WALLBRIDGE GILBERT AZTEC

Canterbury Regional Council

Regional Plan Managed Aquifer Recharge Technical Guidance

TECHNICAL REPORT

Project No. 181511 / Rev E
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Revision History

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ABBREVIATIONS

DBPs	Disinfection By-Products
DO	Dissolved Oxygen
EC	Electrical conductivity
ECan	Canterbury Regional Council
E. coli	*Escherichia coli*
GAZ	Groundwater Allocation Zone
GRS	Groundwater Replenishment Scheme
LWRP	Land and Water Regional Plan
MAR	Managed Aquifer Recharge
MPN	Most Probable Number
SAT	Soil Aquifer Treatment
TIN	Total Inorganic Nitrogen
TSS	Total Suspended Solids
WGA	Wallbridge Gilbert Aztec

1 INTRODUCTION

1.1 BACKGROUND

The term ‘Managed Aquifer Recharge’ (MAR) generally refers to the abstraction of water from a source and the conveyance and discharge of that water, together with any associated contaminants, into one or more groundwater recharge structures for the purpose of improving groundwater quality and/or quantity and potentially for improving the flow and water quality in hydraulically connected surface waterbodies. Groundwater recharge structures may include infiltration basins, trenches, galleries, wells or natural features such as historic flood plains which lay outside the bed of the river. MAR activities include feasibility assessments, design, consenting, construction, commissioning, testing, control and monitoring of the system.

With specific respect to the MAR rule being considered for the Canterbury Land and Water Regional Plan, MAR consists of a set of physical tools designed to capture clean surface water and purposefully recharge that water into aquifers, thereby supplementing groundwater storage, improving groundwater quality and enhancing flows and ecosystems in rivers and streams that are dependent on groundwater discharges.

The use of MAR for water management is a relatively new concept in New Zealand. In contrast, MAR has been applied in different forms for almost a century in places like Orange County, California, (OCWD 2015) to improve groundwater management at the catchment-scale. However, during the past decade several MAR projects have been developed within New Zealand to help manage local, regional and national challenges around groundwater quantity and quality.

Internationally, MAR is widely utilised[1], applying a wide variety of techniques to a much broader range of water management situations and objectives, including rainwater harvesting, municipal and industrial recycled water management and as a tool to help protect coastal groundwater systems against saline water intrusion (Figure 1). Many of international examples are beyond the scope of this Canterbury-specific report and would likely require specialised technical work to assess the potential impacts.

1.2 INCIDENTAL AND MANAGED AQUIFER RECHARGE IN CANTERBURY

In Canterbury, incidental artificial aquifer recharge arising from border dyke or flood irrigation and water distribution via thousands of kilometres of leaky races has occurred since the early 1900s. This incidental recharge declined as irrigation efficiency improved and water delivery systems were piped to reduce water losses.

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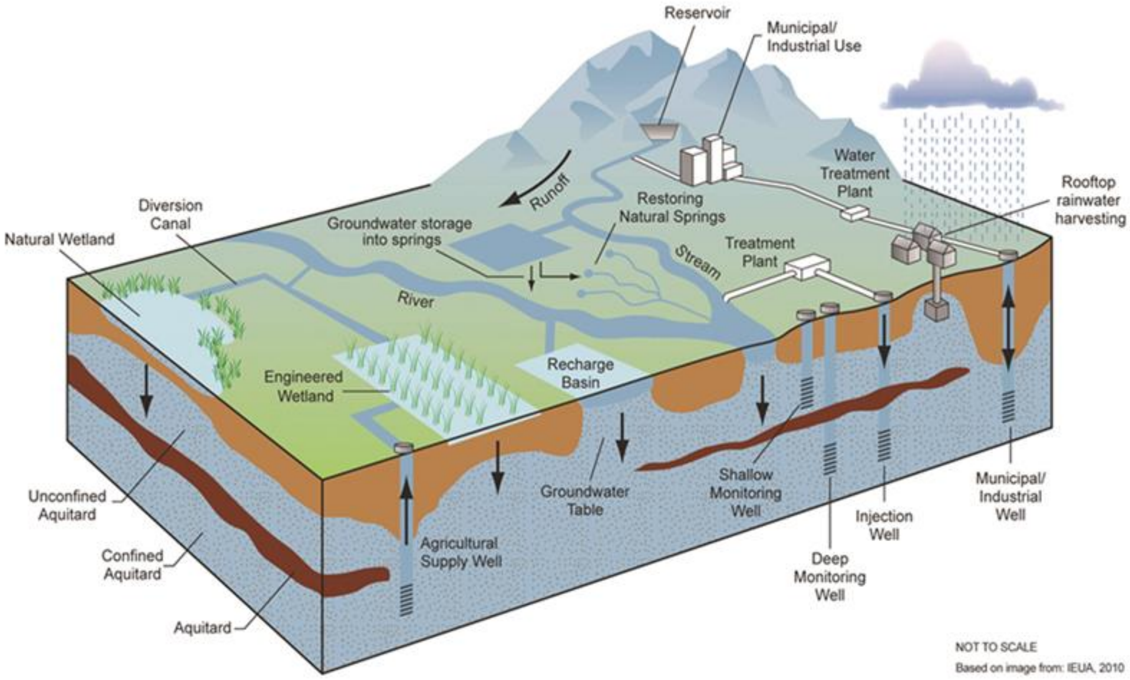
[1] https://www.un-igrac.org/special-project/mar-portal



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Based on image from: IEUA, 2010

Figure 1. International examples of MAR systems, including components not assessed in this report.

Groundwater abstraction in Canterbury started in the early 1900s, mainly for domestic and stockwater purposes. There was a significant increase in the consenting of groundwater wells for irrigation in the mid-1990s, plateauing around 2004 when the Canterbury Regional Council (ECan) set Groundwater Allocation Zone (GAZ) limits for Canterbury. Of the 43 GAZ, 15 are now considered by ECan to be over-allocated by a total of more than 500 million m^3/year (per comms, Matt Dodson, ECan, 2019). The Ashburton-Lyndhurst, Ashburton River, Rakaia-Selwyn and Valetta GAZ, which are all located in Mid-Canterbury, make up 65% of this regional over-allocation (over 335 million m^3/year). In parts of Canterbury the reduction in incidental recharge (e.g. irrigation efficiencies and the decommissioning of leaky stockwater races), coupled with a significant increase in groundwater abstractions, has contributed to downward trends in groundwater levels (Bower 2014, Golder 2014).

Groundwater quality in Canterbury has declined since the 1990s. Intensification of farming and increased leaching of nutrients has resulted in increasing nutrient loads to the groundwater system. In some parts of Canterbury, concentrations of nitrate-nitrogen in groundwater have increased to exceed New Zealand drinking water criteria (NZMoH 2018).

The first documented Canterbury MAR trial was undertaken in 1986 at Level Plains (Bird 1986). Subsequently further trials were undertaken:

- During 1991 at Yaldhurst (Callander et al 1991)
- During 1992/1993 at West Melton (Moore 1992, 1994)
- During 2005 at the Eyre River (PDP 2007)
- During 2012 at the Hinds River (Golder 2012a, Golder 2012b).

Further evaluations of the potential for MAR in the Canterbury region included:

- An assessment of the applicability of artificial recharge to the Christchurch / West Melton area (PDP & Broadbent 1996).
- A Canterbury Regional MAR feasibility study (SKM 2010).
- A preliminary strategic assessment of the application of MAR to the Canterbury Region (PDP 2011).
- An assessment of the application of MAR to the Selwyn – Te Waihora catchment (Golder 2013).

As part of the Canterbury Water Management Strategy (CWMS), the Ashburton Zone Committee (AZC) in their ZIP addendum, made recommendations through their Zone Implementation Plan Addendum for the testing of MAR in the Hinds Plains catchment (AZC 2014). Starting in 2015, large scale MAR assessments and trial sites have been operating in the Hinds Plains catchment, within the Ashburton GAZ (Golder 2015). These trials have been supported by substantial technical investigations and assessments undertaken since 2012, when an initial Hinds River recharge trial was performed (Golder 2012b).

