MANAGED AQUIFER RECHARGE: SUSTAINABLE WATER RESOURCE MANAGEMENT ON THE CANTERBURY PLAINS

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ABSTRACT

Demand on water resources for irrigated agriculture on the Canterbury Plains is strong. Against a backdrop of tightening regulatory controls, demand for water has not abated, which is perhaps unsurprising given the significant economic benefits to be generated within the region from irrigated agriculture. Current demand is tangibly impacting on surface water resources in some places and there is concern about unrealised impacts from consented takes that have not yet been exercised.

Cumulative impacts from the various surface water and groundwater abstractions are the key issue associated with water allocation on a regional scale. However, understanding and quantifying cumulative impacts is complex because of the interaction between surface waters and aquifers - particularly within shallow riparian aquifers, which have different hydrodynamic functionality to deeper aquifers.

The degree of coupling between surface waterways and aquifers in a fluvial-glacial sedimentary aquifer system generally decreases with depth. The heterogeneous and vertically anisotropic nature of the sediments, impart progressive confinement at depth on the aquifer system, with the compaction of fine grained materials from the weight of the sediment pile above.

The implication for water allocation of this conceptual hydrogeological understanding of the Canterbury Plains is that the system behaves significantly differently with depth below the surface, with longer residence times and flow paths. If the system is managed in a manner cognisant with environmental flow safeguards (i.e. what we are trying to protect) and the conceptual understanding of the systems' hydrodynamic functionality, opportunities arise for optimising water allocation.

The complex hydrodynamic functioning of the aquifer-surface water system, coupled with the significant increase in demand for water and the need to manage water resources sustainably, has meant that in the absence of perfect knowledge of the system, water is regulated in a precautionary or conservative manner. This management approach in principal is not at fault, but there are well documented concerns over the rate at which the resource management process (investigation, policy development, and implementation) has adapted to the significant increases in demand.

The question that resides is "what can be done about this resource management conundrum and quickly?". This paper explores a method for optimising water allocation using the concept of managed aquifer recharge (MAR) on the Central Plains in Canterbury. From the preliminary analysis presented in this paper, MAR would appear to offer significant cost benefits when compared to the current Central Plains Water (CPW) Irrigation Scheme, and represents a more sustainable outcome for enhancing water allocation from the entire system.

KEYWORDS

Managed aquifer recharge, groundwater, optimising water allocation, sustainable resource utilisation.

1 INTRODUCTION

Sinclair Knight Merz (SKM) was commissioned by Environment Canterbury (ECan) in 2009 to carry out a desktop review of the concept of Managed Aquifer Recharge (MAR), the potential for MAR to provide a sustainable water resource management option for the Canterbury Plains and to develop a hypothetical but potentially realistic MAR concept for the Central Plains area.

The intent of the commission was firstly to establish whether there was potential benefit in the use of MAR and thereafter if warranted, to disseminate information on the concept of MAR with the intent of raising awareness so that it could be considered in the present consideration of water management and water storage in Canterbury.

The preliminary assessment has demonstrated that there is considerable potential for MAR to increase groundwater availability for both agricultural and environmental benefit in Canterbury, either as a stand-alone option or in conjunction with other water management and irrigation approaches, and that there is merit in further and more detailed assessment of the technical, economic, environmental and social aspects of MAR.

The intent of this paper is to continue the process of education about the concept of MAR and its potential applicability in Canterbury.

At the outset of this paper, it is highlighted that the assessment undertaken to date has been a high level and conceptual review, intended to identify if there is merit in further and more detailed investigations. In this regard, the hydrogeological, civil infrastructure and economic concepts presented are preliminary in nature and subject to further investigation, discussion and debate.

This paper provides an overview of the concept of MAR and its application both overseas and in New Zealand, the hydrogeological reasoning why MAR has the potential to be utilised in the Canterbury Plains and then presents a conceptual example of the use of MAR in the Central Plains area. In closing, we provide some discussion on how the concept of MAR in Canterbury may be further progressed.

2 MANAGED AQUIFER RECHARGE

2.1 DEFINITION AND OVERALL OBJECTIVES

Managed aquifer recharge (MAR) is the intentional and active management of water to recharge aquifers for subsequent recovery and use or environmental benefit. It is a proven technology at the leading edge of integrated water management and presents opportunities for conjunctive and sustainable management of surface water and groundwater resources.

The technique involves supplementing natural recharge to an aquifer system under controlled conditions by diversion of water into recharge wells or by infiltration of water through the floor of infiltration basins, galleries or riverbeds. The resulting increase in groundwater inflow into the aquifer system can then be stored, utilised for consumptive purposes or left to enhance environmental values associated with the water resource, such as increase of stream base flow.

In many overseas applications MAR is utilised as a means to recycle wastewater or stormwater flows by utilising the natural treatment and retention time of water within an aquifer system as a means to improve water quality. However, the primary focus of the assessment on the Canterbury Plains context has been on the diversion and capture of river water to augment naturally occurring aquifer recharge.

2.2 POTENTIAL BENEFITS

The use of MAR as a technique to assist water resource management has a number of potential benefits including:

- Providing a means to capture and store seasonal water surpluses or "water banking";
- Increasing the rate and/or volume of water available for consumptive use;
- Increasing the reliability of supply for existing groundwater users;
- Decrease in infrastructure requirements associated with surface water storage and distribution;
- Ability to scale schemes or progressively develop to match growth in demand;
- Mitigating situations where the current level of abstraction exceeds sustainable limits; and
- Providing storage of water on a long-term (inter-annual) basis.

In this context, the concept of MAR effectively enables access to "new" water which in turn enables greater utilisation of agricultural land and/or enhancement of environmental values including increased baseflows to rivers and streams and enhancement of groundwater dependent ecosystems such as wetlands and phreatophytic vegetation.

2.3 MAR REQUIREMENTS

MAR must also be considered in terms of a range of factors including:

- The ability to reclaim a significant proportion of the recharged water from the aquifer system if it is intended for consumptive or irrigation purposes;
- Potential water quality impacts due to the quality of the recharge inputs or as a result of interaction between the recharge flows and the natural aquifer materials;
- Potential raising of the groundwater table in low lying areas with consequential increase in surface flood risk due to decreased ground assimilative capacity and increased base-flow in surface waterways.

The key to the establishment of a successful and sustainable MAR scheme lies in the identification of these factors.

Geology, lithology and hydrogeological parameters for the area of interest are of principle importance, as this information is required to development of an understanding of aquifer systems and confinement, vertical and lateral permeability and overall transmissivity and storativity for the system. This information in turn enables the identification of the preferred recharge mechanism and location (spatially and at depth), expected hydrogeological response, potential rate of recovery (or loss) and preferred extraction mechanism, or in summary, the technical feasibility of the project.

Thereafter, this information enables the assessment of project economics and environmental and social effects.

Regulatory, governance and financial arrangements will also impact on the scheme design and feasibility and in the New Zealand context, this may require a departure from the existing first-in first-served water allocation mechanism.

2.4 COMPONENTS OF A MAR SCHEME

A MAR scheme consists of a number of individual components required to supply water of adequate quantity and quality to achieve the overall scheme objectives. The components listed in **Table 1** are common to all systems however the exact configuration of each of these components will vary between individual MAR schemes.

Table 1. *Components of a MAR scheme (adapted from NRMMC, 2009).*

Component	Example
Capture zone	Harvesting using weirs and wetlands in urban catchments Diversions from rivers and streams Discharge from a water treatment plant
Pre-treatment	Passive treatment systems such as settlement ponds and wetlands Engineered treatment systems producing water of a suitable quality for recharge
Recharge	Injection wells Infiltration basins Infiltration galleries
Subsurface storage	The aquifer materials in which water is stored and passive treatment occurs
Recovery	Recovery (pumping) bore Discharge via stream baseflow discharge

2.5 TYPES OF MAR SYSTEMS

There are many possible configurations for a MAR scheme. **Figure 1** illustrates a range of MAR configurations, and a summary of these is provided in SKM (2010).

The MAR configurations considered most likely for the Canterbury plains is referred to aquifer storage and recovery (ASR), which involves the injection of water into an aquifer system via a recharge well for subsequent recovery down gradient.

2.6 SELECTION OF APPROPRIATE RECHARGE METHOD

All MAR schemes are premised on the assumption that there is a suitable aquifer for recharge of water. A suitable aquifer for MAR is defined here as an aquifer having permeability and storage characteristics appropriate to accept a sufficient rate and volume of water to realise the scheme objectives within practicable costs of establishing the scheme.

Given this aquifer prerequisite, when selecting the MAR recharge method, considerations of a range of additional site-specific conditions are required, including:

- ***Lithological profile*** of the system, with respect to infiltration characteristics of the soil and surficial sediments;
- ***Confinement status*** of the target aquifer (unconfined, semi-confined, confined);
- ***Hydrogeological characteristics*** of the entire system (both above, within and below the target aquifer);
- ***Geomorphological characteristics*** of the land, with respect to the landform and nature of sediments or rock (e.g. sand dunes and swales, shallow bedrock ridges or volcanic intrusions beneath alluvial aquifers);
- ***Source-water quality*** may also influence recharge method selection as well as dictate the likely requirements for pre-treatment, which can add significant cost and impact on the feasibility of the various methods (see below and **Section 2.6.5** for a detailed discussion);
- ***Cost of land*** will determine the expansiveness of the scheme (i.e. rural versus urban settings);
- ***Investigation costs***, which vary depending on method and site configuration, may also have a bearing on the type of recharge method selected if more than one option is available for any particular site.

The following sections discuss these key considerations.

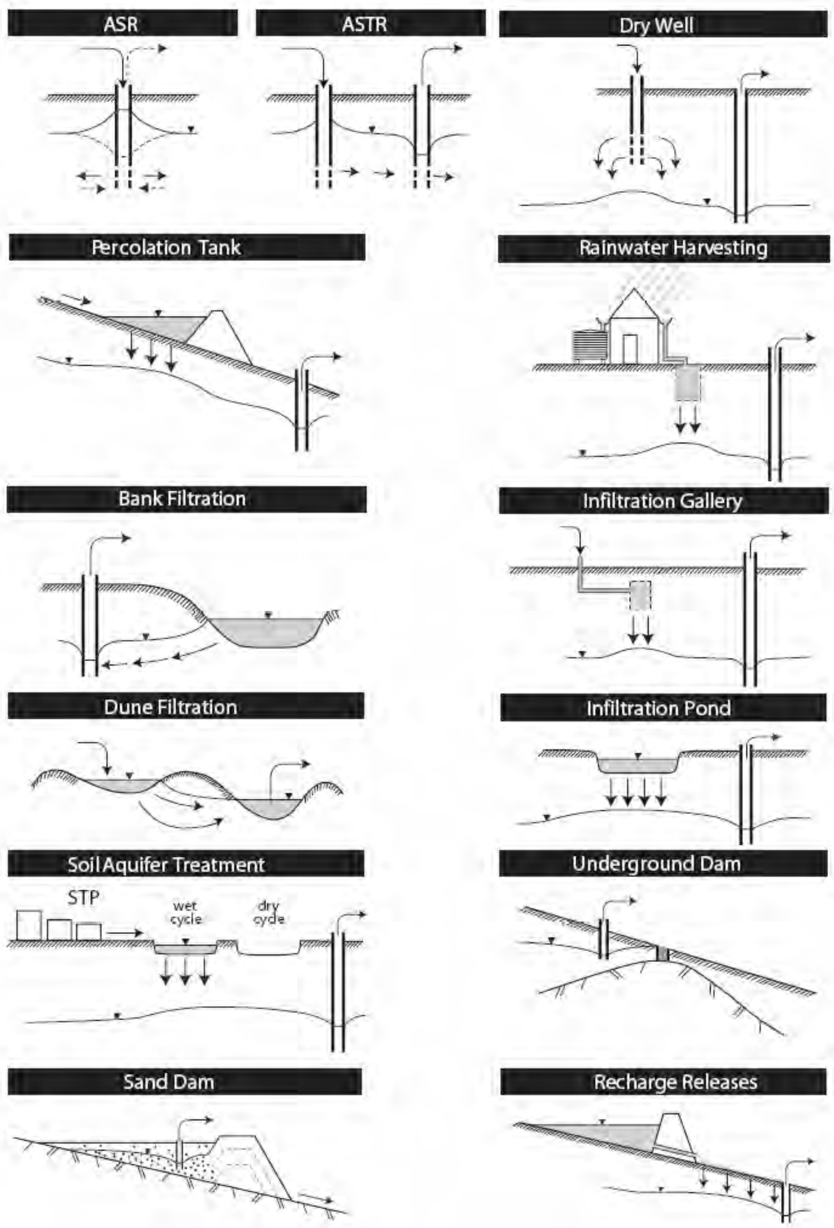


Figure 1. *Types of MAR schemes. (from Dillon, 2005).*

[ASR = Aquifer storage and recovery, ASTR = Aquifer storage transfer & recovery]

2.6.1 CONFINED AND UNCONFINED SYSTEMS

In the case of confined aquifers well injections methods (ASR, ASTR) are likely to be required to enable direct utilisation of storage where the hydraulic connection between the land surface and target aquifer is impeded by the presence of intervening low permeability sediments.

In unconfined aquifer areas, where significant depth to the groundwater table and no restriction in permeability prevail, surface infiltration methods would normally be considered the most cost effective method in rural areas. Consideration needs to be given to proximity to existing waterways and in particular lateral flow and the loss of recharge water to these.

In unconfined areas where surface infiltration is restricted by near-surface low permeability layers, galleries, basins, sumps or wells may be constructed to by-pass the impeding layer and allow recharge to underlying formations that have higher permeability.

The final configuration and recharge option selected for unconfined aquifer recharge systems will be influenced by:

- The thickness of the low permeability layer;
- The required infiltration rate;
- Proximity and connectivity to surface water;
- Land availability and cost; and
- Compatibility with existing and/or surrounding land use.

2.6.2 SOURCE WATER QUALITY

Source-water quality may also influence recharge method selection as well as dictate the likely requirements for pre-treatment. In general, if the turbidity or nutrient concentration is high or variable, well-injection methods are likely to lead to rapid clogging of aquifer materials restricting the rate of recharge, unless pre-treatment is undertaken. In this situation, infiltration basins that can be periodically scraped or ploughed are preferred as a MAR option in their own right, or as form of pre-treatment (i.e. sediment settlement) prior to recharge via well injection.

Other options exist for source water pre-treatment to minimise potential for clogging within injection wells although many of these have significant construction and maintenance costs. Regardless of the level of pre-treatment it is recommended that recharge wells are intermittently back flushed to purge accumulated sediment and/or biomass, and maximise their injection capacity.

2.6.3 SURFACE INFILTRATION SYSTEMS

Surface infiltration systems for artificial recharge of underlying unconfined aquifers can be constructed in streambeds (in-channel systems) or outside stream channels (off-channel systems).

In-channel systems typically consist of weirs or dams (small and closely-spaced where channel gradient is steep, larger and more widely spaced where slopes are flat) across the streambed to back the water up and spread it over a greater width of the streambed to increase hydraulic gradient and maximise wetted area to increase natural infiltration rates.

