Water reuse through managed aquifer recharge (MAR): assessment of regulations/guidelines and case studies

Jie Yuan, Michele I. Van Dyke and Peter M. Huck

ABSTRACT

Managed aquifer recharge (MAR) with reclaimed water is an important water reuse application. As an intentional way of recharging water into aquifers, MAR can be used to address water shortages and contribute to sustainable water resources management practices. The establishment of a MAR system depends on the source of recharge water, the selection of a recharge method and site, the type of water treatment system, and the ultimate purpose of recovered water, and these components are closely related and integrated. However, at present, detailed regulations or guidelines that specifically guide MAR with reclaimed water are unavailable in most countries. The complexity of MAR systems and the lack of a sophisticated regulatory framework increase the difficulties of MAR implementation. This review provides an introduction to MAR with reclaimed water and a comparison of current worldwide water reuse regulations or guidelines, including a proposed approach for MAR implementation. An analysis of selected MAR with reclaimed water case studies was also done within the context of this proposed approach. This paper recommends the development of specific regulatory or design criteria, including a complete quantitative risk assessment framework for the evaluation and operation of MAR systems.

Key words | groundwater, managed aquifer recharge, potable, recharge, regulation, reuse

INTRODUCTION

Various locations currently or will potentially experience the problem of water shortage due to rapid population growth, water contamination, groundwater exhaustion, and unbalanced allocation of water resources caused by geographical and seasonal variations (Asano & Cotruvo 2004; Chen et al. 2012). For this reason, an emerging paradigm of sustainable water resources management is developing. Some strategies, including water conservation and water reclamation and reuse, aim to ensure that current water demands are met without compromising future needs (World Commission on Environment and Development 1987; Asano et al. 2007). Water reclamation and reuse is an integrated process in which different water treatment technologies are used to treat wastewater. The reclaimed water can be used for irrigation, urban uses, industrial uses, and supplementing potable water resources (Anderson 2003). This strategy is a promising water resources management option and has been widely applied around the world. The recycling of wastewater can not only provide a reliable alternative water source but also reduce the environmental pollution caused by the discharge of wastewater.

One water reuse application, managed aquifer recharge (MAR) with reclaimed water (Figure 1), is an intentional process of recharging water into aquifers for further recovery or environmental uses (Dillon et al. 2009). Unlike natural aquifer recharge processes, in which aquifers are replenished by rain or stream-bank infiltration, MAR is an artificial means to replenish groundwater. The advantages of MAR are numerous, and include the provision of additional natural treatment to enhance water quality, replenishment of groundwater basins to mitigate subsidence and to increase water supplies, prevention of salt water or...
seawater intrusion, storage of water underground to buffer seasonal supply and demand variations and to reduce water evaporation, maintenance of groundwater-dependent ecosystems, mitigation of floods and flood damage, and improvements of urban landscapes (Kazner et al. 2012; USEPA 2012). In particular, this process shows potential for well-based potable water supply and stream-based wastewater treatment systems, which are common in many areas of Canada. However, implementing a MAR system is quite challenging since multiple aspects of urban planning, storm management, wastewater management, and water supply must be taken into consideration (NRMMC-EPHC-NHMRC 2009). In addition, the lack of a mature regulatory framework for MAR system planning increases the difficulties (Asano & Cotruvo 2007; Hochstrat et al. 2013). Due to a wide range of technical and regulatory challenges involved with MAR, there is currently a great deal of research being conducted in various aspects of this area. Most studies have focused on performance monitoring or operational considerations of specific MAR systems, such as the removal of pathogenic or chemical contaminants during MAR processes (Levantesi et al. 2010; Patterson et al. 2010; Pitoi et al. 2011; Sidhu & Toze 2012), the selection of appropriate recharge locations (Rahman et al. 2012, 2013), or MAR design and operational issues (Maliva et al. 2009; Cockett & Pidlisecky 2014). Other studies have investigated MAR from a more general perspective, by addressing political or legal considerations (Asano & Cotruvo 2004; Hochstrat et al. 2010), the management of MAR (Bouwer 1996), or the economics of MAR systems (Shah 2014). However, few studies have reviewed and critically assessed the general worldwide regulatory framework for MAR using reclaimed water. This area will be important as water reuse continues to be developed and implemented globally. Therefore, the objectives of this review are to critically summarize and compare worldwide water reuse guidelines or regulations for MAR with reclaimed water, and to propose an approach for MAR implementation based on current guidelines and regulations. Within the context of this approach, selected MAR case studies that use reclaimed water were analyzed. To provide background knowledge, this review also presents the general principles that are involved in MAR.

### TYPES OF MAR

Design of an appropriate MAR system will depend on site-specific requirements and conditions. Existing MAR systems can be classified into eight different types, as shown in Figure 2, and described below. Besides these eight types, the Australian water reuse guidelines for MAR (NRMMC-EPHC-NHMRC 2009a) also include sand dams, underground dams, bank filtration, dune filtration, and soil-aquifer treatment (SAT) as additional MAR types; however, these types can be included within the categories outlined below. Specifically, sand dams and underground dams can both be used to retain floods, and therefore can be considered as a sub-category of recharge release. Bank filtration, dune filtration, and SAT are the only infiltration processes that can remove contaminants, but can be included within other MAR types such as percolation tanks, infiltration galleries, or infiltration ponds.

- **Aquifer storage and recovery (ASR).** ASR is the underground storage of water through injection and recovery from the same well (Pyne 1995). This type of MAR is a cost-effective water storage option with a small surface footprint (Maliva et al. 2007).

- **Aquifer storage, transport, and recovery (ASTR).** ASTR refers to the injection and recovery of water from separate wells. This method is an upgraded version of ASR and is quite effective for improving stored water quality due to a longer residence time (Maliva & Missimer 2010).

- **Vadose zone wells.** Also called ‘dry wells’, these are shallow wells where groundwater is deep. Common uses are...
for infiltration and disposal of storm runoff where rainfall is low and no storm sewers or combined sewers are available (Bouwer 1996).

- **Percolation tanks and recharge weirs.** These are dams constructed in transient streams, to retain stormwater that can then penetrate through the stream bed to increase the storage in unconfined aquifers (NRMMC-EPHC-NHMRC 2009a).

