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Lessons from 10 Years of Experience with Australia's Risk-Based Guidelines for Managed Aquifer Recharge

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Abstract: The Australian Managed Aquifer Recharge Guidelines, published in 2009, were the world's first Managed Aquifer Recharge (MAR) Guidelines based on risk-management principles that also underpin the World Health Organisation's Water Safety Plans. In 2015, a survey of Australian MAR project proponents, consultants and regulators revealed that in those states advancing MAR, the Guidelines were lauded for giving certainty on approval processes. They were also considered to be pragmatic to use, but there was feedback on onerous data requirements. The rate of uptake of MAR has varied widely among Australian state jurisdictions, for reasons that are not explained by the drivers for and feasibility of MAR. The states where MAR has progressed are those that have adopted the Guidelines into state regulations or policy. It was originally intended that these Guidelines would be revised after five to ten years, informed by experience of any hazards not considered in the guidelines, and by new scientific developments including advances in monitoring and control methods for risk management. As such revision has not yet occurred, this paper was prepared to give a precis of these Guidelines and review ten years of experience in their application and to identify issues and suggest improvements for consideration in their revision by Australian water regulators. This paper also discusses the factors affecting their potential international applicability, including the capabilities required for implementation, and we use India as an example for which an intermediate level water quality guideline for MAR was developed. This paper is intended to be useful information for regulators in other countries considering adopting or developing their own guidelines. Note that the purpose of these Guidelines is to protect human health and the environment. It is not a guide to how to site, design, build and operate a managed aquifer recharge project, for which there are many other sources of information.

Keywords: environment protection; health protection; safety; risk; ecosystems; contaminants; recycling; drinking water; regulation; governance

1. Introduction

The first Managed Aquifer Recharge Guidelines [1] based on risk-management principles that also underpin World Health Organisation's Water Safety Plans [2] were published in July 2009, within the framework of the Australian National Water Quality Management Strategy. These Australian Managed Aquifer Recharge (MAR) Guidelines are one of four documents in the Australian Water Recycling Guidelines [1,3–5] (Figure 1). The others address founding principles and non-potable applications of recycled water [3], recycling to augment drinking water supplies [4] and harvesting stormwater for non-potable use [5]. The MAR Guidelines cover all types of water intentionally recharged to aquifers for recovery and use or for environmental benefit. These Guidelines were developed consultatively over three years and approved by three Ministerial Councils of the Council of Australian Governments (COAG), that include all state and national ministers whose portfolios address natural resources management, environment and heritage protection and public health.

Figure 1. National Water Quality Management Strategy, showing the foundations for protecting human health and the environment, and innovation in Australian water management ([6] ARMCANZ-ANZECC (1994); [7] ANZECC–ARMCANZ (2000a), [8] WQA (2018); [9] ANZECC–ARMCANZ (1995); [10] WQA (2013); [11] ANZECC–ARMCANZ (2000b); [12] NHMRC–NRMMC (2004), [13] WQA (2011); Australian Water Recycling Guidelines - [3] NRMMC–EPHC–AHMC (2006); [4] NRMMC-EPHC–NHMRC (2008); [1] NRMMC-EPHC–NHMRC–(2009a); [5] NRMMC–EPHC–NHMRC (2009b)). Where Guidelines have been updated, both dates are given to show the evolution of guidelines but only the latter is applicable. All current guidelines are accessible from: https://www.waterquality.gov.au/guidelines.

The MAR Guidelines were immediately welcomed and implemented in the three states most active in MAR: South Australia, Western Australia and Victoria. In other states implementation of MAR was not progressing, despite obvious needs, opportunities and viability (as described later). Now that ten years have passed, a review of Australia's experiences with MAR Guidelines is warranted, with a view to informing revision which is normally expected on a five- to ten-year cycle to account for experience, such as any hazards that may have emerged that were not considered in the Guidelines and advances in science and technology, especially related to environmental monitoring and contaminant fate. This review could also assist other states where MAR Guidelines are still not in regular use and countries that currently do not have guidelines to consider the benefits of adopting or adapting risk-based guidelines.

2. Australian MAR Guidelines

The Australian Guidelines for MAR [1] define managed aquifer recharge as purposeful recharge of an aquifer using a source of water (including recycled water) under controlled conditions, in order to store for later use or for environmental benefit while protecting human health and the environment. It is not a method for waste disposal. The Guidelines allow for an attenuation zone beyond which at all times, all ambient environmental values (i.e., beneficial uses) of the aquifer are protected. This relies on information concerning inactivation rates of pathogens and degradation rates of degradable organic chemicals. The risk management framework common to drinking water and recycled water guidelines applies. In the MAR Guidelines, this is extended beyond water quality issues to also address aquifer pressures, discharges and leakages and impacts on groundwater-dependent ecosystems [14].

The Guidelines provide for staged development of projects. They are intended to provide a confident pathway forward for proponents, regulators and other stakeholders. The Guidelines also reinforce the need for public consultation processes where other people may potentially be impacted by managed aquifer recharge projects.

Hazards addressed in the Guidelines are:

1. Pathogens,
2. Inorganic chemicals,
3. Salinity and sodicity,
4. Nutrients,
5. Organic chemicals,
6. Turbidity/particulates,
7. Radionuclides,
8. Pressure, flow rates, volumes and levels,
9. Contaminant migration in fractured rock and karstic aquifers,
10. Aquifer dissolution and aquitard and well stability,
11. Impacts on groundwater-dependent ecosystems, and
12. Greenhouse gas emissions.

For each hazard, the Guidelines describe sources or causes, the effect on public health and environment, how it can be managed, including preventive measures, the proposed validation, verification and operational monitoring, and list the acceptance criteria for the various stages of risk assessment that parallel the stages of project development. The first seven hazards are common across all four recycled water guidelines, but the management of these is specific to MAR. The last five hazards are unique to the MAR Guidelines.