In-channel systems work most successfully where there is a good hydraulic connection to the surrounding aquifer through the streambed materials. In-channel infiltration systems can be formed using natural streambed materials pushed up into dikes or berms that force water into a more circuitous path increasing the area of streambed through which infiltration can occur. High flow events are likely to destroy these structures but will also act to remove accumulations of fine sediment and other clogging materials. In-channel infiltrations are most effective if utilised in combination with upland catchment storage which can be utilised to reduce sediment loadings and deliver water during to maintain infiltration during periods of natural groundwater level decline.

Such systems in New Zealand could be utilised to harvest spill flows from canal fed hydropower dams and maximise the power generating potential of these spill flows in situations where additional dams intercept groundwater baseflows derived from the upgradient recharged aquifer.

Off-channel systems consist of infiltration basins constructed either utilising the existing topography (e.g. depressions, gullies) or via engineered structures such as excavated basins, trenches or soakage holes. Infiltration basins are the most commonly used surface infiltration systems and consist of an infiltration area either excavated into the underlying soil materials or surrounded by a raised berm to allow sufficient water depth to maximise infiltration rates.

Trench infiltration systems typically consist of a length of perforated pipe buried in a trench backfilled with permeable materials. Shallow recharge (or vadose zone in the case of structures that do not reach the underlying water table) wells are typically constructed in the same manner as pumping wells and typically have a large diameter and coarse screens to maximise contact with the surrounding sediments and may be surrounded by a gravel or sand pack to further increase hydraulic connection. In terms of off-channel structures infiltration basins have the advantage of being relatively simple and low cost structures which allow ready access for maintenance.

WATER DEPTH

If there is no clogging layer and the water table is relatively deep, downward flow through the vadose zone is by gravity and the water depth in a recharge basin has only a minor effect on infiltration rate (Bouwer and Rice, 1989). If the rate of infiltration is controlled by the accumulation of a clogging layer and the underlying material is unsaturated, then infiltration rate theoretically increases linearly with water depth, so that a doubling of the water depth will double the infiltration rate.

However, in practice, clogging layers are typically soft sediments that are compressible so increasing water depths in the recharge basin often result in an increase in inter-granular pressure resulting in a corresponding decline in clogging layer permeability. Combined with slower turnover of water in the recharge basin allowing increased biological growth, in some applications increasing water depth in recharge basins to promote recharge has been observed to actually reduce infiltration rates (Bouwer, 1990).

INFILTRATION RATES

Infiltration rates are expressed as a depth of water moving into a soil material per unit time (e.g. mm/hour). Predicting and managing infiltration rates are one of the most crucial components of planning, designing and managing surface infiltration system as they determine the land area required to achieve a nominated recharge volume or alternatively dictate the volume of groundwater recharge achievable for an available land area.

For surface infiltration systems in uniform soils, infiltration rates are approximately equal to the vertical hydraulic conductivity of the soil materials. In most situations infiltration rates are generally dictated by the physical properties of the clogging layer materials, which act to reduce the rate of vertical infiltration. However, where clogging is limited groundwater mounding beneath a recharge area may also reduce the rate of vertical infiltration if the water table rises to a point where the capillary fringe is close to the base of the recharge basin.

2.6.4 INJECTION/RECHARGE WELLS

MAR may be undertaken utilising injection wells where subsurface permeability is insufficient to allow unimpeded vertical drainage through the vadose zone or where the target aquifer is confined. As indicated above, the main issues experienced with recharge wells are related to physical clogging of the well screen and/or surrounding formation either due to the accumulation of suspended sediment or as a result of biological growths.

Clogging of recharge wells can be controlled by an appropriate level of source water pre-treatment coupled with intermittent backflushing of the well as part of routine operation. Depending on the quality of the recharge water pre-treatment may involve removal of suspended sediment, reduction in nutrient concentrations and reduction in organic carbon content. Biological clogging, such as the formation of biofilms, can be controlled to some degree by disinfection of the recharge well (e.g. by maintaining a residual chlorine level in the water). However, periodic redevelopment of recharge wells by flushing and chemical dosing is inevitably required to overcome clogging effects. As for water depth in surface recharge basins, increasing injection pressures in an attempt to overcome clogging can act to hasten the effects of clogging.

Air entrainment in the injected water is another key mechanism that can quickly reduce the injection capacity of wells constructed within unconsolidated or poorly consolidated sedimentary aquifers. This can be overcome through the use of a flow control valve to prevent cascading of aerated water down the injection well.

2.6.5 SOURCE WATER QUALITY

One of the key success elements of a successful MAR scheme is a good understanding of the source and receiving water quality.

Where water is introduced to an aquifer system, management of groundwater quality is of primary importance where the aquifer system is used for potable supply or will discharge to a surface water receiving environment. While retention and movement of water through the aquifer system will attenuate contaminant concentrations via the processes of die-off, filtration and adsorption, the quality of recharge water has to be managed to ensure that resulting impacts on water quality will not adversely impact on values associated with the resource.

Key criteria determining the suitability of water source to a particular MAR application is the suspended sediment content. Where source water contains appreciable levels of suspended sediment clogging of the infiltration basin, galley or recharge wells is likely to occur relatively rapidly unless water is pre-treated prior to committing to the recharge system.

Clogging is caused by inorganic (e.g. clay, silt) and organic (e.g. algae) suspended solids that accumulate on the infiltrating surface, and by microorganisms that grow on the soil particles (biofilms) and produce polysaccharides and other metabolites which form a soil clogging biomass. Bacteria can also produce gasses (nitrogen, methane, carbon dioxide) that can block soil pores.

Geochemical reactions may occur as a result of mixing oxygenated surface waters with anaerobic groundwaters resulting in clogging or other undesirable reactions between the mixed waters and aquifer matrix. A thorough understanding of the chemistry and redox potential of both the source water and groundwater within the receiving aquifer is necessary to determine the extent of any chemical reactions likely to occur as a result of the mixing process.

In the case of well-injection gas can also be entrained in the recharge flow or released in the aquifer due to dissolution as a result of temperature changes. The formation of gas bubbles in the aquifer system or introducing cascading aerated water to the aquifer can act to rapidly impede the permeability of the aquifer materials (a process termed air binding). This process is reversible but it is preferable to mitigate this likelihood during the investigation and design stage.

2.6.6 MANAGEMENT OF CLOGGING

As discussed above, clogging is a potential issue for MAR schemes utilising both surface infiltration and well injection options and is typically a function of source water quality. Clogging of MAR systems is best controlled by prevention, i.e. by removing those parameters likely to reduce infiltration rates. For surface water sources this typically requires settlement to reduce suspended sediment concentration. However, depending on the grain size distribution of the sediment particles, settlement may not reduce suspended sediment concentration sufficiently to facilitate efficient recharge so additional treatment involving coagulation and/or mechanical filtration may be required. The use of wetlands and/or sand filtration may be suitable options to reduce suspended sediment content although use of application of such options will likely increase construction, operational and maintenance costs of the MAR scheme.

Biological clogging can be reduced by removal of nutrients (primarily nitrogen and phosphorus) and organic carbon from the water. This is particularly important where trenches, shafts or wells are utilised for recharge of wastewater or water containing elevated nutrient concentrations. Disinfection (using chlorine or similar) may be used to reduce biological activity and hence clogging in trenches, shafts and wells. Clogging rates typically increase with increasing infiltration rates due to the higher loading rates of suspended solids, nutrients and organic carbon. As a result, increasing injection pressures in wells showing signs of clogging may actually hasten the clogging process. A programme of routine back-flushing supplemented by occasional well maintenance such as high capacity airlifting and chemical dosing can help to maintain well injection capacities.

For surface infiltration systems, clogging is typically managed by periodically drying infiltration basins and physically removing the accumulated sediment using mechanical plant. Ploughing of clogging layers provides a temporary increase in infiltration rate but eventually fines or other clogging materials will accumulate in the upper layer of the soil profile to the point where the entire upper layer must be removed.

2.7 COMPARISON OF MAR SYSTEMS

Table 2 provides an overview of the typical advantages and limitations of the different MAR methods, and in particular draws focus on hydrogeological conditions where the various schemes would likely be more applicable.

Table 2. Summary of advantages and limitations of potential MAR methods.

Method	Technique	Advantages	Limitations
Deep Well Injection	■ Injecting water into deep confined or semi-confined aquifers for later recovery through individual wells. ■ Applicable for deep aquifer systems where lower permeability semi-confining or confining layers preclude vertical infiltration methods.	*Environmental / Social / Cultural* ■ Can be used to restore aquifer pressures and maintain environmental flows. ■ Can be used to improve groundwater quality, reduce subsidence, and enhance sustainable yield (groundwater abstraction) from the aquifer. ■ Can increase the overall water availability avoiding the requirement for surface storages. ■ Can be used to "bank" water. ■ Minimises evaporative losses.	*Environmental / Social / Cultural* ■ Potential to impact on existing users if generating (or modifying) artesian pressures. ■ There may be cultural issues surrounding mixing of waters that need to be addressed.
		Aquifer Hydrogeology ■ Due to low storativity and high permeability the area of aquifer pressurisation may potentially be very large in a confined or semi-confined aquifer system. ■ Aquifer throughflow can be utilised as a means of distributing water thereby reducing infrastructure requirements and potential development impacts. ■ Can be used as a hydraulic barrier to prevent seawater intrusion or contain aquifer contamination. ■ Useful where native groundwater is of poor quality (if appropriate attenuation time is applied).[a]	*Aquifer Hydrogeology* ■ Potential to modify natural patterns of inter-aquifer leakage (can be a positive impact in some situations, particular where the water table aquifer is depressurised). ■ If operating pressured too, high potential to rupture confining beds causing cross aquifer contamination. ■ If in the unlikely event contamination of the aquifer occurs, options for water quality remediation may be limited.
		System Development, Operation, Maintenance ■ Relatively small footprint therefore applicable in urban areas where space is at a premium.[d] ■ Storages can be small with multiple fill and empty cycles through harvest season. ■ Can increase available water without the need to increase existing impoundment structures thereby maximising existing capital investment. ■ Operation suitable for remote operation via telemetry. ■ High level of monitoring and control of what is recharged. ■ If appropriately designed wells are relatively low maintenance compared to surface infiltration systems. ■ Schemes can be incrementally expanded as demand increases ■ Can be used for multiple water sources rainwater, urban stormwater runoff, and treated wastewater.	*System Development, Operation, Maintenance* ■ Requires detailed knowledge (investigation) of subsurface conditions and potential impacts for a successful scheme.[d] ■ Recharge water quality requirements to mitigate clogging are usually high i.e. water normally requires pre treatment to reduce turbidity and/or other possible contaminants. ■ Potential dissolution of aquifer matrix materials. ■ Technology can be more complicated and expensive than simple infiltration basin or other methods.[d] ■ Requires careful control of injection rates and air entrainment to prevent binding up of unconsolidated sediment aquifers. ■ Depending on well construction, remediation methods to manage clogging may be limited. ■ If a wetland is used as part of the pre-injection treatment periodic removal of sediments is required. If sediments contain high levels of contaminants require special procedures for handling and disposal which can be costly.
Shallow "Vadose Zone" or Dry Well Injection	■ Injecting water above the water table in unconfined aquifers. ■ Where: - Depth to groundwater is significant	*Environmental / Social / Cultural* ■ The same advantages as Deep Well Injection methods apply. ■ Reduce nutrients in agricultural runoff.	*Environmental / Social / Cultural* ■ The same limitations as Deep Well Injection methods apply.

Method	Technique	Advantages	Limitations
	(>20 m). - Groundwater tables have been lowered significantly through over exploitation. - Distant from hydraulically connected surface water ways.	*Aquifer Hydrogeology* ■ Likely to be successful with significant distance from surface waterways (i.e., long residence time within the aquifer) ■ Aquifer is used to improve water quality and pathogen attenuation. ■ The same advantages as Deep Well Injection methods apply.	*Aquifer Hydrogeology* ■ Unlikely to be successful in close proximity to waterways as lateral outflow from the aquifer is likely to reduce any beneficial impact of recharge. ■ The same limitations as Deep Well Injection methods apply.
		System Development, Operation, Maintenance ■ Existing infrastructure (dry wells) can be used, reducing the overall costs of a scheme reactivating stranded assets.	*System Development, Operation, Maintenance* ■ Additional costs to connect wells together to create a network of recharge wells. ■ Old wells may be in poor condition through disuse ■
Infiltration Basin	■ Surface water is diverted into infiltration ponds and allowed to infiltrate (through the unsaturated zone) into an underlying aquifer. ■ A series of ponds are typically operated on a rotational basis to enable basin maintenance and maximisation of infiltration capacity. ■ Extraction is via a pumped well nearby, or at some position downgradient of the recharge location.	*Environmental / Social / Cultural* ■ Can be used as indirect means of enhancing local vegetation and birdlife habitats. ■ Intermittent floodwater can be stored for later recovery. ■ Easily integrated into landscape. ■ Can be constructed in stream channels if legislation permits. ■ Retention basins can be used as a balancing storage to meet summer demand. ■	*Environmental / Social / Cultural* ■ Storage of surface water may increase breeding of surface water related disease.
		Aquifer Hydrogeology ■ The same advantages as Shallow Well Injection methods apply. ■ Percolation through the unsaturated zone provides rapid attenuation of some contaminants.[a] ■	*Aquifer Hydrogeology* ■ Clogging of pore space, bed erosion during floods, varying infiltration velocities, changing redox conditions (e) ■
		System Development, Operation, Maintenance ■ Expected flows can be accommodated by constructing basins of different sizes. ■ Clogging can be mitigated through design or pre-treatment. ■ Intake can be stopped during periods where source water is of poor quality. ■ Relatively easy to maintain. ■ Generally relatively cost effective compared to deep bores, depending on land values.	*System Development, Operation, Maintenance* ■ Not suitable on fill sites or slopes.[d] ■ Risk of groundwater contamination in coarse soils. ■ Periodic maintenance to remove silt to maintain infiltration efficiency. ■ If silt contaminated may require special handling for disposal which can be costly.
Induced Bank Infiltration / Riverbank Filtration Scheme	■ Pumping from an aquifer that is hydraulically connected to a lake/river induces seepage from the surface water body.[a] ■ Commonly used in alluvial aquifers in Europe for improving water quality.	*Environmental / Social / Cultural* ■ Improves water quality	*Environmental / Social / Cultural* ■ May impact on ecosystems or third parties during periods of low flow in the river. ■ May lead to an increase in total river diversions during summer periods when flows required to meet environmental needs. ■ Cultural issues associated with mixing of the two water bodies.