The Hinds MAR trial programme has generated a substantial amount of information on the design, community consultation and education, consenting, management and monitoring of MAR systems. The results from the trials have supported ongoing innovation in optimising MAR systems for the Mid-Canterbury Plains (Golder 2017, WGA 2018). The community steering committee (Hinds MAR Governance Group) has also been working on the development of a catchment-wide Groundwater Replenishment Scheme (GRS) that consists of over 170 potential MAR sites identified and a cost-benefit analysis undertaken as part of a business plan development.

The identification and expansion of MAR opportunities within Canterbury has resulted in the need to develop policies and rules in the Land and Water Regional Plan (LWRP) that enable MAR to be utilised more widely, whilst providing adequate protections, particularly when contemplating developments ranging from a cluster of MAR site through to a larger catchment-wide Groundwater Replenishment Scheme. Currently there are rules in the LWRP for MAR (in subchapters Hinds and Selwyn Te-Waihora) but there are no specific region-wide provisions for undertaking MAR. Boffa Miskell (2018) summarises the operative LWRP provisions applicable for MAR, some of the main issues that have arisen with regard to consenting MAR projects, and potential options for the development of new region-wide provisions for MAR systems. Developing region-wide policies and rules is important to ensure adequate safe guards are in place with respect to a range of potential environmental effects that may be associated with the operation of MAR sites.

1.3 SCOPE OF REPORT

WGA has been commissioned to provide ECan with technical information to support the development of a new LWRP provisions for MAR for a plan change. This report provides the requested supporting technical information together with a list of referenced material.

This report is structured to present scientific information to support the proposed LWRP MAR rules and policies. The information contained is focused on providing guidance relevant to the technical aspects of the proposed MAR provisions.

2 APPLICABILITY AND KEY SUPPORTING MATERIAL

2.1 CONCEPTS AND REPORT COVERAGE

For regional planning purposes, MAR is being defined to help clarify what the proposed policies and rules may and may not apply too. Due the wide range of potential definitions of MAR, we have provided the following defining concepts specific to the proposed MAR provisions in the plan change to the LWRP:

- MAR utilises ‘natural’ sources of water from Canterbury’s rivers, lakes and streams, which are known to have high water quality values (e.g. alpine rivers).
- MAR utilises infiltration techniques where water moves from surface water sources into a targeted groundwater aquifer.
- MAR is an activity for groundwater recharge.
- MAR is primarily utilised for the one or more of the following beneficial outcomes:
  - Improving groundwater quantity (i.e. levels and overall net aquifer storage).
  - Improving groundwater quality.
  - Improving baseflows to hydraulically connected springs, streams or rivers and thereby supporting groundwater dependent ecosystems (GDEs).
  - Improving water quality in hydraulically connected springs, streams, rivers or lakes and thereby supporting groundwater dependent ecosystems (GDEs).
  - Improving the quality or quantity of groundwater or spring water for drinking water supply purposes.

The proposed provisions for the LWRP that are informed by this report **<u>are not intended to cover</u>:**

- Projects that seek to capture and infiltrate sources of water other than surface water (i.e. stormwater).
- Projects that seek to utilise MAR techniques that are not intended to achieve the beneficial quantity, quality or environmental outcomes noted above (e.g. oil industry water disposal, fracking for coal seam gas development).

Throughout this report the following terms have been used to describe specific aspects of MAR operations and effects.

Source water	This term refers to water captured and diverted to a MAR site for the purposes of infiltration or injection. In terms of water quality, it refers specifically to the water being entering a MAR site, which may then be subject to pre-treatment prior to being recharged to groundwater.
Receiving water	This term refers to the groundwater beneath and surrounding the MAR site, into which the MAR water will be introduced and with which the MAR water will become mixed.

The focus on microbiological contaminants in this report is on *E. coli*, as an indicator organism for pathogen contamination of water. However, experience gained internationally and within New Zealand has emphasised the importance of other pathogens (e.g. viruses, protozoa, other bacteria) when considering water quality. Although the microbiological focus in this report is on *E. coli*, the assessment of water quality for MAR projects should also take into account risks arising from other pathogens and this report should be read with this intent.

2.2 GUIDELINES AND KEY REFERENCES

The information presented in this report is based on international best practices, existing international guidelines and outcomes from trials underway in Canterbury. Key guidelines and technical supporting material for this report include:

1. American Society of Civil Engineers (ASCE), 2019. *Draft* Standard guidelines for managed aquifer recharge.
2. Schijven, J., Pang, L., and Ying, G.G. 2017. Evaluation of subsurface microbial transport using microbial indicators, surrogates and tracers.
3. Environmental Protection Authority, Victoria 2009. Guidelines for managed aquifer recharge (MAR) – health and environmental risk management.
4. Environment Protection Authority, South Australia 2004. Code of practice for aquifer storage and recovery.
5. Pyne, R.D.G. 2005. Aquifer storage recovery: a guide to groundwater recharge through wells.
6. Martin, R. 2013. Clogging issues associated with managed aquifer recharge methods. IAH Commission on Managed Aquifer Recharge, Australia.
7. The National Policy Statement for Freshwater Management 2014, updated August 2017.
8. Schedule 8 of the LWRP, region-wide water quality limits.

A complete list of material referenced in this report is provided in Section 7.

2.3 PHYSICAL COMPONENTS OF MAR

Whilst there are numerous MAR techniques that may be applied on a site-specific basis, there are also fundamental concepts and principles that apply generally to all MAR systems and/or a wider Groundwater Replenishment Scheme (GRS).

In the context of the proposed LWRP provisions, MAR systems are typically comprised of the following primary components:

- Source water capture – the take and delivery to the site for purposes of recharge. The take can occur from rivers, streams, races or piped systems. Other water capture options have been applied, trialled or proposed both within New Zealand and overseas, including the diversion of groundwater from one aquifer to another, however these specialised options are not addressed in this report.

- Source water pre-treatment – processing of the source water to improve the quality of the water being recharged, thereby reducing risks to the receiving environment or water users or reducing the risk of operational issues arising such as recharge system clogging. The word *pre-treatment* is used as a general term to describe a range of potential methods of source water treatment, from passive (e.g. retention ponds for sediments) through to more engineered or active (e.g. filtering system on an injection bore for sediments).

- Recharge – the physical structure(s) that recharge water to the receiving aquifer, together with the operational control, maintenance and monitoring systems installed.

- Recovery – the physical features to which the recharged water discharges naturally (e.g. natural groundwater discharge to surface waters).

There is a lot of international information available on design principals for various components of a MAR project. Best practice guidelines are also available that can help an applicant make cost effective design decisions, such as provided by the EPA South Australia (2004).

The term *pre-treatment* used above is specifically used as applying to source water before it is introduced to the sub-surface. It is differentiated from water treatment technologies that have been specifically researched, designed and installed to utilise MAR techniques to improve the quality of recharged water as it seeps through either the vadose zone or the saturated aquifer. For example, some infiltration sites are specifically designed to utilise the natural soil profile to reduce sediment and contaminant loads in the source water (known as Soil Aquifer Treatment or SAT) prior to the water being abstracted and treated for potable water supply purposes. These natural water treatment processes should however be taken into account when assessing risks with respect to the receiving aquifer water quality, the water quality of hydraulically connected surface water bodies and groundwater users (refer Section 4).

The ‘recharge’ component will likely fall into one of the following physical techniques (Figure 2):

- Surface infiltration recharge through spreading or infiltration basins.

- Unsaturated (vadose) zone recharge through soakage pits, galleries or ‘dry wells’.

- Saturated zone recharge through injection wells.

Design and construction requirements for MAR systems vary greatly, depending on the technique to be utilised at any given site. Infiltration systems are typically the least complex. Injection systems are typically the most complex, requiring construction of specialised bores with water filtering systems, automated operations and monitoring systems. The decision on which technique(s) should be used at a site needs to be scoped as part of a pre-feasibility evaluation process. There are numerous guidelines and books available that provide guidance on the scoping of MAR sites (e.g., ASCE 2019, EPA South Australia 2004, EPA Victoria 2009, NHMRC 2009a, 2009b, Pyne 2005).

