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Critical Review

A review on risk assessment in managed aquifer recharge

Anne Imig,[1] Zsóka Szabó,[2] Olha Halytsia,[3] Maria Vrachioli,[3] Verena Kleinert,[1] and Arno Rein[1]
[1]School of Engineering and Design, Technical University of Munich, Munich, Bavaria, Germany
[2]Department of Geology, ELTE Institute of Geography and Earth Sciences, Eötvös Loránd University, Budapest, Pest, Hungary
[3]Chair Group Agricultural Production and Resource Economics, Technical University of Munich, Freising, Bavaria, Germany

Abstract

Managed aquifer recharge (MAR) refers to a suite of methods that is increasingly being applied worldwide for sustainable groundwater management to tackle drinking or irrigation water shortage or to restore and maintain groundwater ecosystems. The potential for MAR is far from being exhausted, not only due to geological and hydrogeological conditions or technical and economic feasibility but also due to its lack of acceptance by the public and policymakers. One approach to enable the safe and accepted use of MAR could be to provide comprehensive risk management, including the identification, analysis, and evaluation of potential risks related to MAR. This article reviews current MAR risk assessment methodologies and guidelines and summarizes possible hazards and related processes. It may help planners and operators select the appropriate MAR risk assessment approaches and support the risk identification process. In addition to risk assessment (and subsequent risk treatment) related to the MAR implementation phase, this review also addresses risk assessment for MAR operation. We also highlight the limitations and lessons learned from the application and development of risk assessment methodologies. Moreover, developments are recommended in the area of MAR-related risk assessment methodologies and regulation. Depending on data availability, collected methodologies may be applicable for MAR sites worldwide. *Integr Environ Assess Manag* 2022;18:1513–1529. © 2022 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Groundwater management, Guidelines, Managed aquifer recharge, Methodologies, Risk assessment

INTRODUCTION

In the Sixth Sustainable Development Goal, the United Nations aims to ensure the availability and sustainable management of water and sanitation for all by 2030 (United Nations [UN], 2016). Groundwater is an essential source of water supply worldwide, and an increase in global groundwater extraction from ~100 km³/year in 1950 to 734–1000 km³/year in 2000 reflects growing demand (Shah et al., 2013; Wada et al., 2010). Overexploitation of the aquifers and effects of climate change can lead to a local decrease in groundwater recharge (e.g., Biswas et al., 2018; Casanova et al., 2016; Green et al., 2007; Kundzewicz & Döll, 2009; Wada et al., 2012; Woldeamlak et al., 2007). Pumping of groundwater can result in a variety of chemical impacts on the pumped aquifer, including the intrusion of saltwater in the case of coastal aquifers, influx of poor-quality water such as river water, or stormwater runoff contaminated by agrochemicals (e.g., Chilton & Foster, 2004; Vbra & Richts, 2015).

One method to address these challenges is managed aquifer recharge (MAR). Excess water from rainfall or flooding, water treatment plants, rivers, or desalinated seawater, for example, can be infiltrated into an aquifer to store and recharge groundwater (e.g., Gale, 2005). As a result, the availability of groundwater is maintained or enhanced and groundwater can be extracted in times of need. Moreover, the water quality can be increased by (engineered) natural attenuation processes of the aquifer and soil matrix.

Dillon et al. (2019) document an increase in MAR implementation of about 5% per year since the 1960s, but this does not match the increasing groundwater abstraction. In countries applying this technology, about 2.4% of total groundwater abstraction is provided by MAR (or ~1% worldwide). Although geological and hydrogeological conditions are among the predominant factors influencing MAR potentials, psychological and policy-related aspects are also

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Correspondence Arno Rein, TUM School of Engineering and Design, Technical University of Munich, Munich, D-80333 Bavaria, Germany.
Email: arno.rein@tum.de

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important for the acceptance and implementation of MAR schemes. Such aspects support the fact that the full potential for using MAR is often far from being exploited (e.g., Dillon, 2005; Mankad et al., 2015).

Fernández Escalante et al. (2020) and Page et al. (2020) claim that the lack of regulatory frameworks often hinders the implementation of MAR schemes. Building trust in key regulating organizations, such as drinking water regulators, health agencies, and public water systems, can potentially help promote the use of MAR systems (Leviston et al., 2006; Mankad et al., 2015). Nandha et al. (2015) point out that a key step in promoting MAR would be to reduce uncertainties related to MAR implementation and operation, such as human health and environmental aspects. Furthermore, the authors suggested the development of economic components that aim to ensure the feasibility and successful implementation of MAR systems (e.g., Casanova et al., 2016; Dillon, Fernández Escalante, et al., 2020). To consider MAR as an integrated water management option for achieving the UN's Sixth Sustainable Development Goal, adequate risk management is required to ensure its safe implementation.

It has been pointed out that MAR risk management should include methodologies that enable a comprehensive assessment of human health, environmental, economic, and social risks (e.g., Assmuth et al., 2016). With regard to such a comprehensive approach, Nandha et al. (2015) reviewed existing risk assessment methods that can be applied for MAR when establishing risk assessment guidelines for the United Kingdom. Furthermore, the World Health Organization (WHO) reported the state-of-the-art risk assessment and management approaches for aquifer recharge, focusing on risks to human health (Aertgeerts & Angelakis, 2003). Rodríguez-Escales et al. (2018) summarized possible causes on a multidimensional level of MAR failure to establish a new fault tree-based probabilistic risk assessment approach. Fernández Escalante et al. (2020) reviewed the current state of MAR policies and identified a lack of risk assessment approaches, with the known exception of the Australian policies.

The goal of this paper is to present a review of current and applied risk assessment guidelines and methods, as well as frequently considered types of risk. This review aims to provide an overview of existing methods and guidelines and their application, rather than evaluating their applicability. As a description of the state of the art, it may serve as a starting point for further evaluating potentially suitable methods or guidelines and selecting the associated literature. We also highlight the limitations and lessons learned from application and development of the summarized risk assessment methodologies.

RISK MANAGEMENT PROCESS

Harm can be described as an injury or damage to human health, as well as damage to property or the environment. Hazard is the potential source of harm, which can, for example, be a biological, chemical, physical, or radioactive agent, and a hazardous event is an event that can cause harm. The combination of probabilities for the identified hazard to occur in a specific time frame and the magnitude of its harm is termed risk (International Organization for Standardization and International Electrotechnical Commission [ISO/IEC], 2014; NRMMC, 2006).

The ISO proposes an iterative process for risk management (ISO, 2018), as summarized in Figure S1. After establishing the scope and context of the evaluation, risk assessment is carried out, followed by risk treatment. The risk assessment procedure consists of three steps: risk identification, risk analysis, and risk evaluation (Figure S1). Risk identification is conducted to identify and describe hazards that aid or prevent the achievement of an aim. Risk analysis describes the likelihood of a hazard or hazardous event by taking into consideration consequences and their sensitivities. Risk evaluation intends to identify risks for which actions have to be undertaken such as further analysis, maintain existing control structures, or risk treatment options (ISO, 2018; ISO/IEC, 2014).

REVIEWING PROCEDURE

Publications were selected according to the following criteria: (i) scientific quality (articles in peer-reviewed scientific journals were preferred, followed by reports of recognized research projects and guidance documents prepared by regulatory agencies) and (ii) recent research. On the basis of the latter, we have focused our review on studies published between 2000 and October 2020. Selected older publications are mainly related to background and pioneering literature in the field of risk assessment. Publications were searched with common search engines such as Google Scholar and online databases (including Scopus), as well as the software Publish or Perish (Harzing, 2020); the search phrases used are summarized in the Supporting Information. Further references were found within reviewed articles and reports.