Method	Technique	Advantages	Limitations
	■ Also used to improve water quality in adjacent aquifers. ■ Requires a constant demand to use water that is pumped from the aquifer to draw in water from the river.	*Aquifer Hydrogeology* ■	*Aquifer Hydrogeology* ■ Contaminants from the surface water may be drawn down into the aquifer system resulting in possible long term contamination of the aquifer.[d]
		System Development, Operation, Maintenance ■ Possibility to extract large volumes of water (only limited by the filtration capacity of the bank), including drawing on groundwater stored in the aquifer. ■ Improved security of supply and lower susceptibility to being affected by variations in the surface water source such as flooding, turbidity and maintenance of intake facilities. ■ Can be used as pre-treatment for recharge through wells or infiltration basins. ■ Treatment requirements are reduced compared to using surface water directly. [d]	*System Development, Operation, Maintenance* ■ Stream bed clogging can occur during extended periods of low flow in the river, resulting in a reduction in abstraction capacity.
Infiltration Gallery	■ Infiltration via buried trenches in the unsaturated zone into an unconfined aquifer.[b]	*Environmental / Social / Cultural*	*Environmental / Social / Cultural* ■ Clogging issues difficult to remediate and require ongoing maintenance ■ Problems with air entrainment in unsaturated portion of aquifer reducing infiltration efficiency ■ Smaller area for infiltration compared to spreading basin, so are less effective for regional scale applications. ■ Possibility of groundwater contamination in coarse soils. ■
		Aquifer Hydrogeology ■ Can be used where shallow impermeable clays may impede vertical infiltration. ■ Percolation through the unsaturated zone provides rapid attenuation of some contaminants.[a]	*Aquifer Hydrogeology*
		System Development, Operation, Maintenance ■ Relatively cheap and easy to construct compared to recharge wells. ■ Intake can be stopped during periods where source water is of poor quality. ■ Intermittent floodwater can be stored for later recovery. ■ Retention basins can be used as a balancing storage to meet peak demands.	*System Development, Operation, Maintenance*
Infiltration Dams	■ Surface and subsurface infiltration dams in stream beds and wadis are used to capture or slow down runoff. ■ Filled annually or perennially, larger dams can be used to release water for infiltration along the streambed.[a]	*Environmental / Social / Cultural*	*Environmental / Social / Cultural*
		Aquifer Hydrogeology	*Aquifer Hydrogeology* ■ Slow recharge rates, groundwater contamination, cost of extraction, recoverable fraction.[c] ■ Restricted to riparian aquifer (shallow profile)

Method	Technique	Advantages	Limitations
		System Development, Operation, Maintenance ■ Low technology structures. ■ Many small structures can help to reduce soil erosion.[(d)] ■ Low evaporation rates, widely distributed, operation efficiency, available on demand water quality.[(c)]	*System Development, Operation, Maintenance* ■ Silt needs removing.[(a)] ■ Large storm floods wash in stream structures away which requires rebuilding and opportunity for harvesting lost.

Notes:

[a]. IAH-MAR (2003),

[b]. MAR guidelines SA

[c]. NNC IAH (2002)

[d]. International Groundwater Resource Assessment Centre (2008)

[e]. Dillon (ed) 2002

3 ASSESSMENT AND DEVELOPMENT OF AMAR SCHEME

By following a logical process for the planning and implementation of MAR projects, the probability for ultimate success of the project is maximised. An essential element of the process is a phased approach, in which the level of effort and associated financial investment is commensurate with the level of risk. Development of MAR schemes typically follow a sequence of key stages, as listed below:

- Concept design
- Preliminary investigations
- Regulatory approvals
- Construction
- Commissioning trials
- Implementation and operation

From the above, the following sections briefly outline the considerations for concept design and the investigations that are typically required in the development of MAR schemes.

3.1 CONCEPT DESIGN

Concept design generally involves the preliminary development of a MAR concept based on broad knowledge of the local geology, hydrogeology, water quality, water demand and variability, and water availability. It is important that this phase clearly defines the overall recharge objectives and/or purpose of the scheme. This is something that is commonly overlooked and occasionally leads to projects that are located incorrectly or within an inappropriate aquifer, or that fail to provide the degree of benefit that could otherwise have been achieved (Pyne, 2005). The concept design may include consideration of the regulatory framework including water availability and potential environmental effects associated with the MAR scheme.

Commonly, the most time consuming part of the concept design stage is the assessment of hydrogeology. This is fundamentally important as it dictates the selection of suitable storage zones, recharge water sources and treatment requirements, and usually affects the location and design of the MAR facility and associated infrastructure. While the main aquifer to be recharged is commonly obvious it is important to consider all options as attention is typically focussed on shallow aquifers for which there is the most information, while deeper less well understood aquifers may have equal or better storage potential. For example, there may be an opportunity for "stacking" the storage zones where multiple aquifers are recharged at a single site, thereby saving on infrastructure investment.

3.2 INVESTIGATIONS

Table 3 provides an overview of the investigation required at various stages of MAR development.

Table 3. *MAR Investigations at various stages of project development (modified from NRMMC, 2009).*

Investigation Stage	Issues Addressed
1. Desktop	▪ Type and scale of scheme ▪ Source-water availability ▪ Compatibility with planning framework ▪ Existence of a suitable aquifer ▪ Source-water, native groundwater and end-use environmental values ▪ Similarity to other successful MAR projects ▪ Management capability ▪ Planning and development requirements ▪ Preliminary evaluation of project viability
2. Preliminary Investigations	▪ Source-water quality ▪ Source-water catchment land use assessment ▪ Groundwater quality ▪ Soil, aquifer and aquitard hydraulic characteristics ▪ Aquifer storage competence ▪ Groundwater pressures and gradients ▪ Reactions between recharge water, groundwater and aquifer materials ▪ Water treatment options and effectiveness ▪ Management of clogging ▪ Biodegradation and inactivation of contaminants (fate and transport)
3. Detailed Investigations	▪ Effectiveness of preventative measures and operational controls ▪ Recovery efficiency ▪ Size of attenuation and impact zones ▪ Targeted studies covering identified hazards

4 CONSTRAINTS AND RISKS

DWAF (2007) provides a good overview of the constraints and risks associated with developing MAR schemes. The following has been adapted from there.

It is not possible to implement MAR schemes in all environments. The successful implementation is based on a number of criteria – some of which have been mentioned previously within this report. If the necessary assessment of these criteria is undertaken to a sufficient level of confidence, then the risk of scheme failure is small.

In the feasibility stage of MAR projects, most potential risks are identified and an assessment of their severity is made. The ability to deal with the risks usually hinges on economic and management factors. However, in some cases the scale (and to a lesser extent the nature) of the risks only become apparent during operation.

The constraints and risks of implementing artificial recharge usually comprise the following:

1) ***Clogging.*** MAR generally results in an increased resistance to flow near the point of recharge. This is a result of clogging or plugging, which results in a decreasing rate of recharge or the need to continually increase the recharge head to maintain a constant recharge rate. As indicated previously, clogging can be caused by physical factors (such as air entrapment and suspended matter), bacteriological factors and chemical factors. In an ASR well, clogging also has a negative impact on the recovery of recharged water, since it increases drawdown during pumping (if the recovery borehole is clogged).

2) ***Uncertainty in aquifer hydraulics.*** In the case of new MAR schemes that involve deep aquifers or saline aquifers, little will be known about the aquifers' hydraulic properties. This will either mean that intensive research should be conducted on the aquifer prior to implementation, or that an extensive monitoring system is installed given acknowledgement that the project would be commissioned with an acceptable level of risk (albeit some risk).

3) ***Recovery of stored water.*** Where the characteristics and extent of the aquifer are known in sufficient detail, the MAR scheme can be located and designed, and water levels can be managed to prevent losses of recharged water. *Recovery efficiency* is of concern in borehole injection schemes where the quality of the recharge water and the native groundwater are vastly different. I n the case of ASR systems, recovery efficiency is defined as the percentage of water volume stored that is subsequently recovered, while meeting a target water quality criterion (Pyne, 1995). The water quality criteria are typically total dissolved solids (TDS), electrical conductivity (EC) or chloride concentration. Most schemes can be developed to 100 percent recovery efficiency, except those in very transmissive, highly saline aquifers which typically reach 70 to 80 percent efficiency (Pyne, 1995).

4) ***Controlled recovery by different users.*** The concept of whoever stores the water has the right to recover it is generally accepted throughout the world. It would be highly problematic if there was uncontrolled usage of the stored water.

5) ***Regulatory constraints.*** Storage of water in the sub-surface needs to comply with the relevant environmental legislation. From the South African experience, in certain circumstances, approval of a scheme may take a long time, or even be prevented, since implementation of new legislation is untested in relation to MAR.

6) ***Damage to aquifers.*** This concern refers to the negative effects of recharge such as the precipitation of solids, the dissolution of aquifer material and of contaminants such as arsenic. Precipitation has been observed near injection boreholes, evident as clogging, but has not been observed as widespread aquifer clogging. The dissolution of arsenic has been observed in a number of instances, and needs to be assessed in the feasibility stage of most projects. Aquifer collapse, due to large-scale dewatering during the recovery stage of the artificial recharge cycle, may be a concern for specific aquifer types (such as unconsolidated, unconfined aquifers). Most artificial recharge schemes around the world are in these types of aquifer, but this problem has not been widely observed.

7) ***High outlay before feasibility of ASR can be established.*** In certain circumstances (e.g. where there is a poor understanding of the hydraulic properties of the aquifer), it may require a high financial outlay in order to establish the feasibility of the scheme. This will need to be compared with the feasibility studies required for other options.

8) ***Operational issues.*** Lack of experience can be an obstacle to artificial recharge development.

9) ***Environmental concerns relating fluctuating groundwater.*** MAR could result in groundwater levels being raised above and below the norm, and this can have negative environmental consequences such as affecting groundwater level dependant ecosystems, increased aquifer vulnerability to contamination and sinkhole formation in karst aquifers.

5 INTERNATIONAL CASE STUDIES

This section provides an overview of a number of MAR projects in similar alluvial aquifer settings elsewhere in the world. The objective of this section is to provide a broad understanding of how MAR has been used in these settings and demonstrate that proof of concept has been achieved for a range of conditions and techniques. Significantly more literature is available than summarised within the scope of this review.

MAR is not a new concept. For centuries, nomads of the Kara Kum Plain desert in Turkmenistan have enhanced recharge by diverting infrequent surface runoff from clay-rich areas to pits dug into porous sandy areas via long trenches. In Europe, artificial recharge schemes have been in operation for over a hundred years. At Mt Gambier in Australia, surface runoff has been diverted into limestone pits and wells for over a hundred years. The scheme is still an integral part of the city's water supply system (DWAF, 2007).

Although MAR is practised throughout the world, much of the literature, research and guideline documents are sourced in Europe, the USA, Israel and Australia. Countries such as India, Pakistan, Kuwait, Japan, Namibia and many others, have contributed to the international pool of knowledge in various degrees, usually, but not exclusively, with well documented case studies (DWAF, 2007).

5.1 UNITED STATES OF AMERICA

The USA has a long history of both infiltration and injection schemes. Text books, guideline documents, regulations and many case studies have emerged from the USA, particularly over the past two decades. This section focuses on hydrogeologically relevant MAR schemes in the USA, of which the oldest, a seasonal storage scheme in New Jersey, has been in operation since 1968. In most cases the aquifers used for storage are confined, with the MAR boreholes drilled through the confining sediments into the most porous and permeable parts of the aquifer.

5.1.1 WEBER RIVER BASIN AQUIFER STORAGE AND RECOVERY (WRBASR), UTAH

The Weber River is the primary source of recharge to aquifers in the Weber Delta district. The Weber Delta, which covers an area of 1,000 km^2, was deposited mainly by the Ogden and Weber Rivers and consist of interlayered, unconsolidated gravels, sands and fine grained deposits which are approx 450 m thick at the mouth and thin to the north, west and south (Lowe et al, 2003).

In March 2004, as part of a pilot study, water from the Weber River was diverted into four shallow (0.3 to 0.6 m deep) infiltration ponds on course grained river deposits covering an area of approximately 0.015 km^2 (Lowe and Hurlow, 2005).

Figure 2. *Photographs of WRBASR pilot study.*

A) Looking east to the mouth of Weber Canyon (site is middle right margin)
B) Infiltration ponds (Lowe and Hurlow, 2005)

By July 2005, 990 ML had been recharged into the aquifer beneath the project site, resulting in a groundwater level rise of approximately 0.3 m at a monitoring well on site. A low permeability layer 150 m below ground surface caused the infiltrating water to spread laterally, resulting in a lower than anticipated groundwater level rise (Lowe and Hurlow, 2005). However, during the same period, groundwater levels in nearby wells had declined 1.2 to 3 m indicating groundwater levels on site would have declined in absence of recharge. Lowe and Hurlow (2005) report a net water level rise of approximately 1.2 m.

As a result of this pilot, the Weber Basin Water Conservancy District has purchased the site property with plans to implement an ASR scheme at the site on a permanent basis.

5.1.2 NAUSP BASIN RECHARGE FACILITY, ARIZONA

The New River Agua Fria Underground Storage Project (NAUSP) is located on the western side of the Phoenix metropolitan area. The key driver for the implementation of the project was the extensive depletion of the graben valley fill alluvial aquifers due to groundwater abstraction for agricultural use which resulted water levels declines of over 100 m. The impact of this drawdown is known as the Luke Cone of Depression and extends over an area of more than 370 km^2. In some places ground subsidence of over 5.5 m has occurred in response to aquifer depressurisation.

The NAUSP recharge facility comprises 7 recharge basins covering a total area of 526 hectares and recharges in excess of 170 ML/day of water diverted from the Colorado River via the Grand Canal. One of these recharge basins is shown in **Figure 3**.

The recharge facility has been successfully operating since 2007 and after some initial issues with basin floor clogging this has been overcome through routine basin maintenance and rotation of basins. Restrictions in the hydraulic capacity of basin soils have been overcome by maintaining a relatively shallow water depth (<0.6 m) which provides maximum infiltration rate.

Figure 3. *Recharge basin at the NAUSP recharge facility (note the desiccated clogging layer).*

5.1.3 LAS VEGAS VALLEY WATER DISTRICT, NEVADA

MAR operations began in the Las Vegas Valley at two wells in 1987. The aquifer being recharged comprises basin-fill clastic deposits from the surrounding mountain ranges consisting of sandy gravels with a trace of sandy clay. As of January 2005 the Las Vegas Valley wellfield contained 99 active wells recharging 390 ML/d (4.5 m^3/s), 77 of which are equipped for pumping. This is one of the largest ASR operating wellfields in the world. The expanded wellfield is located on an alluvial fan in poor to highly cemented sands and gravels. Production intervals from within the sediments are generally semi-confined although unconfined conditions frequently develop associated with delayed drainage.

Individual well yields average 13.5 to 22.7 ML/d (156 to 262L/s). Aquifer hydraulic characteristics are highly variable within the sedimentary sequence. Transmissivity ranges from 12 to 3,726 m^2/day and storativity is 0.001 in semi confined areas. The specific yield ranges from 5 to 30 percent with an average of around 15 percent.

The system operates with paired wells one for recharge and a second for recovery. The production wells are completed at depths of approximately 366 mBGL, whilst the recharge wells are completed at slightly shallower depths at approximately 244 mBGL. The wells are constructed using 500 to 667 mm mild steel casing with stainless steel wire wrap screens. Recharge rates vary among the wells, with a typical range of about 3.8 to 11.4 ML/day (43 to 132 L/s).