2.1. Reactions between Recharged Water and Aquifers

The MAR Guidelines were unique in that they were not simply a set of numerical standards for water quality parameters considered fit for recharge. The Guidelines reflect that aquifers are biogeochemical reactors and local information on aquifer mineralogy and structure and ambient groundwater quality are needed in order to determine the quality of recharge water that would result in acceptable quality of recovered water, protection of the aquifer and related ecosystems, and ensure sustainable operation. They also account for pressure, flow rate, volumes and levels in confined, semi-confined and unconfined aquifers, and address energy and greenhouse gas considerations. They regard clogging and recovery efficiency as matters for the proponent to address but provide advisory information on managing these operational issues that impact most on the proponent.

While proponents would have preferred that the MAR Guidelines specified maximum values of analytes in recharge water, such as by treating water to drinking standards before recharge, this was considered not to assure protection of the aquifer and recovered water. Experience had already shown that e.g., chlorination, which removes pathogens that would have been inevitably removed over time in a warm aquifer [15] can result in water recovered from some (oxic) aquifers containing persistent excessive chloroform [16]. In some locations, drinking water injected into potable aquifers has resulted in excessive arsenic concentrations on recovery due to reactions between injected water and pyrite containing arsenic [17]. Source water that has been desalinated to a high purity dissolves more minerals within the aquifer than water that has been less treated and can also react with dispersive clays to cause clogging [18–20]. Also, in some experiments biodegradable organic carbon in recharge water has been found to enhance microbial diversity and assist co-metabolism of some trace organics thereby enhancing their removal and supplementing removal processes under oligotrophic conditions deeper in the aquifer [21–23]. The American Water Works Association Research Foundation, along with Australian, European and American partners have supported much of the research in this area [15,17,24]. Consequently, the MAR Guidelines adopt a scientific approach that takes into account three ways that aquifers interact with recharged water [25]:

1. Sustainable hazard removal. The Guidelines allow for pathogen inactivation, and biodegradation of some organic contaminants during the residence time of recharged water in the soil and/or aquifer within an attenuation zone of finite size.
2. Ineffective hazard removal. These hazards need to be removed prior to recharge because they are either not removed (e.g., salinity) or removal is unsustainable (e.g., adsorption of any metals and organics that are not subsequently biodegraded, or excessive nutrients or suspended solids).
3. New hazards introduced by aquifer interaction (e.g., metal mobilization, hydrogen sulphide, salinity, sodicity, hardness, or radionuclides). There is a need to change the quality of recharge water to avoid these (e.g., change acidity/alkalinity, reduction/oxidation status or reduce nutrients).

In undertaking this 10-year review it was of interest to determine whether the Guidelines were sufficiently comprehensive to address all water quality deterioration processes encountered in MAR projects.

2.2. *Zones of Influence of a MAR Operation*

The response of an aquifer to any water quality hazard depends on specific conditions within the aquifer, including temperature, presence of oxygen, nitrate, organic carbon and other nutrients and minerals, and prior exposure to the hazard. The Guidelines indicate the state of knowledge in 2009 on attenuation rates of pathogens and organic compounds under a range of conditions. They also allow for new local knowledge to be taken into account in assessing risks and determining sizes of attenuation zones and siting of monitoring wells.

In most aquifers, with appropriate pretreatment of water to be recharged, the attenuation zone will generally be a small zone around the recharge area or well (see Figure 2). Water that travels further has had sufficient residence time in the aquifer for attenuation of pathogens and contaminants to below the relevant guideline values for native groundwater and intended uses of recovered water.

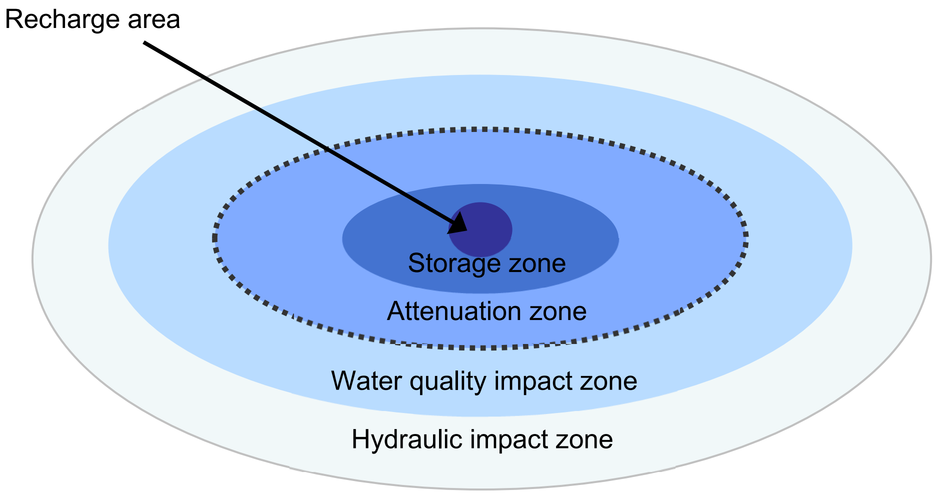

Figure 2. Schematic showing plan view of zones of influence of a managed aquifer recharge (MAR) operation.

The zone of aquifer in which water quality may be measurably affected by MAR may be larger, but in this outer domain the water quality should continuously satisfy the initial environmental values of the aquifer (Figure 2). The effects of managed aquifer recharge operations on hydraulic heads (pressures) may be measurable over a much larger area, especially in confined aquifers. If the aquifer is originally too saline for the uses of recovered water, a storage zone can be identified that contains water which, when recovered, is fit for its intended use (Figure 2).

