended end uses of recovered water, then there is a reliance on attenuation of hazards within the subsurface	Q2. Does source water meet the water quality requirements for the environmental values of intended end uses of water on recovery? If Yes — low risk of pollution of recovered water is expected. However, this is not a sufficient condition for low risk due to aquifer reactions. If **No** — high maximal risk is likely. Expect Stage 2 investigations to assess this risk.
3	**Source water quality with respect to clogging**	
	• Where source water quality is poor and soil or aquifer are fine-grained, clogging of the infiltration basin and gallery or recharge well is likely to occur, unless the water is pretreated before recharge • Clogging is most prevalent when water contains moderate or high levels of suspended solids or nutrients, such as nitrogen or labile organic carbon • Clogging can also occur when oxygenated water is introduced into an aquifer that contains iron. If the soil or aquifer are coarse grained or contain macropores, clogging with such waters is less likely, but the risk of pollution of groundwater is high (as covered in Q1 and Q2) • Lack of evidence of clogging is insufficient to indicate that risk of pollution is low, even in fine-grained media.	Q3. Does source water have low quality, for example: • total suspended solids >10 mg/L • total organic carbon >10 mg/L • total nitrogen >10 mg/L? And is soil or aquifer free of macropores? If **Yes** — high risk of clogging of infiltration facilities or recharge wells. Pretreatment will need consideration regardless of answers to Q1 and Q2. If No — lower risk of clogging is expected. However, this is not a sufficient condition for low risk, due to dependence of clogging on aquifer characteristics that would be revealed by stage 2 investigations.
4	**Groundwater quality with respect to recovered water end use environmental values**	
	• Where samples are available, the highest parameters detected in each sample should be used in the analysis; unless there is justification that events resulting in those values will be prevented when the MAR project is established • Alternatively, in the absence of data on groundwater quality from the proposed site, data from nearby wells in the same aquifer may be used	Q4. Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery? If Yes — low risk of inadequate recovery efficiency is expected. If **No** — some risk of inadequate recovery efficiency is expected. See Table A1.2 for degree of difficulty expected.

	Information required for assessment	Questions and indicators of degree of difficulty
5	**Groundwater and drinking water quality**	
	• The environmental values of the aquifer need to be defined by the relevant authority. These will depend on the ambient groundwater quality and any groundwater-affected ecosystems, and as identified in the NWQMS *Groundwater Protection Guidelines* (ANZECC–ARMCANZ 1995) • Setting these values involves a stakeholder consultation process, and in practice will possibly be related to groundwater allocation planning processes • In the event of an absence of defined environmental values (for entry-level assessment purposes), all environmental values that are met by the native groundwater quality need to be protected. Such environmental values may include: • raw water for drinking supplies • irrigation • aquaculture, recreation or livestock water • support of aquatic ecosystems with various conservation values • The water quality requirements for these environmental values are referenced in Table A1.1.	Q5. Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer? If **Yes** — high risk of groundwater pollution if recharged by water if answer to Q2 is No. If No — low risk of groundwater pollution is expected. However, this is not a sufficient condition for low risk. For a broader view on this topic for the spectrum of environmental values, see Table A1.2.
6	**Groundwater salinity and recovery efficiency**	
	• If native groundwater has high salinity, its proportion that can be present as a mixture with source water in recovered water is limited • At such sites, density affected flow may also occur. Fresh recharge water can form a lens above the native saline groundwater, making recovery difficult and reducing recovery efficiency (ie the volume of recovered water meeting the environmental values for its intended uses as a proportion of the volume of recharged water)	Q6. Does the salinity of native groundwater exceed (a) 10 000 mg/L or (b) the salinity criterion for uses of recovered water? If **Yes** to both — high risk of achieving only low recovery efficiency. Aquifer hydraulic characteristics, especially layering within the aquifer will need careful examination in Stage 2. If Yes to only (b) — moderate risk of low recovery efficiency is expected. However, this is not a sufficient condition for low risk (eg in brackish aquifers with high rates of ambient lateral flow). If No to both — low risk of low recovery efficiency.

	Information required for assessment	Questions and indicators of degree of difficulty
7	**Reactions between source water and aquifer**	
	• Reactions between source water and aquifer minerals may result in deterioration of water quality for recovered water, and possibly for water in the aquifer beyond the attenuation zone; or cause excessive clogging or dissolution of the aquifer • A full evaluation may be undertaken in Stage 2, but a simple indicator of the likelihood of potential problems at entry-level stage is to note the extent of contrasts between quality of source water and native groundwater	Q7. Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water? If Yes — low risk of adverse reactions between source water and aquifer is expected. However, this is not a sufficient condition for low risk. If **No** — high risk of adverse reactions between source water and the aquifer is possible, and will warrant geochemical modelling in Stage 2 (refer to sections 5.2, 5.4 and 6.1).
8	**Proximity of nearest existing groundwater users , connected ecosystems and property boundaries**	
	• Proximity of nearest existing groundwater users and groundwater-connected ecosystems is likely to influence the extent of investigations required in Stage 2 • Typically, attenuation zones will have aquifer residence times of up to a year • If property boundaries are close to the MAR site, then the attenuation zone may extend beneath a neighbouring property • Groundwater pressure effects in confined aquifers due to MAR may propagate over considerably longer distances than water quality effects	Q8. Are there other groundwater users, groundwater–connected ecosytems or a property boundary near (within 100–1000 m) the MAR site? If **Yes** — high risk of impacts on users or ecosystems is possible, and this will warrant attention in Stage 2. If No — low risk of impacts on users or ecosystems is likely. However, this is not a sufficient condition for low risk.

	Information required for assessment	Questions and indicators of degree of difficulty
9.	**Aquifer capacity and groundwater levels**	
	• Groundwater mound height induced by MAR depends on aquifer hydraulic properties, size of recharge area and recharge rate • Mounding is normally calculated in Stage 2 when aquifer properties are measured. However, excessive mounding can cause: • waterlogging • soil heave • flooding of below-ground infrastructure • salt damp • soil salinisation • Hence, unconfined aquifers with shallow watertable sites are generally unsuitable as storage targets for large-scale recharge projects • For confined artesian aquifers, care needs to be taken against overpressurisation, and to seal existing wells that might otherwise start to flow	Q9. Is the aquifer confined and not artesian? or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas? In either case: If Yes — low risk of water logging or excessive groundwater mound height is expected. However, this is neither a necessary nor a sufficient condition for low risk. If **No** — high risk of water logging or excessive groundwater mound height is expected. However, Stage 2 investigations may reveal that risk is acceptable.
10	**Protection of water quality in unconfined aquifers**	
	• If the aquifer is unconfined and the intended recovery is for drinking water supplies, then overlying land and waste disposal (including intensive horticulture and septic tanks) should be managed carefully or precluded from the groundwater capture zone	Q10. Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies? If **Yes** — high risk of groundwater contamination from land and waste management. If No — lower risk of groundwater contamination from land and waste management.

	Information required for assessment	Questions and indicators of degree of difficulty
11	**Fractured rock, karstic or reactive aquifers**	
	• If the aquifer is fractured rock or karstic, the ability to recover stored water will require evaluation, especially if the ambient groundwater is saline, or hydraulic gradient is steep • Provision will also need to be made for a larger attenuation zone, due to more rapid migration of recharge water from the recharge area	Q11. Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals? If **Yes** — high risk of migration of recharge water is expected. There is a need for an enlarged attenuation zone, beyond which pre-existing environmental values of the aquifer are to be met. Dissolution of aquifer matrix and potential for mobilisation of metals warrant investigation in Stage 2. If No — low risk of the above is expected. However, this is not a sufficient condition for low risk.
12	**Similarity to successful projects**	
	• A founding principle of MAR is that all validation and verification monitoring data should be in the public domain, and include sufficient operational data to enable accurate interpretation • This information is of value for future MAR projects, for improving design and operation and reducing costs and further refinement of these guidelines • A national or state repository for these data should be accessible for proponents	Q12. Has another project in the same aquifer with similar source water been operating successfully for at least 12 months? If Yes — take validation and verification data from the existing project(s) into account when designing the current project and the Stage 2 investigations and subsequent risk assessments. If **No** — expect that all uncertainties will need to be addressed in the Stage 2 investigations.