Original technical concerns included the potential for calcite precipitation, trihalomethane (THM) formation and well clogging. To date the calcite precipitation issue has not become a problem as predicted by the PHREEQE modelling. THM formation occurred only around the wellbore, reflecting aerobic conditions in the storage zone and were easily pumped out each summer prior to placing the well in service. Well clogging has also not eventuated, which suggests the periodic backwashing during recharge as part of the standard operating procedure is effective.

After 16 years of recharge the average depth to water levels in the original MAR wellfield ranges between 20 m and 44 mBGL. This represents a recovery in the watertable of over 30 m since the system was commissioned.

5.1.4 CITY OF SCOTTSDALE WATER CAMPUS, ARIZONA

Since 1951 the city of Scottsdale has grown in population from less than 2,000 people to more than 230,000 people. An Integrated Water Master Plan was developed to improve the sustainability and security of the community water supply, which was historically reliant on surface water resources for more than 70% of the community requirements (Carrollo Engineers, 2008). This created concerns with regard to security of supply during drought and in response to climate change, and led to a strategy to increase groundwater supply, while acknowledging that groundwater needed to also be managed in a more sustainable manner.

The implementation of MAR initiatives over the past decade has resulted in the supply of an increased proportion of groundwater (>50%) to the Scottsdale municipal system. One of the main recharge facilities is at the Scottsdale Water Campus where vadose zone wells and ASR wells are used to artificially recharge treated wastewater and surface water harvested during periods where excess is available.

The vadose zone recharge system comprises 27 operational wells which are 100 mm in diameter and up to 55 m deep within a sequence of alluvial sediments. Combined, these have a daily recharge capacity of 45 ML, which represents an average recharge rate of approximately 20 L/s per bore.

In 1997, a deep ASR well was drilled within the Scottsdale Water Campus to a depth of 497 m through a 320 m thick sequence of alluvial sediments and into underlying metamorphic basement. This well has proven to be highly effective, with rates of 114 L/s and 157 L/s achieved for recharge and recovery, respectively. The success of the ASR well has resulted in a decision to drill an additional four wells for the purpose of deep recharge and recovery (Tatlow and Brown, 2007).

5.1.5 MAIN LESSONS FROM THE USA

Probably the best "judge" of ASR schemes are the operators themselves – the agencies responsible for day-to-day operations and scheme maintenance. Many of these agencies also operate other schemes, including surface water schemes, and they are thus well-placed to have a good perspective of a range of different schemes. Key perceptions, issues and concerns raised by 46 operators in the American Water Works Association (AWWA) ASR survey (AWWA, 2002) are summarised below.

SATISFACTION WITH ASR SCHEMES

Forty six operators were interviewed and the results are graphed in **Figure 4**. Only one out of the 46 respondents stated that their scheme would not use ASR again, as there were geological constraints that had prevented the system from operating as planned. In this case, it is presumed that either the permeability or storage capacity of the aquifer is not suitable for ASR; or that the recovery of the water is problematic due to steep hydraulic gradients or uncertainty in groundwater flow characteristics; or that there are problem constituents in the aquifer such as arsenic. Three respondents had reservations due to cost-benefit ratios and lower than expected pressure heads in the aquifers. The remaining respondents were satisfied, although three respondents stated that they would make changes to how they would develop their systems with the benefit of hindsight (DW&F, 2007).

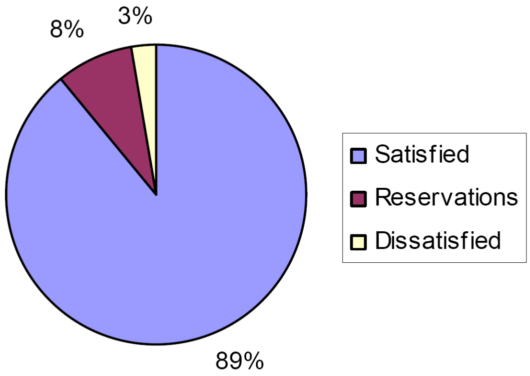


Figure 4. *Satisfaction with ASR schemes.*
(Source: AWWA, 2002).

The benefits and challenges relating to MAR in the USA as specifically emphasised by the operating agencies are as summarised in **Table 4**.

Table 4. *Summary of benefits and challenges as seen by MAR operators in the USA.*
(after DWAF, 2007).

Benefits	Challenges
▪ Water conservation and reuse (especially in states that allow treated effluent MAR); ▪ Recovery of groundwater levels; ▪ Prevention of saltwater intrusion; and ▪ Increasing the capacity to meet water demands while minimising impacts on the environment and protected species habitat (particularly in comparison with surface reservoir development.	▪ Permitting issues; ▪ Geochemical problems; ▪ Geological constraints (e.g. low permeability, low storage capacity, poorly understood groundwater flow characteristics); ▪ Water rights issues (ownership of injected water); and ▪ Public relations.

Some agencies reported problems with:

- Clogging (which is more common when the recharge water is not of drinking quality)
- Lower than expected yields.

In many instances, MAR agencies indicated that there would have been value in extending the pilot test stage of the projects (particularly where geochemical problems were anticipated), as this would have affected the design of the schemes, and ultimately made the operation and maintenance more efficient and cost-effective. A key lesson from this is that feasibility studies need to be sufficiently comprehensive to allow a good indication of the viability of the schemes.

5.2 SOUTHERN AFRICAN

5.2.1 OMARURU RIVER DELTA, NAMIBIA

The Omaruru River Delta Aquifer (OMDEL) is one of two major aquifers of the Namibian coast supplying water to the three coastal towns and a large open pit mine.

River run off is collected in the 40 Mm^3 OMDEL Dam constructed in 1993 and after settling to remove silt and clay the water is released in a controlled manner and directed along the 6 km of the riverbed to recharge basins in constructed sites in the sand and gravel river bed. Photographs of this recharge scheme are shown in **Figure 5**.

Figure 5. *Photographs of Omaruru River Delta Artificial Recharge Scheme.*

a) Aerial view of the OMDEL dam
b) Pre sedimentation basin in front of flow divider with infiltration basin in the background (IAH-MAR, 2003).

The schemes successfulness is exemplified by the statistics recorded for the rainy season of 1997, which was considered a good rain season. During this season, 53% of the flood event was artificially recharged, which was more than seven times the expected artificial recharge based on historical performance. It was calculated 29% of the water was lost to evaporation and 11% remained in the OMDEL Dam.

5.3 HUNGARY

There are many examples of Induced Bank Infiltration in Hungary. This is mostly due to the large river systems which flow through the country resulting in areas of flooding in the winter months. In some areas, there is an overlap in the locations which suffer from flooding in the winter and drought in the summer (**Figure 6**) which makes Induced Bank Infiltration particularly suitable.

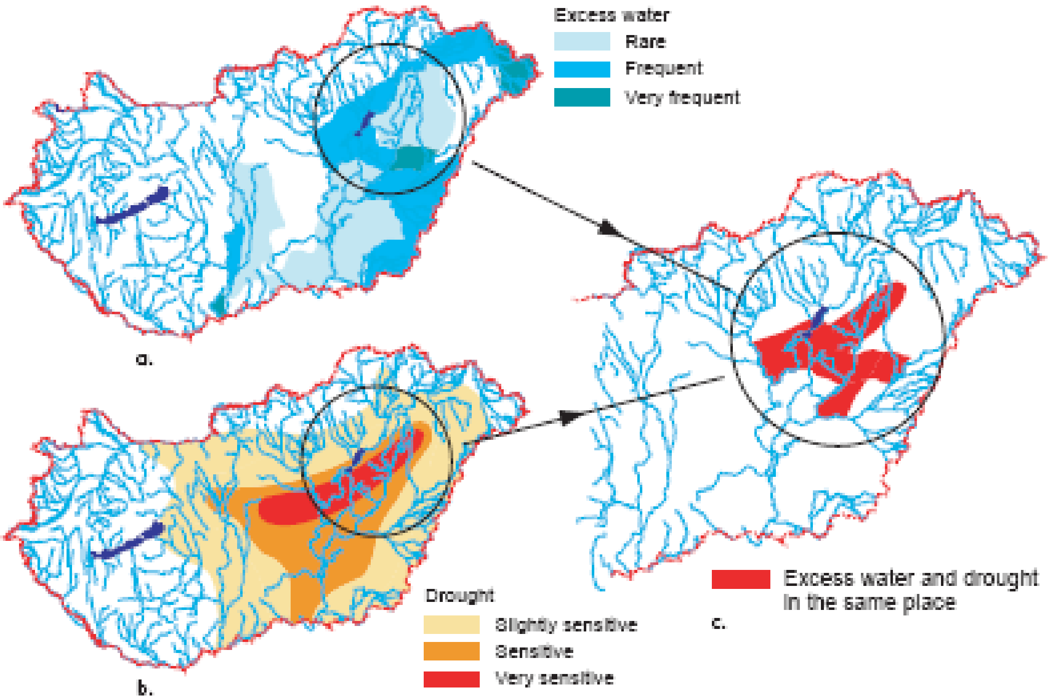


Figure 6. *Existing and future bank filtered river sections in Hungary.*

(NNC-IAH, 2002).

5.3.1 SZENTENDRE ISLAND

Due to the lack of thickness in the gravel terrace, specialist well shafts have been developed with a horizontal screen. Although this makes the travel time very short, the bank filtered water does not require any further treatment and the average abstraction in this well field is 300,000 m^3/day contributing 60% to the drinking water supply of Budapest.

5.3.2 CSEPEL ISLAND

In the Szigetszentmiklos well field of Csepel Island a combination of bank infiltration and artificial recharge from an infiltration basin are used to improve the water quality. The bank filtered water is moving through an artificially made bank, constructed of dredged sediment. Due to the high organic content of the bank material, the water is reduced; consequently high iron and manganese content can occur in the wells. As active protection, recharge ponds have been created between the bank and the well field. The infiltrated water is pumped from the Danube branch, providing sufficient dilution of the original bank filtered water. The reed cover on the infiltration ponds have been found very efficient for maintaining infiltration capacity.

5.4 CYPRUS

5.4.1 EZOUSAS AQUIFER STORAGE AND RECOVERY

Substantial alluvial aquifers in Cyprus constitute the most important aquifers in the island. The Ezousas aquifer is based in a closed unconfined basin where the valley infill consists of layers of sand and gravelly material of moderate to high permeability, with occasional silty clay lenses and silt. Infiltration occurs in the rainy season (November to April) and as infiltration is generally in excess of outflow to the sea, the water table rises and saturation can occur. Due to the river bedrock lying deep below the present sea level coast there is potential for saline intrusion in the aquifer. Part of the system included a network of monitoring wells to observe the position of the seawater-freshwater interface (Christodoulou et al, 2007).

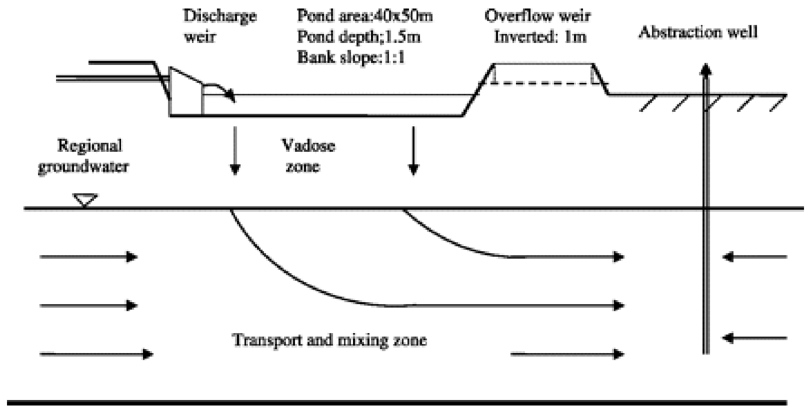


Figure 7. *Schematic diagram of Ezousas recharge basin.*

A pilot study consisting of eight tests at several locations was implemented. The recharge network consisted of five shallow infiltration basins arranged in series. Each infiltration basin contained two, four or six recharge ponds, each basin having a surface area of 2,000 m^2 and a depth of 1.5 m. A recharge pattern of wet-dry fill cycles was implemented in order maintaining a significant unsaturated zone so as to maximise the amount of water recharged and optimise water quality (Christodoulou et al, 2007).

Extraction was via six wells located between infiltration basins. It was found the 5 ML of recycled water produced annually from the waste treatment plan could be recharged, provided the abstraction-recharge cycle was continuous. This has prevented either seepage to the sea or seawater encroachment on the aquifer. Since 2004 6.6 ML has been recharged to the aquifer and 8 ML extracted, with the difference being due to natural recharge and storage within the aquifer.

6 NEW ZEALAND CASE STUDIES

6.1 EYRE RIVER AQUIFER RECHARGE TRIAL

During September 2005 a managed aquifer recharge trial was conducted on the Eyre River in the Horreville area using water derived from the Waimakariri Irrigation Scheme. The trial involved the discharge of approximately 2.7 m^3/s into the channel of Eyre Rive at the Warren Road siphon in close proximity to the river over a continuous period of 24 days.

The trial was undertaken during a period when the Eyre River was naturally dry and groundwater levels relatively low and stable. During the trial period groundwater levels were monitored in a network of bores located around the river channel and concurrent gaugings were undertaken at a series of points downstream to quantify the rate of flow loss from the river bed.

Over the period of the test the downstream extent of surface flow increased as groundwater levels in the surrounding unconfined aquifer increased, reaching a distance of approximately 12 kilometres at the end of the trial period. Groundwater levels rose relatively rapidly following commencement of the trial in bores situated close to the river near the discharge point. Groundwater levels in bores further downstream and set back from the river showed a progressive increase over time as the extent of surface flow increased downstream. Overall, groundwater level monitoring indicated the trial resulted in a rise in groundwater levels of more than 2.5 metres over an area of approximately 4,315 hectares extending approximately 15 kilometres along the length of the river and extending between 0.5 and 5 kilometres either side of the river channel.

Near the end of the trial period a series of concurrent gaugings undertaken at various points downstream of the discharge point indicated a general decrease in flow downstream of the discharge point. Gauging results suggest some return flow to the river channel in upper portion of the trial reach possibly due to the peak in groundwater levels in this area. However, downstream reaches indicated an infiltration rate of between 0.3 and 0.7 L/s/m across the lower 6 kilometres of the flowing channel.

Following the end of the test groundwater levels remained elevated above pre-test levels for a period roughly equivalent to the test period in bores close to the river in the upper reach. Further downstream and remote from the river groundwater levels remained elevated for a period of 2-3 months over and area of approximately 3,800 hectares.

Overall, the release of water into the Eyre River channel demonstrated that managed aquifer recharge can effectively raise groundwater levels over a significant area. This indicates that augmentation of surface flow can be an effective method for the conveyance and storage of water in a riparian aquifer system. However, the main limitation highlighted by the trial was the limited residence time of the water in the aquifer system due to the highly permeable nature of the unconfined aquifer and high rate of groundwater throughflow. As a result, application of surface infiltration in close proximity to natural water courses in the Canterbury Region is likely to be limited to providing only relatively short-term augmentation of groundwater levels or stream baseflow rather than as an option to effectively utilise aquifer storage capacity to retain water for subsequent consumptive use.