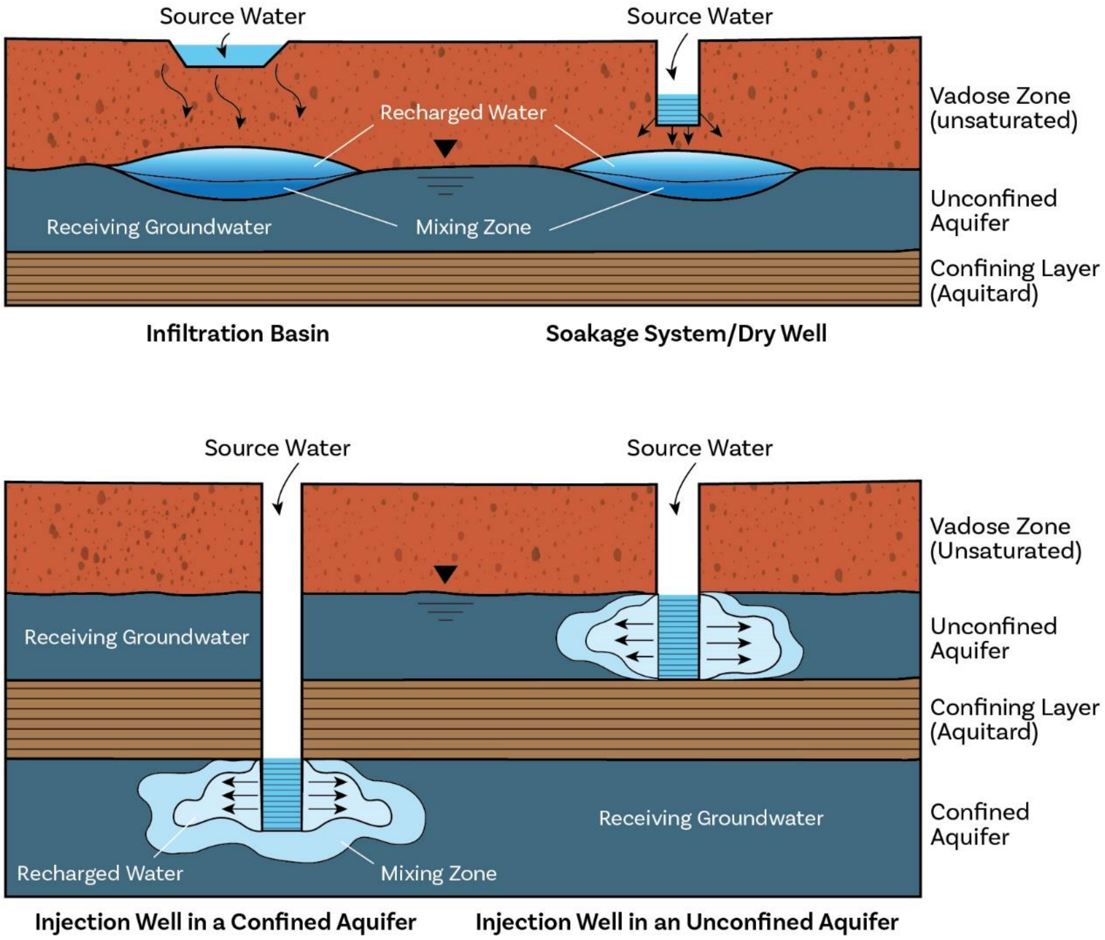


Figure 2. Hydrological components and processes for three primary recharge methods (ASCE 2019).

Any MAR project should have very clear and concise set of targeted objectives or outcomes. In scoping the project, a set of evaluation criteria should be established to ensure the major considerations are appropriately assessed for any potential MAR site. A generic list of potential scoping criteria for MAR projects that should be considered as part of the pre-feasibility and feasibility assessment process is provided in Table 1. Assessments undertaken for many of these factors would also be important to support an application for consents to the regulatory authorities.

In terms of the specific design of primary components of any MAR project, detail should be adequate to show that the applicant has enough understanding of how the project will be operated, the range of likely recharge rates and the various potential risks of recharging groundwater (both above and below ground).

Table 1. Indicative MAR feasibility evaluation criteria.

Category	Criterion	Description/Applicability
Water sources and demand.	Source water availability.	Water available both physically and through an allocation process. Any trends and variability that may affect seasonal and annual water availability.
	Source water proximity and access.	Distance from water source to MAR site. Degree of risk for contamination or losses.
	Source water quality.	Operational factors such as Total Suspended Solids (TSS) loads relative to potential site clogging. Environmental or human health effects factors such as pathogens, nutrients, organic and inorganic contaminants.
Site hydrogeology.	Hydrogeologic suitability.	Hydrogeological factors that limit recharge rates. Aquifer characteristics support transmission of recharged water away from MAR site. Leakage between aquifers.
	Available storage.	Physical space available in aquifer. Unsaturated pore space for unconfined conditions, pressure head and porosity for confined conditions.
	Proximity and hydraulic connection to objective focal areas.	MAR site appropriately located to address the project objectives, especially where project objectives include improvements in groundwater quality or increases in spring-fed baseflows.
Environmental and cultural considerations.	Waterlogging	Where groundwater mounding (elevated water table conditions) may impact soils and structures.
	Non-beneficial use.	Water loss through evapotranspiration.
	Habitat concerns.	Possible impact on sensitive environments.
	Effects on aquifer water quality.	Effects of introducing water with differing chemistry or contaminants on down-gradient groundwater users and groundwater dependent surface water bodies.
	Cultural values of importance to Maori.	Moving water from one catchment or water body to another. Impacts wāhi tapu, wāhi taonga and/or mahinga kai.
Implementation considerations.	Source water proximity, access and abstraction system design.	Overall project cost.
	Existing water delivery infrastructure proximity, access and management.	Overall project cost. Management of water availability. Water delivery control systems.
	MAR site land ownership and previous land use(s).	Affects costs, consenting and potential for the introduction of contaminants.
	Conditions surrounding site.	Affects costs, consenting, and environmental and infrastructure considerations.

	Consenting.	Source water accessed under existing or new consents? Affects project schedule and costs.
	Design, construction, monitoring and operational costs.	Total costs to implement and maintain.
	Site access and security.	Affects cost and consenting. Protection of water supply.
	Operational risks.	Monitoring and control system sensitivity and real time application to control risks. Layered water management systems and inbuilt redundancies. Includes passive systems such as emergency spillways and bunds.
	Health and safety.	Health and safety risks. Minimise risks to operators and visitors. Mitigate risks that cannot be eliminated or avoided.

Note: Table adapted from ASCE (2019).

3 GROUNDWATER LEVEL RESPONSE ASSESSMENT METHODOLOGY

3.1 INTRODUCTION

One objective of a MAR project is to artificially raise groundwater level(s) or pressure(s) in the underlying aquifer(s) for the purpose of increasing groundwater storage. This is achieved through the intentional infiltration or injection of water to an aquifer. The operation of MAR sites generates transient mounding or up-coning (level or pressure increases) that can be quantified against distance to the recharge site and tracked during on/off operational cycles.

Mounding or up-coning are operational outcomes of the recharge process. Increased groundwater storage, which is the objective of these types of MAR project, is calculated from the cumulative change in groundwater level measured over periods of seasons to years, and sometimes decades.

The magnitude and extent of the rise in groundwater level or pressure beneath and around the site is primarily dependent on:

1. The design of the recharge system used in the MAR operation.
2. The thickness and horizontal hydraulic conductivity of the receiving aquifer.
3. The degree of aquifer confinement.
4. The specific yield or storativity characteristics of the receiving aquifer.
5. The rate of recharge and changes in rate over time.
6. The period over which recharge occurs.