The dotted line in Figure 2 marks the outer boundary of the attenuation zone. This represents the maximum separation distance between the recharge structure and well(s) for verification monitoring to ensure that the ambient groundwater quality is protected. As the attenuation zone is defined only for enduring attenuation processes, on cessation of the MAR operation, it will shrink and disappear as ultimately the whole aquifer will meet all its initial environmental values. Attenuation rates under various aquifer conditions as known in 2009, are summarised in the appendices of the Guidelines. These warrant updating with results of subsequent studies, in which aquifer environmental conditions and attenuation rates and mechanisms have been documented.

In the entry level assessment stage, the Guidelines refer proponents to water resources planning and management regulations, which require an ability to gain an entitlement to take water for recharge, to recharge an aquifer, to recover water from the aquifer and for appropriate uses of the recovered water. This may also require consideration of cumulative impacts on water level, pressure and quality in the aquifer of multiple recharge operations. For confined aquifer systems where the hydraulic impact zone can extend tens of kilometres from a recharge well, or where ambient groundwater is brackish and neighboring injection and recovery wells reduce the recovery efficiency of an aquifer storage and recovery (ASR) system, this may be a significant consideration for approvals [26].

3. Experience that Suggests Future Refinement of MAR Guidelines

Both experience with the application of the MAR Guidelines and recent research suggest ways in which the MAR Guidelines could be improved if they are to be revised in the near future. These two elements will largely be addressed separately here, starting with experience. The following list of experiences have provided sources of information that have resulted in changes in state regulations or suggest potential improvements for future inclusion in the MAR Guidelines. While there have been many MAR projects undertaken in Australia (see [27] ESM1), few have resulted in suggestions for changes, and so this list below largely focuses on these exceptions and related regulatory change:

- A survey on MAR in Australia by the National Centre for Groundwater Research and Training (NCGRT) in 2015 with 134 respondents from all states.

- An update of the Guidelines for Groundwater Protection in Australia [9,10] and the South Australian Environmental Protection Policy for Water Quality [28] to enable a pathway to pragmatically define the environmental values of an aquifer, where these have not already been defined or where default values were unsupported by the facts, driven by MAR.
- An update on the South Australian Environmental Protection Policy for Water Quality [28] in 2015 where a previous arbitrary requirement for zero concentrations of herbicides was revised to conform with Aust. and N.Z. Guidelines for Fresh and Marine Water Quality 2000 [7] as periodically updated [8].
- Victorian Civil and Administrative Tribunal ruling in 2017 on reinjection of spent geothermal water into a geothermal aquifer.
- Experience in reinjection of desalinated, deoxygenated associated saline water from coal seam gas wells into a fresh water aquifer capable for use as drinking water supplies in Queensland.
- Experience in Western Australia in reinjection of dewatering water from iron ore mines to protect a groundwater-dependent salina and replenish needed groundwater resources.
- Experience in injection of advanced-treated recycled water into deep aquifers beneath Perth that contribute to public drinking water supplies.
- Lack of confidence in managing water quality, quantity and reliability of a recharge project on the Darling River in New South Wales for a drinking water supply for Broken Hill, that resulted in an alternative project being selected at four times the cost and with higher vulnerability to drought.
- Review of responses made since 2015 to the detection of per- and poly-fluoroalkyl substances (PFAS) in stormwater and aquifers in aquifer storage and recovery projects.
- Experience with cumulative impacts of aquifer storage and recovery schemes resulting in uncapped third-party wells overflowing in South Australia.
- Potential for problems of rising water table due to expansion of water sensitive urban design with increasing reliance on stormwater infiltration systems as a means of stormwater management but currently not considering potential groundwater impacts.

The NCGRT survey on MAR in Australia in 2015 revealed the perceived main drivers for MAR (Figure 3) and perceived main deterrents (Figure 4) in each Australian jurisdiction. The three largest drivers were perceived as water security in drought, meeting demand for water and mitigating decline in groundwater levels. Main deterrents were seen to be lack of information on aquifer suitability, lack of confidence that MAR will work and lack of funding mechanisms (Figure 4). However, 'lack of definition of water quality requirements for health and environmental protection' (Figure 4, item 11) was among the least deterrents, along with 'onerous water quality requirements for health and environmental protection' (Figure 4, item 12). However, the states where these both received their highest rankings as deterrents were the ones where the MAR Guidelines had been quickly adopted. This seems to suggest that in other states where MAR had not progressed, potential proponents had yet to identify water quality concerns as an issue. Where MAR Guidelines were regularly applied, the monitoring requirements increased but, on the whole, this was seen as a very minor issue. This suggests that implementation of MAR Guidelines would be accelerated if there were water quality and risk management training programs for proponents and regulators in states where uptake is lagging, as drivers for MAR are not lacking in those states.