6.2 WEST MELTON ARTIFICIAL RECHARGE TRIAL

The potential for artificial recharge of groundwater in the West Melton-Yaldhurst area was investigated by a Technical Advisory Group during the early 1990's. Initial investigations into the viability of this concept included a trial involving diversion of approximately 110 L/s of water into an infiltration basin located at the corner of Old West Coast Road and State Highway 73 over the period June to September 1991. Results of this trial indicated formation of a groundwater mound of at least 0.2 metres over an area of approximately 4 km^2 after 3 weeks of recharge (Callander et.al, 1991).

A second recharge trial was then conducted at Bells Road west Melton from August-October 1992 with a flow of approximately 112 L/s diverted to ground by way of an infiltration basin. Groundwater level monitoring in a network of 25 bores in the area surrounding the trial site did not indicate any appreciable rise in the water table that could reliably be distinguished from an above average seasonal water level recovery. The cause of the limited groundwater level response was in part attributed to the presence of lower permeability clay-bound gravel strata between the water table and underlying aquifer in which the monitoring bores were screened.

Given uncertainties in the interpretation of the initial monitoring results a further recharge trial was undertaken at the Bells Road site between June to September 1993. For the second trial changes were made to the operational methodology including:

- Installation of a shallow monitoring bore close to and in hydraulic connection with the infiltration basin; and

- Intermittent recharge into the pit (two weeks on, two weeks off) to generate a characteristic water level response that could be used to distinguish the effects of artificial recharge.

Groundwater level monitoring indicated the formation of a groundwater mound of approximately 0.5 metres in the shallow monitoring bore located 65 metres from the infiltration basin. However, no response to the recharge trial was again observed in deeper bores in the area. Soil analysis indicated the accumulation of approximately 9 percent by weight of silt in the upper 0.5 metres of soil in the 25m^2 infiltration basin with a consequent reduction in infiltration capacity.

Findings of the study supported the further investigation of artificial recharge as a method to mitigate low groundwater levels in the West Melton/Yaldhurst area. The potential for using recharge wells rather than infiltration basins was suggested as a means to overcome issues related to the semi-confinement of target aquifers. Findings of the report also highlighted that development of a clear understanding of the hydrogeological setting is a critical component of any artificial recharge project.

6.3 HERETAUNGA PLAINS GROUNDWATER ARTIFICIAL RECHARGE SYSTEM

The Heretaunga Plains artificial recharge trial in the southern Hawkes Bay region was initiated in 1984 to mitigate declining groundwater pressures within an artesian aquifer heavily utilised for domestic, industrial, agricultural and horticultural applications. The heavy reliance on the groundwater resource coupled with reduced recharge of the aquifer during prolonged dry periods, has resulted in abstraction exceeding recharge and serious concerns regarding the sustainability of this nationally significant groundwater resource.

The interconnected unconfined-confined aquifer system contains groundwater recharged from the Ngaruroro River at the inland margin of the plain approximately 20 km from the coast. At the coast the gravel aquifers extend to a depth of 250 m (Brown et al, 1999) with the deeper artesian aquifer covering an area of approximately 280 km^2. Natural leakage through the gravel bed of the river enters an unconfined aquifer and flows laterally for 6 km until it reaches a series of confining beds, then a further 12 km toward the coast under confined conditions (Koutsos and McBryde, 1989).

The recharge site is located over an unconfined part of the aquifer and comprises four shallow infiltration ponds. The recharge system utilises water from the Ngaruroro River which is diverted into the infiltration ponds through a sluice gate that is activated by a pre-set limit in river turbidity. Further reduction in suspended sediment within the recharge water is achieved using a pre-infiltration sedimentation basin prior to discharging into the infiltration ponds. An electric fish fence is used to prevent stranding of fish in the recharge ponds.

Natural recharge of the groundwater system from the Ngaruroro River is estimated to occur at an average rate of approximately 5.5 m^3/s, however this recharge significantly reduces during extended dry periods and flood-free years due to a reduction in channel forming activity and natural clogging of the river bed. The implementation of the Heretaunga Plains recharge trial system supplements the rate of natural recharge by 1 m^3/s (i.e. 20%), although the design allows for increasing the recharge rate by three times this amount (Koutsos and McBryde, 1989). The scheme was converted to a permanent recharge system in 1989, however was subsequently decommissioned after it was found that there was higher than anticipated connection with the Ngaruroro River.

As with the earlier examples, this case study indicates that while artificial recharge was proven feasible there is a need to have a comprehensive understanding of the hydrogeology to inform the most effective recharge design in terms of both location and technique. In this case a deeper MAR solution might well have proven sustainable over a longer term.

6.4 LEVEL PLAINS IRRIGATION SCHEME

The Level Plains Irrigation System near Washdyke in South Canterbury uses water abstracted from the Opihi River. An assessment of the groundwater recharge in response to irrigation shows that the irrigation is an effective groundwater recharge mechanism and has been estimated to supplement natural rainfall recharge by approximately 0.5 m^3/s or 15.7 x 10^6 m^3/yr (Bird, 1986), which equates to 400 mm/year over the 4,000 hectare scheme area. A proportion of this additional water could be abstracted by downgradient groundwater users, therefore enhancing the sustainability of the aquifer supply.

The relative merits of alternative recharge approaches were also considered and investigated within the Levels Plain area and reported in Bird (1986). These included recharge using an infiltration trench and a pit, with each site conservatively estimated to have enhanced groundwater recharge by approximately 600,000 m^3 over a 120 day period, equating to an average rate of 60 L/s (Bird, 1986).

Well recharge has also been undertaken for many years at a water supply bore at the Levels Golf Course. This has been reported to have been highly successful with no reported decline in production potential following extended injection at 20 L/s. Furthermore, the well has not been affected by clogging and hence has not required significant maintenance (Bird, 1986).

7 CONCEPT MAR SCHEME FOR CANTERBURY

Given the topical discussion surrounding the Central Plains Water (CPW) irrigation scheme and consents granted for surface water abstraction, a concept MAR scheme was developed for the Central Plains area in order to compare costs and benefits.

7.1 HYDROGEOLOGICAL PROPERTIES OF THE CENTRAL PLAINS AQUIFER

Information on the hydrogeological properties of aquifer materials in the Central Plains area is fundamental to understanding the ability of the aquifer system to store and transmit water, and hence feasibility for the MAR concept.

This hydrogeological knowledge is also important for helping to understand 'fate' of the recharge water and for determining the potential effects on downgradient groundwater users and the receiving environment. At the investigation and design stage the hydrogeological understanding needs to be both project and site specific, however for the purposes of this study the broader hydrogeological context is sufficient for the identifying potential schemes at concept level.

7.1.1 CONCEPTUAL HYDROGEOLOGICAL MODEL

The structure and hydrogeological properties of the Central Plains aquifer system is intimately related to the fluvial-glacial fan depositional environment, in particular the various glacial and interglacial periods (i.e. sea level change) and contrasting energy regimes between the inland erosional environment and lower level depositional environment. A conceptual representation of the Central Plains aquifer system is provided in **Figure 8** and the following sections describe the conceptual model with respect to geology and hydrogeology.

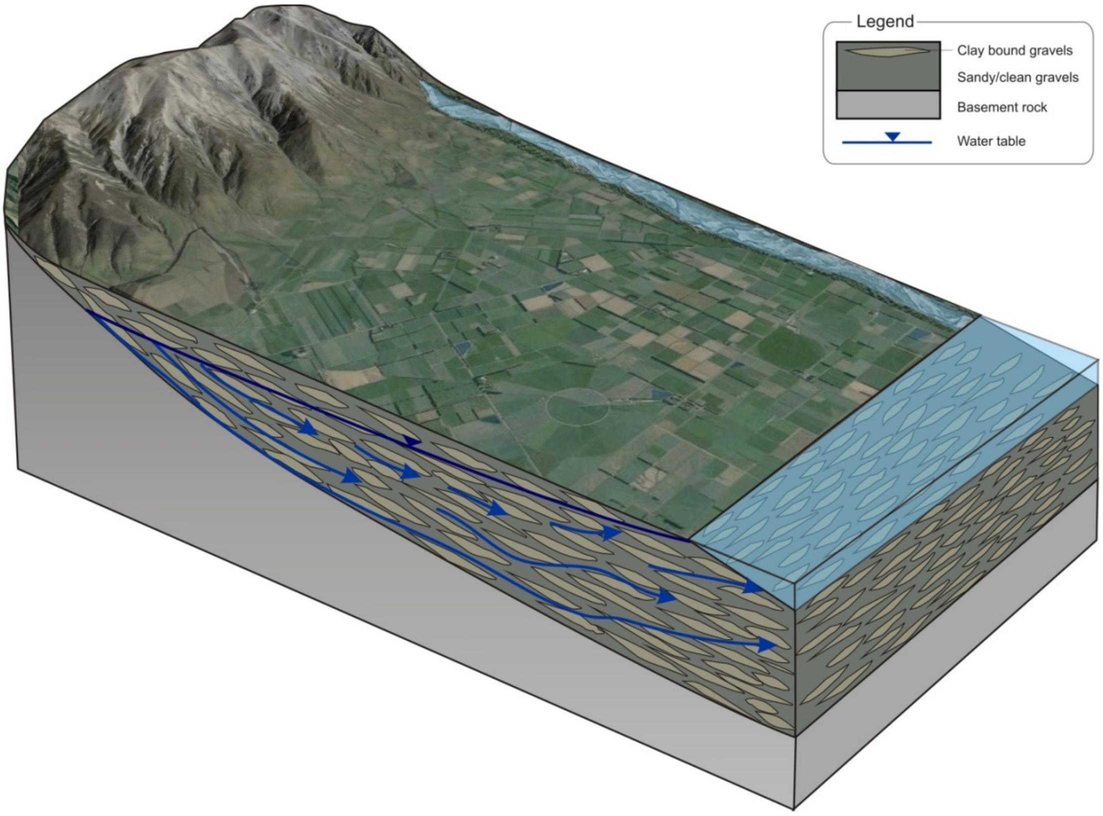


Figure 8. *Conceptual hydrogeological representation of the Central Plains Aquifer System.*

GEOLOGY

- The nature of fluvial-glacial fan deposition, being changeable in spatial scale and subject to reworking, is unlikely to be conducive to the formation of discrete, thick, spatially extensive and homogeneous deposits. Instead the stratigraphy is highly variable and comprises heterogeneous deposits that are typically lensoidal and semi-randomly distributed;
- Sediment sorting is a function of transport distance from the source and the energy dissipation downgradient. In the upper areas of an alluvial fan, alluvial layers are generally more coarse grained and intermixed than in the lower plains area, where the sediments become progressively finer and better sorted;
- The aquifer system becomes progressively confined with depth due to the mechanical compaction of the pile of fluvial-glacial sediments, comprising multiple layers and lenses of fine grained sediments interspersed with the coarser grained aquifers;
- The total thickness of the sediment pile in the Central Plains area is considered to be approximately 550 m. The hydraulic characteristics and water bearing potential of the deeper sediments is not well characterised due to a lack of deep drilling and testing below approximately 250 m.

HYDROGEOLOGY

- Away from the influence of rivers, depth to groundwater is typically greatest in the upper plains, while in the lower plains groundwater is generally encountered at shallow depths;
- Recharge and hence downward vertical pressure gradients generally occur in the upper plains;
- Negligible vertical pressure gradient over much of the middle plains due to horizontal flow significantly exceeding vertical flow under natural conditions;

- In the lower plains, topographic and bathymetric controls (i.e. incised waterways and the seabed) act as sinks or pressure relief blankets, which allow a low pressure zone to exist at the surface. This coupled with the high horizontal inflows and generally lower bulk permeability in the lower part of the plains, results in vertical upward pressure gradients to develop.

7.1.2 AQUIFER HYDRAULIC PROPERTIES

A significant amount of aquifer test pumping data exists for the Central Plains area, which provides a relatively comprehensive understanding of the distribution of key aquifer hydraulic properties, namely transmissivity, storage coefficient, and leakage. Results of a detailed review of reliable testing data from 54 bores for the Central Plains (SKM, 2008) and Ashburton Valletta (SKM, 2009) groundwater management areas are considered to be representative of typical hydraulic properties expected for the aquifers within the Central Plains, Ashburton River and Valetta groundwater zones. The results and key trends for the aquifers drilled and tested are summarised as follows:

TRANSMISSIVITY

Calculated aquifer transmissivity values range from 200 to 15,770 m^2/day with a geometric mean value of 2,050 m^2/day.

As illustrated in **Figure 9**, estimated transmissivity values appear to be weakly correlated to some extent with bore depth, although the limited number at tests at depths greater than 150 m implies that this observation is less reliable in this depth range. In general, the upper bound aquifer transmissivity appears to decrease with depth, the exception to this pattern being high transmissivity outliers near the Ashburton River. In this area the high calculated aquifer transmissivity values may be influenced both by the degree of reworking of the gravels materials adjacent to an active river channel as well as recharge from the river itself.

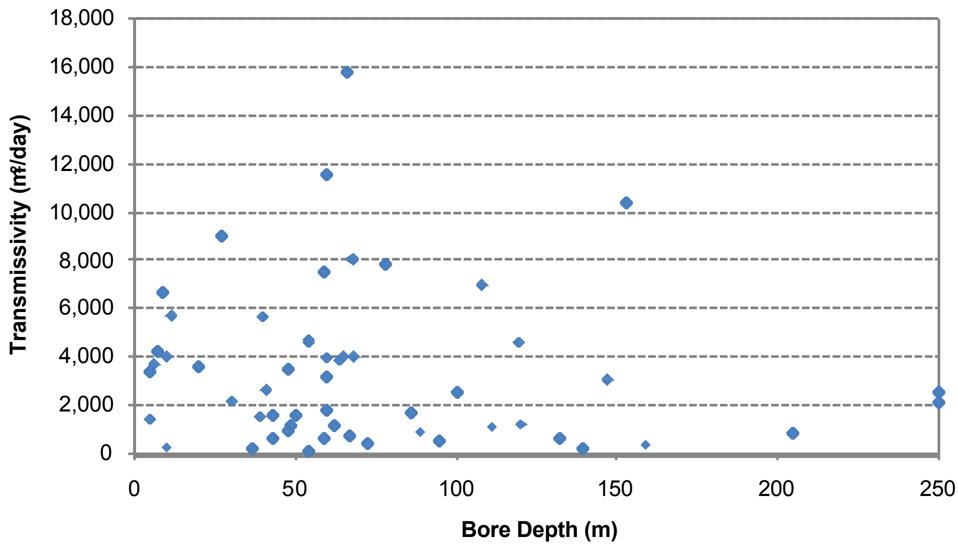


Figure 9. *Variation in transmissivity with depth.*

STORAGE COEFFICIENT

Calculated aquifer storage co-efficient values range from 4×10^{-6} to 0.36 with a geometric mean value of 5.6×10^{-4}. The higher values are representative of and unconfined clean gravel aquifer, although the upper bound figure is higher than would be expected, hence is likely to be an artefact of data quality or data analysis. The lower values are typical of semi-confined fluvial aquifers.