	Information required for assessment	Questions and indicators of degree of difficulty
z	**Management capability**	
	• A proponent new to MAR operation needs to gain appropriate expertise in parallel with Stage 2 investigations, to demonstrate a low level of residual risk for the precommissioning risk assessment.	Q13. Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty (see Table A1.2), or with water treatment or water supply operations involving a structured approach to water quality risk management? If Yes — low risk of water quality failure due to operator experience. If **No** — high risk of water quality failure due to operator inexperience. The proponent is recommended to gain instruction in operating such systems (eg a MAR operator's course or aquifer storage and recovery course) or engage a suitable manager committed to effective risk management in parallel with Stage 2, to reduce precommissioning residual risks to low.
14	**Planning and related requirements**	
	• Proximity of nearest neighbour • Provision for safe public access or exclusion • Dimensions and slopes of water holding structures • Location and dimensions and design of any buildings or engineering structures, • Method by which power will be brought to site and water connections • Nuisance insect abundance before and after construction and proposed control measures • Noise emissions of any mechanical plant and abatement measures • Earthmoving and construction plans and measures for dust and noise control • Provision of information to neighbours concerning the development • Information to address other provisions of planning and development regulations within the relevant jurisdiction •	Q14: Does the proposed project require development approval; is it in a built up area; built on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health or safety issues (eg falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (eg from waste products of treatment processes)? If Yes – Development approval process will require that each potential issue is assessed and managed. This may require additional information and steps in design. If No – Process for development approval, if required, is likely to be considerably simpler.

MAR = managed aquifer recharge

Assessment of impact of MAR structures by hydrogeological methods

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Abstract. Managed aquifer recharge (MAR) is commonly used in India and elsewhere. Quantitative and qualitative impact of the MAR structure can be investigated by an appropriate set of hydrogeological methods. Field measurements and observations are the essential basis for any further empirical based study and require careful planning and accurate conduction on site. This text tries to give an overview of methods/techniques and highlights tips and tricks during field work. In the second part, examples from a check dam site in Tamil Nadu are given.

Introduction to hydrogeological methods

Managed aquifer recharge (MAR) comprises a wide range of technical structures of different purposes (Dillon 2005). One common feature of many MAR structures is the infiltration/injection/percolation of surface water into an aquifer. Therefore, estimation of water fluxes between surface- and groundwater is an important key to understand the impact of MAR structures. A methodological overview with a short description of each method along with advantages and disadvantages is given in table 1. It is clear that several other methods exist and this overview is certainly not complete, but it tries to highlight the most important methods and techniques.

After a brief description of selected methods from table 1, water sampling techniques will be discussed. Water sampling, either from surfacewater or groundwater is the basis for any qualitative study. Standard methods for water sampling and techniques will be presented and discussed. Additionally, tips and tricks for field sampling and field observations will be given.

Check dam is one MAR structure which is being constructed across the non perennial rivers and it is one of the suitable methods for unconfined aquifers. Various hydrological measurements will be helpful to evaluate the efficacy of check dam to understand the improvement on water level and water quality. Many research work is been carried out by using hydrological measurements such as water level measurements, water quality parameters and isotopic analysis.

Table 7 Summary of methods and techniques for estimating water fluxes between surface- and groundwater

Method		Brief description	Advantage	Disadvantage	Literature examples
Watershed-Scale Rainfall-Runoff Models	Analytical	baseflow determination by hydrograph separation, gives integrated value for flow between stream and groundwater	good for small streams	in large streams the error in discharge measurement often greater than surface-/groundwater interactions	Herbert and Thomas 1992; Kaleris 1998; Rutledge 2000
	Numerical	relates precipitation, groundwater recharge and baseflow to temporal variability of flow in a stream	detailed determination of temporal and spatial variability of SW/GW interactions	large datasets required	Beven and Feyen 2002
Stream Discharge Measurements		comparison of discharge measurements between upstream and downstream at a specific stream reach	integrated value for flow between a stream and ground water along a specific stream reach	only for small streams, net exchange of water through streambed must be greater than the cumulative error in streamflow measurements	Oberg and others 2005
Groundwater modelling		Simulation of SW/GW fluxes by calibration with hydraulic heads and tracers	determination of temporal and spatial variability of SW/GW interactions	large datasets required	Anderson and Woessner 1992
Wells and flow net analysis		based on Darcy or Dupuit equation, direct measurement of hydraulic properties	relatively easy to use	boundary conditions in nature often too complex	Davis and DeWiest 1991, Rushton 2003
(Environmental) Tracer tests		tracers added to water or environmental tracers i.e. stable isotopes, radon/radium isotopes, temperature	huge number of tracers exist, each with advantages and disadvantage, indicate the direction and rate of water movement, travel time, residence time		Mattle et al. 2001, Sprenger et al 2012
Seepage meter		isolation of small areas (0.5 - 1.5 m^2) at the streambed with a seepage cylinder connected to a water filled bag	direct measurement of water flux	only suitable for low flow and shallow water	Rosenberry and LaBaugh 2008

SW = Surfacewater; GW = Groundwater

1.1 Calculating evaporation losses due to evaporative enrichment

Fractionation caused by evaporation can be considered as a non-equilibrium process (Dansgaard 1964). Gonfiantini 1986 describes the kinetic fractionation in relation to humidity with the following equations:

$$\varepsilon\ ^{18}O_{kinetic} = 14.2\ (1-h)\ \ (\times 10^3‰)$$

$$\varepsilon\ ^{2}H_{kinetic} = 12.5\ (1-h)\ \ (\times 10^3‰)$$

where h is the humidity (100% = 1). The total fractionation between the water body and the open air is then the sum of the fractionation factor for equilibrium water-vapour exchange ($\varepsilon_{\ equilibrium}$) and the kinetic factor ($\varepsilon_{\ kinetic}$). For $\delta^{18}O$ according to:

$$\delta^{18}O_l - \delta^{18}O_v = \varepsilon^{18}O_{equilibrium} + \varepsilon^{18}O_{kinetic} = \varepsilon^{18}O_{total}$$

The indices l and v are for liquid and vapour, respectively. Since atmospheric water forms under about 85 % humidity a displacement of the evaporation line towards a d-excess (or intercept) is observable. If now evaporation rates are high due to high temperatures and low relative humidity in the atmosphere at the initial formation of water vapour, a strong kinetic effect takes place. Evaporation rates were calculated, according to a Rayleigh enrichment, in relation to temperature and humidity and plotted in $\delta^{18}O$ vs. δD diagrams (Fig.2.5), according to

$$\delta = \delta_o + \Delta\varepsilon_{total} * \ln(f)$$

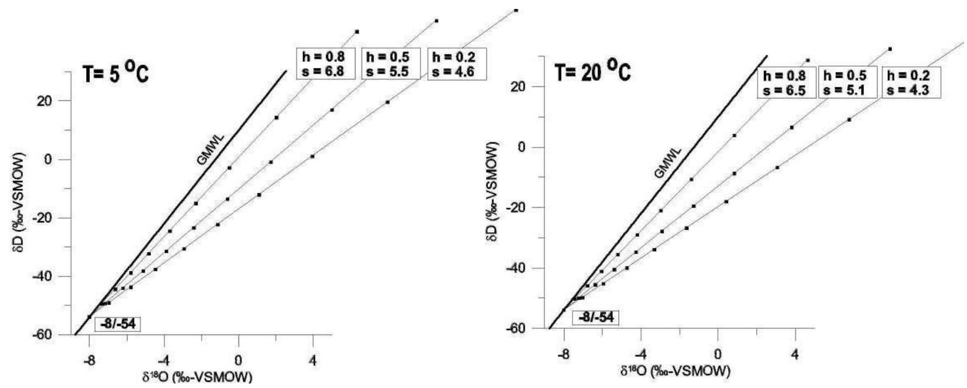

Fig.4 Differences in evaporation rates in relation to humidity (h) in a $\delta^{18}O$ vs. δD (‰-VSMOW) diagram for 5°C and 20°C showing the predominating exchange fractionation process at values for f from 1 to 0.1. (s = slope of evaporation line)

where δ_0 is the initial value (here $\delta^{18}O$= -8 ‰; δD= -54 ‰) and δ is the resulting value. The resulting graphs (**Fig.4**) are useful to estimate the conditions during evaporation and the proportion of fractionation with factors *f* from 1 to 0.1. According to the above mentioned equations strong kinetic fractionation, due to low humidity (h = 0.2) and high temperatures (T = 20 °C), result in more shallow slopes around 4.3. Higher humidity (h = 0.8) and lower temperatures (T = 5 °C) results in evaporation lines which are closer to the GMWL and have slopes around 6.8.