For the purposes of this report, two terms are used to describe the rise in groundwater level or pressure resulting from a MAR operation:

- *Mounding* is the magnitude and shape of:
  - The groundwater level rise in an unconfined aquifer resulting from infiltration via a spatially distributed recharge system, such as a basin, trench or flood plain; or
  - The piezometric pressure rise in a semi-confined aquifer resulting from diffuse MAR-induced infiltration downward from a higher aquifer to an underlying aquifer.

- *Up-coning* is the magnitude and shape of:
    - The groundwater level rise in an unconfined aquifer resulting from water introduction via a focused recharge system, such as a well or small diameter soakage system; or
    - The piezometric pressure rise in a semi-confined or confined aquifer resulting from water introduction via a focused recharge system, such as a well or small diameter soakage system.

These two terms are differentiated to support the provision of clear guidance on techniques that may be applied for the assessment of MAR effects on groundwater levels or pressures within a groundwater system.

The effects of both operational mounding and up-coning on groundwater levels or pressures may be extensive. To support an assessment of potential effects, a survey of properties within two kilometres of a planned MAR site should be undertaken to identify features that may be susceptible to unacceptable effects from groundwater mounding, including water delivery races, drainage systems, basements, gravel pits and other excavations, septic tank systems, shallow groundwater bores, etc. The extent of this survey may need to be increased as the evaluation of mounding or up-coning progresses.

3.2 MOUNDING

Groundwater mounding occurs from the spatially diffuse introduction of water, in excess of natural recharge, to an unconfined or semi-confined aquifer. As defined, groundwater mounding may arise from artificial recharge to anything from a spatially compact basin, an isolated historic river floodplain (outside of the riverbed) or a long narrow trench.

The operational criteria applied to a diffuse infiltration site should ensure any potential negative effects on features or other sites arising out of groundwater level or pressure rise (mounding) are avoided or minimised. To achieve this an infiltration basin, pit or trench should have a maximum operational water level defined to avoid risks of:

- Surficial ponding on adjacent sites, unless that is an objective of the operation as specified in the resource consent.
- Water wastage through uncontrolled seepage to the surrounding ground surface.
- Recharged water being diverted to nearby water storage basins, drains, water races, etc, thereby ensuring the water allocated for the project is not inadvertently utilised for other purposes.
- Rising groundwater levels leading to unintended inundation of basements or other excavated features that are normally maintained in a dry state, or the development of unacceptable groundwater pressures around these features. For example, the structural design of a tanked basement may incorporate an assumed maximum external groundwater pressure in the stability analysis. If a MAR project results in excessive external groundwater pressures developing, this could potentially result in structural damage to the basement.

The assessment of groundwater mounding needs to take into account both the vertical seepage component through an unsaturated zone overlying the receiving aquifer and the lateral seepage of groundwater moving away from beneath the recharge system.

The extent and magnitude of groundwater mounding can be assessed through applying:

1. Analytical equations to calculate the form of a generic groundwater mound in an unconfined system, based on a rectangular infiltration basin or trench over time (Hantush 1967; Bouwer 2002; Carleton 2010).

2. Axisymmetric 2D numerical groundwater models to approximate the magnitude of groundwater mounding in unconfined or semi-confined systems beneath a circular infiltration basin or shallow soakage system (Izbicki et al 2008).

3. 3D numerical groundwater models of the MAR operation.

These assessments can be used to evaluate the cumulative effects of multiple MAR sites on an unconfined or semi-confined groundwater system and to evaluate the potential recharge rate achievable at a single MAR site. In the case of the first two options the sites are simulated separately, and the cumulative effects are evaluated through the use of GIS or similar.

3.3 UP-CONING

Groundwater up-coning occurs from the spatially focused introduction of water to an aquifer, generally leading to a radial outward flow of groundwater away from the point of recharge. The focused recharge of water to the groundwater system should be managed to avoid the risk of:

- Groundwater pressures in confined aquifers increasing to the extent that the hydraulic properties of overlying confining strata are changed. In extreme cases, changes to the properties of confining strata may lead to confinement being compromised.

- The hydraulic properties in the receiving aquifer being changed as a result of over-pressurising the aquifer (e.g. hydraulic jacking).

- Upward seepage through a confining layer leading to or contributing to groundwater levels in overlying aquifers rising above the ground surface, as described in Section 3.2.

- Groundwater flows to artificial features, including bores and basements, resulting in uncontrolled water discharges to these features or the development of unacceptable groundwater pressures around these features.

Groundwater infiltration through an injection bore may be carried out passively, with the water introduced to the bore through gravitational forces alone, or actively with the water pumped into the bore. In either case, the injection bore may be sealed to minimise the risk of contaminants being introduced, which in turn may allow water pressures to build up inside the bore.

As a general advice note, when recharging a confined aquifer the groundwater pressure in the aquifer surrounding the bore should not exceed the dry overburden pressure (p) on the base of the aquitard. This pressure (in kPa) can be conservatively estimated as being 15 times the depth in metres from the land surface to the base of the aquitard overlying the MAR target aquifer. This calculation assumes that the average dry weight density of the aquitard and overlying strata equals or exceeds 15 kN/m^3 (NHMRC 2009a).

In contrast to the assessment of groundwater mounding, the techniques used to assess groundwater up-coning tend to focus on the lateral seepage of groundwater away from the recharge system, and the consequent pressure gradients with increasing distance from the MAR site. The extent and magnitude of groundwater up-coning can be assessed through the application of:

1. Analytical equations developed to assess the effects of pumping tests (Kruseman & De Ridder 1991). In using these equations, it is important to take into account frictional losses in and immediately surrounding the recharge system, especially where an injection bore is being used. These frictional losses generally result in the operational pressures developed inside an injection bore (impress head) being significantly greater than the groundwater pressures developed in the surrounding aquifer.

2. 2D radially symmetrical numerical groundwater models to approximate the magnitude of groundwater up-coning surrounding an injection bore.

3. 3D numerical groundwater models of the MAR operation in situations where the surrounding aquifer is complex, has identified boundaries or may contribute to upward seepage into overlying aquifers.

These assessments can also be used to evaluate the cumulative effects of multiple MAR sites on the unconfined groundwater system and to assess the potential recharge rate achievable at a single MAR site.

3.4 APPROPRIATE MODELLING

The intensity and complexity of the assessment of effects on groundwater levels and pressures increases in accordance with:

1. The stage of project assessment, with pre-feasibility assessments generally associated with analytical assessments and 3D models potentially required to support the consenting and final design processes.

2. The nature of any perceived risks identified during the project evaluation process.

3. The complexity of the underlying groundwater system.

4. The scale of the proposed MAR project.

If digital models are utilised to support the project assessment and consenting process, these should be developed and documented in accordance with a modelling guideline acceptable to ECan (e.g. Barnett et al 2012).

If groundwater modelling is being undertaken to evaluate operational and environmental aspects of a MAR programme, it is important to be aware of the limitations to any software package used and apply the packages appropriately. It is recommended that a qualified and experienced professional be consulted for advice on site-specific modelling requirements.

4 WATER QUALITY ASSESSMENT METHODOLOGY

4.1 SOURCE WATER

The overall quality of the potential source surface water needs to be evaluated early in the feasibility assessment process to:

1. Assess whether the MAR system can potentially achieve any project objectives linked to water quality in the receiving groundwater (and any hydraulically connected surface water bodies).
2. Understand the potential MAR operational requirements with respect to clogging and identify potential mitigations (e.g. settling basin, filtering).
3. Understand any potential risks to source water quality (e.g. unfenced water delivery races).
4. Help develop a source water monitoring programme focused on key parameters for the project.

Source water quality should be monitored, managed and documented because:

1. The overall quality of the source water entering groundwater (receiving water) needs to be understood, protected and if possible enhanced by a MAR project.
2. The nature and extent of any potential localised negative effects on groundwater quality need to be understood to avoid unintended impacts on existing or possible future groundwater users or surface water bodies receiving groundwater discharges.
3. Contaminants (e.g. suspended sediment) that may lead to operational issues and reduced recharge rates at the MAR site need to be assessed and managed.
4. The extent of the MAR water plume may need to be monitored and clearly differentiated from background groundwater, which requires a good understanding of how the source surface water quality differs from the baseline receiving groundwater quality.