The literature reviewed in this paper can be subdivided into three categories: (i) articles and reports about risk assessment case studies and methodological papers, (ii) review articles on possible risks and risk assessment approaches for MAR, and (iii) risk assessment guidelines. With regard to point (i), selected studies were further evaluated for the application of risk methodologies, such as in case studies. For this goal, 43 papers with 138 case studies from 23 countries were collected (Figure 1; for further details, see Table S1 [Supporting Information] and the Discussion section).

RISK ASSESSMENT APPROACHES

Several of the risk assessment approaches described in this section involve two international frameworks that have been developed for risk assessment in general (without specific attention to MAR): (i) the framework of hazard analysis and critical control points (HACCP) and (ii) the framework of water safety plans (WSP) suggested by the WHO.

Hazard analysis and critical control points (HACCP). The HACCP framework was developed in the 1960s as a

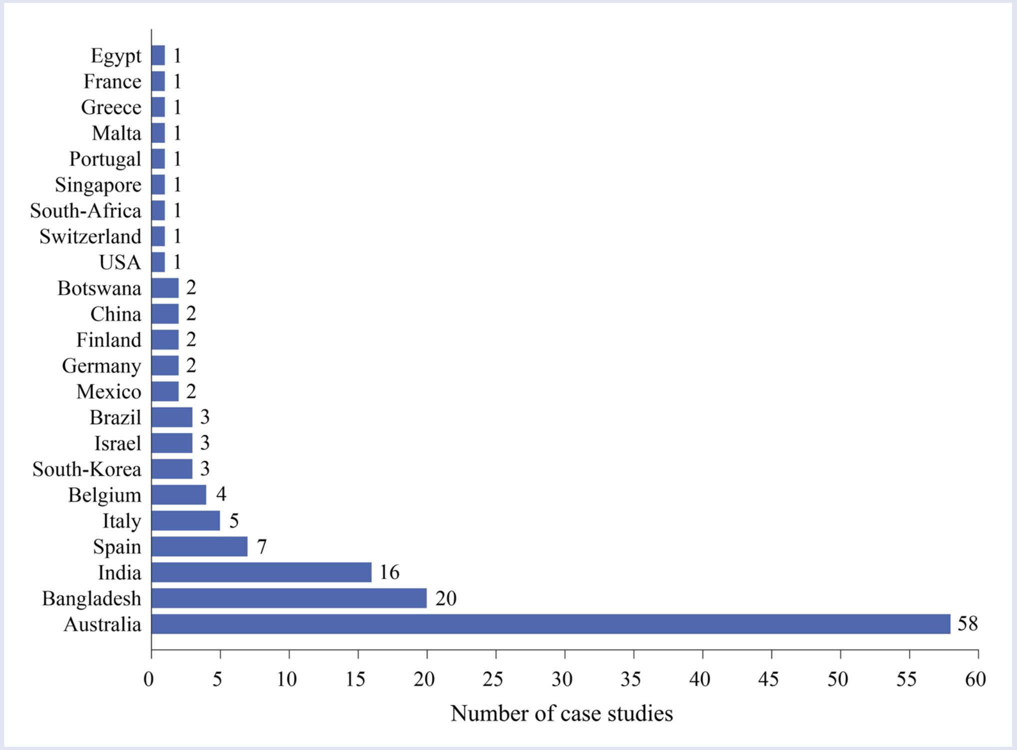

FIGURE 1 Number of reported case studies per country in the reviewed publications (based on Table S1)

universal, scientifically based approach for food safety (Havelaar, 1994; WHO, 1997; WHO and FAO, 2006). In a 12-step procedure, a control system is established by identifying hazards and their critical control points. A critical control point is defined as a step in the procedure where control can be applied and can lead to hazard prevention, hazard elimination, or the reduction of a hazard to an acceptable level. An effective HACCP plan focuses on prevention, by defining precautions for preventing hazards (European Commission [EC], 2015). Application of the HACCP framework is compulsory in EU countries where water utilities fall under the provision of food safety (EC, 2015).

Water safety plans (WSP). The WHO published the Stockholm Framework 2001, in which it was agreed that future guidelines for drinking water, wastewater, and recreational water should include risk assessment and risk management (Bartram et al., 2001). Based on this, the creation of WSP was proposed in 2004 (WHO, 2004). The WSP are partly based on principles of the HACCP framework, but are tailored to the water industry (Page, Ayuso-Gabella, et al., 2012). Human health risks related to drinking water use (potentially arising from microbial, radiological, and chemical hazards) are assessed for the whole process of providing drinking water ("from catchment to consumer"). This risk assessment forms the basis for decision-making to target the human health risks of the system on a multibarrier principle (Davison et al., 2005). Operational monitoring and control measures are also defined within the WSP since they are important for ensuring that the health-based targets are met.

Risk assessment guidelines related to MAR

This section describes MAR-related guidelines, which include detailed instructions for risk assessment. Reported strengths and weaknesses of those, together with references for application examples, are summarized in Table 1.

Australian guidelines for MAR risk assessment. Australia has recommended specific risk assessment methodologies for MAR, as laid down in national guidelines for water recycling (NRMMC, 2006, 2009). These guidelines aim to develop a 12-step MAR risk management plan and address a variety of water sources. The risk assessment framework incorporated within the Australian guidelines has four iterative stages for identifying human health and environmental risks: (i) entry-level assessment; (ii) assessment of maximum risks; (iii) assessment of residual risks for MAR precommissioning, after having considered preventive measures that could minimize the determined maximum risks; and (iv) assessment of residual risks for the operational phase of MAR.

The Australian guidelines offer advice on adequate management for 12 potential hazards to human health and the environment related to MAR implementation and operation. This includes possible preventive measures, monitoring strategies (validation, verification, and operational monitoring), and acceptance criteria for the four risk assessment stages. Methods suggested by the Australian

TABLE 1 Short overview of reported strengths and weaknesses of risk assessment guidelines applied for MAR, as well as references for application examples (including case studies)

Risk assessment guidelines	Strengths	Weaknesses	Examples for guideline application (references)
Australian guidelines (NRMMC, 2006, 2009)	Tailored to specific MAR-related hazards with detailed indications of acceptable risks	Detailed input data needed (e.g., Nandha et al., 2015; WHO, 2012)	Bartak et al. (2015), Gibert et al. (2015), Page, Dillon, Toze, et al. (2010), Page, Dillon, Vanderzalm, Bekele, et al. (2010), Page, Dillon, Vanderzalm, Toze, et al. (2010), Seis et al. (2015), Sprenger et al. (2020), and Vanderzalm et al. (2011)
Water safety plans (WSP) (WHO, 2004)	Comprehensive approach “from catchment to customer”	Conservative approach; may tend to overestimate risks (e.g., when available data on likelihood are limited)	Bartak et al. (2015), Dominguez-Chicas and Scrimshaw (2010)
Hazard analysis and critical control points (HACCP) framework (e.g., EC, 2015; Havelaar, 1994; WHO, 1997; WHO and FAO, 2006)	Not limited to specific hazards	Hazard identification is subjective; critical control point identification for MAR is more difficult than for water treatment options (MAR as a complex system); failures and risks are not quantified	Dewettinck et al. (2001), Gonzalez et al. (2015), Page et al. (2009), and Swierc et al. (2005)
Indian guidelines (Dillon et al., 2014)	Low data need	High-risk schemes (e.g., infiltration of wastewater) cannot be evaluated	Wintgens et al. (2016)
Chilean guidelines (CNR Ministerio de Agricultura and CSIRO Chile, 2020)	Low data need (no application documented to date)	Limited to nonpotable water use (no application documented to date)	No application documented to date

Abbreviation: MAR, managed aquifer recharge.

guidelines to evaluate acceptable risks are based on qualitative risk assessment for environmental risks and quantitative risk assessment (QRA) for human health risks (if data are available about environmental hazards also environmental risk assessment is possible).