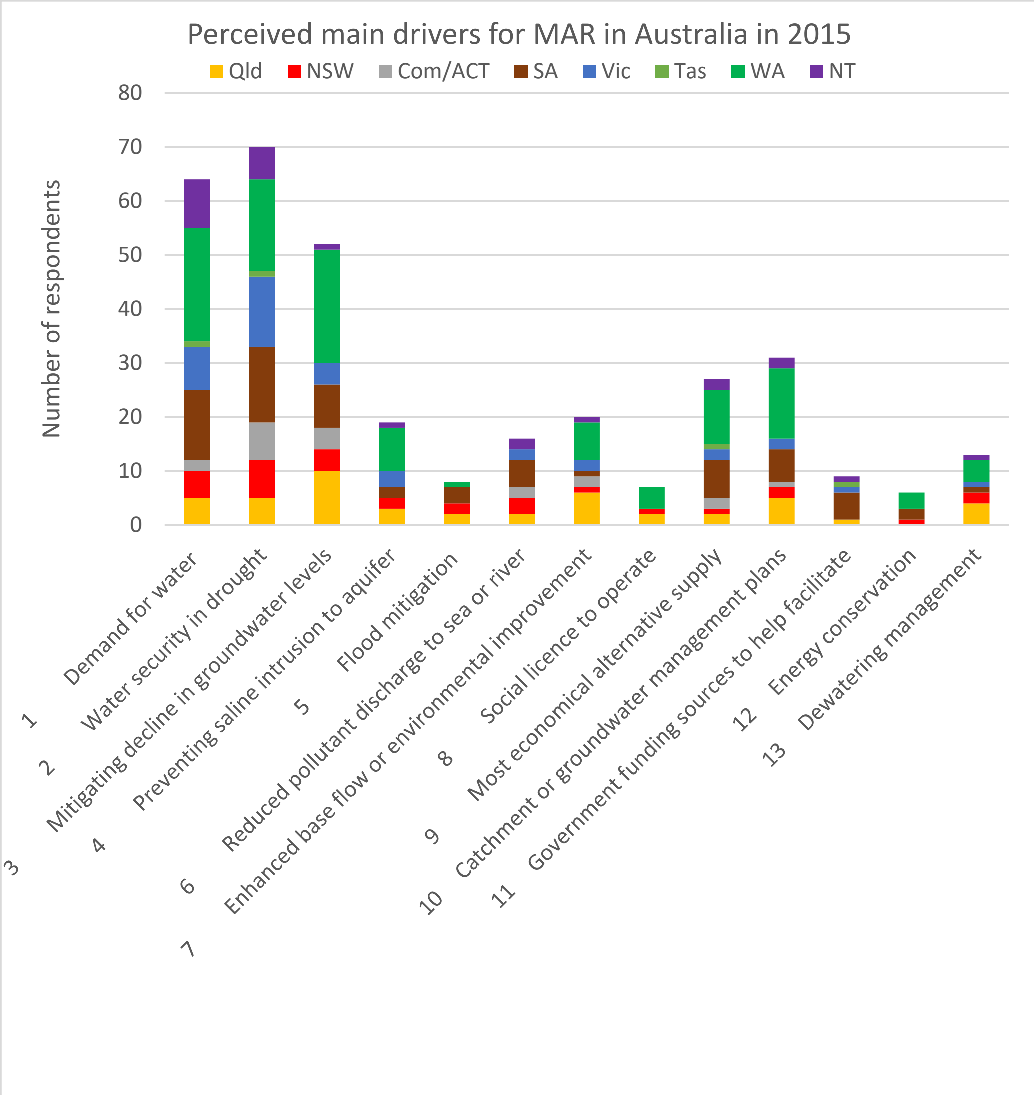

Figure 3. The main drivers for MAR perceived by 134 Australian respondents in a survey of the National Centre for Groundwater Research and Training (NCGRT) May–July 2015. This shows the number of respondents reporting perceived importance of each identified factor driving the development of MAR in their jurisdiction. (Total number of respondents = 134, total responses = 342, and average number of responses per category = 26.) (Also reported in supplementary info to [27].)