Key parameters of interest in achieving the above outcomes are listed in Table 2, together with the justification for inclusion in the list. Other water quality parameters may also be monitored for site and project specific reasons.

Table 2. Source water quality parameters for monitoring.

Parameter	Justification for monitoring
Total Inorganic Nitrogen (TIN), which is the total of nitrate-nitrogen, nitrite-nitrogen and ammoniacal nitrogen.	Improvement in nitrogen concentrations in groundwater is likely to be an objective for many MAR projects in Canterbury. Ensuring improvements in groundwater quality for drinking water supply, if this is an objective of the project. Ensuring improvements in nutrient levels in spring-fed streams, if this is an objective of the project.
Microbiological contaminants (e.g. *E. coli*) or appropriate surrogates	Protection of groundwater utilised for water supply purposes.
Pesticides, Herbicides and Fungicides	Protection of groundwater utilised for water supply purposes.
Total Suspended Solids (TSS)	MAR site operational clogging management.
Electrical conductivity (EC)	Used as a surrogate for total dissolved solids. Can be used for monitoring of MAR water spread within an aquifer.
Dissolved iron	MAR site operational clogging management.
Dissolved oxygen (DO)	Clogging management in MAR projects targeting confined aquifers with reducing geochemical conditions.

Each MAR system has a different risk profile with respect to contaminants that may be introduced to the source water upstream from the site. It is therefore important to incorporate a survey of potential risks to source water quality into an overall MAR site risk assessment.

Pre-treatment of source water to remove, inactivate or destroy microbiological contaminants can be achieved through a range of techniques, many of which have arisen out of the wastewater treatment industry (NHMRC 2006, NHMRC 2009b). These techniques include passive treatment measures such as the installation of sand filters or water treatment wetlands. These techniques may also include active pre-treatment measures such as the use of ozone, ultraviolet light and chlorination to manage pathogens in the source water. In general, active pre-treatment measures should not be required in Canterbury as the focus of MAR is to access high quality source water for introduction into the groundwater system.

The use of cased and screened wells to introduce source water into targeted semi-confined or confined aquifers generally requires well sterilisation processes as part of the maintenance regime to manage microbiological clogging. These sterilisation processes may include dosing of the well with chlorine and then purging to remove the treatment water. The use of chlorine to manage microbiological contaminants can result in the generation of disinfection by-products (DBPs), some of which are potentially carcinogenic. Extensive research has been undertaken internationally into the generation of DBPs at MAR sites and their subsequent attenuation within the groundwater system (e.g. Izbicki et al 2010). This research has been focused on the continuous pre-treatment of the source water as being the predominant risk factor for DBPs. Well sterilisation processes to help manage potential issues, such as operational clogging, are considered to represent a very small risk by comparison (Pyne 2005).

4.2 RECEIVING GROUNDWATER

4.2.1 Introduction

The assessment of the effects of MAR on receiving groundwater quality needs to be considered with respect to the change between up-gradient and down-gradient groundwater quality. It should be noted that groundwater mounding or up-coning induced by MAR, as described in Sections 3.2 and 3.3, changes the groundwater hydraulic gradients around the MAR site. The term *“down-gradient”* does not simply refer to groundwater flow paths under natural conditions, but also takes into account the changes in groundwater flow directions induced by site operations.

The receiving groundwater quality during both operational and shut-down periods should be monitored and evaluated to:

1. Verify that MAR site operations do not result in a decline in receiving groundwater quality.
2. Verify that groundwater users are not negatively affected by changes in receiving groundwater quality arising from the MAR activities.
3. Monitor the extent and rate of movement of the MAR receiving water plume, if the project objectives require it (e.g. restore baseflow and quality to a local spring).
4. Verify that any groundwater quality improvement objectives for the MAR program are being achieved.

MAR operations can influence groundwater quality over considerable areas down-gradient from the recharge site(s). The water quality data and the results of the above evaluations should therefore be documented, and the outcomes reported to ECan.

In many areas of the Canterbury Plains, local water supply bores may be screened at different depths and target different aquifers, reflecting the complexity of the alluvial depositional environment. Maps indicating the extent of the MAR water plume should be presented to assist in an assessment of potentially affected users and future monitoring requirements. Cross sections through the MAR site should also be presented indicating the vertical extent of the plume compared to the location and screen depths of local water bores.

4.2.2 Baseline and Background Receiving Groundwater

To understand the effects of a MAR project on receiving groundwater quality, it is important that baseline and background groundwater quality is clearly understood. As applied in this report:

- Baseline groundwater quality refers to the historical groundwater quality at and around the proposed site.
- Background groundwater quality refers to the quality of groundwater flowing into or past the site from up-gradient during the MAR operational period, into which the recharged water is being mixed.

Groundwater quality therefore needs to be monitored and quantified at and around the MAR site prior to the start of the MAR system operations and up-gradient from the discharge point during the operational period.

Baseline and background groundwater quality needs to be monitored and documented to enable:

1. The temporal and spatial variability of the existing receiving groundwater quality to be understood, both prior to the start of MAR operations and during the operational period(s).
2. The objectives of the MAR system to be clearly defined with respect to projected improvements in groundwater quality.
3. An assessment of the geochemical effects (if any) of mixing source water with receiving water to be undertaken prior to the start of operations and subsequently validated during operations.
4. The changes in groundwater quality that arise out of the MAR system to be identified and compared to the project objectives.
5. The rate of movement of MAR water within the groundwater system to be evaluated and the extent of the MAR water plume to be tracked.
6. Differentiation between changes in groundwater quality arising from the MAR operations and those that may arise from other nearby land use activities (e.g. effluent irrigation). Receiving water monitoring in this context provides operators with the capacity to address concerns about possible negative effects from MAR projects.

Not all of the above reasons for monitoring receiving water quality may necessarily apply to an individual MAR project. Therefore, the design of a receiving water quality monitoring programme should be targeted to address project specific objectives and risks. Where appropriate, manual groundwater sampling may be supplemented through the installation of automated water quality monitoring systems.

General parameters of interest in achieving the above outcomes are the same as those listed for monitoring in source water (Table 2), with the exclusion of Total Suspended Solids (TSS), which is primarily monitored for MAR site operational purposes.

4.2.3 Geochemical Reactions

Infiltration or injection of oxygenated source water into an aquifer characterised by reducing conditions can influence the geochemical state of the aquifer, at least on a transient basis. This change in geochemical conditions may result in:

- The release of metals or other contaminants from the host sediments or rocks of the aquifer into groundwater.
- Localised precipitation of metals and other contaminants that may already be present in the receiving groundwater.
- Either an improvement or decline in down-gradient water quality, depending on the nature of the changes.

An assessment of the potential effects on receiving water quality that may arise from changes in the target aquifer's geochemical conditions as a result of planned MAR operations should be undertaken prior to the start of operations. Initially, this assessment should compare source and baseline receiving water qualities to determine whether mixing of the two waters underground will lead to a change in geochemical conditions within the aquifer. If changes in geochemical conditions are likely to arise, further assessment should at the least include:

1. Sampling of the aquifer host rock or sediment for geochemical analysis; and

2. An evaluation of the effects of mixing source and receiving waters within the context of the receiving aquifer. The evaluation should be undertaken by a qualified and experienced geochemistry professional.

Prior to the start of MAR operations, it should be verified that geochemical reactions within the aquifer will not result in the release of unacceptable concentrations of metals / metalloids (e.g. arsenic) or other contaminants from the aquifer host rock.

Some types of MAR projects that utilise well injection techniques into the un-saturated and saturate parts of aquifers are susceptible to geochemical or biological clogging (e.g. precipitation of iron hydroxides in and around a well screen). Clogging generally represents an operational rather than an environmental risk, however it still needs to be managed (Martin 2013). The evaluation of the effects of mixing of source and receiving waters should include an assessment of clogging risk. Geochemical reactions leading to clogging represent an operational risk that can be managed, provided appropriate measures are put in place for this purpose.