Indian guidelines for MAR risk assessment. Dillon et al. (2014) developed a water quality guide related to the implementation of MAR in India. This guide is structured by a sequence of steps, including the first stage from the Australian guidelines: entry-level risk assessment combined with sanitary surveys as proposed by the WHO (2017).

Chilean guidelines for MAR risk assessment. As recently reported by Page et al. (2020), the National Irrigation Commission of Chile has developed guidelines for MAR application, which implement risk assessment. The Chilean guidelines address human health and environmental risks and restrict the applicability to nonpotable water derived from MAR (e.g., agricultural irrigation, environmental benefit, or saline intrusion barrier) (CNR and CSIRO, 2020). The guidelines are based on the Australian and Indian guidelines, as well as the (interconnected) HACCP, WSP, and sanitary survey principles.

Risk assessment methodologies related to MAR

This section describes the methodologies that are frequently applied for a MAR-related risk assessment. Reported strengths and weaknesses of these methodologies, together with references for application examples, are summarized in Table 2.

Qualitative risk assessment. A risk factor score matrix is defined for qualitative risk assessment (Figure S2). The likelihood of a hazard actually occurring is identified by the expected recurrence of the hazard (indicated in units of years), using a five-step scale on one axis of the matrix; for example, a hazard recurrence interval of 100 years is defined as “rare” (lowest scale). On the other axis, the severity of the consequence of the hazard is defined in five scales. For example, if the integrity of regional ecosystems is endangered, a catastrophic consequence (highest rank) is specified. If both the likelihood and the consequence of the hazard are ranked high, the resulting risk is identified as being very high (Figure S2). This method was suggested in

TABLE 2 Short overview of reported strengths and weaknesses of risk assessment methodologies related to MAR, as well as references for application examples (including case studies)

Risk assessment methodologies	Strengths	Weaknesses	Examples for methodology application (references)
Qualitative risk assessment	Low data need	Detailed processes cannot be highlighted	Sultana and Ahmed (2016) and Swierc et al. (2005)
Quantitative microbial risk assessment	Precise predictions possible	Detailed input data needed	Ayuso-Gabella et al. (2011), Bekele et al. (2008), Bloetscher (2001), Page, Dillon, Toze, et al. (2010), Page, Dillon, Vanderzalm, et al. (2010), Page, Gonzalez, Dillon (2012), Page et al. (2013), Page, Gonzalez, Sidhu, et al. (2015) Page, Gonzalez, Torkzaban, et al. (2015), Page et al. (2016), and Toze et al. (2010)
Quantitative risk assessment	Precise predictions possible	Detailed input data needed	Page et al. (2008, 2009)
Integrated human health risk frameworks for MAR	Multidimensionality of risk	Detailed input data needed; limited to human health risks	Assmuth et al. (2016)
Pollutant release and transfer register	Low data need for risk quantification; objectivity in hazard identification is ensured	Limited to chemical hazards; detailed input data needed	Ji and Lee (2016a, 2017)
Probabilistic risk assessment based on fault trees	Integrated approach: technical and nontechnical risks are incorporated	Probability determination based on MAR operator judgments: methodology suited for existing structures	Rodríguez-Escales et al. (2018)
Screening-level assessment of human health risks arising from micropollutants	Unregulated contaminants can be incorporated	Health-based benchmarks are conservative and might lead to overestimation of risks	Rodriguez, Cook, et al. (2007) and Rodriguez, Weinstein, et al. (2007)
Public health and economic risk assessment	Consideration of environmental, economic, and human health risks; different steps do not rely on each other's output as input data	Input data for scenarios subject to uncertainty	Juntunen et al. (2017)
Assessment of economic risks arising from clogging	Economic viability can be assessed	Large amount of input data (e.g., pilot studies)	Dillon, Vanderzalm, et al. (2016)
Environmental impact assessment	Considers a broad range of environmental and ecological risks	Not designed specifically for MAR	El-Fakharany (2013)

Abbreviations: MAR, managed aquifer recharge; PRTR, pollutant release and transfer register.

the Australian guidelines as well as in the Stockholm Framework for water (Swierc et al., 2005).

Quantitative risk assessment (QRA). The Australian guidelines also propose a methodology for quantitative risk assessment (QRA) for MAR, which is based on chemical risk assessment procedures that have been developed by the US Environmental Protection Agency (USEPA, 1987, 1998, 2002). This methodology compares chemical concentrations in an environmental matrix (such as groundwater) to reference values (such as drinking water limits; e.g., USEPA, 1987, 1998, 2002; WHO, 2017). Four steps are considered for quantitative human health risk assessment, as shown in Figure S3. The hazard, together with its variability, and related impacts are initially identified. Second, the dose–response relationship is quantified, which describes how the likelihood and severity of adverse human health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided) (e.g., Alcade-Sanz & Gawlik, 2017; US EPA, 1987, 1998, 2002). Subsequently, the size and nature of the exposed population to the hazard are identified, including an assessment of the amount (such as contaminant intake), the exposure route (such as the ingestion of contaminated drinking water), and the duration of exposure. The last step combines the information obtained so as to characterize the risk, that is, to predict the probability of adverse human health effects, where the magnitude, variabilities, and uncertainties are determined (e.g., Haas et al., 1999; NRMMC, 2006).

Quantitative microbial risk assessment (QMRA). The QMRA follows the same steps as QRA, but focuses on the quantification of human health risks arising from indicator microorganisms in water (Haas et al., 1999). Indicator or reference pathogens are assessed to maintain reasonable effort for the determination of concentrations, dose–response relationships, and related impacts (NRMMC, 2006, 2009; WHO, 2006). The first step of the proposed QMRA procedure identifies pathogen-related hazards posing potential risks to human health. Then, the likelihood of the occurrence of illness (for a given population) is calculated using dose–response curves of the reference pathogens. In a next step, the daily probability of infection is transformed into a probability of infection occurring per year, taking into account a certain number of exposure events per year. Information from the previous steps is integrated into the final step to determine and evaluate the magnitude of risks. Both the WHO (2006) and the Australian guidelines refer to the disability-adjusted life years (DALYs) method for risk evaluation. This method describes the disease burden by calculating accumulated years of life that are lived with disability and/or are lost due to an early death.

Integrated human health risk framework for MAR. Assmuth et al. (2016) have developed and applied a methodology for the regional-level human health risk assessment of chemical and microbiological water contamination. This methodology aims at aiding water management and also incorporates socioeconomic aspects of health risks. A model of risk and its impact chain is proposed, combining the related social and economic aspects, as well as factors related to the ecosystem and technical tasks (e.g., design, application, monitoring, and control of the MAR scheme). Input data for evaluating risks and their adverse impacts are collected in a first phase. It is suggested that health risks related to pathogens be quantified by QMRA, determining DALYs or quality-adjusted life years. The data obtained should then be used for a structurally integrated risk analysis, considering pollutant sources, release mechanisms, environmental transport and fate pathways, exposure routes, health effects, and resulting socioeconomic impacts, as well as management responses.