- **Rainwater harvesting.** In this MAR system, rainwater is collected and redirected to a deep pit with percolation and then reused for further purposes. This process is efficient to augment the natural filtration of rainwater to underground formations, and is beneficial to restore the hydrological cycle in urban areas (Kim et al. 2012).

- **Infiltration galleries.** Infiltration galleries are percolation trenches in which a permeable medium has internal void spaces to facilitate infiltration (Bekele et al. 2013). They are among the oldest known ways of harvesting clean water (Kresic 2006).

- **Infiltration ponds.** These are large open water ponds that are either excavated or located in an area surrounded by a bank. This practice has good pollutant-removal efficiencies and is considered to be an effective means to recharge groundwater and increase base flow to stream systems (New Jersey Department of Environmental Protection 2004).

- **Recharge releases.** In this type of MAR, dams are built on ephemeral streams to detain flood water. Therefore, the release rate of the water downstream can be slowed so it can be directly recharged into underlying aquifers (NRMMC-EPHC-NHMRC 2009a).

**KEY ELEMENTS OF A MAR PROCESS**

The six key elements of MAR for reclaimed water include the sources of recharge water, water treatment, recharge method, recharge site, water recovery, and ultimate uses of recovered water, and each element is further explained as follows. These elements are based on those defined by the USEPA (2012) *Guidelines for Water Reuse*, but water treatment was added as an additional element due to its importance in the process, and sub-surface storage was renamed as recharge site to more accurately reflect the various factors involved in defining the site characteristics.

- **Sources of recharge water.** In terms of water reuse through MAR, aquifers can be recharged using reclaimed
wastewater from municipal wastewater treatment plants. Other sources of recharge water that are not directly related to water reuse can include stormwater, surface water from rivers or lakes, groundwater drawn from other aquifers or remotely from the same aquifer, or drinking water from potable water distribution systems (NRMMC-EHC-NHMRC 2009a). Water quality is an important consideration, and will be guided not only by the end purpose but also by environmental water quality standards. As such, additional treatment will likely be required for reclaimed water.

- **Water treatment.** Water treatment refers to artificial purification processes for the recharge water. To achieve the required water quality, different engineered technologies are combined to pre-treat recharge water or post-treat recovered water in order to remove specific contaminants. In addition, the appropriate design of water treatment can alleviate the potential for accumulation of pollutants in aquifers.

- **Recharge method.** Two recharge methods used in MAR are direct injection and surface spreading. Selecting a recharge method depends on many factors such as aquifer type, aquifer depth, land availability, groundwater quality, and costs. Figure 3 shows a typical procedure for selecting a suitable aquifer recharge method (USEPA 2012), where several levels of criteria are considered. The first criterion is aquifer type; if the aquifer is confined, direct injection should be chosen, otherwise, the second criterion (groundwater depth) should be considered. For unconfined aquifers, the cost of direct injection wells will be higher when the depth to groundwater increases. Therefore, a critical value of groundwater depth, which usually ranges from 100 to 201 m (USEPA 2012), should be determined for each situation. If the depth of groundwater is less than the critical value, direct injection is preferable. If not, the third criterion (land availability) should be considered. If cost-effective land is available, surface spreading basins can be chosen; if not, vadose zone injection wells are more suitable. Besides these key factors, other considerations such as groundwater quality, ultimate uses, and environmental impacts on neighboring areas should also be taken into account.

- **Recharge site.** The recharge site will have a great impact on the performance of a MAR system, since this element has a close relationship with the methods used for recharge and water recovery. Once the recharge location is chosen, the sub-surface characteristics are identified so that storage capacity and hydrogeological conditions can be determined. The selection of recharge sites is a complex decision-making process. Different levels of factors including geological and hydrogeological characteristics,
social and economic policies, natural conservation, and environmental impacts should be considered (Rahman et al. 2012).

- Water recovery. Water recovery specifically refers to the natural purification processes for the recharge water. Underground natural purification is considered to remove some microbial and chemical contaminants, mainly through adsorption or biodegradation (Schmidt et al. 2007; Maeng et al. 2011). Managing the travel time of the recharge water has been the key operational consideration to ensure the recovery of water (USEPA 2012).

- Ultimate uses of recovered water. The ultimate uses of water recovered from aquifers can vary. Normally, aquifer water is used for purposes such as drinking, agriculture, industry, and environment. Other uses include barriers against aquifer salinization, flood mitigation, and coastal water quality improvement through the reduction of urban discharge (Dillon et al. 2009).

In terms of water reuse through MAR, water quality and treatment processes will be particularly important and need to be considered in various aspects of planning. Water quality is an essential consideration in MAR systems since it greatly influences the choice of water treatment technologies, MAR site selection, and MAR system design and operation. The final uses of the recovered water from aquifers will guide the design and water quality that is required. Even though water passage through underground natural systems, or SAT, can provide some treatment for contaminant removal, these processes are quite complex and not easily controlled (Asano & Cotruvo 2004). Therefore, additional engineered processes should be used to pre-treat or post-treat the recharge water to guarantee that the pollutants do not contaminate or accumulate in aquifers and the required quality of recovered water is achieved. The selection of water treatment units or trains is usually based on the source and quality of water that is used for recharge. As an example, if nitrogen is identified as a critical constituent whose concentration is significantly higher than the specified value, de-nitrification should be considered.

The subsurface characteristics of MAR sites also have a close relationship with water quality. During underground geochemical processes, different physicochemical and biological reactions can change the water quality (Essandoh et al. 2011). Reactions such as iron precipitation, biological degradation, oxidation, soil filtration or adsorption can help remove contaminants (Bouwer 1996; Cha et al. 2006; Essandoh et al. 2011). However, some processes may increase the concentration of certain substances in the water. For example, when water flows along an aquifer, small quantities of sodium chloride in soil can dissolve into the water, thus increasing the sodium and chloride content (Fox 2007). As well, clogging of wells or subsurface pores may occur depending on the quality of recharge water. Typical water quality parameters such as the Langelier saturation index, silt density index, and membrane fouling index are defined to characterize the potential of recharge water to cause well corrosion or fouling (USEPA 2012). For the successful implementation of MAR systems, MAR site hydrogeological and geochemical characteristics should be suitable to maintain or improve the quality of water traveling underground, while good recharge water quality is important for the maintenance of the aquifer matrix so that further successful infiltration or percolation of water can be ensured.