4.2.4 Microbiological Assessment

If microbiological contaminants are present in the source water, an assessment should be undertaken to determine the extent of an attenuation zone of the contaminants (specifically enteric bacteria indicators such as *E. coli*) from the point of discharge. Microorganism concentrations in groundwater are reduced by inactivation or die-off, attachment to the aquifer host rock and soil or physical filtration of the microorganisms during seepage of the MAR water through the aquifer. These processes cumulatively result in attenuation of the microorganism load, with the overall natural attenuation process being time dependent (Schijven et al 2017). The rate of attenuation should be evaluated on the basis of both contaminant residence time in the groundwater system and distance transported. The type of MAR technique being used should also be considered as part of that assessment. Microorganism attenuation arising from infiltration through a thick unsaturated zone, or through the use of techniques such as SAT, should be incorporated in the overall attenuation assessment to help manage overall risks to groundwater quality.

In addition to microbiological attenuation within the groundwater system, the concept of SAT is widely recognised as providing additional attenuation capacity. SAT consists of the removal of microorganisms during the passage of infiltrating water through a biologically active layer coating the base of an operational MAR basin. Viral (Mayotte et al 2017), bacterial (WGA 2018) and protozoan (Levantesi et al 2010) attenuation through several orders of magnitude occurs through processes active in SAT and in the unsaturated zone beneath infiltration basins.

The protection of nearby water supply bores requires an adequate separation distances (setbacks) between the MAR site and the bores. This separation distance is calculated based on the microbiological contaminant counts in the source water prior to establishment of a MAR site and the projected time required for the MAR water to reach a potentially affected bore.

The objective of the defined setback is to ensure microorganism counts in any influenced bore improve or remain at the pre-MAR levels. This can be achieved through a combination of source water pre-treatment, SAT, vadose zone attenuation and an appropriate set-back distance. Treatment and attenuation requirements are currently assessed based on the behaviour of *E. coli* as a surrogate for other pathogens. If it is assumed that counts of *E. coli* introduced to an aquifer in MAR water should be attenuated to a target of <1 MPN/100mL, which is the compliance criteria for potable water under the New Zealand Drinking Water Standards, site-specific attenuation factors applying to a MAR project can be evaluated and an appropriate combination of water quality management factors built into the project design.

It is important to recognise that MAR cannot resolve issues of microbiological contaminants introduced to aquifers from surrounding land uses. A resource consent condition that requires *E. coli* counts in down-gradient bores to be below 1 MPN/100mL at all times, which is defined in the New Zealand Drinking Water Standards as appropriate for drinking water supplies, is likely to be unreasonable in many situations. A decline in the microbiological quality of water in a bore, especially where the bore is screened in a shallow aquifer, can occur for many reasons and is not necessarily linked to the installation of a MAR project hydraulically up-gradient from the bore.

The receiving groundwater quality during both operational and shut-down periods should be monitored and evaluated to:

1. If the project objectives require it (e.g. restore baseflow and quality to a local spring), mon*itor th*e extent and rate of movement of the MAR receiving water plume.

2. Verify that any groundwater quality improvement objectives for the MAR project are being achieved.

Appropriate monitoring of receiving groundwater quality provides protection both to down-gradient groundwater users and to the operators of a MAR site. For example, the groundwater quality data can potentially be used to verify that MAR site operations are not resulting in increased microorganism counts in the receiving groundwater, should a concern be raised by a potentially affected groundwater user.

4.3 CUMULATIVE MICROORGANISM TRANSPORT ASSESSMENT

A risk assessment of the potential effects of a MAR project on down-gradient receiving water quality with respect to microorganism contaminants should be undertaken in support of a pre-feasibility assessment and the consenting process. Such an assessment should be similar to the assessment of a contaminant exposure pathway evaluation. In effect, the MAR water flow path from the recharge water's source through to a down-gradient point of interest should be described, changes in microorganism counts for each component of the flow path evaluated and the cumulative effect on microorganism counts at the point of interest calculated. Each risk assessment should be site-specific. However, in situations where a group of similar MAR sites are to be operated as a pod with common source water, generic microorganism attenuation calculations can be utilised to support the consenting process.

A generic microorganism pathway calculation process is summarised below as guidance to the potential components of an attenuation assessment. This guidance does not exclude other methods of evaluating the effects of a MAR project on down-gradient groundwater quality. Numerous methods have been documented in publicly available literature by which microorganism attenuation at each stage of a MAR process can be evaluated and incorporated in a cumulative pathway assessment.

The attenuation parameters applied to a single pathway calculation process should all apply to one microorganism, as attenuation factors differ between organisms. Commonly, *E. coli* is the parameter of interest as it is accepted as an indicator parameter for other pathogenic organisms. This does not exclude a pathway calculation process being applied to other microorganisms.

The first stage in the pathway calculation process is the definition of the water flow path, incorporating all stages in water movement from the source to the final point of interest in the down-gradient groundwater. In general, these stages should include some of or all the following:

1. Source of water at point of diversion or abstraction.

2. Pre-treatment processes (e.g. wetlands, forebay sediment settling basins, filters, active water treatment processes).

3. Infiltration system (e.g. infiltration basin, dry well, gallery, injection well).

4. SAT components for infiltration basins or galleries, including the “schmutzdecke” (biologically active layer that develops on the floor of an infiltration basin or on top of a slow sand filter system) and soil horizons beneath an infiltration basin.

5. Vertical saturated and unsaturated flow components beneath an infiltration basin or gallery.

6. Saturated flow paths within the receiving aquifer outward from the MAR site to one or more down-gradient points of interest.

Based on the above generic stages for a pathway, the following general steps should be incorporated in assessing cumulative microorganism attenuation.

1. Define a maximum expected microorganism count expected in the source water from a baseline monitoring programme and convert this to a $\log_{10}$ value per 100 mL sample (e.g. 1,000 MPN/100mL = log 3).

2. Allocate log-reduction factors that would apply to any pre-treatment processes that are planned for incorporation at the MAR site. These factors are dependent on the design for each pre-treatment process and should be obtained from the design engineer. Subtract the log reduction factor from the source water log count.

3. If SAT components are applicable to the pathway, define attenuation factors for the *schmutzdecke* and any underlying soil horizons. For guidance on *E. coli*:

   a) Log reductions within the *schmutzdecke* of slow sand filters of 1.5 to 2.1 have been identified (Pfannes et al 2015).

   b) Based on general bacterial attenuation in most soils (Schiven et al 2017, Pang 2009), for every $\log_{10}$ reduction in microbial concentration, it takes 0.2–0.6 m depth of soil (i.e. 1.7 $\log_{10}$/m to 5 $\log_{10}$/m). As this attenuation factor is seepage rate dependent, and the infiltration rates for MAR basins would be at the upper end of the ranges documented, reduction rates at the lower end of the range are more appropriate.

   c) Add the log reduction factors described above, then subtract these from the treated water log count calculated under Stage 2 above.

4. In vertical seepage flow components, both saturated and unsaturated, from the base of an infiltration system or the base of the soil horizons considered under Stage 3 above are applicable, define the attenuation factors for each flow type.

   a) From field assessments, identify the likely depth of saturated and unsaturated flow zones beneath the operational MAR site. If it is not clear that an unsaturated zone will be present beneath the operational site, assume the full thickness of material from the floor of the basin or base of the soil horizon down to the baseline groundwater table will become saturated.

   b) Based on the surface infiltration rates (m/day) and an effective porosity for the soil or rock beneath the MAR site, calculate the time required for infiltrating water to reach the groundwater table, assuming fully saturated conditions. For guidance, coliform bacteria reduction rates in saturated conditions, which are temperature dependent, have been documented as ranging from 0.03 – 0.4 $\log_{10}$/day (John & Rose 2005) within a temperature range from 0ºC to 10ºC. Calculate the total attenuation factor based on the water travel time and the time dependent reduction rate.

c) If an unsaturated zone will continue to be present beneath the MAR site during operations, a distance-based factor can be used to calculate microorganism reductions within the unsaturated zone. For guidance, microbe removal rates within the vadose zone for different media have been summarised from literature by Pang (2009). Work by Sinton (1986) indicated faecal coliform (and presumably equally E. coli) attenuation within unsaturated coarse gravels ranged from 0.27 to 0.50 $\log_{10}$/m.

d) Add the log reduction factors described above, then subtract these from the SAT log count calculated under Stage 3 above.