Pollutant release and transfer register (PRTR). Ji and Lee (2016a, 2016b, 2017) proposed and applied a PRTR together with deterministic and stochastic methods to assess potential chemical risks for a MAR site. A PRTR provides data to determine (i) the quantity of emitted chemicals (discharged to water systems, soil, and the atmosphere) and (ii) the transfer of these chemicals (from their source to the MAR facilities) as a function of time. Potential accumulated chemical risks are proposed to be determined from the toxicity of the chemicals, the distance from the source to the MAR site, and the total quantity of chemicals to be transferred from the source over time. If recorded data are lacking or predictions for future developments are intended, Ji and Lee (2016b, 2017) propose the application of PRTR in combination with a stochastic approach to estimate potential risks. The PRTRs can be used to carry out risk assessments as part of the HACCP procedure and/or the setup of WSP, such as was done by Ji and Lee (2017) for two different MAR sites.

Probabilistic risk assessment based on fault trees. Rodríguez-Escales et al. (2016) developed a probabilistic risk assessment methodology for the operational phase of MAR based on fault trees, which considers a series of quasi-independent events that contribute to the total risk. This subdivision aims to simplify the risk assessment process, that is, the events can be managed individually; probabilities are computed for the occurrence of these individual events, and these probabilities are systematically recombined to assess the overall risk for the MAR system. The open-source application MAR-RISKAPP is available for this approach (Rodríguez-Escales et al., 2018). A fault tree, to be evaluated by the user, includes 65 basic events that can potentially lead to MAR failure (these basic events were assumed to be potentially relevant, based on a literature review considering 47 different MAR sites; for details, see Rodríguez-Escales et al., 2018). Probabilities of the individual events and the resulting probability for the failure of the global system are determined, forming the basis for the next step; risk treatment should then be conducted for the events identified as most significant.

Public health and economic risk assessment. Juntunen et al. (2017) proposed a risk assessment methodology for MAR with the goal of decreasing the uncertainty of risk prediction and enabling more accurate decision-making for the mitigation of adverse effects. The authors combine methods for economic, environmental, and human health assessments with different computational techniques. Their proposed methodology is composed of four steps. First, flow and (reactive) transport models are applied to predict contaminant and pathogen transport and related potential risks for the use of MAR. The second and third steps include the prediction of public health risks, where QMRA for the determination of human health risks (related to pathogens causing diarrheal diseases) was combined with chemical risk assessment using acceptable daily intake levels, as proposed by the WHO (2010). The final step investigates regional economic effects resulting from the assessed health impacts, including the illness probability (and related change in labor productivity) estimated using a computable general equilibrium model.

Screening-level assessment of human health risks arising from micropollutants. Rodriguez, Cook, et al. (2007) and Rodriguez, Weinstein, et al. (2007) proposed a methodology for human health risk assessment at the screening level to evaluate potential risks to MAR arising from contamination with micropollutants (considered as chemicals of concern for indirect potable reuse schemes). To calculate health risks arising from a chosen chemical, the risk quotient is calculated by relating the measured chemical concentration in the recovered water to a benchmark (no-effect) concentration. Such benchmark values are available for regulated compounds, for example, defined by the accepted maximum level of the compound in drinking water. The risk quotient can then be used to evaluate potential health risks arising from defined chemicals of concern, and policymakers can include risk quotients within specific guidelines.

Quantitative assessment of socioeconomic risks. Currently available literature lacks studies that present a specific approach to quantify economic risks associated with MAR. Nevertheless, sensitivity analysis and quantitative probability modeling are two potential approaches to a socioeconomic risk assessment associated with MAR implementation (Maliva, 2014; Maréchal et al., 2020).

Cost–benefit analysis (CBA) can be carried out to obtain the net present value and the economic rate of return. Sensitivity analyses can be used to investigate the economic feasibility of a MAR scheme with substantial variations in critical parameters, such as the willingness-to-pay (WTP) of primary beneficiaries (Damigos et al., 2016). In addition, Arshad et al. (2014) performed a break-even analysis of cross-over points to address uncertainty while conducting CBA. The authors provided thresholds that denote points where MAR and surface storage have equal financial returns for key variables that are characterized by high levels of uncertainty. To incorporate uncertainty while conducting CBA, Damigos et al. (2016) also applied sensitivity analysis coupled with the Monte Carlo method to simulate uncertainties that affect the value of the critical parameters.

At the operational stage of MAR, economic risks are mainly a result of the realization of human health, technical, and environmental risks. Thus, expected value analysis can be used to address uncertainty and consequently to estimate the magnitude of economic losses. In particular, each potential contingency (e.g., excessive clogging, flooding, insufficient aquifer water level) should be identified and weighted by a probability assigned to its occurrence (based on historical data or expert opinions; Maliva, 2014). The magnitude of the economic risk can then be proxied by the difference between WTP values that are calculated with and without accounting for uncertainty.

Rupérez-Moreno et al. (2017) calculated values of profitability indicators for MAR under different scenarios, such as considering climate change or varying irrigation demand (if this is the primary objective of the MAR scheme). Maréchal et al. (2020) incorporated risks and uncertainty into cost-effectiveness analysis by performing a systematic sensitivity analysis to determine the effect of various parameters on the levelized cost of the MAR scheme.

Finally, multicriteria decision analysis (MCDA) coupled with geographic information system (GIS) tools (GIS-MCDA) can help identify suitable sites for MAR by taking social, economic, human health, and environmental aspects into account. An overview of different GIS-MCDA approaches applied for MAR is provided by Sallwey et al. (2019). The MCDA is based on weights that reflect the relative importance of a criterion and are determined based on experts' opinions or survey outcomes and can vary quite noticeably. Bouwer et al. (2008) proposed a fault-tree analysis for risk assessment to identify a set of weighting criteria for the MCDA.

Assessment of economic risks arising from well clogging. Dillon, Vanderzalm, et al. (2016) proposed investigating the economic risks arising from groundwater well clogging with prior pilot or laboratory studies to support decision-making for MAR operation schemes (in particular, for aquifer storage and recovery). The cost for managing well clogging, estimated from prior pilot or laboratory studies, can be compared to the costs of water treatment that are required for maintaining human health and environmental requirements.

Environmental impact assessment (EIA) for MAR. El-Fakharany (2013) applied EIA for a MAR scheme based on an environmental checklist developed by the International Commission on Irrigation and Drainage (ICID, 1993). Using this checklist, effects from irrigation, drainage, and flood control projects can be evaluated by considering eight groups: hydrology, pollution, soils, sediments, ecology, socioeconomic criteria, human health, and (ecological) imbalances. These groups contain 53 environmental issues, in total, such as “low flow regime” or “soil salinity.” El-Fakharany (2013) applied a semiquantitative scoring scheme with three categories: positive, negative, or no effects were assigned to each environmental issue.