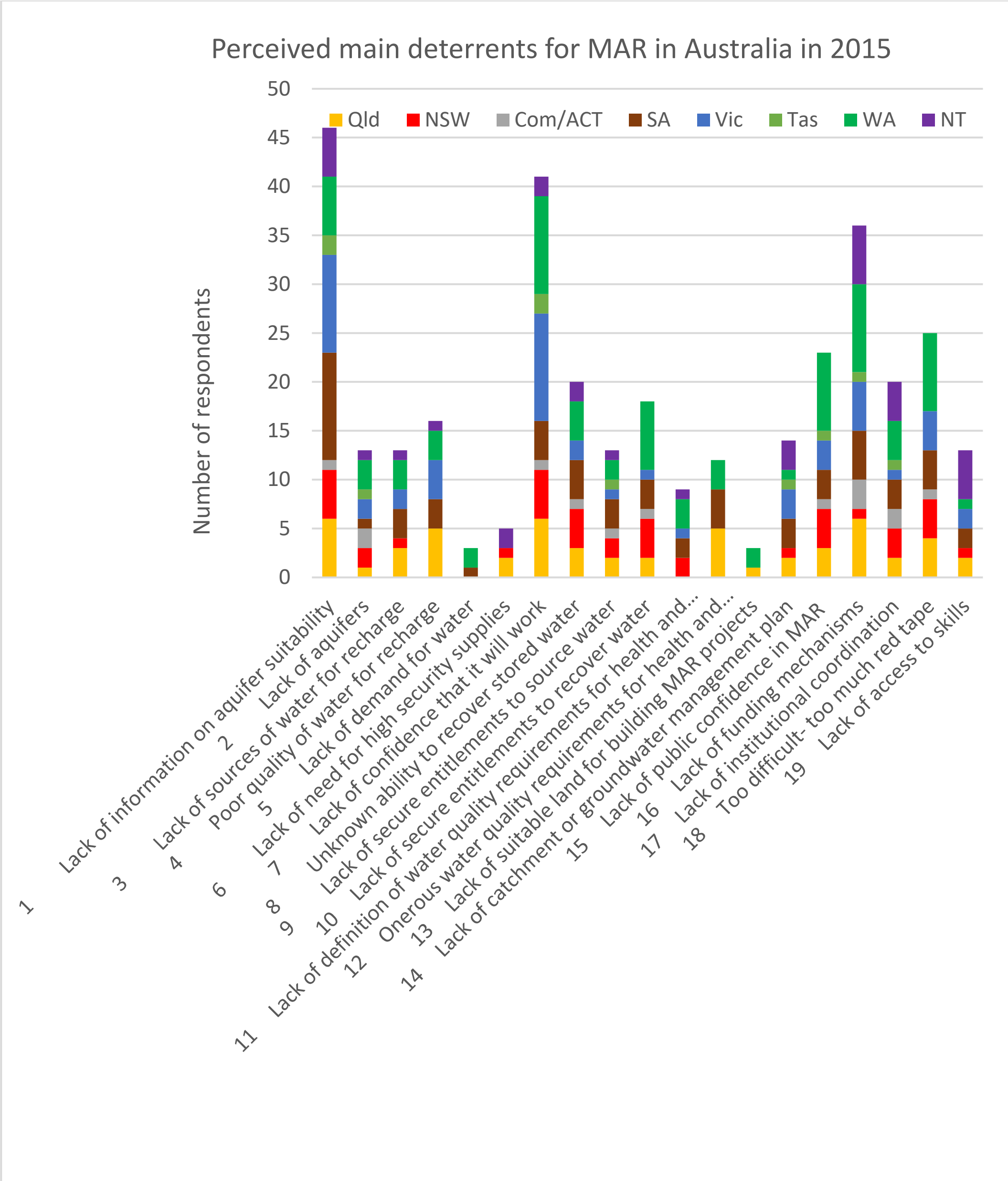

Figure 4. Number of respondents reporting perceived importance of each identified factor deterring MAR in their jurisdiction (NCGRT survey 2015). (Total number of respondents = 134, total responses = 343, and average number of responses per category = 18.).

The MAR Guidelines rely on other guidelines to specify the environmental values of the aquifers. These are for example; water for drinking, water for irrigation, water for livestock, and aquatic ecosystem protection, such as the aquifer itself and any connected rivers and wetlands that may be in pristine, good or degraded status. This differential protection policy therefore requires more effort to go into managing MAR operations where higher water quality requirements need to be sustained in the receiving aquifers and connected ecosystems. However, in Australia, as in other countries of the British Commonwealth, while there are common principles set nationally for managing water, each state enacts its own legislation and formulates its own policies. It was found in states aside from Victoria [29], that setting environmental values for aquifers could be a difficult task. Hence, in 2013, this process was laid out quite directly at national level [10]. In South Australia, this led to the SA Environment Protection Policy—Water Quality 2003 being revoked and replaced in 2015 [28] to enable the differential protection policy to be implemented within the intent of the original and revised Groundwater Protection Guidelines [9,10].

In this revised SA policy, the opportunity was taken to remove the requirement for zero concentrations of herbicides in groundwater. This was untenable scientifically due to ever lower detection levels being now well below the levels considered as acceptable for all environmental values, including drinking. This was replaced by reference to the guideline values for each beneficial use as recorded in the Aust. and N.Z. Guidelines for Fresh and Marine Water Quality 2000 [7] as periodically updated [8]. Until 2015 this had been a major impediment in ASR of stormwater in brackish aquifers where measured values for simazine and atrazine at lower than drinking water guideline values had resulted in shut-down of ASR under the former 2003 Water Quality Policy.

In 2017, the Victorian Civil and Administrative Tribunal made a ruling [30] in a case where a groundwater user was required to reinject spent geothermal water to its source aquifer if extraction exceeded a specified amount. The ruling supported increasing the licensed allocation of groundwater by the amount reinjected, within limits. (However in Western Australia geothermal waters reinjected into aquifers are currently not regarded as MAR and do not create allocation credits.) There were questions concerning impacts of reinjection reducing the temperature of extracted groundwater for both the licensed user and potential future users. Although not mentioned in the judgement, it is evident that temperature would be a useful inclusion in the MAR Guidelines as a hazard at least in relation to geothermal waters. Temperature could also be an important indicator of adverse interference effects between proximal aquifer thermal energy storage systems (ATES). Even in simple aquifer storage and recovery systems, where there is a large difference in temperature of source water and ambient groundwater, this could also have a bearing on ecosystem protection, inactivation rates of pathogens and biodegradation and sorption of contaminants [31]. Hence, consideration should be given to inclusion of water temperature as a hazard to be evaluated in MAR Guidelines and risk management strategies developed where needed.

In addition, the following points may be drawn from the ruling:

- A licenced allocation of groundwater for non-consumptive uses may be specified as an allowable net extraction (extraction minus reinjection);
- Reinjection of water is warranted to sustain the groundwater resource, even when the sustainable use limit is uncertain;
- Improving water use efficiency and reinjection are preferred to disposal of spent geothermal water to sea and much more so than disposal to leaky evaporation basins that increase the salinity of shallow groundwater;
- Reinjection gives benefits to groundwater users over a wide area by sustaining pressures whereas any residual risks of lowered temperature are primarily experienced by the holder of the licence;
- The benefits of carefully managed reinjection to the sustainability of the resource outweigh any residual risks to the resource attributes (such as reduced temperature);
- Good management of water quality and the reinjection system may make reinjection feasible, even in a complex, deep, aquifer used for geothermal operations;
- The costs of reinjection are considered commensurate with the benefits and not out of proportion with other costs of developing and utilising the groundwater resource;
- Reinjection is a part of the set of tools for adaptive management of groundwater for non-consumptive uses.

In the Surat Basin of Queensland, coal seam gas (CSG) production requires the extraction of groundwater. At two sites operated by Origin Energy, this water is desalinated, deoxygenated and reinjected into a fresh water aquifer in which pressure has been declining over many years due to extraction for irrigation, town water supplies and livestock water supplies (OGIA 2016) [32]. In Queensland, there is no clear State government guidance on MAR, and approval has been on a case by case basis. MAR associated with the CSG production is also encumbered with the need to obtain approval under the Commonwealth Environmental Protection Biodiversity Conservation Act. Despite significant investment by the CSG industry in MAR trials into multiple aquifers at several geographical sites with general adherence to the MAR Guidelines, the uncertainty in regulatory approval pathways has curtailed further CSG schemes. Key considerations for future updates to the MAR Guidelines include potential impacts to springs and groundwater-dependent ecosystems from rising heads/pressures due to multiple reinjection operations, and improved advice to operators on the effects of non-isothermal conditions on wellbore hydraulics.