The design and operation of MAR systems are, to a large extent, impacted by water quality. Normally, better recharge water quality requires less underground retention time, and therefore the distance between the discharging water and the withdrawing water can be shorter (Bouwer 1996). Poor recharge water quality is more inclined to clog recharge areas such as infiltration basins or wells, and can lead to reduced infiltration rates. To maximize infiltration, operational strategies such as water pre-treatment, well redevelopment, physical removal of the clogging layer, or the use of infiltration basin wetting/drying cycles may be implemented during the MAR system operation (Bouwer 2002).

GUIDELINES AND REGULATIONS

A number of water reuse guidelines and regulations have been developed by specific countries/regions or international organizations. The World Health Organization (WHO) has produced three editions of guidelines for water reuse (WHO 2006). In North America, two provinces in Canada (British Columbia and Alberta) have regulatory
guidelines for water reuse, while in the USA there is a national water reuse guideline published by the US Environmental Protection Agency (USEPA), 25 state-specific water reuse regulations, and 16 state-specific water reuse guidelines or design standards (Schafer et al. 2004; Asano et al. 2007). In Europe, there are no European Union level documents, but seven countries including Belgium, Cyprus, France, Greece, Portugal, and autonomous regions in Italy (Sicily, Emilia Romagna, and Puglia) and in Spain (Andalucía, Balearic Islands, and Catalonia) have released their own water reuse standards or regulations. Australia has developed comprehensive national water recycling guidelines (NRMMC-EPHC-AHMC 2006; NRMMC-EPHC-NHMRC 2008, 2009a, 2009b). In Asia, water reuse regulations have been established by countries such as China, Singapore, Japan, and Korea, mainly for agriculture, aquaculture, municipal, and industrial water reuse purposes (Jiménez & Asano 2008). In other places, including South America and Africa, few water reuse guidelines or regulations have been published, and instead, most countries are following the WHO water reuse guidelines (Jiménez & Asano 2008; Adewumi et al. 2010).

Among these water reuse guidelines and regulations, the most notable and widely used are those developed by the WHO, USEPA, and California. The latest edition of the WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater, published in 2006, not only illustrates the assessment of health risks, health-based targets, and health protection measures in the practice of wastewater reuse in agriculture, but also establishes a framework for assessing the sociocultural, environmental, economic and financial, and policy aspects of water reuse projects (WHO 2006). The WHO guidelines are generally less stringent than regulations or guidelines in some US states or European countries (Asano et al. 2007), but have been broadly adopted all over the world, especially in areas that have no water reuse regulations and no capacity to produce higher quality reclaimed water.

The USEPA (2012) Guidelines for Water Reuse were updated in 2012 by the EPA and the Agency for International Development. This document covers various types of water reuse purposes, water reclamation technologies, water reuse program funding, public involvement, and water reuse regulatory programs or applications in different states of the USA and even around the world (USEPA 2012). In terms of state-specific regulations, the California Department of Public Health updated the Regulations Related to Recycled Water in 2014 to clearly define 54 terminologies related to water reuse, and contains requirements of recycled water sources, uses, distribution, treatment, system design and operational considerations, and reliability requirements (California Department of Public Health 2014). This California regulation is comprehensive and stringent to establish a high level of public protection. Therefore, the California regulation has been followed by some developed countries, including European countries and high-income African countries.

Although many water reuse guidelines or regulations have been established throughout the world, few have specific requirements regarding MAR with reclaimed water. The existing regulations or guidelines mainly contain MAR regulatory considerations from the following aspects: (1) recharge water quality requirements, (2) MAR design, operation and maintenance, and (3) ultimate uses of recovered water. To understand the current rules for MAR with reclaimed water, three regulatory documents (California, Florida, and Australia) which contain relatively more detailed MAR criteria or guidance information in this regard will be discussed.

California groundwater replenishment regulation

In June 2014, the Groundwater Replenishment with Recycled Water regulation was released by the California Department of Public Health (California Department of Public Health 2014). In this regulation, groundwater replenishment using recycled wastewater for indirect potable reuse via surface application and subsurface application is addressed. Since the ultimate use of recovered water from aquifers is normally for drinking water, the regulation requires a public hearing prior to the implementation of such an aquifer recharge project. In addition, the criteria propose a multi-barrier approach to ensure the safety of recovered water. Different kinds of groundwater replenishment controls are specified, including those relating to the water source, artificial and natural treatment, dilution control, monitoring, and operations. For each control, the requirements are stringent and comprehensive. For example, in the control of pathogenic microorganisms,
more specific microbial indicators are used including enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts, but not *Escherichia coli* or total coliforms. This specific microbial requirement will require more sophisticated wastewater reclamation and monitoring methods. Moreover, ongoing monitoring is required, as well as remediation methods to deal with problems in a timely way so as to achieve microbial reduction targets. The most innovative part of the Californian code is the concept of reclaimed water dilution, which can reduce the concentration of contaminants in reclaimed water without the need to upgrade the wastewater reclamation processes.

**Florida administrative code**

Chapter 62–610 of the Florida Administrative Code, entitled *Reuse of Reclaimed Water and Land Application*, describes groundwater recharge with treated wastewater via rapid infiltration basins or injection wells (Florida Department of Environmental Protection 1999). For surface spreading, secondary treatment and disinfection are the minimum reapplication treatment requirements for the recharge water. Based on different subsurface characteristics and neighboring potable water sources, additional levels of reapplication treatment, setback distances (distance between the recharge site and nearby protection zones), and hydraulic loading rates are set. For direct injection, the receiving groundwater quality will set the recharge water quality limits and required pre-treatment levels. When the total dissolved solids (TDS) level in the groundwater is less than 3,000 mg/L, wastewater is required to receive full treatment and disinfection (secondary treatment, filtration, disinfection, and multiple barriers for control of pathogens and organics) to meet drinking water quality requirements. When TDS level of the groundwater is more than 3,000 mg/L, principal treatment and disinfection (secondary treatment, filtration, and disinfection) of the wastewater are required. Water quality requirements in the code not only specify typical wastewater quality parameters but also include total organic halogen (TOX) as a surrogate parameter, to measure the concentration of halogenated organics that may be toxic to humans (Glaze *et al.* 1977; Williams 1984). Pilot testing is also required before the implementation of full-scale projects.