As shown in **Figure 10** the data show a clear break between higher values in shallow unconfined bores and those derived from deeper semi-confined/confined water-bearing layers. However, no obvious relationship with depth is evident in storage coefficient values from bores greater than 40 metres deep.

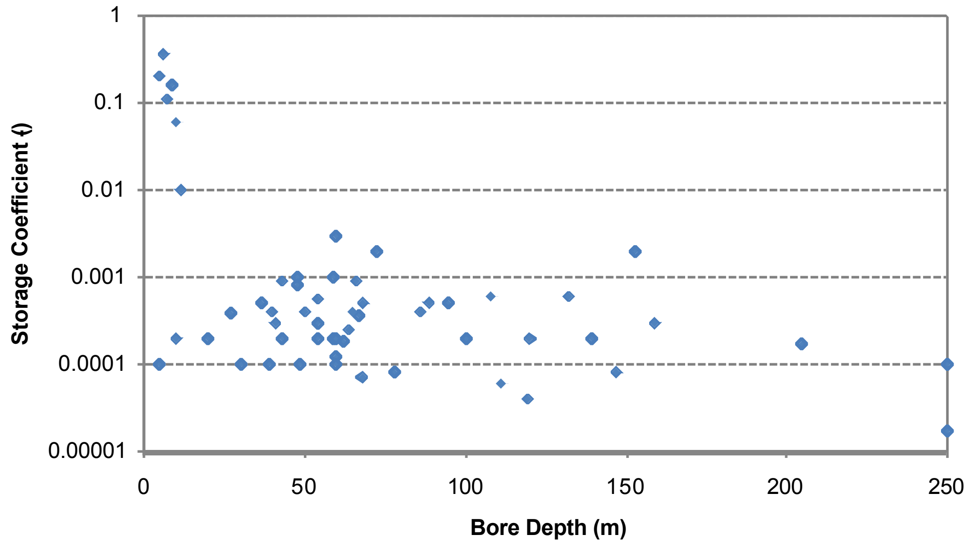


Figure 10. *Variation in storage coefficient with depth.*

The analysis showed no obvious spatial trends in calculated aquifer storage co-efficient other than the highest values are generally associated with shallow bores near the Ashburton River.

7.1.3 LEAKAGE FACTOR

The Leakage factor (symbol L; m) is the ratio of the aquitard conductance and aquifer transmissivity through the following expression:

$$L = \sqrt{\frac{T}{K'/B'}}$$

Where: T is aquifer transmissivity (m^2/day),
K' is aquitard hydraulic conductivity, and
B' is saturated thickness of the aquitard.

This term provides a combined measure of the resistance to vertical flow within overlying strata and the permeability of an aquifer.

Large leakage factor values indicate that there is a significant contrast between the transmissivity of the aquifer and the vertical conductance of the overlying aquitard(s), suggesting that potential to transmit water within the overlying strata is low in comparison to that within the underlying aquifer.

An implication of large leakage factors within deeper aquifers for abstractions and artificial recharge (MAR), is that depressurisation or repressurisation effects on shallow aquifer water tables will be smaller in magnitude, than the same abstraction or MAR occurring within the shallow aquifer directly (i.e. the effects is largely constrained within the target aquifer).

Calculated aquifer leakage values range within the zones considered range from 300 to 65,830 m with a geometric mean value of 2,521 m. This range extends from relatively leaky (lowest values) through to highly confined aquifer conditions (highest values). Most bores exhibit leakage factors in the range of 1,000 to 4,000 m, which given the average transmissivity above of 2,050 m^2/day, and assuming a saturated aquitards thickness of 50 m, relates to aquitard conductivity values of 1×10^{-8} to 1×10^{-7} m/s. These conductivity values are what would typically be expected for low permeability silts and clays, indicating that leakage over much of the area is likely to be at low rates.

Figure 11 shows the correlation between calculated leakage values and bore depth. The data generally shows that the leakage factor increases with depth, hence the aquifer is becoming progressively more confined. This suggests that the potential for vertical leakage is reduced in deeper water-bearing layers, which has significant implications for deep well MAR options.

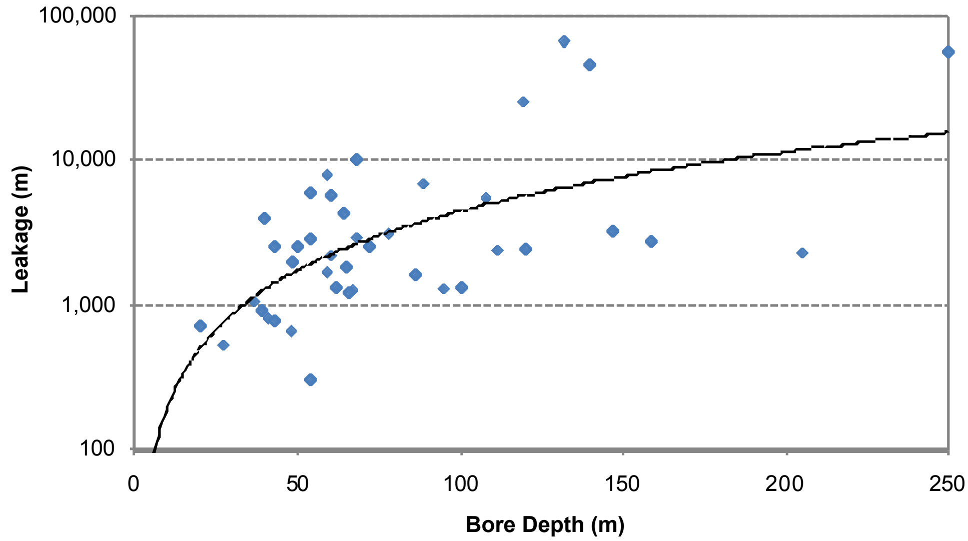


Figure 11. *Variation in aquifer leakage with depth.*

7.2 OVERVIEW OF MAR OPTIONS FOR CANTERBURY

A review of available technologies and relevant case studies indicate that MAR has good potential to enhance recharge of the Central Plains aquifers and help alleviate some of the emerging groundwater availability issues in the region. The general concept would involve capturing excess water available from one or more of the Canterbury river systems and recharging the aquifer using either basin and/or well recharge techniques.

Selection of the most appropriate recharge technique would require consideration of various site specific factors as described in **Section 3.** On the basis of the current hydrogeological understanding several generic concepts considered likely to be most applicable to the Canterbury setting are summarised in **Table 5** and illustrated conceptually in the various figures referenced in the table.

Table 5. *MAR Concept Options for Canterbury.*

Option	Target Aquifer	Location	Features
Infiltration Basins **Figure 12**	▪ Unconfined aquifer. ▪ Preferred sites would not have low permeability sediments at shallow depth. ▪ Where depth to water table is significant and hence storage potential is high.	▪ Middle of the Upper Plains at an intermediate position between river systems to minimise loss of recharge water back to the rivers. ▪ Reclaimed water recoverable downgradient in central and lower plains areas.	▪ No pre-treatment of source water for silt would be required, as this occurs in the infiltration basins. ▪ Could implement sediment forebays to reduce on-going maintenance costs to mitigate clogging. ▪ Permits water to mound in areas some distance from surface waterways, and hence percolate vertically downwards and horizontally down the plains. ▪ Would require reticulation infrastructure to convey water to recharge sites.
Shallow Injection Wells **Figure 13**	▪ Unconfined aquifer ▪ These wells could be used facilitate injection beneath shallow low permeability sediments. ▪ Well depths of 30 to 100 m	▪ Middle of the Upper Plains. Need to be located away from rivers to minimise potential returns to surface water. ▪ Reclaimed water recoverable downgradient in central and lower plains areas.	▪ Pre-treatment of source water would be required to prevent clogging. This could be achieved through the use of RBF wells as shown in **Figure 15**. ▪ Similar, if not enhanced recovery result to basins. ▪ Not affected by evaporation losses. ▪ Not necessary to drill to depth of water table. Could use vadose zone wells, similar to what is used in Nevada. ▪ Less expensive drilling and well construction compared to deep injection, but would require reticulation infrastructure.
Deep Injection Wells (in conjunction with shallow riverbank filtration (RBF) wells) **Figure 14**	▪ Semi-confined or confined aquifer ▪ Injection well depths of 100 to 500 m deep ▪ Shallow RBF filtration wells within upper alluvial aquifer(<30 m)	▪ Adjacent to river source ▪ Anywhere upgradient of demand within the plains	▪ Little likelihood of injection returns to the river due to depth of injection. This means injection could occur close to source and minimise infrastructure requirements. ▪ Pre-treatment could be achieved through RBF wells – see **Figure 15** below. ▪ Opportunity to undertake 'stacked' injection into a number of aquifers within individual wells or a series of nested wells. ▪ Location is not as important from an injected water recovery perspective, as residence time of injected water is likely to be high.
Deep Injection Wells (in conjunction with existing irrigation race)	▪ Semi-confined or confined aquifer ▪ Wells 100 to 500 m deep to at least beneath upper confining unit.	▪ Adjacent to irrigation race ▪ Anywhere upgradient of demand within the plains	▪ Existing infrastructure can be used as a cost effective means of spreading the distribution of injection sites. ▪ Location is not as important from an injected water recovery perspective, as residence time of injected water is likely to be high. ▪ Pre-treatment is probably required unless fines settle in canal or settlement pond first. ▪ Could potentially be used as recovery wells to supply water to irrigation races when there is inadequate supply from the river.
ASR (using existing water distribution	▪ Both shallow unconfined and deep semi-	▪ Utilising existing water races infrastructure,	▪ Utilises existing water race infrastructure, hence start-up costs likely to be lower. ▪ Conversely, location selection is

Option	Target Aquifer	Location	Features
infrastructure)	confined aquifers.	hence located wherever this occurs. ■ Shallow bores would be more effective in the middle of the plains (between alpine rivers), while deep bores would likely be effective anywhere.	restricted to those locations, which may not represent optimal site selection.

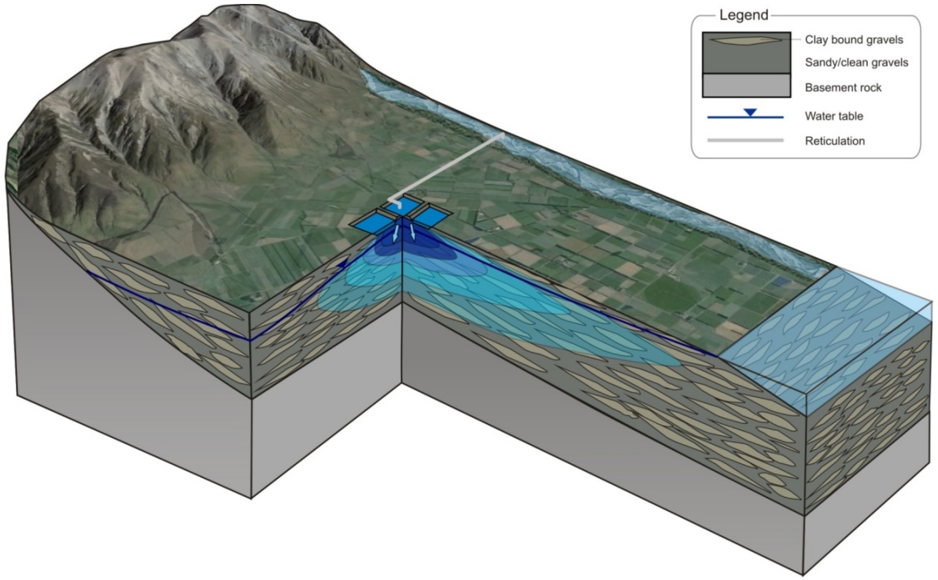


Figure 12. *Infiltration basin concept scheme.*

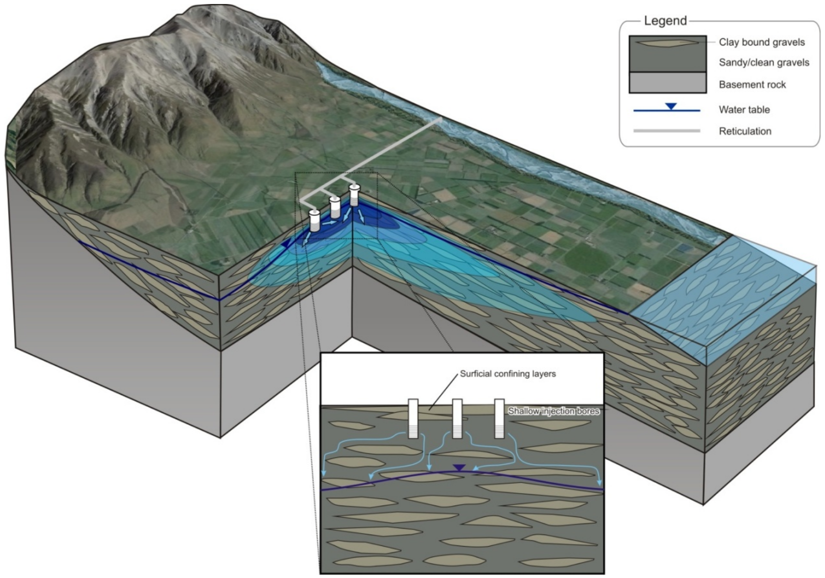


Figure 13. *Shallow recharge well concept scheme.*

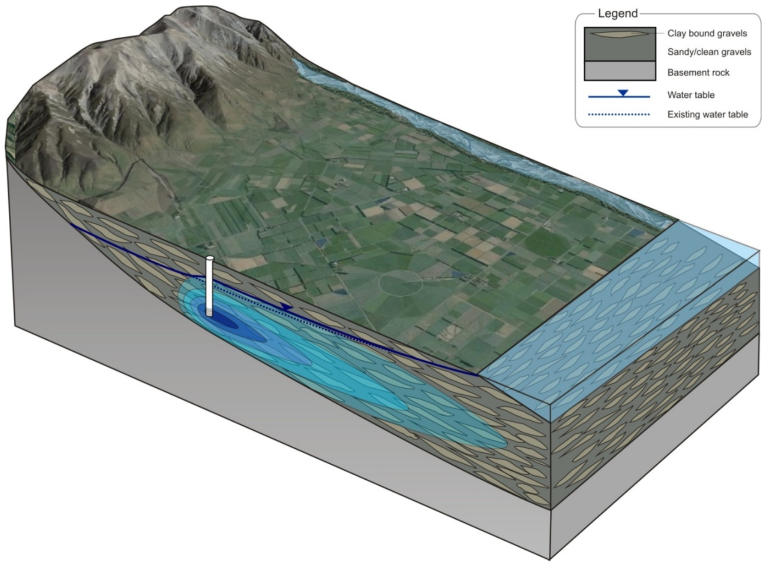


Figure 14. *Deep recharge well concept scheme.*

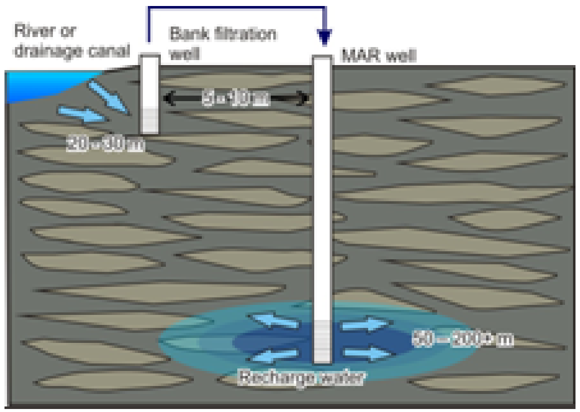


Figure 15. *Deep injection well concept using bank filtration for pre-treatment.*

8 HYPOTHETICAL MAR CONCEPT FOR THE CENTRAL PLAINS AREA

8.1 GENERAL

In order to assess the technical, hydrogeological and economic feasibility of a MAR scheme in the Canterbury region, it would be necessary to undertake detailed assessment that would likely include sub-regional hydrogeological modelling, concept design of intakes / conveyance / treatment and injection, detailed economic analysis and probably some field testing.