Water from dewatering of several Western Australian iron ore mines has been reinjected to restore groundwater levels and thereby protect natural groundwater-dependent salinas, and to reduce net loss to the aquifer accounting also for extraction for mineral processing. These operations have been in use since 2012 and are now embedded in mine site management plans. To date no issues have arisen to suggest that a change in MAR Guidelines is warranted, although the considerations for decommissioning of MAR operations used for environmental benefits could be expanded.

Injection of advanced-treated recycled water into deep aquifers beneath Perth that contribute to public drinking water supplies was intensively monitored during a three-year pilot project. This initial extensive study expedited health and environmental approvals, increased knowledge of proponents and regulators, and communications of results created a well-informed public willing to trust and support the project [33]. The approval process was supported by the MAR Guidelines and at the time of approval revealed that no additional requirements for the MAR Guidelines were necessary. Approval processes also took account of the economics of MAR versus alternative water sources, effective and transparent monitoring and reporting by the proponent (Water Corporation) and ongoing community engagement and support for the project that enabled subsequent expansion to a full-scale scheme to proceed. Following the MAR Guidelines enabled all water quality deterioration processes to be determined. Some of these had not been anticipated such as minor release of fluoride and phosphate [34], but these require no specific revision of the Guidelines.

In contrast, the New South Wales government claimed that lack of confidence in managing water quality, quantity and reliability of a well-investigated MAR project in alluvial aquifers at Jimargil, on the Darling River for a drinking water supply for Broken Hill [35], led to selecting an alternative surface water pipeline from the Murray River at a cost of US $350 M. This was approximately four times the estimated cost of the MAR project and had higher vulnerability to drought than the MAR project. This was caused by a combination of NSW government's lack of experience in MAR and political posturing for conspicuous infrastructure. This demonstrates that in addition to comprehensive investigations and access to MAR Guidelines there is an element of capability building required at jurisdiction level to realise the potential for MAR.

In each Australian State, per- and poly-fluoroalkyl substances (PFAS) have been found in groundwater at airports, fire-stations, landfills and have also been detected in stormwater at some MAR sites. This group of man-made PFAS chemicals have been used since the 1950s, and although their use has ceased in Australia and exposure is declining, they are highly persistent and mobile in soils and aquifers. Their human health impacts have been studied but evidence is incomplete on whether this level of exposure is harmful to human health [36]. Page et al. (2019) [37] reviewed the risks of PFAS for sustainable water recycling via aquifers. PFAS substances can be removed from drinking water by sorption to Granular or Powdered Activated Carbon (GAC, PAC), or Ion Exchange Resins or by nanofiltration with reverse osmosis. At several MAR sites, where advanced monitoring was undertaken and PFAS detected, recharge was shut down as a safety precaution until a risk assessment could be performed. While the MAR Guidelines do not mention PFAS specifically, they do cover a process to address risks for all organic chemicals, and the procedure to estimate the threshold limit in drinking water, is contained in the Augmentation of Drinking Water Supplies Guideline [4] but not as yet in irrigation supplies.

In another South Australian stormwater recharge case it was found that multiple aquifer storage and recovery wells in close proximity, operated by different organisations, in some cases resulted in heads becoming artesian in third-party wells that were not equipped for this, and so water overflowed, causing a nuisance. The possibility for unacceptable cumulative impacts of multiple recharge operators had been forewarned and solutions proposed in a national document on robust policy design for MAR [26], but this had not as yet been taken up in South Australia. While such policies are not essential on the outset of MAR operations in an area, they warrant consideration to enable sustainable MAR operations. In Australia, the MAR Guidelines start with an entry level assessment that includes identifying (**a**) demand for the recharged water, (**b**) an allocation of source water, (**c**) a suitable aquifer for storage and recovery, (**d**) sufficient land for water detention and treatment, and (**e**) capability to design, construct and operate. Governance of MAR operations should be under the auspices of water resources departments, rather than environment protection authorities or health departments, because entry level issues need to be addressed first, and the primary drivers and constraints for MAR relate to ability to harvest, recharge and recover water. Some water quality matters that must be subsequently addressed would normally demand participation of environment protection and health authorities that contain the necessary skills for evaluation. This could for example include assessing MAR interactions with contaminated sites.

The expansion of water sensitive urban design in South Australia has a high reliance on stormwater infiltration systems. While this is ostensibly for increasing tree canopy cover, there is no requirement to balance increased infiltration with increased evapotranspiration. Such infiltration systems comply with the South Australia Planning Minister's Specification in 2003 for On-Site Retention of Stormwater [38], but are used as stormwater disposal, and fail to account for impacts on groundwater levels and quality. As unmanaged aquifer recharge, they do not need to comply with MAR Guidelines. Infiltration pits and trenches and permeable pavements clearly have benefits for stormwater systems and potentially for greening of cities. It is proposed that linking infiltration with tree water use in the Planning Minister's Specification is the most effective solution. However, if this is not done then the MAR Guidelines could potentially be brought to bear to prevent adverse impacts on groundwater.

4. Research that Suggests Future Refinement of MAR Guidelines

While there has been a plethora of research on MAR-related topics [27] in recent years, the vast majority of this adds new knowledge but does not require revision to the Guidelines. However, the following aspects were considered to potentially warrant revisions because they address gaps not previously covered or expose additional information that would otherwise not normally be taken into account in assessments of risk. It is recognized that a weight of evidence is needed before guidelines are changed. Hence, more than a single peer reviewed paper on a topic is needed, due to the range of circumstances to which guidelines apply. Guidelines usually follow a precautionary approach, and so guidelines may lag the latest scientific evidence.