**Australian guidelines**

The *Australian Guidelines for Water Recycling: MAR* is one of three modules which comprise Phase 2 of the National Water Reuse Guidelines (NRMMC-EPHC-NHMRC 2009a). This document includes a framework for hazard identification and risk assessment of MAR projects, MAR operational management, as well as monitoring issues. To be applicable for a variety of MAR projects, this document covers different types of aquifers, reuse purposes, and source water including both wastewater and stormwater. Since the main purpose of this guideline is to provide general principles for the implementation of MAR projects, it does not specify recommended water quality parameters, operational factors, or monitoring frequencies. The guidelines’ major characteristic is the establishment of a logical, staged process for risk assessment and management in MAR projects. The procedure consists of four stages: (1) collection of the available information and entry-level assessment; (2) risk assessment and preventive measures identification; (3) project construction and residual risk assessment; and (4) project operation and verification. Two types of qualitative risk assessment are described in the document; the first is a broad assessment for general projects, and the second is a simplified assessment for specific projects in defined conditions.

**Other guidelines or regulations**

Several other water reuse directives are available; however, unlike the guidelines or regulations discussed above, these documents either do not include MAR as an end-use option for reclaimed water or do not provide information on all aspects of MAR planning, design and operation. Instead, these directives only specify general requirements of MAR in terms of water quality or setback distances. For example, the USEPA (2012) *Guidelines for Water Reuse* regulates groundwater recharge for non-potable or indirect potable use, and includes the required reclaimed water quality and setback distances. To ensure the required water quality, reclaimed water monitoring frequencies are also specified. Idaho’s Recycled Water Rules state that recycled reclaimed water quality should follow the Idaho Ground Water Quality Rule (Idaho Department of Environmental...
Quality 2001), and the determination of a system’s design or operation parameters should be site-specific (Idaho Department of Environmental Quality 2009). In Pennsylvania, the Reuse of Treated Wastewater Guidance Manual specifies that groundwater recharge by directly injecting reused water requires Class A+ water quality and a minimum retention time of 12 months for potable uses, while groundwater recharge by infiltration basins requires Class A or better and a nine-month retention time for drinking purposes (Pennsylvania Department of Environmental Protection 2012). The Chinese Standards of Reclaimed Water Quality set limits on 21 water quality parameters for reclaimed water to be used for recharge aquifers (Ministry of Water Resources 2006).

The water quality needed for MAR is an important consideration, as treatment and monitoring requirements will play a large role in the design and operation of the system. Therefore, the guidelines or regulations discussed above were compared to determine the required quality of the recharge water for MAR, and the results are summarized in Table 1. In terms of microbial limits, it can be seen that most documents include limits for fecal coliforms or total coliforms, but only the latest California regulation specifies the treatment targets for other groups of pathogen indicators including enteric viruses, Giardia cysts, and Cryptosporidium oocysts. As discussed above, Australia uses quantitative microbial risk assessment (QMRA) to establish acceptable microbial water quality limits. Since the water recovered from aquifers is often used for potable purposes, inorganic or organic contaminants that are regulated in the drinking water standards have been taken into consideration. In some cases, limits have been set for specific chemical and physical parameters, including those that measure typical wastewater monitoring parameters (e.g., total suspended solids, biological oxygen demand, and total nitrogen). However, in many cases, and in particular, for inorganic and organic chemicals, the guidelines state that values must meet environmental or drinking water standards. The only regulations to set specific levels for chemical parameters are the California and China regulations.

The treatment and setback requirements for MAR in the various guidelines or regulations were also surveyed and are summarized in Table 2. Overall results show that different levels of water treatment apply for various categories of MAR with reclaimed water. Secondary treatment is the basic treatment requirement for recharge water. To ensure the quality of recharge water and groundwater, additional treatment such as filtration, disinfection, and advanced treatment processes are also required to treat reclaimed water. Additionally, SAT serves as a natural treatment barrier for the removal of contaminants, and therefore MAR via direct injection requires a higher level of pre-treatment than MAR via surface spreading. The performance of SAT depends on the underground traveling time or distance of water. Normally, a longer traveling time or distance will result in better water quality. To ensure the quality of recovered water and the safety of neighboring areas, the setback distances between recharge site and water withdrawal site, or neighboring sensitive areas such as water bodies, are specified in some regulations/guidelines. When no specific numbers are specified for the setback distance in the documents, methods to calculate or determine these values are provided. Normally, determination of the setback distance is based on experimental tracer studies or numerical modeling.

**PROPOSED REGULATORY APPROACH**

Building on the currently available worldwide water reuse regulations and guidelines for MAR with reclaimed water, an approach for MAR implementation can be developed. Because many countries do not currently have MAR guidance documents, a standardized approach can be used by regulatory agencies, municipalities, and other water providers with long-term planning of water and wastewater options to ensure sustainable development. Figure 4 shows an overview of a scheme for MAR with reclaimed water. The approach comprises three steps that include planning, design, and operation.