5. Calculate the lateral distance from the MAR site to the down-gradient point of interest, whether it be a potentially affected groundwater user, a monitoring point or another point of interest. For the Canterbury Plains, a distance-based reduction factor can be applied to evaluate microorganism attenuation. In hilly areas, attenuation can be calculated based on MAR water residence times within the groundwater system.

    a) Distance based attenuation factors from literature have been summarised by Pang (2009) on a log10/m basis. For guidance, reduction rates for faecal coliforms (and presumably equally *E. coli*) applicable to coarse gravels of the Canterbury Plains range from 1×10^{-3} to 4×10^{-3} $\log_{10}$/m.

    b) As described above, reduction rates based on residence time have been documented as ranging from 0.03 – 0.4 $\log_{10}$/day (John & Rose 2005).

    c) Calculate one of the log reduction factors described above, then subtract this from the log count calculated for beneath the MAR site under Stage 4 above. Convert the final log10 value back to a normal count (MPN/100mL) and compare this value to background counts in the aquifer.

It is important to note that microbial attenuation rates vary greatly depending on:

- The type of microbe being considered.
- Saturated or unsaturated conditions.
- Soil or rock types, which also influence effective porosity of the aquifer.
- Flow rates within the aquifer or infiltration rates.
- Oxidising or reducing conditions in the receiving aquifer.

Furthermore, ongoing monitoring and research into the transport of microorganisms within the groundwater systems of Canterbury is likely to improve certainty associated with the attenuation factors applied in difference situations. Experience at the Lagmhor MAR trial site (WGA 2018) indicates the guideline values summarised above can substantially underestimate the degree of *E. coli* attenuation associated with a MAR project. Appropriate microorganism attenuation factors need to be derived from up-to-date research and project monitoring outcomes.

A pathway assessment process as described above can be utilised to support the planning and design phase of a MAR project. During this process down-gradient water quality objectives and points of interest are defined as well as potential water pathways. Microorganism counts in the source water should also be quantified from baseline monitoring. The microorganism attenuation calculations can consequently be used to evaluate the attenuation at a potential MAR site.

Guidance has been provided above with respect to a methodology appropriate to calculate microorganism attenuation beneath and down-gradient from a MAR site. However, monitoring and validation of the calculated attenuation is an important component of any MAR project, as described in Section 6.

5 DESIGN, CONSTRUCTION AND OPERATION

5.1 LOCATION

The primary environmental factors restricting the location of a MAR site are:

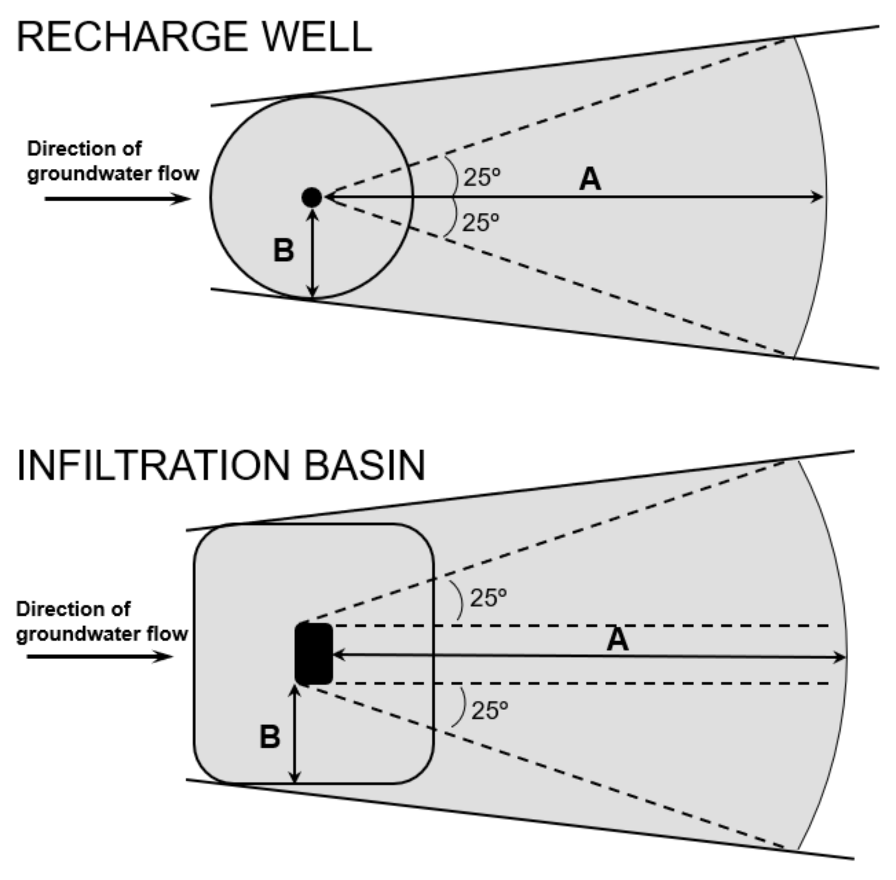
- The presence and structure of water supply wells. MAR sites should be located with appropriate setbacks from existing water supply wells to ensure the protection of these wells from possible microbiological contamination. The objective of the defined setback is to ensure the microbiological count in the well remains equal to or better than the background receiving water quality.

- The presence of local natural topographic low areas or excavated features. MAR sites should be located with appropriate setbacks from such features to minimise the risk of potential ponding or ponding exacerbation as a result of the recharge operations.

- Depth to groundwater. The depth to groundwater plays a significant role in determining potential recharge rates (infiltration) and potential storage capacity for recharged water. /or potential microorganism attenuation rates beneath an infiltration basin. Furthermore, the shallower the depth to groundwater, the greater the risk of localised waterlogging of soils or surficial ponding arising from a MAR project.

Irrespective of the setback calculations described in Section 4.3 (downgradient and radially), initial guidance regarding areas of potential risk could also be provided for future groundwater users in the form of advisory zones. Such zones could generically indicate an area around a MAR site where groundwater quality could potentially be influenced by the operation of the MAR site. Potential examples of such advisory zones, which have been adapted from the provisional community drinking water protection zones as provided for under the Canterbury LWRP, have been presented in Figure 3. Should landowners close to or down-gradient from the MAR system seek to install new water supply bores in the future, advisory zones of this type can be used for guidance with respect to potential water quality risks arising from the MAR operation. These zones may be modified in response to site-specific setback calculations or as groundwater quality monitoring results and MAR plume layouts become available.

The siting of water supply wells down-gradient from MAR sites may offer water quality benefits for the well owners. The recharge of high-quality source water to the groundwater system may improve the quality of the receiving groundwater, for example through reductions in nitrate nitrogen concentrations.



Advisory distances (m)	
Downgradient from MAR system (A)	Radial from MAR system (B)
1,000	200

Figure 3. Examples of groundwater quality advisory zones.

5.2 DESIGN AND CONSTRUCTION

MAR sites should be designed and constructed to incorporate the following features:

- A targeted recharge system consisting of an infiltration basin, trench or soakage pit, a cased soakage pit or a cased and screened well.
- A source water delivery system incorporating a flow metering system and an automated flow control system that is linked to water level in the recharge system. The flow control system should be able to progressively reduce and, if necessary, shut off flows to the recharge system without external input.
- A source water level monitoring system.
- A source water quality sampling point.
- Bunding or equivalent around the MAR site to reduce the risk of off-site ponding should the site flow management system fail.