- Research on deep well injection of brines from oil wells in USA suggests that fluid injection between 2 and 4 km in depth may be inducing seismicity with only marginal increases in pore pressure, suggesting that more explicit consideration of such risk for aquifer storage and recovery using deep wells in relevant geological settings.
- The update in 2018 of the Australian and New Zealand Environmental and Conservation Council (ANZECC) Water Quality Guidelines [8], based on research including that which has yielded improved genomics techniques to allow ecological impacts on aquifers and their connected ecosystems to be determined with higher reliability and reduced cost.
- Research has also resulted in improved methods to assess the sources and fate of pathogens recharged to aquifers to allow improved public health risk assessment.
- The advisory section of the Guidelines concerning the likelihood and extent of clogging and effectiveness of preventative and remedial strategies warrants updating.

Research on deep well fluid injection induced seismicity in Oklahoma associated with oil production and brine reinjection between 2 and 4 km in depth within 15 km of faults has reported induced seismic activity at a level significantly above background levels [39]. Increasing pore pressure reduces effective intergranular stress hence reducing resistance to shear stresses on faults and fractures to the point of instability and the possibility of earthquakes. Deep well fluid injection in Oklahoma was largely unregulated, however, this research raises an additional risk, not addressed in the current Australian MAR Guidelines, that warrants review for consideration of possible inclusions in the Australian MAR Guidelines. This could illuminate the factors affecting risk, and procedures to assess and mitigate risk for deep well injection and recovery in hard rock.

Advances in measuring and understanding ecosystem impacts of groundwater systems over the last decade have included genomics methods to allow changes in relative abundance of micro-organisms in aquifers and connected ecosystems to be assessed. The current Guidelines address microorganisms, stygofauna, phreatophytic vegetation and aquatic flora and fauna including discharge to marine ecosystems. They mention a range of tests for toxicity, genotoxicity and mutagenicity and biomarker methods, but reference to the increasing wealth of available -omics tools available and their applications is now warranted. During this evolution current knowledge has been incorporated into Guidelines for Groundwater Quality Protection in Australia (2013) [10] and Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2018) [8,40,41]. New methods include those using fungi [42], and analyses of DNA in groundwater [43], that can be incorporated into new indices for groundwater health [44]. A recent review of available ecotoxicity data for subterranean fauna [45] may provide a starting point for establishing aquifer-specific water quality guideline values.

Research has also resulted in improved methods to assess the sources and fate of pathogens recharged to aquifers to allow improved methods for public health risk assessment. Research over several MAR sites within Australia demonstrated that pathogens are removed although there are local aquifer conditions that need to be considered, particularly low redox conditions for the removal of enteric viruses [46]. Sasidharan (2016) [20] identified factors affecting removal of virus surrogates. Viral indicators of sewage such as pepper mild mottle virus [47] and protozoan surrogates such as *Bacillus subtilis* spores [48] are becoming increasingly available as are methods to assess fate of antibiotic resistance genes [49]. It is anticipated that validation testing of pathogen removal in full scale systems using appropriate viral surrogates will become possible in the near future once a validation protocol has been established such as are used for engineered treatment systems.

Concerning the advisory section of the Guidelines that addresses clogging in MAR, there have been many papers since 2009 that have better-defined clogging processes (e.g., [50–53]) that would enable refinements to the current general guidance. Such refinements could include approaches to mitigate and remediate clogging, such as where statutory approvals may be required.

5. Discussion and International Relevance

Guidelines have reduced the uncertainty of approval processes, made clear what information was needed in order for project approval and shortened the time for decisions compared with the period before Guidelines, when in some cases years of discussion occurred before approval decisions were made. MAR has certainly advanced faster in States that adopted the Australian MAR Guidelines than those that had not [54] (Victoria [1,55], Western Australia [1,56] and South Australia [1,28]). While it cannot be claimed that Guidelines were the cause of increased uptake, there was a beneficial project that did not proceed due to lack of knowledge by regulatory authorities. There are to date no known examples of projects that have failed as a result of inadequacies of the MAR Guidelines having been followed throughout project investigations and commissioning. However, in parts of Adelaide the cumulative impacts of multiple aquifer storage and recovery sites caused artesian conditions in third party wells, which was in breach of the entry level requirements within the Guidelines. Cumulative impacts had not been addressed in awarding entitlements to recharge the aquifer. However, this was quickly identified as a potential issue and a national document to inform entitlement policy for MAR was published [26] that suggested pragmatic measures to avoid such problems. Due to the partitioning of water governance in Australia between water entitlements, and environmental and health protection, and institutional alignment with quantity and quality objectives, it is suggested that cumulative impacts of MAR are specifically accounted for in entitlement policies that form the basis for groundwater management plans.

There are also economic reasons for failures of MAR sites that relate to over-optimistic assessment of either demand for water or of water available for harvesting, or of inadequate understanding of operating costs, for example because trials were too short to reveal clogging and the processes necessary to manage it [57–59]. In short, there was no uncontestable business case. A tool to help assess the time series of costs and benefits of recycling schemes, and providing for the recovery efficiency of MAR systems has been developed and is freely available to help proponents to properly elucidate costs [60]. Public acceptance of stormwater and recycled water for MAR has been strong in Australia (e.g., [61]), and it is considered that the MAR Guidelines in conjunction with the other relevant guidelines do help to give the public confidence that there is an established auditable process to ensure human health and the environment are protected.

There are, however, a number of small improvements to the Guidelines that are warranted.