In the first planning stage, existing problems should be thoroughly analyzed to determine whether there is a need to establish a MAR project. This step identifies the sources of recharge water and ultimate purposes of recovered water. The amount of recharge water and recovered water should be evaluated together with current water sources to ensure that the required water demand can be met. In using reclaimed water as a source of recharge water, the
Table 1 | Required recharge water quality parameters for MAR with reclaimed water

<table>
<thead>
<tr>
<th>Regulation or guideline</th>
<th>Category</th>
<th>Typical reclaimed water quality parameters</th>
<th>Additional parameters and/or requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Groundwater Replenishment with Recycled Water</strong>&lt;sup&gt;a&lt;/sup&gt; (California, USA)</td>
<td>Surface or subsurface application for indirect potable reuse</td>
<td></td>
<td>Enteric viruses, <em>Giardia,</em> <em>Cryptosporidium,</em> radionuclides, organics, inorganics, disinfection by-products</td>
</tr>
<tr>
<td><strong>Reuse of Reclaimed Water and Land Application</strong>&lt;sup&gt;b&lt;/sup&gt; (Florida, USA)</td>
<td>Rapid infiltration basins, absorption fields</td>
<td></td>
<td>Comply with drinking water standards</td>
</tr>
<tr>
<td></td>
<td>Injection (groundwater with TDS &lt; 3,000 mg/L)</td>
<td></td>
<td>Comply with drinking water standards</td>
</tr>
<tr>
<td></td>
<td>Injection (groundwater with TDS &gt; 3,000 mg/L)</td>
<td></td>
<td>Comply with drinking water standards</td>
</tr>
<tr>
<td><strong>Australian Guidelines for Water Recycling: MAR</strong>&lt;sup&gt;c&lt;/sup&gt; (Australia)</td>
<td>13 types of MAR</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>Pathogen removal (QMRA), inorganic/organic chemicals (environmental standards), radionuclides</td>
<td></td>
<td></td>
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<tr>
<td><strong>USEPA (2012) Guidelines for Water Reuse</strong>&lt;sup&gt;d&lt;/sup&gt; (USA)</td>
<td>Non-potable uses</td>
<td>Surface spreading to potable aquifers</td>
<td>Site and use specific</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct injection to potable aquifers</td>
<td>Comply with drinking water standards (after SAT), requires Cl₂ residual</td>
</tr>
<tr>
<td><strong>Recycled water rules</strong>&lt;sup&gt;e&lt;/sup&gt; (Idaho, USA)</td>
<td>Not specified</td>
<td></td>
<td>Comply with Ground Water Quality Rule&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Reuse of Treated Wastewater Guidance Manual</strong>&lt;sup&gt;g&lt;/sup&gt; (Pennsylvania, USA)</td>
<td>Infiltration basins</td>
<td></td>
<td>Comply with drinking water standards</td>
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<tr>
<td></td>
<td>Direct injection</td>
<td></td>
<td>Comply with drinking water standards</td>
</tr>
<tr>
<td><strong>Standards of Reclaimed Water Quality</strong>&lt;sup&gt;h&lt;/sup&gt; (China)</td>
<td>Not specified</td>
<td></td>
<td>Color, odor, dissolved oxygen, hardness, chemical oxygen demand, fluoride, cyanide</td>
</tr>
</tbody>
</table>

FC, fecal coliforms; TC, total coliforms; BOD, biochemical oxygen demand; TOC, total organic carbon; NTU, turbidity; TSS, total suspended solids; TDS, total dissolved solids; TN, total nitrogen; TOX, total organic halogen.

<sup>a</sup>California Department of Public Health (2014).
<sup>b</sup>Florida Department of Environment Protection (1999).
<sup>c</sup>NRMMC-EPC-NHMRC (2009a).
<sup>d</sup>USEPA (2012).
<sup>e</sup>Idaho Department of Environmental Quality (2009).
<sup>f</sup>Idaho Department of Environmental Quality (2001).
<sup>g</sup>Pennsylvania Department of Environmental Protection (2012).
<sup>h</sup>Ministry of Water Resources (2006).
<table>
<thead>
<tr>
<th>Regulation or guideline</th>
<th>Category</th>
<th>Treatment process</th>
<th>Setback distance</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Groundwater Replenishment with Reclaimed Water</strong> (California, USA)</td>
<td>Surface application, indirect potable reuse</td>
<td>Secondary treatment: Disinfection, SAT, Nitrification/Denitrification, RO</td>
<td>0.25 to 1 month (based on tracer study or numerical modeling)</td>
<td>≥3 treatment units and wastewater dilution required</td>
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<tr>
<td>Subsurface application, indirect potable reuse</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Reuse of Reclaimed Water and Land Application</strong> (Florida, USA)</td>
<td>Rapid infiltration basins, absorption fields</td>
<td>Advanced oxidation: Nitrification/Denitrification</td>
<td>7.62 to 152.4 m (based on sensitive areas and system operation)</td>
<td>Multiple barriers for pathogens and organics required</td>
</tr>
<tr>
<td>Injection (groundwater with TDS &lt;3,000 mg/L)</td>
<td></td>
<td></td>
<td>304.8 m from potable water supply wells</td>
<td></td>
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<tr>
<td>Injection (groundwater with TDS &gt;3,000 mg/L)</td>
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<td>13 types of MAR</td>
<td></td>
<td>Not specified</td>
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</tr>
<tr>
<td><strong>USEPA (2012) Guidelines for Water Reuse</strong> (USA)</td>
<td>Non-potable uses</td>
<td>Site and use specific: ≥2 months to potable water extraction wells</td>
<td>Site and use specific: ≥2 months to potable water extraction wells</td>
<td>Advanced treatment required</td>
</tr>
<tr>
<td>Surface spreading to potable aquifers</td>
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<td>Direct injection to potable aquifers</td>
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<tr>
<th>Regulation or guideline</th>
<th>Category</th>
<th>Treatment process</th>
<th>Secondary treatment</th>
<th>Filtration</th>
<th>Disinfection</th>
<th>SAT</th>
<th>Advanced oxidation</th>
<th>Nitrification/Denitrification</th>
<th>Coagulation</th>
<th>RO</th>
<th>Setback distance</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse of Treated Wastewater Guidance Manual</td>
<td>Infiltration basins</td>
<td></td>
<td>√</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td>≥12 months to potable water</td>
<td>potable water extraction wells</td>
</tr>
<tr>
<td>(Pennsylvania, USA)</td>
<td>Direct injection</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>≥12 months to potable water</td>
<td>extraction wells</td>
</tr>
<tr>
<td>Standards of Reclaimed Water Quality</td>
<td>Not specified</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not specified</td>
<td></td>
</tr>
</tbody>
</table>

*California Department of Public Health (2014).  
*NRMMC-EHC-NHMRC (2009).  
*USEPA (2012).  
*Idaho Department of Environmental Quality (2009).  
*Pennsylvania Department of Environmental Protection (2012).  
ultimate purposes, such as potable, agricultural, or recreational uses may cause concerns, and therefore public involvement is important in the whole project implementation process.