1.0 Assessment of check dam at the Aranyar River in Tamil Nadu

Chennnai basin is spread across Thruvallur, Kancheepuram and Vellore districts of Tamil Nadu. Araniar, Kosasthalaiyar, Cooum and Adyar are the four important rivers draining the basin. The city also gets its groundwater supply from well fields in the Araniyar-Koratlaiyar (A-K) basin and southern coastal aquifer. Though contribution of groundwater is very less, this quantity of groundwater is given greater importance during lean period. Fast rate of depletion of groundwater level in A-K basin is due to the continuous pumping of groundwater for city's water supply, extraction of groundwater by farmers and insufficient water management. Hence, in order to maintain the yield of the aquifers and to supply assured water supply to the city as well as native community certain long-term water management measures such as construction of check dam across A-K rivers have proposed by the Government to augment the groundwater resources. One such check dam constructed across Arani river is considered for the present study. This check dam is of 260m length with the crest height of 3.5m used to store 0.8 Million cubic meter of water is constructed across Arani River near Paleshwaram village. Assessment of impact of MAR by using the water level measurements, electrical conductivity and chloride/stable isotope measurements discussed in the following sections.

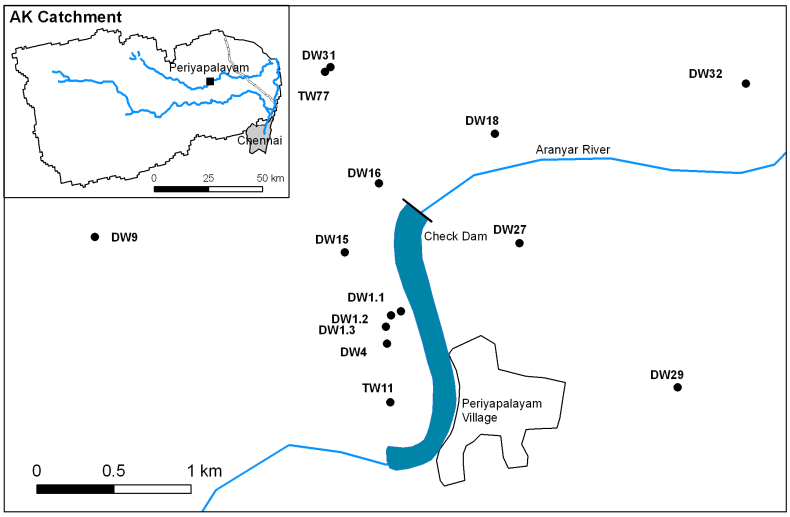

Fig. 5 Location map of check dam close to the Periyapalayam village and sampling stations. (DW = dug well, TW = tube well)

1.1 Groundwater levels

Groundwater level measurement is a good indicator to identify the efficacy of MAR structures. Groundwater fluctuation for a particular year is depended upon the amount of groundwater recharge, which in turn depends on, among other parameters, rainfall. Fig.2 shows water levels during middle of July 2010 (before the construction of check dam). This fluctuation is due to the result of rainfall of 483mm occurred in May to July 2010. Mid of July is the end of the lean period, during which most of the wells in the study area are dry. Fig.1 shows the cross section of the water level fluctuation. Minimum and maximum water levels observed in this cross section varies from 13.8m to 15.8m above mean sea level (MSL). Water level measured during mid of July 2011 (After the construction of check dam) is shown in Fig.2, this fluctuation is due to the result of 267 mm rainfall occurred in May to July 2011 and recharge by check dam. It is observed that, the rainfall occurred in

May to July 2010 (before construction of check dam) is 483mm and is about 50% higher than the rainfall occurred in May to July 2011. Even though the amount of rainfall in May to July 2011 is less than that of the previous year, there is considerable increase in groundwater level as can be observed from figure 2. It can be concluded that the higher water level in 2011 is due to recharge by the check dam. The highest water level of 17m is measured near the check dam and the wells located near the check dam were not dry in July 2011. Further, this study area is located in the agricultural area and similar pattern of agricultural activities are practicied, hence increase or decrease in groundwater level due to abstraction and irrigation return flow will be almost the same for all years.

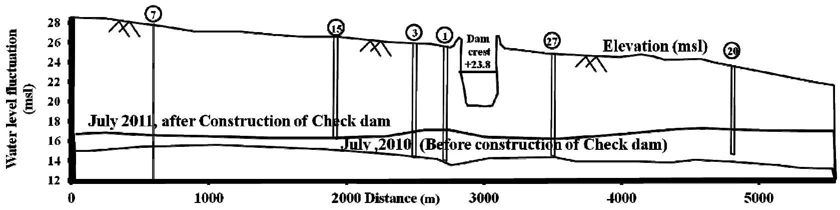

Fig.6 Water level fluctuations before and after construction of check dam

1.2 Electrical conductivity measurement

Electrical conductivity is one of the field measurements used to identify the efficacy of the check dam. In the present study, the measurement on electrical conductivity is made between July 2010 to July 2011. Fig. 2 shows the variation in minimum and maximum electrical conductivity values with respect to distance from the check dam.

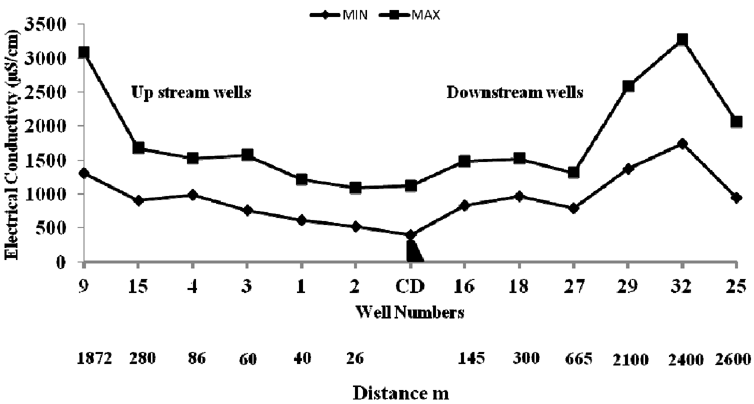

Fig.7 Minimum and maximum electrical conductivity of water samples

Electrical conductivity values in the check dam varied from 400µS/cm to 1117 µS/cm. Electrical conductivity values of groundwater samples varied from 514 µS/cm to 3270 µS/cm. Electrical conductivity values gradually increases as the distance of wells increases from the check dam. The wells located within 60m in the upstream of the check dam and the wells located 665m in the downstream of the check dam are highly benefitted by the recharge from check dam. The electrical conductivity values of the wells located within distances are having similar electrical conductivity values of the water in the check dam.

1.3 Evaporation from check dam water

The surface water samples from the Periyapalayam check dam show, as expected under the climatic conditions, an evaporative enrichment with time (Fig.8). At the beginning of the monsoon November 2011 isotope values are on the LMWL with -3.7‰/-18.6‰ and the following samples show a successive enrichment with a composition of -0.19‰/-1.2‰ in March 2012 leading to overall enrichment in $\delta^{18}O$ of 3.51‰. Regression line calculated with the 5 samples is $\delta D = 4.8 \times \delta^{18}O - 1$, the slope of 4.8 is very typical for evaporation from open water bodies. The evaporative enrichment can be calculated with the equations given in the methods section. Mean annual temperature is 28.6°C, humidity during Oct – Nov- Dec – Jan – Feb – Mar approx. 0.5 resulting in 20% losses by evaporation in March 2012.