Accepting that such an approach will be costly and take significant time, for this report we have focused on developing a broad MAR concept and applying a first order assessment of technical and economic feasibility, in order to determine whether or not there is reason or merit to investigate the MAR concept further.

The concept discussed below has been developed for the Central Plains area, due to the elevated state of knowledge of this scheme and the availability of an irrigation scheme concept and costs against which the MAR scheme can be considered. It is also an area in need of water storage to realise the potential of the irrigation scheme that has been consented, and in this regard the MAR concept may have direct and immediate interest if its' feasibility were confirmed.

The MAR scheme discussed below was developed with the following objectives in mind:

- Utilisation of the consents granted for the Central Plains Water (CPW) scheme, including water takes and intake locations;
- Utilisation of Rakaia and Waimakariri River intakes, to enable access to "spring" water over the longest possible period due to the staggered "peak" in river flows between the two rivers;
- Utilisation of a connecting headrace, to facilitate access to water from either river;
- Utilisation of CAPEX and OPEX for these components from the CPW scheme;
- Provision of an equivalent amount of water as the CPW scheme, namely an average irrigation demand of 19 m^3/s and a peak irrigation demand of 36 m^3/s;
- Maintain a generally conservative assessment outlook, to avoid undue criticism of "interpretations" or "assumptions" that need to be made for any first order assessment; and
- Maintain an approach that considers "like" with "like" when preparing comparative economic assessments.

Keeping the above in mind, the scheme as developed is conceptual and makes several assumptions about hydrogeological properties and response, water treatment and injection method and abstraction depths.

8.1.1 HYDROGEOLOGICAL ASSUMPTIONS

The hypothetic MAR concept explained later in **Section 8.1.3** is premised on the site specific hydrogeological conditions that were defined through publically available borelogs and aquifer hydraulic testing data.

Three key longitudinal sections down the plains and one along the headrace positioned as shown in **Figure 16** were used in the construction of a conceptual hydrogeological fence diagram (**Figure 17**). This was developed through summarising drillers logs, with materials classified into either aquifer or aquitard, while ignoring thin layers that do not significantly impact on the hydrogeological functioning of a unit. The aquifers were further differentiated by degree of saturation (i.e. dry or saturated) and an indicative water table position is also shown.

At the location of the headrace it is evident that the shallow aquifer is dry within the middle of the plains between the major rivers, with depth to groundwater within the underlying deeper aquifer approximately 140 to 160 mBGL. However, in close proximity to Selwyn River the shallow aquifer and is saturated, although a steep appears evident across the plain with distance from the Selwyn River (**Figure 17**).

Recent analysis of the aquitard overlying the deeper aquifer in the Darfield area suggests that aquitard hydraulic conductivities are in the order of 2.5×10^{-5} m/day (10^{-10} m/s) (SKM, 2010), which suggests the deeper aquifer will behave like a confined aquifer when pressurised through injected water.

The aquifer is assumed to have a transmissibility of 2,000 m^2/day based on the data in SKM (2010) and the regional average reported in SKM (2009).

In a conceptual sense, injection of water along the headrace into the deeper aquifer appears to be highly feasible, given the following key facts:

- high aquifer transmissivity (approximately 2,000 m^2/day), which means that aquifer acceptance will be high and injected water will be readily transmitted away from the bores;
- the presence of confining sediments above suggests that the injected groundwater will remain predominantly at depth and not impact significantly on surface water features within at least 16 km from the headrace where we have undertaken detailed driller log assessment. This constitutes most of the CPW scheme area;

A preliminary analysis was undertaken to provide an indication of the ability of the deeper aquifer to accept the sort of loading rates required for the CPW scheme. The analysis indicated that conservatively (i.e. without any abstraction within the system), the aquifer could accept approximately 9.3 m^3/s continuously. This analysis was premised on 188 bores at 200 m spacing, and the final injection rate per bore deemed conservatively feasible was 50 L/s.

This analysis indicates that to achieve the volumes of water needed by the CPW scheme, MAR would need to operate for much longer periods than just the irrigation scheme, but the required delivery rates are significantly less than the peak flow rate of the existing CPW scheme.

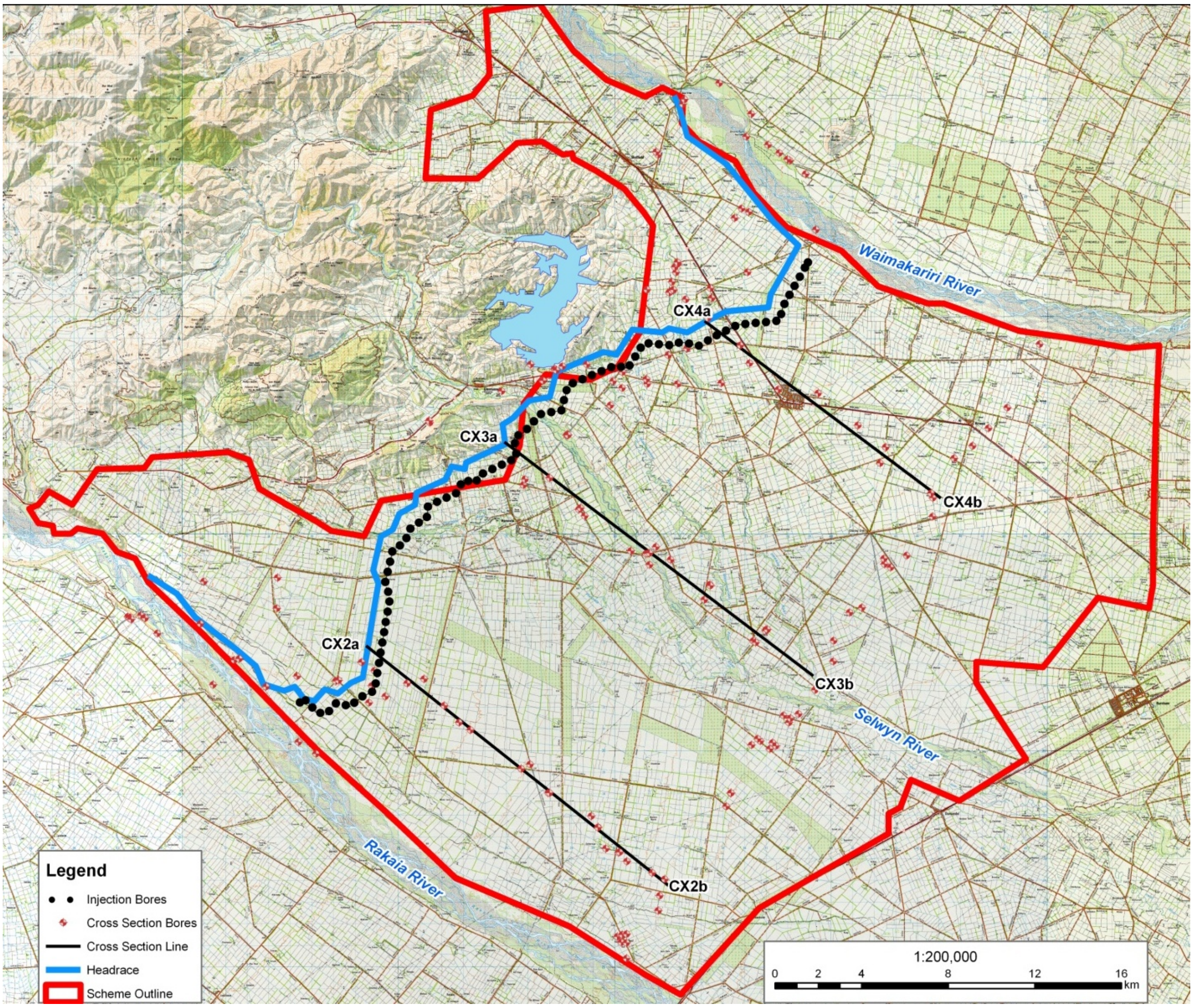
Additional work needs to be completed on assessing the delivery volume of the existing CPW scheme and the duration of supply on a seasonal basis and then comparing that to the MAR option.

Based on the analysis undertaken above, the injection bores specifications used in development of the MAR the scheme are summarised in **Table 6**.

***Table 6.** Summary of injection bore assumptions.*

Total number	187
Indicative spacing (m)	200
Bore depth (m)	200
Indicative groundwater level (mBGL)	150
Well head available at start (m)	150
Injection rate per bore (L/s)	50

***Figure 16.** Central Plains Scheme location map showing headrace, proposed recharge injection bore, and cross section locations.*



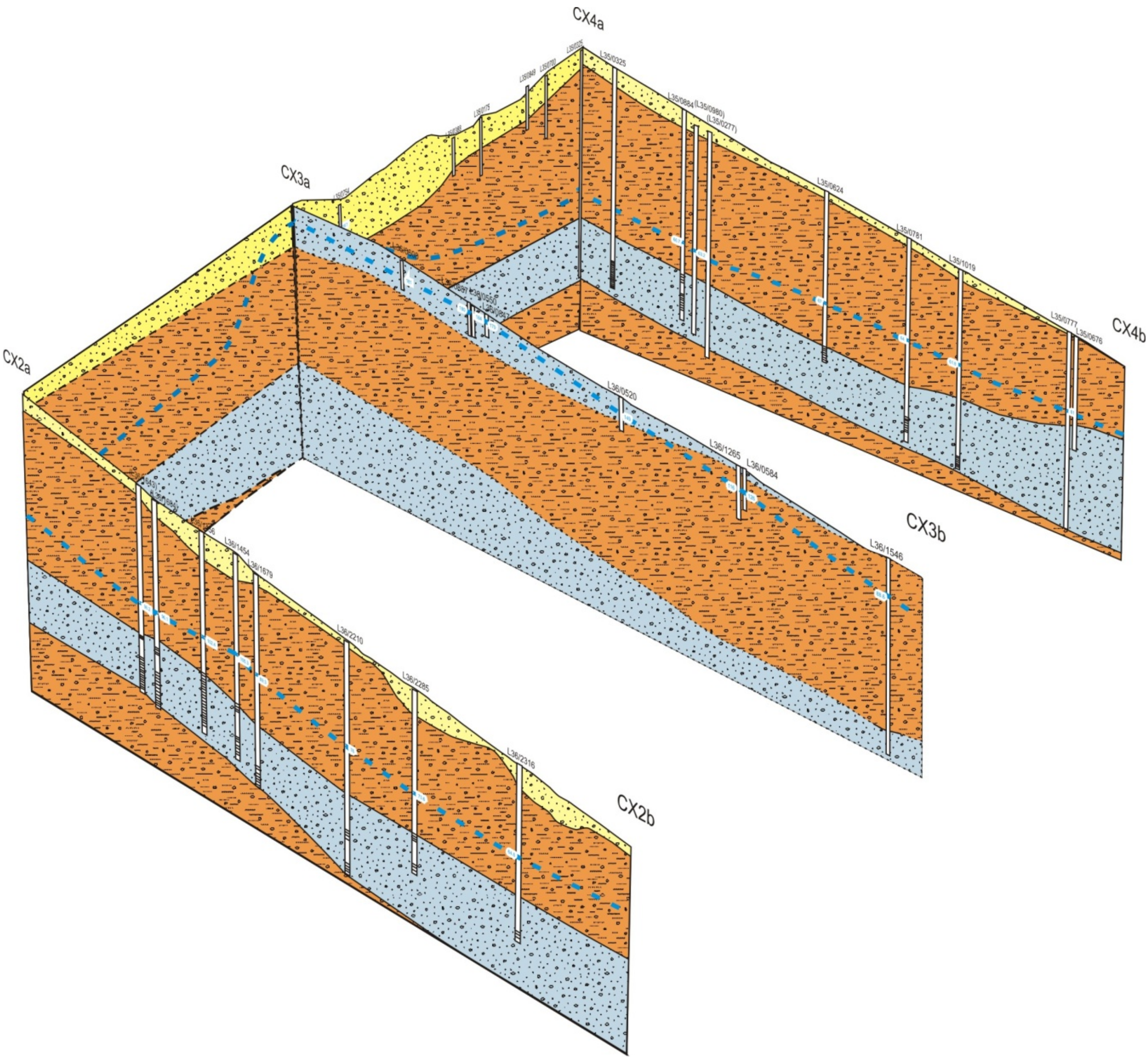


Figure 17. Fence diagram of geology within Central Plains Scheme.

8.1.2 FATE OF INJECTED GROUNDWATER

The injected water will increase pressures in the deeper aquifer with the pressure response propagating preferentially along the path of least resistance, which given the very low aquitard hydraulic conductivities, is in a downgradient predominately horizontal direction. Some upward propagation of pressure (i.e. upward leakage) will occur, although this is anticipated to represent an insignificant component of the flow balance within the immediate area (cross section area) will be significantly delays from the deeper aquifer response. Further downgradient, the pressure response will spread over a wide area and may migrate upwards if the confining layer which appears prevalent in this area is not laterally continuous.

More detailed reconciliation of the bore logs and development of a zone numerical model would be required to accurately define the ultimate fate of the recharge groundwater. However, based on the concept described above, we consider the most likely groundwater outcomes will be as follows:

- the deeper aquifer will be pressurised over a wide area that will encapsulate the entire scheme area of benefit;
- groundwater pressure increases will be largely confined to the deeper aquifer in the immediate area, but some pressure response may be felt within the shallow aquifers, particularly outside the scheme area and further towards the coast;
- the ultimate fate of injected groundwater (if not re-abstracted through groundwater users) will be submarine discharge and/or discharge to spring fed streams in the low lying parts of the catchment near Lake Elsmere.

Mixing of the injected groundwater will increase the average age of groundwater, which is understood to be over 100 years in the deeper aquifer within the upper Central Plains area. However, water quality is unlikely to be affected in a significant way, as Ca:Mg ratios in alpine river (>5) water is similar to old groundwater in the deeper aquifers within the Canterbury Plains.