RISKS ASSOCIATED WITH FACILITIES OF MANAGED AQUIFER RECHARGE

Few studies were found that have attempted to collect a comprehensive summary of potential MAR-related risks and their assessment. Rodríguez-Escales et al. (2018) categorized risks into (i) technical risks and (ii) nontechnical risks. Technical risks can be structural damage, low amounts of water, inadequate water quality, and failure to achieve targeted MAR goals, while nontechnical risks may include legal constraints, social unacceptance, and economic and governance-related problems. In another approach, Nandha et al. (2015) highlighted process-oriented aspects of MAR-related risks, where they distinguished between (i) MAR planning (strategic risk), (ii) water pretreatment, (iii) recharge, (iv) aquifer storage, (v) groundwater recovery, and

(vi) water posttreatment. The authors highlighted the multidimensionality of one hazardous event as it can be related to, and affect, another. For example, flooding events and droughts may affect water quality in addition to the infrastructure of the MAR scheme. This can lead to MAR malfunction, causing water supply shortage and/or a deterioration of water quality.

Lee and Ji (2016) applied HACCP frameworks to cluster hazardous events based on processes occurring in a drinking water-supply system using the MAR scheme of aquifer storage transfer and recovery. One of their clusters (cluster i) is related to hazardous events that may occur in the catchment area and thus outside the MAR facility. The other clusters are related to the MAR facility, that is, (ii) intake structure for recharging water, (iii) storage of recharging water, (iv) water pretreatment, (v) injection to the aquifer, (vi) abstraction from the aquifer, (vii) posttreatment, (viii) storage of treated water, (ix) water distribution, and (x) water end-users.

In the following, we have differentiated between risk types, that is (i) human health risks, (ii) environmental risks, (iii) technical risks, (iv) social and economic risks, and (v) risks related to governance and legislation (e.g., similar to Rodríguez-Escales et al., 2018). Furthermore, we have considered four different stages of MAR implementation and operation: risks may arise from, or relate to, (i) the planning of MAR, (ii) the catchment or water source for MAR, (iii) MAR operation (such as infiltration, storage, recovery) and maintenance, and (iv) water distribution and final water use (e.g., similar to Lee & Ji, 2016; Nandha et al., 2015). Risk-related aspects, including potential hazards, can be clustered according to these risk types and defined stages of MAR operation and implementation, as summarized in Table S2. Table S3 provides an overview of potential hazards that are frequently reported in the literature. In the following, we attempt to describe only the initial ("direct") risk related to the hazard or the hazardous event: the multidimensionality of risk or impact chains is not discussed in detail.

Human health risks related to MAR source water (stages i and ii). The reuse of treated wastewater, from different sources, in particular, has the potential to cause human health risks (e.g., Page, Gonzalez, et al., 2012). Several guidelines are available globally that address the reuse of treated effluents (e.g., EU, 2020; NRMMC, 2006, 2009; US EPA, 2012; WHO, 2006). Wastewater can contain suspended solids, nutrients, dissolved organic carbon, metals and other inorganic chemicals, pathogenic microorganisms, and organic chemicals and emerging pollutants such as pharmaceuticals (e.g., Levantesi et al., 2010; Page, Dillon, Toze, Bixio, et al., 2010; Rodriguez, Cook, et al., 2007; Tchobanoglous et al., 2003; Toze et al., 2010). However, stormwater and surface water can also contain such pollutants, raising concern for human health risks (e.g., Assmuth et al., 2016; Bartak et al., 2015; Page et al., 2013; Vanderzalm et al., 2011). Lee and Ji (2016) propose the consideration of risks related to changing temperatures that may influence source water quality (seasonal temperature changes may cause aerobic conditions at the bottom of lakes and rivers and increased algae growth).

Human health risks related to water quality changes during infiltration and water storage or transport in the subsurface (stages ii and iii). Aquifer and groundwater characteristics can also have a huge influence on water quality and hence may impact MAR. Groundwater salinity or sodicity, dissolved reactive minerals (such as fluoride or pyrite), radionuclides or metals (such as arsenic), and chemical spills, among other things, can lead to a decrease in the quality of water recovered by MAR, and this may induce human health risks (Assmuth et al., 2016; Bartak et al., 2015; Bouwer et al., 2008; Bugan et al., 2016; Lee & Ji, 2016; NRMMC, 2009; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page et al., 2013; Swierc et al., 2005; Vanderzalm et al., 2011). Thus, even if the infiltrated (MAR source) water is of acceptable quality, subsurface contamination can lead to poor quality of water that is recovered by MAR for drinking water or irrigation use (e.g., Dillon et al., 2014; Ji & Lee, 2017). Heterogeneity of the aquifer and spatially and temporally varying groundwater transit times are among the factors that can influence chemical and pathogen retention or removal by natural attenuation processes (e.g., Swierc et al., 2005; Toze et al., 2010).

Human health risks related to water treatment and MAR operation (stages iii and iv). Pretreatment can significantly improve the quality of infiltration water (e.g., Casanova et al., 2016). Dillon et al. (2009) point out that an intensive treatment of MAR source water before recharge does not necessarily protect the aquifer and the recovered water. In addition to unnecessarily high costs and effort, the infiltration of source water that is treated to (almost) meet drinking water quality can be harmful if it allows enhanced dissolution of minerals from the aquifer matrix. Furthermore, using chlorination before infiltration can result in the excessive formation of chloroform in the abstracted water (Dillon et al., 2009), and the formation of other disinfection byproducts can cause environmental and human health problems as well (Pavelic et al., 2005). Overexploitation of the aquifer can endanger a sustainable water supply and may lead to the infiltration of polluted water or saltwater and hence to a decrease in the quality of the recovered water (e.g., O'Leary et al., 2015).

Environmental risks arising from MAR implementation and operation (stages iii and iv)

The construction and operation of a MAR scheme may lead to changes in the natural environment, for example, by excavation, drilling, or surface sealing for infrastructure buildings needed for MAR. The MAR operation can also influence the environment by changing the surface water and groundwater levels. This can have an effect on vegetation and groundwater-dependent ecosystems (GDEs), the consistency of the rock framework, and stream and spring discharge. It may also cause unwanted flooding or landslides affecting natural and built environments (e.g., Assmuth et al., 2016; Page et al., 2009; Rodríguez-Escales et al., 2018; Swierc et al., 2005). The GDEs are especially sensitive to groundwater-level changes: falling groundwater levels can, for example, result in water unavailability, and increasing groundwater levels may cause anoxia. Among others, this can induce stress to vegetation, and changes can initiate a chain of events affecting the whole food chain of the ecosystem (e.g., Bartak et al., 2015; Dillon et al., 2009; NRMMC, 2009; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page, Dillon, Vanderzalm, Toze, et al., 2010; Page et al., 2013; Vanderzalm et al., 2011). Implementation of MAR can potentially also endanger rare species and animal migration through structural changes in the landscape (e.g., infiltration ponds or fencing around groundwater protection zones) or changing groundwater levels (El-Fakharany, 2013).

Moreover, due to differences between the chemical composition of natural groundwater and recharged water, effects such as aquifer dissolution (and resulting instabilities), a decrease in water quality, and consequent environmental impacts can occur (NRMMC, 2009). Common groundwater quality issues include, among others, increasing water salinity and sodicity, nutrient overload (that may cause eutrophication), and contamination of the aquifer (e.g., pesticides, pharmaceuticals) and hydraulically connected surface water bodies (e.g., Casanova et al., 2016; NRMMC, 2006). Furthermore, risks of increasing energy consumption and greenhouse gas emissions, arising from MAR operation, are considered in several studies (e.g., Bartak et al., 2015; NRMMC, 2009; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page, Dillon, Vanderzalm, Toze, 2010; Page et al., 2013; Vanderzalm et al., 2011).