After the project goal and scope have been determined, essential components in the MAR project design should be done. The selection of recharge sites and recharge methods mainly depends on local geological and hydrogeological characteristics. A suitable recharge aquifer can ensure adequate recharge rates, storage and recovery, but also provide additional natural water treatment. To control contaminants, the water treatment system is an essential design component in MAR. Water pre-treatment processes and underground retention distance/time are normally specified in the regulations/guidelines to ensure that natural groundwater quality is protected and recovered water quality requirements are met. In addition, the public should be kept informed in the decision-making process of the MAR system design to ensure that there is no risk to public health or the environment.

The final operation stage includes construction, maintenance, and monitoring. Normally, before the construction of full-scale MAR systems, bench-scale and pilot-scale testing should be conducted to assess the system performance. The efficiency of artificial pre-treatment or post-treatment units and MAR simulation bottles or columns to remove contaminants can be tested in a laboratory. Design alternations such as specific treatment optimization or recharge rate adjustments can then be made based on the test results, and a testing report should be available to the public. After the establishment of a full-scale MAR system, routine monitoring and system maintenance should be performed to mitigate certain operating issues such as clogging or adverse monitoring results, and operation reports can be produced and assessed by the public.

Since the source of recharge water is reclaimed water, which may contain some residual contaminants, health and esthetic issues associated with the recovered water have been the focus of MAR projects. Several controls including the choice of source water, the degree of water pre-treatment and post-treatment, the selection of recharge sites and methods, retention distance and time, and operational details of the MAR system should be addressed when implementing MAR with reclaimed water. To obtain social acceptance, which is an essential part of water reuse.

Figure 4 | A proposed approach for MAR implementation.
projects, the whole process of establishing MAR should involve public consultation.

CASE STUDIES

A number of MAR projects using reclaimed wastewater or stormwater have been established. Most of them focus on solving a water shortage problem, but address different specific issues. The projects involve a wide range of recharge water sources, treatment methods, recharge methods, and ultimate uses of recovered water. Various types of MAR have been applied, including: ASR in Salisbury, Australia; vadose zone wells in Phoenix, USA; bank filtration in Berlin, Germany; dune filtration in Amsterdam, The Netherlands; and infiltration ponds in the Burdekin Delta, Australia.

Although many MAR projects have been established, sophisticated MAR guidelines or standards are still unavailable (Asano & Cotruvo 2004; Kazner et al. 2012). Therefore, reviewing previous MAR planning, design, and operational experiences is of crucial importance for the success of future MAR projects. Since MAR with reclaimed water can effectively mitigate both water shortages and environmental pollution, this type of MAR project has attracted growing interest. To learn from existing practices, three case studies that have used MAR with reclaimed water are discussed in detail in this section, within the context of the proposed approach for MAR implementation as outlined earlier. The first case study was selected to show the typical structure of a MAR project. The significance of artificial pre-treatment for recharge water is described in the second, while the final case study discusses the role of natural treatment in MAR. These case studies show the interdependence among MAR components, advanced water treatment, and natural treatment for MAR implementation.

Montebello Forebay groundwater recharge project (USA)

The Montebello Forebay groundwater recharge project is the oldest system planned for indirect potable reuse in California. Since 1962, this project has been recharging over 1.6 million acre-feet (1,974 million m³) of recycled water to the Central Groundwater Basin, in order to provide a new potable water supply for Los Angeles County (USEPA 2012).

Planning

In the 1950s, rapid population growth in Los Angeles County, whose water supply was well-based, led to increased pumping from the Central Groundwater Basin, resulting in a declining groundwater table and seawater intrusion. To solve this problem, treated wastewater, surface water imported from the Colorado River and the State Project Water, and stormwater were planned as the sources of recharge water to replenish groundwater basins. Mixing three types of water can dilute the concentrations of residual contaminants in the treated wastewater, thus increasing the safety and reliability of water supply.

Design

Since recycled water accounted for 26% of the recharge water, the initial stage of the project used conventional tertiary treatment including filtration and chlorination to purify the water (Water Replenishment District of Southern California 2008). Later, to further improve water quality, nitrification/denitrification and ultraviolet (UV) light disinfection were added as additional barriers for residual contaminants. Due to the effectiveness of water treatment, the amount of recycled water was increased to up to 40% of recharge water (Johnson 2008). In addition to artificial water treatments, natural treatments are used. Two sets of spreading grounds, the Rio Hondo Coastal spreading grounds with 20 individual basins and the San Gabriel Coastal spreading grounds with three individual basins, are used to percolate recharge water into aquifers (USEPA 2012). The selection of surface spreading sites can provide an additional natural treatment for the recharge water, and therefore obviate the need for advanced water pre-treatment.

Operation

During operation, individual spreading basins are operated under wetting/drying cycles (USEPA 2012). This operation mode optimizes the infiltration of water and prevents the
development of vectors, thus ensuring continuous and effective performance. Extensive monitoring is conducted, from the sources of recharge water to the final groundwater aquifers (USEPA 2012). Therefore, the quality of groundwater can be protected and instant responses can be made to deal with adverse monitoring results.

**Successes and lessons learned**

The Montebello Forebay Groundwater Recharge Project is a typical MAR project, and thus, was used as an example to show the key components in the MAR system. Through analysis under the proposed approach for MAR implementation, it can be seen that each element plays an important role for the success of a MAR project. In the planning stage, the identified water shortage problem was helpful to determine the ultimate uses of the recovered water. The selection of source water was consistent with the local available water sources. In the design stage, the combination of natural and artificial treatment provided multi-barrier protection against contaminants in the water. In the operation stage, routine monitoring and maintenance was shown to be essential for the management of MAR.

**Orange County groundwater replenishment system (USA)**

The groundwater replenishment system in Orange County, California, is another groundwater recharge project using recycled water. As the world’s largest wastewater purification system for indirect potable reuse, this system has provided a large amount of high quality water for around 600,000 residents in north and central Orange County since its initial operation in 2008 (USEPA 2012).