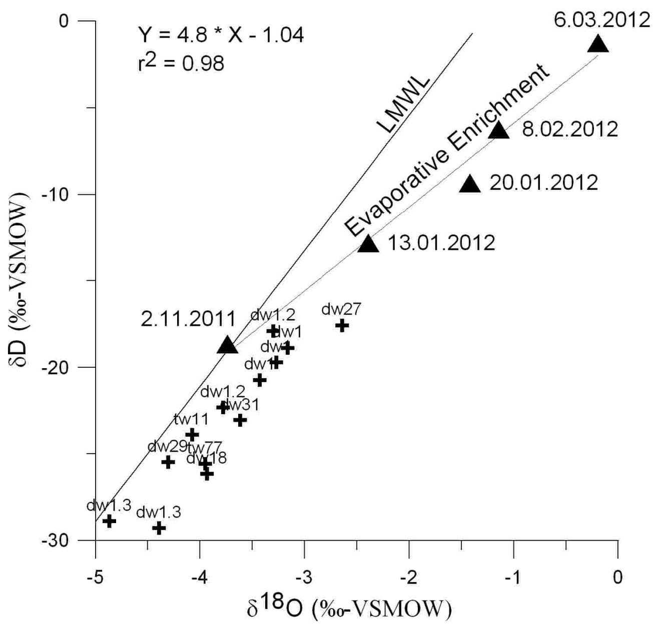

Fig.8 $\delta^{18}O$ against δD plot of surface water from the check dam and groundwater.

1.4 Chloride and stable isotopes as tracers

Chloride and stable isotopes of water ($\delta^{18}O$, δD) are used as tracers to indicate recharge and mixing of ambient groundwater (not influenced by the check dam) with recharge water from the check dam. Isotopic composition and chloride concentration of surface water from the check dam and groundwater is shown in Fig.9. Surface water from the check dam is characterised by low chloride concentration (<120 mg/l) and enriched isotopic composition. Isotopic composition of the surface water shows increasing evaporative enrichment with time as discussed in the earlier section. Ambient groundwater is characterised by high chloride concentrations (80 – 600 mg/l) and depleted isotopic composition. Samples of groundwater which is influenced by check dam infiltration can be found in between the composition of ambient groundwater and the recharge water composition (Fig.9). Mixing of ambient groundwater with recharge water takes place with water from the beginning of the recharge period between November 2011 and January 2012. It can be concluded that recharge is limited or absent during February to March 2012.

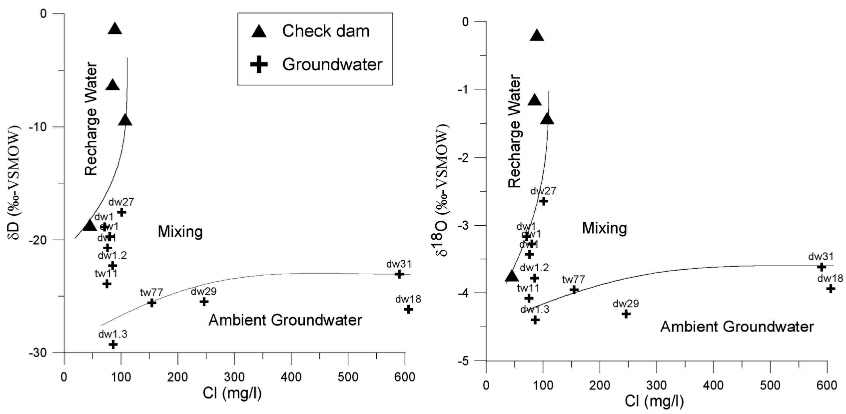

Fig.9 Chloride and stable isotopes of water ($\delta^{18}O$, δD) in check dam (Recharge water) and groundwater.

2.0 Conclusions

- water levels measured before (June 2010) and after (June 2011) the construction of the check dam show an increasing water table despite of less rain in 2011 compared to 2010
- Electrical conductivity of surface water in check dam and groundwater indicate the positive impact of check dam recharge on groundwater quality
- Losses due to evaporation from the check dam water are indicated by the evaporative enrichment of stable isotopes
- Main recharge period of the check dam is from November to January

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Integrated modeling for assessment of impact of MAR structures

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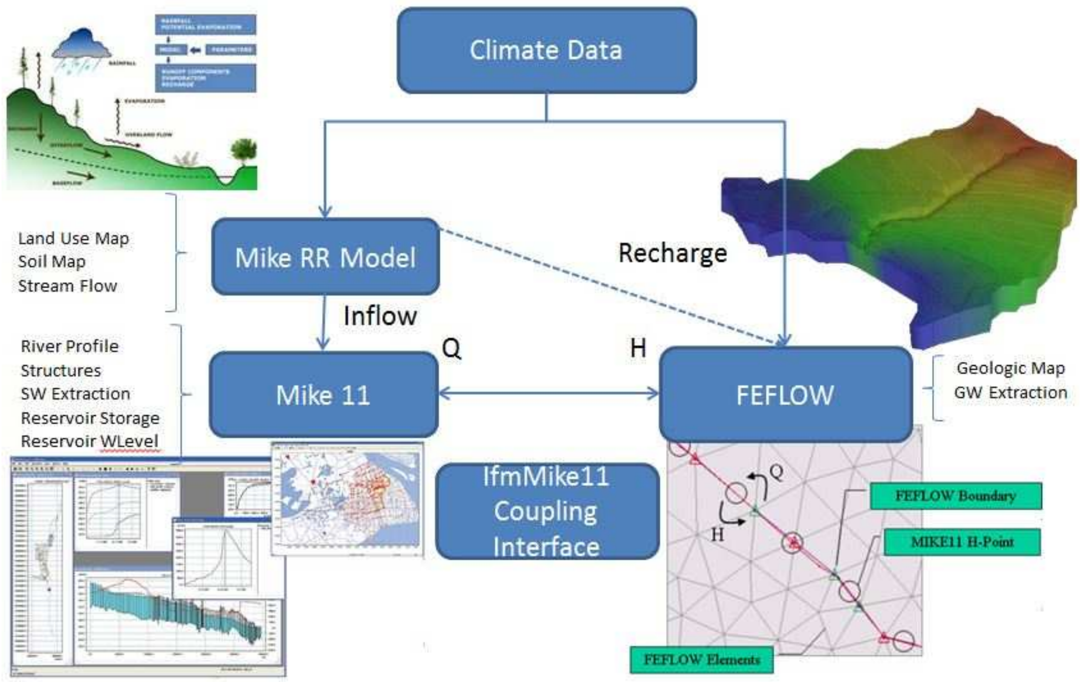

Introduction

In this workshop document a brief introduction to a modeling approach for an impact assessment of MAR structures to counteract saltwater intrusion problems is provided. This approach is based on the software products FEFLOW (groundwater) and MIKE11 (surface water). As FEFLOW is the main component a short description of this software is given in the next section. After that the basic coupling concept, a short overview of the theoretical background of density dependent modeling as well as a basic example are described.

Groundwater Model FEFLOW

DHI-WASY as a daughter of DHI is also responsible for the development of the groundwater model FEFLOW. FEFLOW provides an advanced 3D graphically based modeling environment for performing complex groundwater flow, contaminant transport, and heat transport modeling. Regarding contaminant transport both multiple species as well as kinetic reactions between the species can be modeled. Both saturated and unsaturated flow regimes can be modeled. It uses a Galerkin-based finite element numerical analysis approach with a selection of different numerical solvers and tools for controlling and optimizing the solution process.

FEFLOW is a completely integrated system from simulation engine to graphical user interface including also a public programming interface for user code. FEFLOW is widely recognized as the most complete software package for subsurface porous media simulation and is used by leading research institutes, universities, consulting firms and government organizations all over the world. Its scope of application ranges from simple local-scale to complex large-scale simulations.

Special features like chemical reactions and particularly salt water interaction areimportant for the project under consideration.

Furthermore, FEFLOW offers an integrated Interface Manager (IFM) which allows for external interaction with other source code. In this way new modules can be provided and important coupling routines to other modeling software can be implemented.