Environmental risks related to anthropogenic influences (related to stages i and ii). Agricultural activities such as livestock farming, as well as wastewater release and sewer overflow, can change the environmental conditions in the MAR catchment (e.g., Bugan et al., 2016; Juntunen et al., 2017; Lee & Ji, 2016; Swierc et al., 2005). Furthermore, many studies have investigated environmental risks arising from chemical spills and accidents (e.g., industry, mining, septic tanks, or illegal sewage inflows) or from sabotage (e.g., related to industry, computer hacking, infrastructure, traffic, households, agriculture) in MAR catchment areas (e.g., Assmuth et al., 2016; Bartak et al., 2015; Ji & Lee, 2016a; NRMMC, 2009; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page et al., 2013; Swierc et al., 2005; Vanderzalm et al., 2011). However, it has to be noted that contamination can also occur accidentally due to natural events, such as heavy rainfall and floods (e.g., Assmuth et al., 2016; Lee & Ji, 2016).

Technical risks

During the MAR planning phase (stage i), among others, water demand is assessed to define the scale of a MAR project. If water demand is under- or overestimated, or if demand changes significantly over time, it can cause operational problems (e.g., Lindhe et al., 2020; Nandha et al., 2015; Rodríguez-Escales et al., 2018). Furthermore, the availability of water, in sufficient quantity and quality, is fundamental for MAR operation (e.g., Lindhe et al., 2020; Nandha et al., 2015; Wintgens et al., 2016). Hydrogeological characteristics and the ability to store water in the subsurface are critical constraints on the scale of the MAR project (Bouwer et al., 2008; Casanova et al., 2016; NRMMC, 2009; Page, Dillon, Vanderzalm, et al., 2010; Seis et al., 2015; Shah, 2014). In the planning phase, the influence of climate change can also be incorporated, for example, by considering the resulting changes of water demand and supply changes in the area and hence ensuring supply reliability (Pasini et al., 2012). Groundwater-level changes should be evaluated in view of possible flooding of basements or possible impacts on underground cables, which may require specific management measures (NRMMC, 2006).

Catchment characteristics (stage ii) such as slope instability (e.g., landslides) and erosion can damage MAR infrastructure and lead to malfunction or failure of the MAR scheme (Rodríguez-Escales et al., 2018; Swierc et al., 2005). In addition, inadequately low or high infiltration rates can impair an (effective) MAR operation, having an impact, among others, on the amount of water storage, travel and residence times, and attenuation processes (e.g., Bartak et al., 2015; de los Cobos, 2018; Rodríguez-Escales et al., 2018). Physical clogging of MAR systems can be caused by suspended particulates such as silt and clay particles or organic matter, entrainment, and/or formation of gas bubbles. Physical clogging is often accompanied by biological clogging (biofilm formation and biomass accumulation) and chemical clogging (mineral precipitation) (e.g., Jeong et al., 2018). Furthermore, infiltration of water with increased sodicity can increase the swelling of clay particles in the subsurface and thus decrease the efficiency of water recovery (e.g., Bartak et al., 2015; Bugan et al., 2016; NRMMC, 2009; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page, Dillon, Vanderzalm, Toze, et al., 2010; Page et al., 2013, 2009; Vanderzalm et al., 2011). A way to mitigate clogging can be pretreatment, such as the use of sand filters or sedimentation ponds for reducing the turbidity of infiltration water (e.g., Casanova et al., 2016; Page, Dillon, Vanderzalm, Bekele, et al., 2010; Page, Dillon, Vanderzalm, Toze, et al., 2010; Sultana & Ahmed, 2016). Also, suitable maintenance techniques can be applied for this purpose, such as wetting and drying cycles for infiltration basins, or the use of a single well for injection and abstraction (thus changing the groundwater flow direction) (e.g., Casanova et al., 2016; Pyne, 1995).

Further issues that can pose technical risks, related to both MAR operation and maintenance (stage iii) as well as water distribution and final use (stage iv), can include structural damage of the MAR infrastructure induced by natural hazards such as flooding, heavy rainfall, or drought (e.g., Bartak et al., 2015; Bugan et al., 2016;

Juntunen et al., 2017; Lee & Ji, 2016; Rodríguez-Escales et al., 2018; Swierc et al., 2005). Moreover, problems may arise from the malfunction or failure of technical equipment or infrastructure (e.g., Bartak et al., 2015; Bugan et al., 2016; Ji & Lee, 2016a; Juntunen et al., 2017; Pindoria-Nandha, 2016; Rodríguez-Escales et al., 2018; Swierc et al., 2005) and a lack of (trained) operating staff or technical knowledge (Assmuth et al., 2016; Dillon, Fernández Escalante, et al., 2020; Rodríguez-Escales et al., 2018; Swierc et al., 2005). If water derived from MAR is used for irrigation and this water has high salinity or is contaminated, plant health can be affected, leading to reduced agricultural yields (e.g., Eisfeld et al., 2021; ISO, 2015). When water is stored before final use, microbial regrowth, disinfection byproducts, or algae growth can occur due to malfunction or design flaws of the infrastructure (Bouwer et al., 2008; Bugan et al., 2016; Lee & Ji, 2016; Pavelic et al., 2005).

Social and economic risks

Social risks related to social acceptance (stage i). Public concerns about MAR include exploiting scarce water resources and possible contamination of aquifers (Rawluk et al., 2013). Furthermore, concerns about risks to human health and the environment posed by water recovered from MAR are also common (Alexander, 2011; Leviston et al., 2006). Concerns have also been raised about additional costs resulting from new water supply methods, and consumers are often unwilling to pay higher fees for water supplies (Alexander, 2011; Leviston et al., 2006; Rawluk et al., 2013).

Social risks related to the lack of communication and information (stages i and iv). Informing the public about a planned MAR project in written and oral form is a fundamental step in the early development stage (ASCE American Society of Civil Engineering EWRI Environmental and Water Research Institute, 2020). It is essential to communicate and provide open access to information. Educating the public about the benefits, potential problems, and unknown factors related to MAR and their handling can increase the transparency of the project and social acceptability (Alexander, 2011; Bekele et al., 2008). In a study by Leviston et al. (2006), the availability of information and possibilities for learning more about MAR implementation, monitoring, and maintenance were identified as being essential and more important than a sole assurance of safety. In contrast, it may often not be intuitive for scientists and engineers to engage stakeholders in the planning of MAR schemes (Richter et al., 2014).

Social risk related to source water (stage ii). The behavior of the public can affect groundwater quality around the MAR scheme, for example, washing or bathing near wells or using buffer or groundwater protection zones for recreational purposes (Bartak et al., 2015; Bugan et al., 2016). In a study by El-Fakharany (2013), potential socioeconomic issues were addressed that could arise from required resettlement or the loss of farm land, which may result from MAR-site construction.

Economic risks related to the financing of MAR schemes (stages i and iii). Within the planning stage, primary economic risks are related to the financing of the MAR project and the realization of long-term economic benefits. One of the core discrepancies for financing water projects is that water users, as primary beneficiaries, often have insufficient funds to support such projects; this problem has been identified as being particularly acute in developing countries (Maliva, 2014). Moreover, there is a time lag between paid construction costs and the realization of a project's benefits, which may lead the main beneficiaries to consider the investment in the MAR system infeasible in terms of costs and benefits (Maliva, 2014).