8.1.3 ENGINEERING CONCEPT

The hypothetical MAR concept developed in accordance with the objectives discussed above comprises the following:

INJECTION

- Intakes on the Rakaia and Waimakariri Rivers, nominally sized and hence costed at 70% of that proposed in the CPW scheme, due to the storage an buffering achieved with utilisation of groundwater storage under the MAR approach;
- Headrace canals between intakes, nominally sized and costed at 70% of that proposed in the CPW scheme, due to the storage an buffering achieved with MAR;
- Infiltration treatment beds at the location of injection bores, comprising of reworked site gravels and impermeable base collection layer, to remove fine sediments prior to MAR injection; and
- Injection bores drilled to a depth of 200 m to access deeper aquifers, with "injection" by gravity utilising the considerable available head between the surface and injection bore screened zone.
- As indicated above, utilisation of groundwater storage rather than direct surface water feed means that the bore injection rates for the total scheme can be significantly less than the peak irrigation demand. We have assumed that the average irrigation demand of 19 m^3/s will be recharged by injection bores operating year round at a rate of approximately 9.3 m^3/s.

EXTRACTION

- Conventional irrigation abstraction bores, assumed to be 200 m deep in upper plains area and 100 m deep in lower plains area; and
- Conventional submersible bore pumps sized to provide sufficient pressure to drive a centre pivot irrigator and lift from assumed water tables of 150 m and 50 m for upper and lower plains areas, respectively.

8.1.4 EXPECTED SCHEME PERFORMANCE

The concept as described above responds to a range of factors including hydrogeological conditions, water source, water sediment load and the ability to stage development and spread financial expense.

A summary of the fundamental benefits that such a scheme delivers, along with brief discussion on sensitivity, assumed degree of conservatism and potential for improved or adverse performance is summarised as follows:

- Utilisation of existing CPW scheme consents, most likely utilising lower intake flow rates, commencing earlier and over a longer duration.
- Utilisation of a header race enables sourcing of water from either the Rakaia or Waimakariri Rivers and also enables uniform distribution of injection bores across the command area. Further assessment has the potential to demonstrate the ability to recharge the deep aquifers in close proximity to the main rivers, which could significantly reduce the extent of header race required.
- Reduced size and cost of intake structures and header race, due to the ability to recharge at average irrigation rates or less over a longer time period through utilisation of the available ground storage.
- Water treatment via infiltration beds utilises treatment benefit of flow time in header canal and enables staged construction, with treatment and injection capacity built as extraction uptake occurs. The treatment bed design requires further development, but is based on the assumption that ground filtration is likely to be a cost effective and low maintenance approach to remove fine sediments.
- Injection to lower aquifers will increase likelihood of confined aquifer pressurisation and subsequent spread of water and reduction in abstraction pump costs. Use of deeper bores and abstraction is conservative. Detailed assessment may confirm ability to utilise higher injection rates, a reduced number of injection bores or shallower injection bores (to an unconfined surface aquifer). There is a possibility that some areas within the command area will not benefit from recharge.
- Aquifer transmission has been assumed to be high (i.e. premised on injection depths where known high producing abstraction bores occur). However, transmissivity will not be uniform across the area of interest, although the analysis undertaken is considered appropriate for a first order level assessment.
- Abstraction by conventional bore enables farmers to develop access as and when they require and are financially able to do so. An initial financial commitment would still be required to secure access to water, as for the present scheme however with reduced up-front cost due to the decrease in initial CAPEX. Farmers would fund their on-farm development costs. Existing bores are likely to be able to be utilised, depending upon which aquifer(s) benefit from recharge and where bores are located. The initial economic analysis undertaken in this study takes no account of this benefit.

More broadly, there are some key aspects of MAR that are worthy of note.

- Losses within the groundwater result in direct and attenuated environmental benefits, the later being more relevant if the target recharge zone is deeper within the aquifer profile.
- The ability to reduce initial CAPEX and to defer CAPEX to meet uptake results in favourable economic impacts, despite the increased annual power consumption faced by farmers utilising groundwater.
- The storage capacity of the groundwater system has the effect of enabling earlier water capture and buffering of peaks and troughs in recharge, which ultimately has the effect of increasing reliability. In order to compare against the current CPW proposal, we have assumed the increase in reliability is directly related to the ability to harvest water for a period in advance of demand and in this case, have assumed a continuous recharge at a rate of 9.3 m^3/s, which is an equivalent water capture of 293,000,000 m^3.

In general, despite the risks that some areas may not receive water due to hydrogeological anomalies, the concept as described above is fundamentally sound and responsive to the ground conditions known to existing within the command area.

It is expected that more detailed investigation will identify several areas where performance can be improved over that assumed for this assessment and more efficient ways to structure a MAR project.

8.1.5 FIRST ORDER ECONOMIC ANALYSIS

As introduced previously, a first order economic assessment has been undertaken for the purpose of establishing relative economic merit, on the understanding that irrespective of technical merit, MAR is unlikely to be considered seriously unless it has a similar or better economic framework.

The approach adopted has been one of comparative assessment against the current CPW proposal. Key economic principles adopted include:

- Using cost information from the CPW scheme directly
- Developing appropriate "unit rate" costs then extrapolating them to a scheme wide cost
- Applying percentage on-costs for financing, depreciation and operations and maintenance including application of higher depreciation for pump CAPEX
- Staging CAPEX and OPEX where appropriate
- No power cost escalation has been used, rather a rate approximately 15% above present rates has been used for the duration of the assessment
- Applying a NPV assessment, using an 8% discount rate and a 30-year window, without residual value at the end of the period of economic consideration

A "cost' for storage has been applied to the CPW scheme costs, equivalent to that required to increase scheme reliability to that achieved by the MAR scheme. A cost of $0.75/m^3 storage is considered appropriate if a large storage was constructed and has been determined based on water storage economic assessments previously undertaken for the Canterbury Water Management Strategy and the CPW project. Storage cost will increase considerably if smaller, de-centralised or on-farm storage is adopted. Such an outcome would increase the overall NPV cost of the CPW scheme.

An economic assessment has also been developed for a more optimistic MAR scheme in order to identify the sensitivity in the analysis and to demonstrate the potential benefits of MAR. This assessment assumes a higher treatment rate, recharge to the unconfined surface aquifer, increased recharge rate of 60 L/s, abstraction from the shallower unconfined surface aquifer, headworks costs being 60% of the CPW scheme costs and reduction in the number of abstraction bores by 20% due to utilisation of existing bores. This scenario could become realistic if recharge of the unconfined surface aquifer was found to be feasible.

The first order economic assessment is attached in **Appendix A** and summarised below:

Table 7. *NPV of Scheme Options (8%, 30-yr)*

Scheme	NPV
Central Plains Water	$560 M

Scheme	NPV
MAR as described above	$470 M
MAR more optimistic assessment	$290 M

While the input data to the MAR concept and economic analysis will be subject to debate, the outcomes of this first order assessment clearly identify that MAR is at least on a comparable economic footing to the present CPW scheme, and more likely to have considerable economic benefits.

9 CONCLUSIONS

Managed aquifer recharge is at the leading edge of integrated water management, presenting opportunities for conjunctive management of surface water and groundwater resources, and producing fit-for-purpose water supplies. MAR not only provides an effective means of storing water and enabling better management of available resources, but it can also provide environmental benefits to groundwater dependent ecological systems.

MAR may have an impact on the water quality, usually in a beneficial manner. Changes in quality of both the source water and groundwater result from the physical removal of particulate matter, microbiological removal of pathogens and organic material, dilution or displacement of poor quality groundwater (assuming the injection water is superior quality) and geochemical interactions with the native groundwater and the aquifer material.

There are a number of risks associated with the implementation and operation of a MAR scheme such as:

- Clogging management;
- Poor geology/hydrology conceptualisation;
- Poor design of infiltration structure/borehole;
- Stability of structure/borehole under operating conditions;
- Operation/management of scheme;
- Poor quality groundwater (diffusive mixing);
- Protection of groundwater quality;
- Loss of infiltrated/injected water;
- Transition from trial to operational scale;
- Policy, societal and religious acceptability;
- Availability and dissemination of information/knowledge; and
- Availability of skills and human capacity.

MAR has been sustainably operating for more than two decades in many countries and the body of scientific knowledge supporting MAR operations is quite large. In its infancy, many of the technical issues around MAR focussed on the operational aspects, as the list of risks above identifies. Most of these issues have been resolved and the focus has switched to providing an appropriate regulatory framework within which MAR schemes can be reliably operated. A complimentary regulatory framework is one of the last remaining barriers to the adoption of MAR as an effective management tool.

Within the Canterbury region the hydrological and hydrogeological setting is considered highly attractive for using MAR as a means of more effective and sustainable conjunctive use of surface water and groundwater resources.

The development of a hypothetical MAR concept that responds to the fundamental parameters governing MAR performance has identified a concept with considerable technical viability and economic appeal, and responds in a holistic sense to the principals of sustainable development offering we believe a significant superior sustainable outcome to the region.

Not only would the concept MAR scheme allow additional allocation of groundwater resources, it also provides potential environmental benefits in the form of removing pressure from surface water abstractions and replenishing groundwater dependent ecosystems. In addition, when compared to a conventional irrigation scheme, MAR allows for smaller delivery infrastructure because water can be plumed into the aquifer system all year round and utilise the sub-surface storage. This provided the MAR scheme with significant economic advantage. Two economic scenarios were developed and while both scenarios provide clear economic advantage of at least $90 M, the more optimistic of the two schemes provides considerable potential economic benefit in the order of $270 M.

More detailed site specific analysis would be required to confirm the most appropriate MAR technique from both a technical and cost-benefit perspective.

Currently the project is at a very high level concept stage. Following preliminary stakeholder engagement and agreement that the scheme has merit, the concept itself would need to be further developed to allow a more formal fatal flaw assessment to be made.

In this regard, it is too early to made any firm recommendations on engineering concept other than indicating that significant pre-feasibility work would need to be undertaken to advance the project and that a comprehensive scoping assignment is needed in the first instance to define what this work may entail.

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REFERENCES

Bird, T.D. (1986). Levels Plain Irrigation Scheme Groundwater Supply Simulation. Report prepared for the National Water and Soil Conservation Organisation. Ministry of Works and Development Report Number WS1132 CHCH IRR. 86/2.

Bouwer, H. and Rice, R.C. (1989). Effect of water depth in ground water recharge basins on infiltration rate. *Journal of Irrigation and Drainage Engineering*. 115(4): 556-568.

Bouwer, H. (1990). Effect of water depth and ground water table on infiltration from recharge basins. *Proceedings of the 1990 National Conference of the Irrigation and Drainage Division*. American Society of Civil Engineers, S.C. Harris ed. Durango, Colorado. July 11-13, 1990. Pg. 377-384.

Brown, L.J., Dravid, P.N., Hudson, N.A., and Taylor, C.B. (1999). Sustainable Groundwater Resources, Heretaunga Plains, Hawkes Bay, New Zealand. *Hydrogeology Journal* Vol. 7, Number 5: Pg 440 – 453.

Canterbury Water Management Strategy (2009). Draft Canterbury Water Management Strategy. Discussion document prepared for the Canterbury Mayoral Forum, August 2009.

Carollo Engineers (2008). City of Scottsdale, 2008 Integrated Water Master Plan, March 2009. Website publication available from http://www.scottsdaleaz.gov/Assets/documents/water/2008_Water_Master_Plan_Executive_Summary.pdf

Christodoulou1, G.I., Sander, G.C, & Wheatley, A.D. (2007). Characterisation of the Ezousas aquifer of SW Cyprus for storage and recovery purposes using treated sewage effluent. *Quarterly Journal of Engineering Geology and Hydrogeology*. Vol. 40; pg 229-240.

Department of Water Affairs & Forestry (2007). Artificial Recharge Strategy. Version 1.3, June 2007. Department of Water Affairs & Forestry, in association with Water Research Commission, Republic of South Africa.

Dillon, P.J. (2005). Future management of aquifer recharge. *Hydrogeology Journal*, 13 (1) 313-316.

Dillon, P., Pavelic, P., Page, D., Beringen, H, and Ward, J. (2009). *Managed Aquifer Recharge: An Introduction*. Australian Government National Water Commission, Waterlines Report Series No. 13, February 2009.

IAH-MAR (2003). *Managing Aquifer Recharge. International Association of Hydrogeologists Commission on Management of Aquifer Recharge*. Website publication available from http://iah.org/recharge/index.html accessed 21/08/2009.

International Groundwater Resource Assessment Centre (2008). Publication 155 *Global Inventory of Artificial Recharge* [Website publication available from http://www.igrac.net/publications/155] accessed 25/08/2008]

Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, National Health and Medical Research Council (2009). *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2), Managed Aquifer Recharge.* National Water Quality Management Strategy Document 24, July 2009.

Koutsos, P.T. and McBryde, D.J. (1988). The Heretaunga Plains Groundwater Artificial Recharge System. Hawkes Bay Catchment Board, Napier, Internal Report.

Lowe, M., Hurlow, H.A., & Matyjasik, M. (2003). The *Weber River Basin Aquifer Storage and Recovery Project*. Open-file Report /Utah Geological Survey; 419 (September 2003). Utah dept. of Natural Resources.

Lowe, M. and Hurlow, H.A. (2005). *Pilot Project Shows Promise for Aquifer Storage and Recovery*. Survey Notes Vol 37. pg 8-10 No 1, Utah geological Survey [Website publication available from http://ugs.utah.gov/utahgeo/water/weber_basin_project/article05.htm] accessed 21/08/2009.

Pyne, R. D.G. (2005). *Aquifer storage and recovery: A guide to groundwater recharge through wells*. Second edition. pp608.

Sinclair Knight Merz (2008). Inventory of aquifer test data for the Central Plains. Report No. R08/80, ISBN 978-1-8697-4. Prepared for Environment Canterbury by Sinclair Knight Merz.

Sinclair Knight Merz (2009). Inventory of aquifer test data for the Ashburton and Valetta Groundwater Allocation Zones. Report No. R09/12, ISBN 978-1-86937-928-5. Prepared for Environment Canterbury by Sinclair Knight Merz.

Sinclair Knight Merz (2010). Proposed Canterbury Dairy Factory Darfield – Groundwater Consent Conditions Information. Report prepared for Fonterra Limited.

Stuyfzand, P.J., Segers, W., and Rooijen, N (2007). Behaviour of pharmaceuticals and other emerging pollutants in various recharge systems in the Netherlands. *Proceedings of the 6th International Symposium on Managed Aquifer Recharge of Groundwater, ISMAR6 Phoenix Arizona* Pg. 231 – 245.

Tatlow, M. and Brown, M. (2007). The City of Scottsdale Water Campus. In ISMAR6 Fieldtrip Guide. Phoenix, Arizona, 31 October 2007.

Wilson, D. (1973). The significance of geology in some current water resource problems, Canterbury Plains, New Zealand. *Journal of Hydrology* (N.Z) Vol. 12, Issue 2.