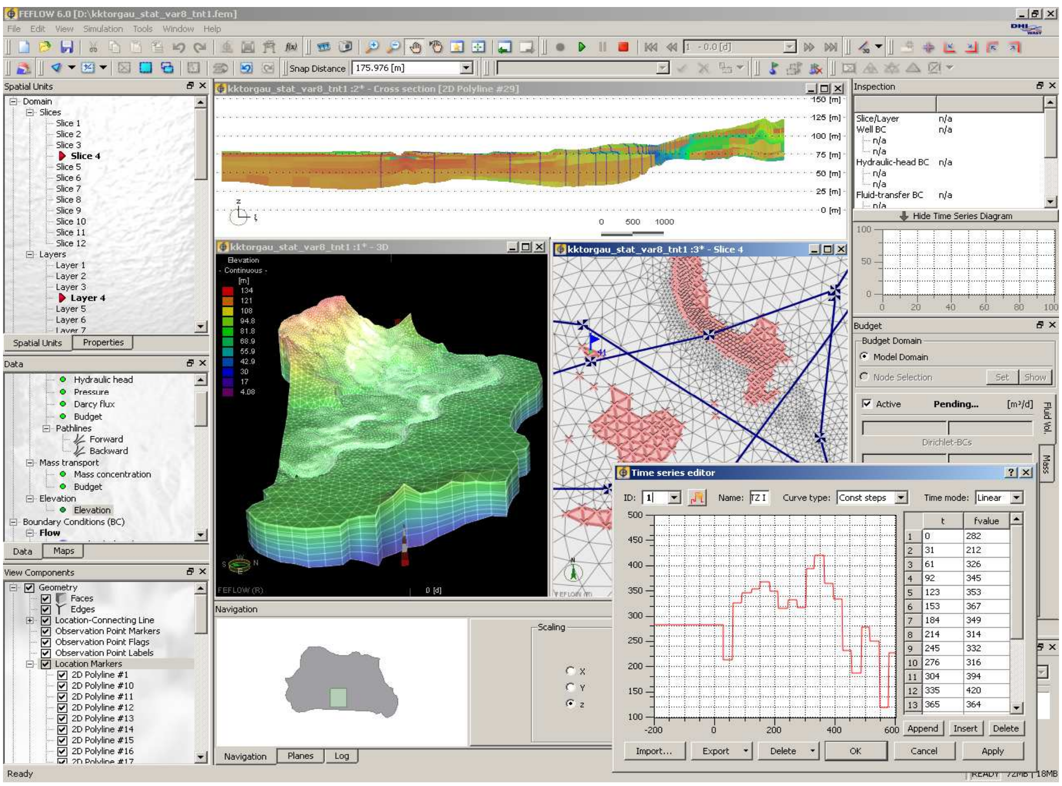

Fig. 1: FEFLOW Example

Coupling concept

Since 2005 the coupling interface IfmMIKE11 has been available. The interface module couples FEFLOW to MIKE11 (DHI 2010, 1D hydrodynamic model) using the FEFLOW InterFace Manager (IFM). From 2006 to 2009, the coupling module was successfully extended for the coupling of polder areas and forelands (Monninkhoff & Li, 2009; Monninkhoff & Kaden, 2007).

Quantity modeling

In FEFLOW rivers can be described by boundaries of the 1st kind (Dirichlet-type) or boundaries of the 3rd kind (Cauchy-type). The latter boundary type is the only type supported by the coupling module IfmMIKE11. At the end of each FEFLOW time step the discharges to these FEFLOW boundary nodes are calculated by the module within FEFLOW. The resulting values are transferred to the MIKE11 calculation points (h-points) as single point source inflow boundary conditions. Then, MIKE11 calculates as many internal time steps as needed to reach the actual time of FEFLOW. This process is ended by transferring the calculated water levels at the end of the FEFLOW time step from the MIKE11 h-points to the FEFLOW boundary nodes. The internal time step of MIKE11 is controlled by the interface. This time step can be constant or adaptive to the dynamics of the model. The time step of the groundwater model is controlled by FEFLOW. The spatial overlay of both meshes is automatically integrated within IfmMIKE11. The exchange discharges (Q) between the ground- and surface water can be calculated within FEFLOW for each single boundary node of the 3rd kind separately. The main parameter to control this discharge is an elemental parameter called transfer coefficient [d^{-1}]:

$$Q = \phi_h A(h_{ref} - h_{gw})$$

In which:

- Q Discharge [m^3d^{-1}] of fluid (positive from river to groundwater),
- A nodal representative exchange area [m^2] of the boundary node and
- h_{ref}, h_{gw} heads [m] in the river and groundwater respectively.

The nodal representative exchange area depends on the finite-element stratigraphy within the model in FEFLOW. Moreover, the stratigraphy is subject to changes using the free and movable option in FEFLOW. In that case, the top slice of a 3D model is located exactly on the position of the head of the first slice and all remaining slices are moved accordingly. To avoid an uncontrolled and unrealistic exchange area in this case, an additional boundary option has been implemented. Using these integral boundary conditions the exchange area of the boundary nodes is determined only once just before the simulation is started. Nevertheless, in most cases, the exact exchange area between the river and the groundwater cannot be described by the stratigraphy of the mesh.

From the stratigraphy point of view, rivers can be defined in FEFLOW by a typical vertical (also areal) or horizontal (or lateral) infiltration scheme. In the first case boundary nodes are only set to the 1st slice of the FEFLOW model and in the latter case boundary conditions are located in more than one slice but within a single slice only as a line element.

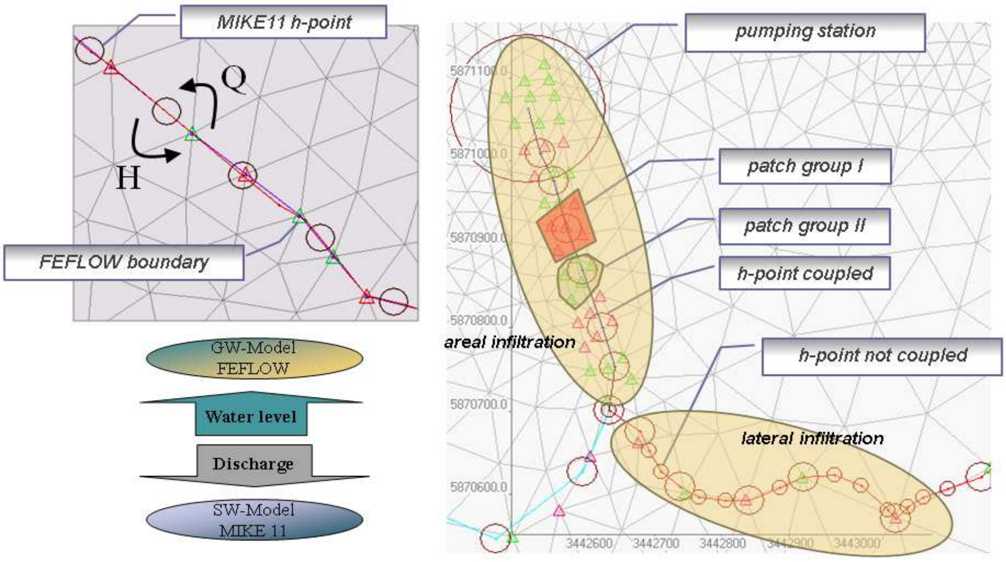

Fig.2: Basic principle of the coupling

In case that the groundwater level drops below the bottom of a river, the above equation indicates that the calculated discharge will continue to increase. Brunner et al. (2009) show that this is not the case in reality and the discharge is limited to a certain maximum. In FEFLOW additional constraints can be set to approximate this process. Using these constraints, a user-defined minimum for hgw is introduced in the above equation, usually equal to the bottom of the river.

Monninkhoff &Hartnack (2009) showed a third mechanism to describe rivers in FEFLOW which is only available within the FEFLOW internal programming interface (IFM). In IfmMIKE11 these boundaries are called special boundaries. It is basically the same as a 3rd kind boundary, but both the exchange area and the transfer coefficient can be defined externally and for each single node. Using this function IfmMIKE11 could be improved by updating the exchange areas according the actual water levels and the profile data available in MIKE11. It was shown that both for triangular and rectangular cross river sections this approach gives results which fit reasonably with analytical solutions of the same problem.