Economic risks related to MAR operation and management (stages iii and iv). When it comes to the operational phase of MAR, failure to meet performance objectives is considered to be a principal source of economic risks and associated uncertainties, for example, if the recharge of water does not result in an adequate increase of groundwater levels (Maliva, 2014). At the same time, the expectation that adequate pretreatment would mitigate clogging is not always true, as clogging during recovery may be a consequence of changes in water quality at the storage stage (Nandha et al., 2015). This important operational risk can result in high maintenance costs and consequently lead to unforeseen expenses during the operation and management stage of MAR schemes (Maliva, 2014).

Economic risks related to water demand (stage i). Another source of economic risks can be that revenues realized from MAR operation are lower than anticipated at the design stage because the expected water demand has not been fully realized. Irrigation demand, for example, is highly dependent on climate conditions, and the profitability of MAR schemes may vary noticeably under different climate change scenarios (Rupérez-Moreno et al., 2017). In addition, MAR systems can be sensitive to extreme climate events. Floods can put riverbank filtration wells at risk of contamination and potential damage that may severely affect drinking water production in flood-prone areas (Sandhu et al., 2018). Finally, MAR water demand for drinking purposes, which is particularly high during dry seasons, depends heavily on the consumers' perception of the safety of MAR water for household consumption (Hasan et al., 2019).

Risks related to legislation and governance. Issues related to regulation and legislation are extremely important, even in the MAR planning phase. This includes, among others, construction permits and an appropriate coordination with governmental agencies. In addition to technical skills, a legislative background is essential for successful MAR implementation and operation (Rodríguez-Escales et al., 2018).

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Risks related to legislation and governance are rarely considered in the reviewed literature. For example, the Australian guidelines (NRMMC, 2006, 2009) highlight potential risks related to inadequate education and information on already permitted MAR uses, which might lead to an unauthorized use of MAR and endanger its proper operation. The absence of clear regulations and the need for several different licenses can make the planning procedure very time consuming and difficult, which may decrease the willingness to start a new MAR project (Nandha et al., 2015). Fernández Escalente et al. (2020) emphasize that a clear approval system and clear water ownership rules must be defined prior to adapting regulations for MAR. Lee and Ji (2016) highlight that government policies can support environmental protection (e.g., by setting up protected natural areas), but may also cause environmental impacts (such as land use changes or urbanization): both can hinder MAR implementation.

DISCUSSION

History and geographic relation of publications on MAR risk assessment

Whereas the assessment of human health, environmental, and socioeconomic risks has been well established for many decades, its specific design and application for MAR implementation and operation has only received increasing attention in recent years. Among the reviewed literature, the total number of published studies on MAR risk assessment has increased steadily since the middle of the past decade (Figure 2A). Australia plays a pioneering role in the development and application of MAR risk assessment, and is referenced in early publications. Among the reviewed literature, an increasing number of publications related to Europe and other regions have been available since 2010 (Figure 2A). This coincides with the publication of the Australian MAR guidelines in 2009, which may have prompted the publication of further studies on MAR-related risk assessment. Also, 16 of the 34 considered publications after 2009 refer to the Australian guidelines for their methodology (cf. Table S1). Publication of MAR research peaked in 2015, which can partly be explained by the publication of results that were obtained from the DEMEAU project (Demonstration of promising technologies to address emerging pollutants in water and wastewater; Gibert et al., 2015; Seis et al., 2015). Other contributions to this peak are the publication of Assmuth et al. (2016) (risk assessment methodology) and de los Cobos (2018) (MAR site in Switzerland). When looking at the regions covered by the reviewed studies, about 40% of the studies available to date refer to Australia (Figure 2B), followed by Europe (~21%), Asia (~14%), North and South America (~5%), and Africa (~5%). Around 16% of the analyzed publications incorporate several case studies (details can be found in Table S1). The contents of the publications varied: some focused on special aspects and did not provide any particular insight into the MAR site (e.g., Song et al., 2019), whereas others provided detailed information and analysis for a case study (e.g., Swierc et al., 2005).

Common MAR risk assessment methodologies and types

The Australian guidelines, including the methodologies of qualitative risk assessment, QRA and QMRA, are applied in about half of the reviewed publications (Table S1). An HACCP analysis was conducted in five case studies, accounting for ~12% of all reviewed case studies. About a

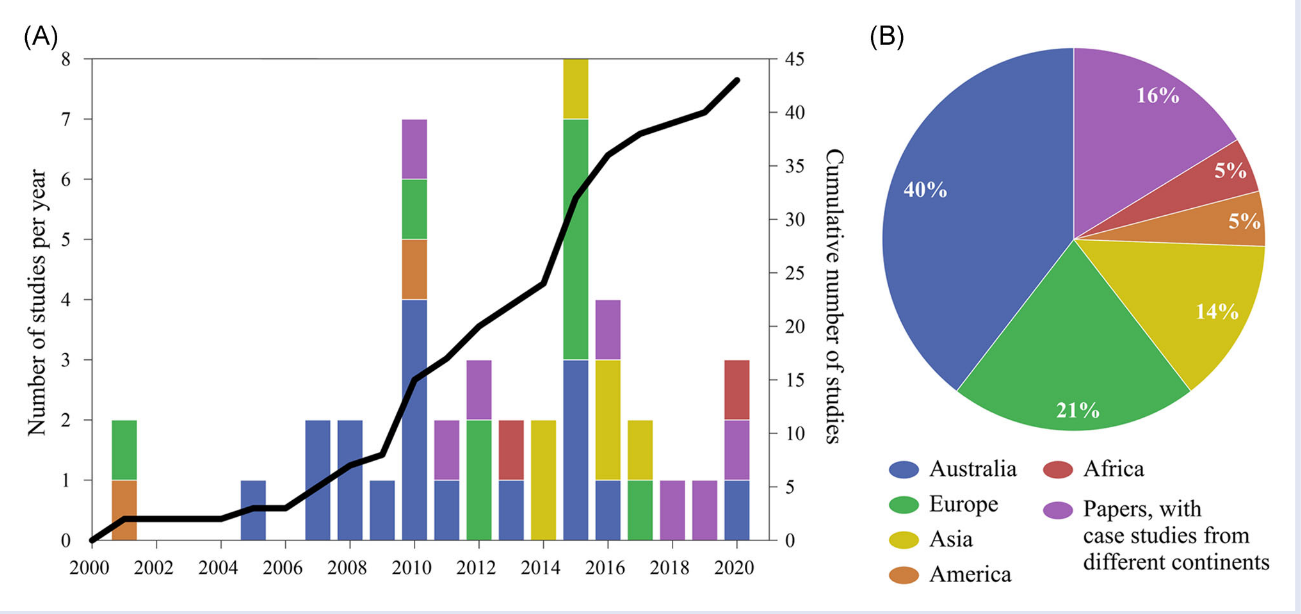

FIGURE 2 Temporal development of publication activity concerning the reviewed literature (based upon data shown in Table S1): (A) cumulative number of available studies (black line) and number of papers that appeared per year (bars), (B): percentage of studies that refer to managed aquifer recharge risk assessment on a specific continent (percentage of all reviewed publications)

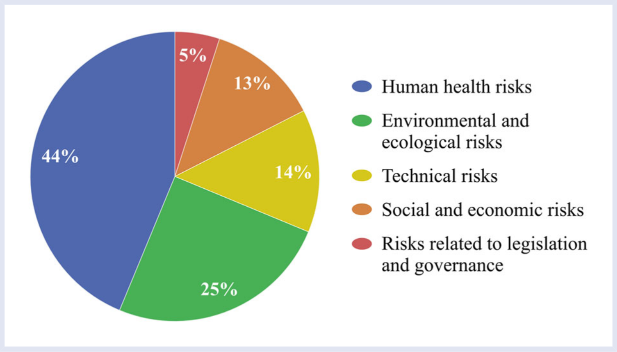

FIGURE 3 Percentages of different risk types in the analyzed publications, that is (i) human health risks, (ii) environmental risks, (iii) technical risks, (iv) social and economic risks, and (v) risks related to legislation and governance. Some of the analyzed publications cover two or more risk types (the presented percentages are based on data provided in Table S1)

third of the considered literature refers to QMRA (cf. Table S1). Among the different risk types, human health and environmental risks were addressed in two-thirds of the reviewed publications, followed by technical and socioeconomic risks and risks related to legislation and governance (Figure 3). The focus on environmental and human health risks can be related to existing regulations for these risks at a national level. Table S4 is intended as an overview on methodologies and guidelines that address specific risk types.