If the MAR system is to incorporate a cased well or deep cased soakage system, the system should be designed to prevent a direct hydraulic connection developing between one aquifer and another unless this connection is specifically intended by design and has been approved through a consenting process.

If there is a risk of natural flowing artesian pressures developing on a seasonal or irregular basis from a MAR well, a backflow control system should be installed to prevent the uncontrolled discharge of groundwater from the well.

Maintenance is integral to the ongoing acceptable performance of MAR sites, unless the infiltration or soakage system is planned as a temporary feature. All MAR site designs should incorporate safe vehicle access routes. If the MAR site consists of a sizeable infiltration basin, the basin design should incorporate vehicle access to the floor of the basin to enable basin maintenance.

If the MAR system consists of an injection well, the design should provide for space to install a pump to enable back-flushing of the well to remove accumulated sediment from in and around the well screen.

One objective of the design and construction of any MAR site should be the minimisation of leakage from the infrastructure installed. Leakage in this sense refers to the unintentional loss of water (excluding evaporation or evapotranspiration) from any component of the MAR system either directly to the ground surface or to an aquifer that was not targeted by the project. In this sense, leakage includes overtopping of any MAR basin, seepage through bunds to the adjacent ground surface, seepage from joints in a bore casing, etc.

5.3 OPERATION

It is envisaged that MAR operations in Canterbury will generally function as passive infiltration or injection systems, with source water levels at the MAR site being at or below ground level. Under this situation there is no risk of groundwater pressures in underlying semi-confined to confined aquifer systems rising to the extent that the hydraulic characteristics of the confining layer(s) can be significantly affected.

Source water may however be pumped through a pipeline to the MAR site and introduced to a confined aquifer under pressure. In addition, in hilly areas the source water capture point may be substantially higher than the MAR site, enabling water piped from the capture point to be passively introduced to a confined aquifer under pressure. In each of these cases, there is a risk that the impress heads (pressures in the MAR well) could rise to the extent that the confining layer may be damaged or hydraulic jacking of the aquifer could occur.

In any situation where source water is to be introduced to the groundwater system under pressure, a qualified and experienced hydrogeologist or geotechnical engineer should undertake an assessment of the risks described above. Under no circumstances should the hydraulic efficiency of aquifer confining layers be put at risk or hydraulic jacking of the aquifer be permitted to occur as a result of MAR operations.

6 MONITORING AND REPORTING

6.1 MONITORING

The minimum factors required for MAR system monitoring (regardless of MAR project scale) are:

1. Flow of source water to the site(s).
2. Quality of source water provided to the site(s).
3. Source water level in the MAR system.
4. Receiving groundwater quality directly influenced by MAR operations.

Each of these parameters may be monitored for individual sites. However, where several MAR sites are located close together, use the same source water and/or target the same interpreted aquifer units for recharge, these sites may be cumulatively treated as a single MAR pod and the monitoring programme optimised accordingly.

Source water flows may be monitored using any automated monitoring device approved by ECan provided:

1. The volume of surface water delivered to the MAR site on a daily basis can be either directly recorded or calculated from the record.
2. The flow monitoring device can be linked to a data telemetry system to provide for data transmission to a remote computer.

Source water quality may be monitored using automated monitoring systems, supported by regular sampling and laboratory analysis. Water quality parameters appropriate for automated monitoring will vary on a site by site basis however the following parameters are recommended for MAR sites:

- Turbidity
- Electrical conductivity
- Temperature

The following parameters may be appropriate for automated monitoring at specific sites:

- pH
- nitrate-nitrogen
- dissolved oxygen

The automated monitoring of these parameters needs to be supported by field measurements and laboratory analysis of samples to validate and enable calibration checks on the automatic monitoring data.

Automated water quality monitoring systems should be set to record at hourly intervals unless project-specific objectives require a different recording frequency.

Source water samples need to be taken periodically and subjected to laboratory analysis for parameters that cannot yet be effectively monitored by automatic systems, including:

- *E. coli*
- Total suspended solids (TSS) to develop correlation with turbidity measurements.

Source water samples should initially to be obtained as close to the MAR site as possible. If several MAR sites are collectively managed and monitored as a group, the source water for analysis should be sampled at a point that provides water quality results representative of the entire group. If there are numerous MAR sites being supplied from the same water capture and distribution system, initial sampling may include sites that are closer to the capture point. Evaluation of water quality changes through the distribution system may result in key sampling points being identified that can be used as source water quality monitoring stations for large sections of the distribution system. If such points are identified, the source water quality monitoring for a group of MAR sites may be optimised to focus on these key points.

Source water sampling and field testing should initially be undertaken on at least a monthly basis until:

1. The variability and range of results expected under normal operating conditions has been quantified.
2. The factors contributing to the variability have been identified.
3. Correlations between turbidity and TSS, and possibly turbidity and *E. coli* counts, have been developed to support the use of turbidity as a monitoring surrogate for these two important parameters.

Source water sampling and field monitoring frequency could be reduced once the above objectives have been achieved.

Source water levels in the recharge system (e.g. infiltration pond or well) need to be monitored for operational purposes. The recharge efficiency is evaluated from a combination of water level and inflow rate. Recharge efficiency in all systems declines over time, necessitating maintenance to improve the recharge rates. Maintenance frequency differs from site to site and can be optimised through evaluation of the recharge efficiency data.

Receiving groundwater quality initially needs to be monitored in a minimum of one monitoring well located down-gradient from the MAR site. The monitoring well should be located at a distance approximately one to three day's MAR water travel time from the recharge point. The location is intended to enable the attenuation rate for *E. coli* to be evaluated based on source water and receiving water analysis results.

The receiving water quality monitoring for a cluster of MAR sites may be optimised by focusing on two or three recharge points and adapting the locations of the monitoring wells to improve the assessment of *E. coli* attenuation. At least one of the wells used for monitoring of a cluster of MAR sites should be located on the groundwater flow path between the nearest down-gradient water supply bore and an up-gradient MAR site.

Receiving groundwater levels or pressures should be measured using monitoring wells installed for this purpose. The data obtained should not generally be critical to ensuring a MAR system can be operated in accordance with any hydraulic criteria suggested in a resource consent application. However, the data is important to enable an assessment of the extent and magnitude of groundwater level or pressure increases within the target aquifer as a result of MAR operations. This information can be used to:

- Support the optimisation of the MAR site operations.
- Evaluate the degree of hydraulic interference between existing and possible future MAR sites, which could be used to support the optimisation process for a group of MAR sites up to a large catchment-scale Groundwater Replenishment Scheme .

6.2 REPORTING

Annual reporting should be a requirement incorporated in any consent authorising the construction and operation of a MAR project. In addition to as-built documentation of the MAR sites, the operating reports should include, at a minimum:

- Source water volumes delivered to the site.
- Source water levels at the MAR site (i.e. levels within wells or basins).
- Site shut-down periods and reasons for shut-down.
- Source water quality data from both automated monitoring systems and laboratory analysis.
- Receiving water quality data from all installed and sampled monitoring wells.
- *E. coli* attenuation rates in the groundwater system and the distance at which attenuation would result in *E. coli* counts decreasing to below background counts in the aquifer.
- Groundwater level data from background and MAR influenced monitoring wells.

To support the evaluation of potential effects of the MAR water on the receiving water bodies and down-gradient users, it is recommended that the reports also contain:

- A map showing the interpreted extent of the MAR water plume in the groundwater system and down-gradient water supply wells and water bodies.
- A cross section showing the interpreted depth of the MAR water plume in the groundwater system and the positions of down-gradient water supply well screens.

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[2] **Courtesy of co-author Adam Hutchinson**, Orange County Groundwater Replenishment Programme (pers. comms. February 2019).

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[3] **Courtesy of Dr. Liping Pang,** ESR New Zealand (http://www.waterpathogens.org) Blanch (eds) Part 2 Indicators and Microbial Source Tracking Markers http://www.waterpathogens.org/book/subsurfacetransport

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