Quality modeling

In 2011, the coupling between MIKE11 and FEFLOW was extended also for mass transport. The numerical solution of the transport equation of MIKE11 (AD simulation) requires, like FEFLOW also, a temporally varying background flow field. With respect to the FEFLOW coupling, the hydrodynamics and the transport equations in MIKE11 are solved in a coupled mode i.e. MIKE11 calculates the river flow field and the concentrations within the same time step. The coupling between FEFLOW and MIKE11 is explicit i.e. FEFLOW completes a time step and then exchanges values with MIKE11 which in turn takes a time step. The exchange of water and mass is calculated by FEFLOW based on values from the previous time step. This approach in turn requires that every time a MIKE11 time step is calculated FEFLOW must pass the following values for each coupling point:

- Flow (in- and outflow to the river in separate parameters)
- Mass flux (kg/s) for each chemical species (in case there is inflow to a river h-point)

In return MIKE11 passes

- Water level at the h-points
- Concentrations (kg/m^3) for each chemical species at the h-pointsback to FEFLOW.

Like the flow boundaries also the mass boundaries can be set as different types in FEFLOW. From these, only the 1st (defined concentration) and 4th (defined mass) kind are useful for mass coupling processes.

IfmMIKE11 automatically generates mass boundary nodes at those FEFLOW nodes which also have coupled flow-boundary conditions. It is therefore not necessary to set mass boundary conditions to the coupled nodes at the beginning of the simulation. The type of boundary is defined by the user settings. Both single and multi-species processes can be coupled. Despite the fact that the mass coupling is mostly automatically, it is useful to be familiar with the basics of mass transport in FEFLOW to be able to couple MIKE11 and FEFLOW also for mass-transport processes.

In that context it is important to know that FEFLOW can run a mass-transport problem applying one of two different formulations of the transport equation; the convective or the divergence form. In Diersch (2009) the difference between the divergence and convective form of a mass-conservation equation is explained in detail. The main difference lies in the convective terms in the transport equations applied to both forms. Both transport equations are physically equivalent, but they lead to different formulations of boundary conditions. When using the divergence form of transport, the mass fluxes prescribed at a boundary denote the sum of both advective and dispersive fluxes. Using the convective form, only the dispersive part of the flux is prescribed. In that case the total flux will be calculated internally as a result of the governing concentration at a node and the fluid flux across the flow boundary located at the same node.

In general it can be stated that the convective method ensures a higher degree of stability, especially at outflow boundaries. This form, however, is rather unsuitable for using mass boundary conditions of the 4th kind in case that there is also a flow boundary condition at the same node (inflow into groundwater). So, if mass-boundary nodes of the 4th kind will be used for the coupling, it is obligatory to use the divergence form, accepting possibly less stability at outflow boundaries. To ensure stability, the mesh discretization around the boundary conditions should then be rather dense and using well-shaped finite elements. The main advantage of this method, however, is that the mass balance is guaranteed. Mass-boundary nodes of the 1st kind (boundary values are defined as concentrations) on the other hand are ideal to use with the convective form. The model is more stable and the resulting parameters of the MIKE11 time step can be transferred directly to the FEFLOW model (both concentrations). This would however imply that the finite-element volume represented by a mass boundary node of the 1st kind would get the same concentration as the concentration at the coupled h-point of the river. The original groundwater concentration within this volume would be neglected and a discrepancy in the mass balance is automatically generated. This error can be reduced by ensuring that the elements around the mass-boundary nodes of the 1st kind are small.

Besides these two options, also an IFM internal option has been implemented, similarly to the special boundaries available for quantity coupling, which can be accessed by the function IfmSetCoupledMassTransBndNodes(). This function enables the definition of a new boundary-condition type which has two main parameters; (1) surface-water reference concentration (c_{ref} [mg/l]) and (2) a parameter representing the product of the mass-transfer rate in [m/d] and the exchange area in [m^2]. This parameter is called PHI [m^3/d]. Using suitable parameters, the result of a special boundary in the convective form will give the same results as a 4th kind boundary in the divergence form. The value of a 4th kind boundary [g/d] for inflow into groundwater can be calculated by multiplying the fluid flux with the concentration in the river. Using this fluid flux [m^3/d] for PHI and setting the river concentration as c_{ref} [mg/l] for the special boundary in the convective form, an equivalent boundary condition will be defined. The practical consequence is that input mass-flux boundary conditions can also easily be simulated by using the standard convective form without resorting to the more complex divergence form of the transport equation.

The quality coupling routine has successfully been tested in a similar project as the one under consideration. In that project the objective was also to analyze the effect of MAR techniques to counteract salt water intrusion in the coastal zone. In the next section a brief overview of the theoretical background of density dependent processes is given after which an example using the coupling mechanism described above will be provided.

Theoretical Backgroundof density dependent flow in FEFLOW

In continuum fluid mechanics, the density ρ of a fluid is found to be dependent of pressure p, temperature T and a partial density ρ k, which is described by the equation of state (EOS). For the groundwater flow equations in FEFLOW, the pressure is defined by the hydraulic head h and the density at a known salinity concentration Cs, thus the EOS can be defined as:

$$\rho = \rho(h, C_s, T)$$

For the purpose of saltwater intrusion, temperature variations will be neglected. Through the linear expansion of the EOS, it can be derived that:

$$\rho = \rho(\mathbf{p}, \mathbf{C}) \approx \boldsymbol{\rho_0}\left[\mathbf{1} + \boldsymbol{\gamma}(\mathbf{h} - h_0) + \frac{\alpha}{((C_s - C_0))(\mathbf{C} - C_0)}\right]$$

where ρ_0 is the reference fluid density, h_0 is the reference head, C_0 the reference concentration, γ is the expansion coefficient for the hydraulic head term, and α the expansion coefficient (or density ration) for the concentration.

The principles of mass conservation, momentum and energy are the basis of the density-dependent flow and transport models. After several approximations the velocity can be derived by the relation of the pressure and gravity-induced flow:

$$q_s = -K(\nabla h + \alpha)$$

Where K is the conductivity (m/s). The density ratio α , relates concentrations in the model to density differences and is described by:

$$\alpha = \frac{\rho(\mathbf{Cs}) - \boldsymbol{\rho_0}}{\boldsymbol{\rho_0}} \approx \mathbf{0}.\frac{\mathbf{7Cs}}{\boldsymbol{\rho_0}}$$

Considering that freshwater has a reference concentration of 0 g/l, with a density of 1000 Kg/m³Considering that freshwater has a reference concentration of 0 g/l, with a density of 1000 Kg/m³ and seawater has a concentration of 35 g/l with corresponding density of 1024.5 Kg/m³, the α -Value in FEFLOW is defined as 0.0245.

As described in the velocity formula, denser saltwater settles underneath lighter freshwater, which results in a stable density stratification and flow conditions. In coastal areas intensive extraction of groundwater can lead to the progression of the saltwater front into the aquifer (see next figure).

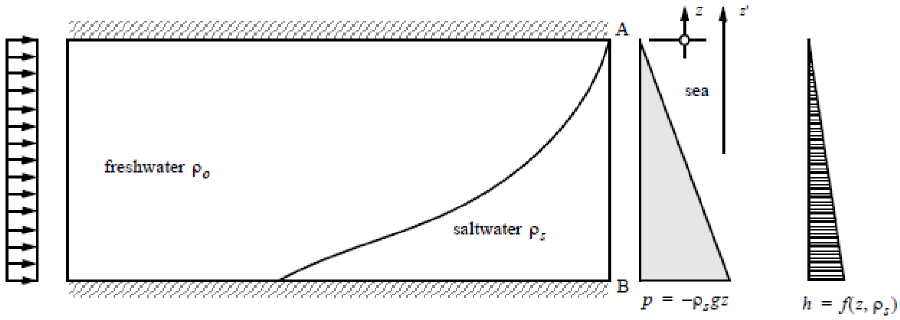

Fig. 3: Saltwater intrusion in a coastal aquifer

Example

Objective

The test case shows how FEFLOW can be used together with MIKE11 to model saltwater-intrusion processes and implements MAR techniques to counteract the effects of excessive pumping.