Limitations of risk assessment methodologies and lessons learned from their application and development

Several risk assessment methodologies also recommended in the Australian guidelines, such as QMRA and QRA, require a large amount of detailed input data (e.g., Dillon, Page, et al., 2020; Toze et al., 2010). These data are usually obtained from monitoring and provide the basis of QRAs. If such detailed data cannot be obtained with reasonable efforts, stochastic risk assessment approaches can help with the interpretation of the available data (e.g., Ji & Lee, 2017). Another important advantage of using stochastic approaches is that the uncertainty and variability of data and assumptions can be addressed (e.g., Page et al., 2009). Page, Dillon, Toze, Bixio, et al. (2010), Page, Dillon, Toze, Sidhu (2010), and Page et al. (2008) coupled QMRA and Damigos et al. (2016) CBA with Monte Carlo simulation to provide a stochastic analysis that accounts for uncertainty and variability and estimate risks based on the outcome.

If no data are available, a qualitative risk assessment (instead of QRA), such as one based on sanitary surveys, can also be used as an adequate option as proposed by Dillon et al. (2014) in the Indian guidelines. Havelaar (1994) argues that risk identification that implements HACCP frameworks may be biased by the opinions of the planners and operators. To overcome such bias, Ji and Lee (2017) suggested, among others, that all chemicals emitted by a source should be investigated with a pollutant release and transfer function, so that all emitting sources are assessed in the same manner. Nandha et al. (2015) state that the Australian guidelines for MAR focus on potential hazards and thus might not be suitable for process-oriented considerations.

A large number of the reviewed studies focused on the MAR planning stage, while fewer dealt with the MAR operation and maintenance stage, the assessment of the MAR catchment (or MAR water source), and the distribution and final use of water provided by MAR (cf. Table S2). However, only five of the recommended risk assessment approaches in the reviewed literature can be applied to cover all four stages of MAR implementation and operation, as well as for the assessment of the four defined risk types. These are (i) the HACCP framework, (ii) the use of WSP, (iii) qualitative risk assessment, (iv) integrated human health risk framework for MAR, and (v) the fault tree approach (cf. Table S4). Nandha et al. (2015), however, found that HACCP and WSP might fail to identify risks specific to MAR-related processes.

The consideration of risk multidimensionality, for example, via impact chains, is important to cover all relevant risk sources and also to take into account influences between different hazards. The following three methodologies were found to include such risk multidimensionality: (i) the fault tree approach developed by Rodríguez-Escales et al. (2018), (ii) the integrated human health risk framework for MAR (Assmuth et al., 2016), and (iii) the public health and economic risk assessment approach developed by Juntunen et al. (2017).

Limitations of reviewed publications

Based on our review focus, we have to take into account certain limitations: we presume that risk assessment studies are often the subject of internal reports, prepared by consultancies or MAR operators (e.g., Bloetscher, 2001; Bouwer et al., 2008; Clark et al., 2005), and in many cases, they are not publically available. Furthermore, our review is restricted to publications in English, so that any studies prepared in other languages are not considered. In fact, we assume that the aforementioned reasons may explain the limited availability of publications on risk assessments for MAR operations in North and South America, even though MAR is practiced there (e.g., Dillon et al., 2019; Zhang et al., 2020), and a risk assessment is required (ASCE American Society of Civil Engineering EWRI Environmental and Water Research Institute, 2020; MOP Ministerio de Obras Públicas, 2014; SEMARNAT, 2009). This is prominent also for MAR in the United States, which is among the countries with the highest installed MAR capacities worldwide (Dillon et al., 2019).

Apart from Australia, Chile, and India, other countries have also published guidelines on MAR implementation and operation: these guidelines acknowledge that a risk assessment should be conducted, but they do not suggest specific methodologies. We found such guidelines for the Netherlands, United States, Italy, and Mexico, among others (ASCE American Society of Civil Engineering EWRI Environmental and Water Research Institute, 2020; Ministero dell'ambiente e della tutela del territorio e del mare, 2016; Minister van Volkshuisvesting Ruimtelijke Ordening en

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Milieubeheer, 1993; SEMARNAT, 2009). A guideline for planning and authorizing MAR schemes is available for South Africa that includes questionnaires for risk identification, but no specific methods for risk analysis or evaluation (Ravenscroft & Murray, 2010).

CONCLUSIONS

Overall, MAR, in connection with holistic risk management, can be seen as a viable option for reaching the UN Sustainable Development Goal #6. Based on the research questions in this review, we can draw the following conclusions:

- Within the past two decades, there was been a marked increase in the literature on MAR-related risk assessment following publication of the Australian MAR guidelines in 2009.
- Human health and environmental risks have been addressed most widely in the literature analyzed (Figure 3), and it can be assumed that the latter risks will be of fundamental importance in the future as well. Concerning environmental risks, where GDEs in particular are expected to be directly impacted by MAR, limited data availability is a common problem that needs attention for selecting adequate risk assessment methodologies. We encourage future research to help identify risks of MAR implementation and operation for comprehensive risk management plans, including human health and environmental risks as well as technical risks and risks related to legislation and governance.
- To date, apart from Australia, there is a lack of legally binding MAR frameworks (including risk assessment approaches). It is recommended that policymakers implement holistic risk assessment approaches in their MAR guidelines. Further research could also focus on effective legislative measures to enhance the implementation and operation of MAR schemes.
- Only a few risk assessment approaches seem to exist, to date, that consider a holistic risk assessment including human health and environmental risks, technical, social, and economic risks, as well as risks related to legislation and governance. We encourage that for the development of risk assessment methodology, a process-based approach is used and risks are considered comprehensively.

The development of holistic risk management plans can improve social acceptability and can contribute to safer implementation and operation of MAR schemes. In addition to a process-based holistic risk assessment approach, we recommend evaluation of a MAR scheme also in the context of sustainability, social acceptability, and economic feasibility.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data, associated metadata, and calculation tools are available from corresponding author Arno Rein (arno.rein@tum.de).

SUPPORTING INFORMATION

Figure S1: Steps in the risk management process.

Figure S2: Risk factor score matrix for qualitative risk assessment.

Figure S3: Steps of quantitative risk assessment addressing human health risks arising from chemicals.

Table S1: Summary of analyzed case studies and methodological publications for MAR risk assessment.

Table S2: MAR-related risk assessment clustered with respect to risk type, together with references.

Table S3: Examples of potential hazards related to MAR.

Table S4: Overview of risk types considered by methodologies and guidelines for risk assessment of MAR schemes.

ORCID

Anne Imig http://orcid.org/0000-0001-6448-3740

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