- adding temperature as a "hazard" in geothermal and open well ATES applications, and for explicit consideration of reactions within aquifers and contaminant removal processes (for organic and inorganic chemicals, microorganisms) and ecosystem impacts
- considering advances in scientific knowledge with respect to fluid-injection induced seismicity, fate of pathogens and organic chemicals, ecosystem monitoring methods, and clogging processes, which will make minor but warranted refinements to the Guidelines and extend their durability
- further elaborating project closure requirements, particularly where MAR is primarily for environmental benefit
- giving specific consideration of cumulative impacts of multiple MAR projects
- in the entry level section of the Guidelines, making more explicit the water entitlement arrangements for sourcing water, recharging aquifers, recovering from aquifers and end uses (e.g., [26]). In basins with groundwater levels in decline, groundwater management policies need to be strengthened to be effective in securing MAR entitlements.

Use of the Australian Guidelines depend heavily on having capabilities to monitor, sample and analyse water quality. In some countries with sparsity or absence of such capabilities, it is suggested that other forms of Guideline be considered. For example, Indian guidelines for water quality management in MAR [62] are an adaption of the sanitary survey within a WHO water safety planning approach, and are based on only visual observations, in order to improve the safety of MAR operations (Figure 5). Those Guidelines exclude MAR practices with urban stormwater, treated sewage or industrial wastewaters or waters likely to be contaminated by anthropogenic activity that are all expected to contain hazards that cannot be adequately managed without sufficient reliable quantitative analyses. This method is recommended only for MAR of natural waters where water is infiltrated through the unsaturated zone, mimicking natural recharge. This method therefore has limited utility and should not be used for recharge of confined aquifers or aquifers in the proximity of wells used for drinking water supplies.

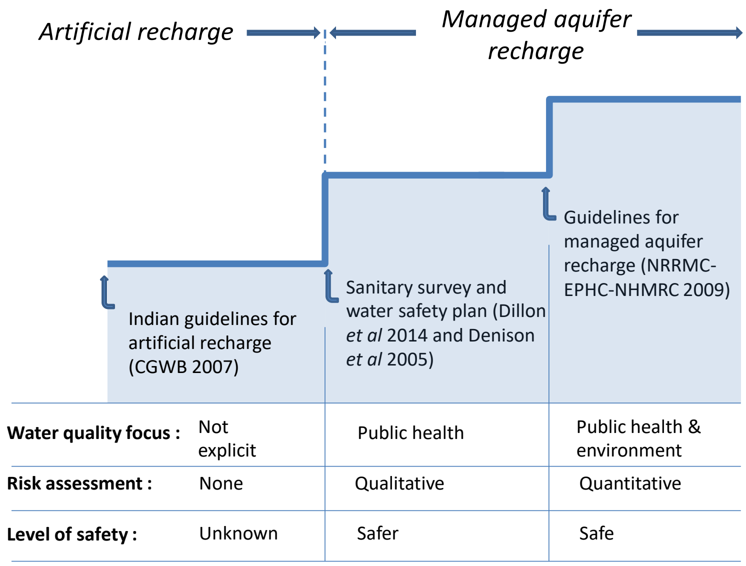

Figure 5. Implementing the Australian MAR Guidelines in India was not possible due to limitations in availability of analyses for viruses and protozoa in environmental water samples and difficulty in being able to get samples from field sites to the lab in time and at a correct temperature for reliable analytical results. Solid state extraction could enable viable delayed analyses of water samples. Hence, an Indian Guideline for MAR was prepared (Dillon et al. 2014) [62] as a step towards safer water supplies and improved groundwater protection than current practice, but without the rigor of data acquisition to support a risk assessment necessary to assure safety.

6. Conclusions

The Australian Guidelines address all types of source waters, all types of aquifers, all types of recharge methods, and all types of end uses of recovered water. While Australian experiences in implementing risk-based MAR Guidelines are currently unique, it is intended that awareness of those experiences in countries considering adopting or adapting risk based MAR Guidelines will become immediately relevant, and potential problems averted. Recent research output is also relevant internationally, as it advances understanding of biogeochemical, hydrogeological or geotechnical processes, improves measurement methods and affords greater awareness of risks that had previously not been as deeply explored. Hence, in aggregate the Australian MAR Guidelines and lessons learned are broadly applicable to a range of hydrogeological, climatic or legal conditions. Adaptation will most likely be required if existing groundwater protection policies do not acknowledge biogeochemical processes in aquifers or otherwise lack a scientific basis.

The Guidelines have served well to ensure protection of health and the environment in Australian MAR operations. Only minor revisions are suggested, and the largest of these is to account for temperature as a specific hazard to be managed in MAR in geothermal operations, for aquifer thermal energy systems and where reliance is placed on contaminant attenuation within the aquifer. Other small revisions recommended are to include more specifically cumulative hydraulic impacts of multiple MAR systems and expanding on decommissioning requirements where MAR is undertaken for environmental benefit. Research now offers a broader range of –omics tools and pathogen fate measures with a view towards future validation protocols for viral and trace organic removal and ecosystem protection. Guideline implementation appears more streamlined, and problems avoided, where they are primarily the responsibility of water resources management agencies, supported by environment protection and health agency expertise (rather than the reverse). Impacts of Guidelines would be accelerated by training at jurisdiction level on water quality and risk management, and on cumulative impact assessment.

Capabilities to measure and manage water quality and to fully understand and anticipate the risks are necessary to apply these Guidelines especially for aquifers used as drinking water sources. For this reason, an intermediate approach has been recommended for India, until such time as the full complement of capabilities is developed though demonstration projects initially with low inherent risk.

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Abbreviations

The following abbreviations are used in this manuscript:

ASR	aquifer storage and recovery (injecting and recovering water from the same well)
ATES	aquifer thermal energy storage
MAR	managed aquifer recharge (the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. It is not a method for waste disposal.)

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