**Planning**

As a semi-arid county in southern California, Orange County’s water supply had relied on imported water from northern California and the Colorado River for decades. However, with population growth and environment constraints, imported water was less available. To provide a reliable water supply, highly treated wastewater was recognized as an alternative water source and recharged into the aquifer to replenish groundwater basins and prevent seawater intrusion. Since the groundwater replenishment system depends solely on wastewater as the source water, gaining social acceptance was significant. To get approvals, an outreach program was established through media and other activities to broadcast the concept of purifying wastewater to drinking water (USEPA 2012).

**Design**

The most innovative part of this case study is its design for water treatment. In order to produce high-quality recharge water, a state-of-the-art wastewater purification plant was constructed. The plant uses a three-step treatment process consisting of microfiltration (MF), reverse osmosis (RO), and UV with hydrogen peroxide to treat secondary effluent from a wastewater treatment plant (Patel 2010). This standard treatment train for potable reuse can remove different types of residual contaminants in treated wastewater. MF and RO remove suspended or colloidal contaminants and dissolved contaminants, respectively. The final UV and peroxide treatment can disinfect microorganisms and oxidize organic compounds. Through the treatment, the quality of the reclaimed water exceeds all state and federal drinking water standards (USEPA 2012).

**Operation**

Water quality monitoring is essential in the groundwater replenishment system operation. Regulated water quality parameters including metals, organics, nutrients, and microbial indicators are tested to ensure that the drinking water standards can be achieved. Unregulated water quality parameters, including pharmaceuticals, personal care products, and endocrine disruptors are also monitored to reduce the health risks. In addition, to secure support from the public, a comprehensive outreach program was established and is still active. Until now, no significant or organized public opposition has been reported (USEPA 2012).

**Successes and lessons learned**

The Orange County groundwater replenishment system is a good example to illustrate the effectiveness of how advanced
water treatment can be applied for MAR to achieve potable water quality. From this case study, it can be seen that membrane filtration and advanced oxidation processes (AOPs) are the future of water reuse. Getting social acceptance is always a difficult step for water reuse. The success of the outreach program used in this project can serve as guidance for the communication between the public and future MAR with reclaimed water project planners, designers, and operators.

Salisbury ASTR project (Australia)

Started in 2003, the ASTR project in Salisbury (a northern suburb of Adelaide), Australia, is a demonstration MAR system for stormwater harvesting. Since the project was established, Adelaide and regional towns have had the ability to store runoff from the short and intense precipitation events that occur from May to September, and therefore have a reliable alternative water source (Kazner et al. 2012).

Planning

Due to the low average annual rainfall, Adelaide is regarded as the driest capital city in Australia. Although the monthly rainfall is higher during May to September, the local high summer evaporation rates make the catchment of stormwater difficult. Therefore, the ASTR project was established to capture stormwater and provide additional drinking water.

Design

The system encompasses the Parafield Stormwater Harvesting Facility, which is used to collect and pre-treat stormwater, and the ASTR well field, which is used to inject and abstract water. In the harvesting system, stormwater from a 16.2 km² mixed industrial and residential catchment is collected and then diverted through two stormwater settling basins into a constructed wetland with a capacity of 25,000 m³ (Page et al. 2010a, 2010b). The application of constructed wetlands provides a cost-effective and robust natural way to pre-treat stormwater. In the well field, four wells are used for injection and two wells are used for abstraction. The separation of these injection wells and abstraction wells gives a longer residence time to ensure the production of higher quality recovered water for irrigation (Kazner et al. 2012).

Operation

Since the stormwater harvesting and ASTR are all passive treatments, their performance cannot be easily controlled. To ensure the water quality, frequent sampling and monitoring are conducted (Kazner et al. 2012). Currently, this site is used as a full-scale trial to evaluate the feasibility of potential drinking water production. Post-treatment, which may include UV and chlorine disinfection, are still under investigation (Page et al. 2010c).

Successes and lessons learned

The Salisbury ASTR project demonstrates the importance of natural systems in MAR. Since natural treatments are green technologies, which can reduce operational costs and environmental impacts, these processes will be widely applied in future systems.