Problem Setting

A 3D confined, flow and mass-transport box-model was setup in FEFLOW. The North and South flow boundaries were defined as Dirichlet kind and the east and west boundaries were set as no flow boundaries. A mass concentration of 35000 mg/l was assigned to the southern sea side boundary. For simplicity the material properties were maintained homogenous.

First, the FEFLOW model was run without coupling to obtain the initial concentration in the domain. Mass transport was initiated with pure advection using the head gradient and the model was run for a period of 145 days.

In a second step, the model was coupled to MIKE11 model using the interface IfmMIKE11. In the MIKE11 River model, fresh water solute with mass concentration of 20 mg/l was transported from north to south, bringing the fresh water in the domain. On the upstream boundary, the fluid inflow was kept constant at 0.25 m^3/s. The water level downstream was assigned constant at sea level. Initial water level was given a global value, higher than the FEFLOW water level to insure the outflow condition (MIKE11 to FEFLOW). The next figure shows the mass concentration of the intersection along the river for t=0 (result from the uncoupled model) and t=15 days. The figure shows that the saltwater front at t=0 behaves as explained in the previous section; the dense saline water predominantly intrudes along the bottom of the aquifer. The fresh water from the river counteracts this and at t=15 the salinity front has clearly being reduced. It has to be noticed that the parameters in the model have been chosen in such a way, that concentrations can change rapidly in time to save time consuming simulations. In reality changes in salt water concentrations can take much longer.

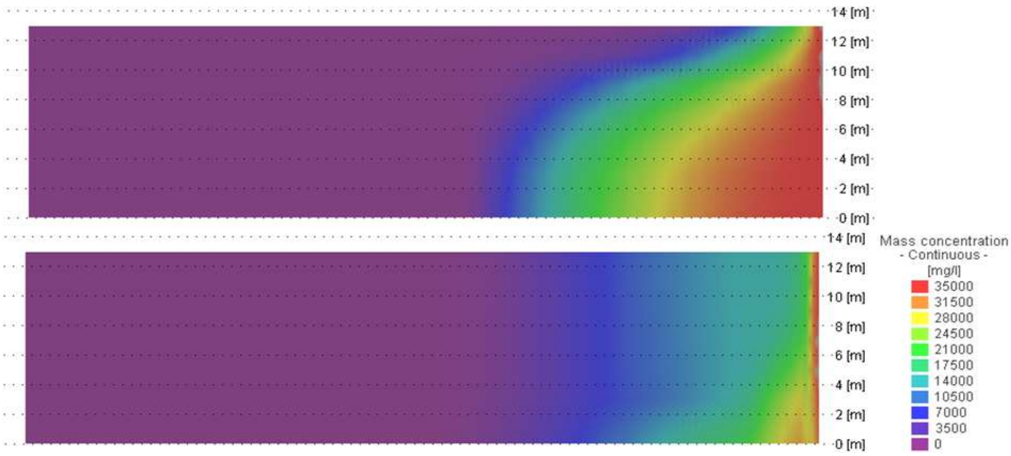

Fig. 4: Mass Concentration Initial Condition (top) and results after 15 days (bottom)

Based on this model, in a first scenario a pump was installed in the FEFLOW model extracting at a rate of 1000 m^3/d from all 7 slices and the effect of the pumping on the concentrations was observed. The next figure shows the mass concentration distribution in the domain caused by the pump. The local concentration at pump location was increasing from a value of 0 to 650 mg/l over a period of 15 days and the blue plume towards the pump shows that this water is attracted by a much higher velocity than the surrounding areas.

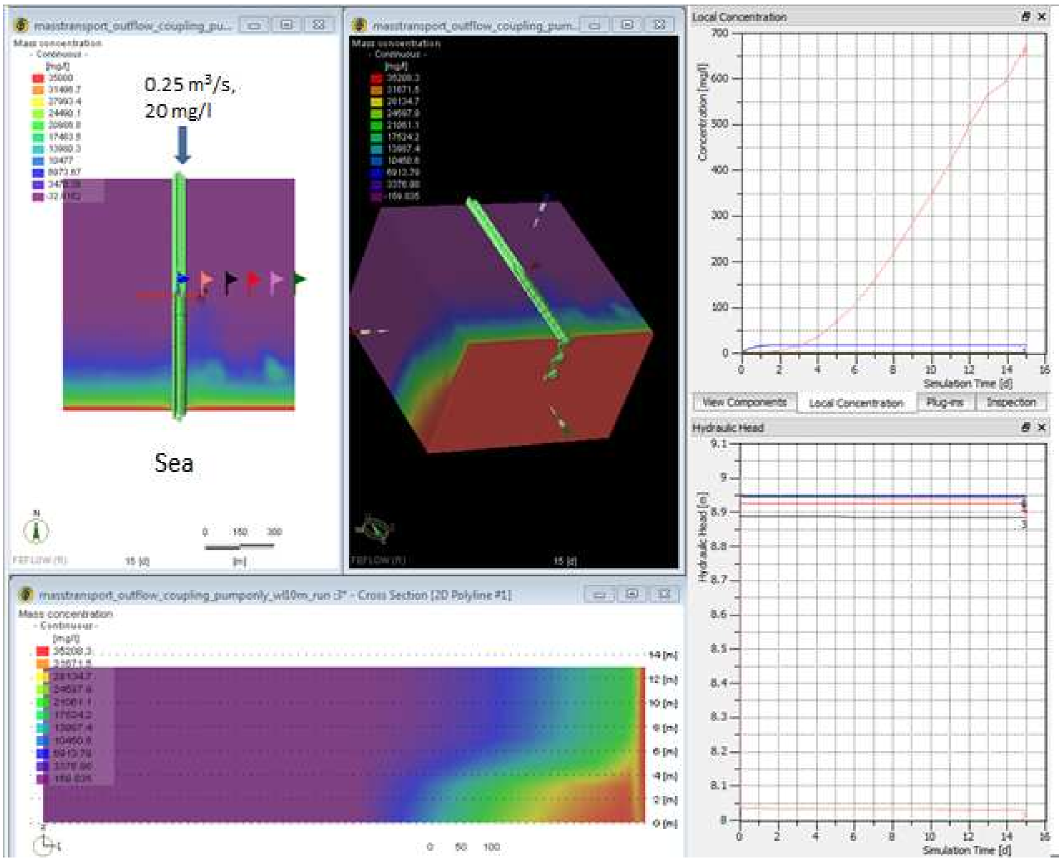

Fig. 5: Simulation using an extraction pumpafter 15 days.

In the second scenario, a weir was installed at the confluence of the river into the sea in order to increase the water level in the river and to increase the effect of artificial recharge. The next figure compares the hydraulic head at a FEFLOW node close to the weir and shows that due to the implementation of the weir the groundwater level is rising (result in an increase of fresh water in the domain).

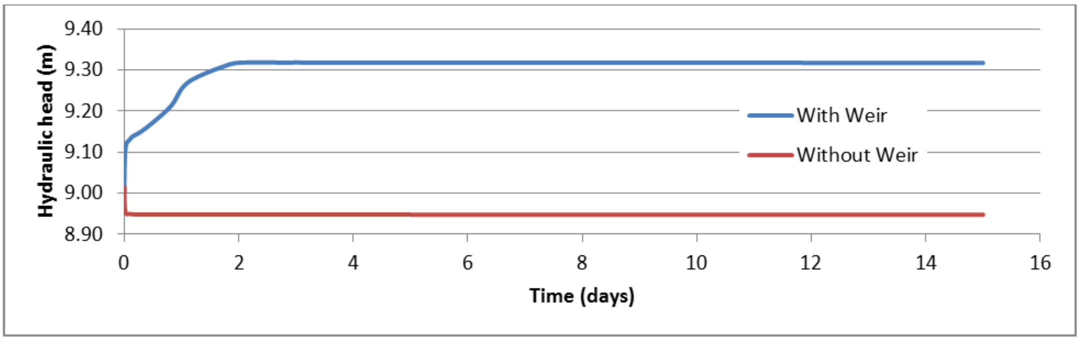

Fig. 6: Comparison of groundwater headsclose to the river for 2 Scenarios.

This can also be seen in the next figure, where negative values represent an increase of groundwater level caused by the implementation of the weir. The strongest increase is in fact located along the river at the location of the well.

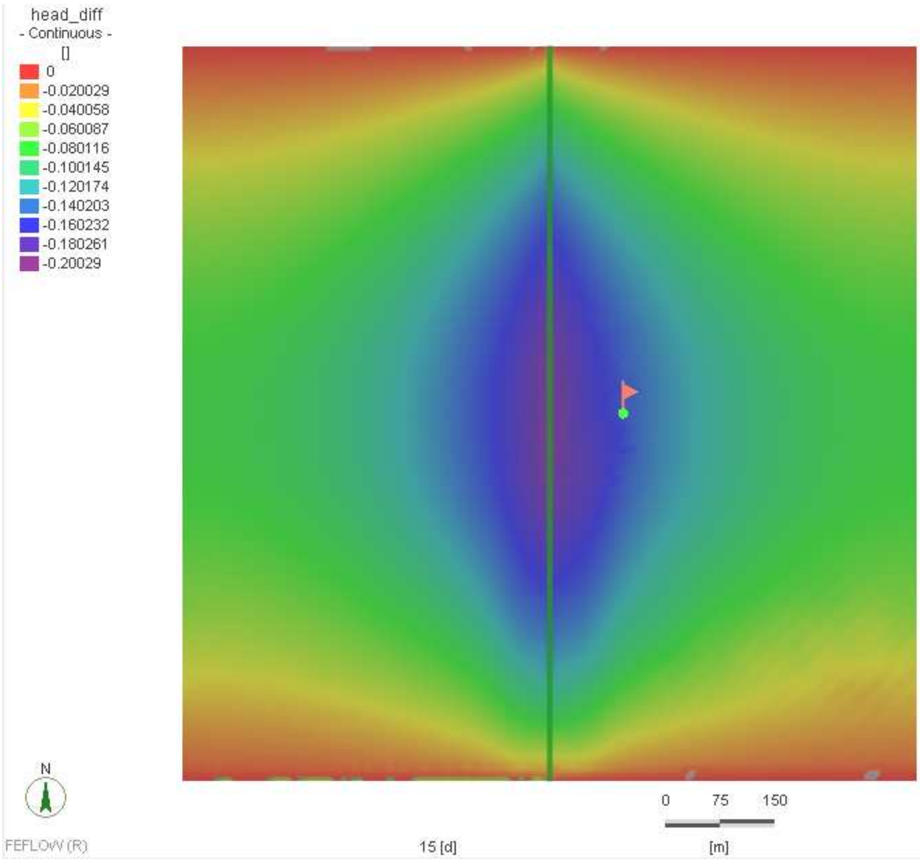

Fig.7: Difference of hydraulic head for 2 Scenarios (heads without weir minus heads with weir).

In the next figure these two scenarios are compared in respect to the concentrations at the well. The second scenario clearly has lower concentrations proving the positive effect of this MAR facility on a potential drinking water well.

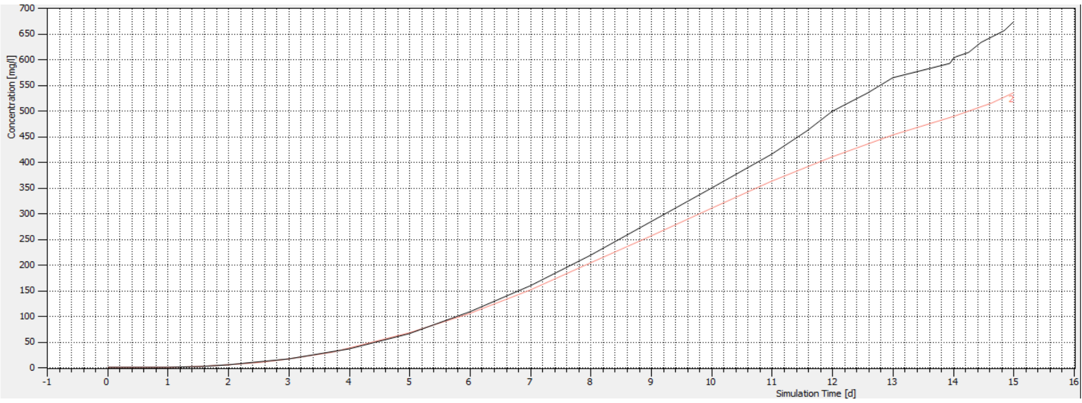

Fig.8: Comparison of concentrations at the well for 2 Scenarios (line 1: scenario without weir, line 2: scenario with weir).

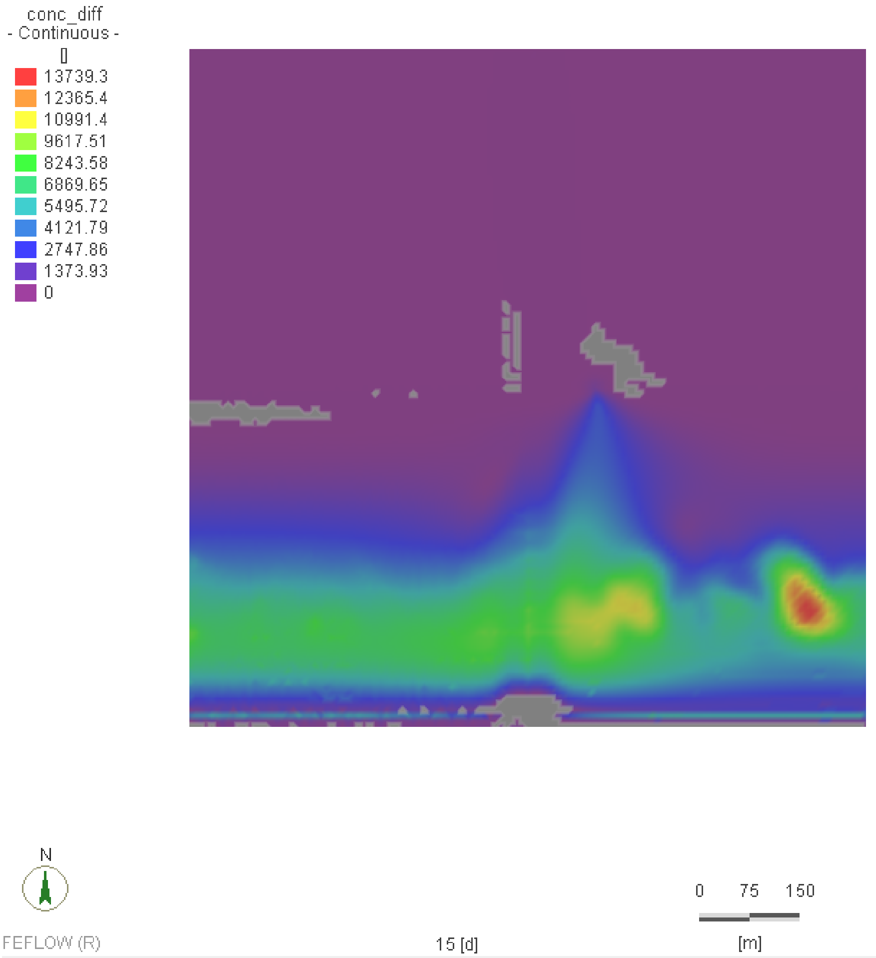

Fig. 9: Comparison of concentration for 2 scenarios.

Finally, the above figure shows the differences in concentrations between the wells. Positive values indicate a reduction of concentration caused by the implementation of the weir. The figure also shows that this basic example still has some numerical instabilities which might be optimized during the next weeks: in some locations further away from the river the differences in concentrations are relatively high and at some locations even negative (grey areas).

Nevertheless, these examples show that the coupling concept presented in this document can be flexibly applied to a wide range of potential MAR facilities, also for the project under consideration.

Acknowlegdements

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