In addition to the case studies presented, several other notable MAR with reclaimed water projects have been established in different parts of the world, including the USA, Australia, Belgium, Italy, Spain, China, and Israel (Table 3). It can be seen that the USA and Australia play the leading roles in MAR with reclaimed water. Due to environmental pollution and water shortages, treated wastewater is becoming more important as a source of recharge water. To reduce the concentrations of contaminants in wastewater and increase the water supply, other types of water, such as stormwater or surface water, are often mixed with wastewater as the source of recharge water. In terms of water treatment, additional advanced water treatment technologies, including high-pressure membrane filtration and AOPs, are included in pre- or post-recovery to ensure the required level of contaminant removal is achieved or surpassed due to their excellent ability to remove different types of contaminants. When the recharge method is surface spreading, SAT normally serves as an additional natural treatment to purify water. As for all MAR systems, recharge methods, sources of recharge water, water treatments, and ultimate uses of recovered water have a close relationship. In all cases, communication and acceptance by the public are needed to ensure that environmental and public health concerns are addressed.
<table>
<thead>
<tr>
<th>Name</th>
<th>Recharge method</th>
<th>Recharge water source</th>
<th>Water treatment</th>
<th>Ultimate use of recovered water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamitos saltwater barrier (California, USA)</td>
<td>Direct injection</td>
<td>Surface water, treated wastewater</td>
<td>Microfiltration, RO, UV light disinfection</td>
<td>Prevent seawater intrusion</td>
</tr>
<tr>
<td>Chino Basin groundwater recharge (California, USA)</td>
<td>Surface spreading</td>
<td>Surface water, treated wastewater, stormwater</td>
<td>Tertiary treatment, SAT</td>
<td>Potable water</td>
</tr>
<tr>
<td>Dominguez Gap barrier (California, USA)</td>
<td>Direct injection</td>
<td>Surface water, treated wastewater</td>
<td>Microfiltration, RO, UV disinfection</td>
<td>Prevent seawater intrusion</td>
</tr>
<tr>
<td>Montebello Forebay groundwater recharge (California, USA)</td>
<td>Surface spreading</td>
<td>Surface water, treated wastewater, stormwater</td>
<td>Tertiary treatment, SAT</td>
<td>Potable water</td>
</tr>
<tr>
<td>Orange County groundwater replenishment system (California, USA)</td>
<td>Surface spreading, direct injection</td>
<td>Treated wastewater</td>
<td>Microfiltration, RO, UV/ hydrogen peroxide, SAT</td>
<td>Potable water, prevent seawater intrusion</td>
</tr>
<tr>
<td>West Coast Basin barrier (California, USA)</td>
<td>Direct injection</td>
<td>Potable water, treated wastewater</td>
<td>Microfiltration, RO, UV disinfection</td>
<td>Prevent seawater intrusion</td>
</tr>
<tr>
<td>City of Desin ASR (Florida, USA)</td>
<td>Direct injection</td>
<td>Treated wastewater</td>
<td>Flocculation, filtration, disinfection</td>
<td>Landscape irrigation</td>
</tr>
<tr>
<td>Winter Garden Water Conserv II (Florida, USA)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Ozonation, RO, SAT</td>
<td>Agricultural irrigation</td>
</tr>
<tr>
<td>Northern Adelaide Plains aquifer recharge (South Australia)</td>
<td>Direct injection</td>
<td>Treated wastewater</td>
<td>Tertiary treatment</td>
<td>Irrigation</td>
</tr>
<tr>
<td>Salisbury aquifer recharge (South Australia)</td>
<td>Direct injection</td>
<td>Stormwater</td>
<td>Wetland treatment</td>
<td>Irrigation, industrial uses, potentially potable</td>
</tr>
<tr>
<td>Perth aquifer recharge (Western Australia)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Microfiltration, RO, SAT</td>
<td>Potable water</td>
</tr>
<tr>
<td>Sydney aquifer recharge (New South Wales, Australia)</td>
<td>Surface spreading</td>
<td>Treated wastewater, stormwater</td>
<td>Tertiary treatment, SAT</td>
<td>Prevent seawater intrusion</td>
</tr>
<tr>
<td>St-André aquifer recharge (Flanders, Belgium)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Ultrafiltration, RO, UV disinfection, SAT</td>
<td>Potable water</td>
</tr>
<tr>
<td>Nardó karstic aquifer recharge (Apulia, Italy)</td>
<td>Direct injection</td>
<td>Treated wastewater</td>
<td>Conventional activated sludge process</td>
<td>Irrigation, prevent seawater intrusion</td>
</tr>
<tr>
<td>Sabadell aquifer recharge (Catalonia, Spain)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Conventional activated sludge process, SAT</td>
<td>Non-potable (irrigation, street cleaning)</td>
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<td>Zhengzhou groundwater recharge (Henan, China)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Coagulation, filtration, adsorption, disinfection, artificial wetland, SAT</td>
<td>Fishery, agriculture, industry</td>
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<tr>
<td>Gaobeidian aquifer recharge (Beijing, China)</td>
<td>Direct injection</td>
<td>Treated wastewater</td>
<td>Coagulation, sedimentation, rapid sand filtration, ozonation</td>
<td>Under investigation</td>
</tr>
<tr>
<td>Shafdan aquifer recharge (Israel)</td>
<td>Surface spreading</td>
<td>Treated wastewater</td>
<td>Conventional activated sludge process, ultrafiltration, SAT</td>
<td>Irrigation</td>
</tr>
</tbody>
</table>
KNOWLEDGE GAPS

There is currently a knowledge gap with regards to the inadequate regulatory systems for MAR with reclaimed water, and this creates a challenge for the implementation of MAR projects. Although some water reuse regulations or guidelines have included requirements for MAR (Florida Department of Environmental Protection 1999; Ministry of Water Resources 2006; Idaho Department of Environmental Quality 2009; NRMMC-EPHC-NHMRC 2009a; Pennsylvania Department of Environmental Protection 2012; USEPA 2012; California Department of Public Health 2014), limited specified planning procedures or requirements are available in the documents. Therefore, the establishment of specific criteria and standards governing MAR with reclaimed water is encouraged.

In addition, an inadequate understanding and control of underground processes hampers MAR design and operation. Although many studies have investigated the removal of contaminants during recharge processes (e.g., Montgomery-Brown et al. 2003; Quanrud et al. 2003; Zhang et al. 2005) and recharge operation or design issues (e.g., Bouwer 1996, 2002; Vanderzalm et al. 2010), system performance can be site specific and this can be a problem when standards for MAR are unavailable. Thus, more work should be conducted in order to establish clear design and operational criteria for MAR.

Finally, a complete quantitative risk assessment of MAR should be developed for each project. Although Australian water reuse guidelines have established a risk assessment framework, and previous studies have taken qualitative and preliminary quantitative approaches to assess the risks associated with MAR projects (Page et al. 2008; NRMMC-EPHC-NHMRC 2009a), mature quantitative risk assessments are still not available to support the feasibility assessment of new MAR projects. Future studies should focus on developing a quantitative risk assessment approach for MAR.

CONCLUSIONS

The problem of water shortages places great value on water reclamation and reuse. MAR with reclaimed water is a beneficial water reuse application but has a wide range of challenges for its implementation. Within a MAR system, diverse aspects including planning, technical design or operational considerations, and political issues should be considered. To date, a number of water reuse regulations or guidelines have been established worldwide and some of them include requirements to govern the implementation of MAR projects. Suggestions or lessons learned from current water reuse regulations/guidelines and MAR case studies are as follows:

- Six components (sources of recharge water, water treatment, recharge method, recharge site, water recovery, and ultimate uses of recovered water) can be used to assess MAR systems. Water quality is an essential consideration and influences the key factors for MAR systems.
- A review of the available water reuse guidelines or regulations identified that a framework for MAR implementation should be based on planning, design and operational requirements for MAR with reclaimed water.
- Established MAR with reclaimed water projects can serve as a reference for the future implementation of MAR projects. All components in the system are important for the establishment of MAR with reclaimed water projects. Artificial and natural treatments should be properly designed and operated to ensure the safety of recovered water.
- Gaining social acceptance is of great importance for the success of MAR with reclaimed water projects.
- Specific regulatory or design criteria for the establishment of MAR systems and a complete quantitative risk assessment framework for the evaluation and operation of MAR systems should be established.

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