Assessment of Managed Aquifer Recharge through Modeling—A Review

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Abstract: Managed aquifer recharge (MAR) is the purposeful recharge of an aquifer for later recovery or environmental benefits and represents a valuable method for sustainable water resources management. Models can be helpful tools for the assessment of MAR systems. This review encompasses a survey and an analysis of case studies which apply flow and transport models to evaluate MAR. The observed modeling objectives include the planning or optimization of MAR schemes as well as the identification and quantification of geochemical processes during injection, storage and recovery. The water recovery efficiency and the impact of the injected water on the ambient groundwater are further objectives investigated in the reviewed studies. These objectives are mainly solved by using groundwater flow models. Unsaturated flow models, solute transport models, reactive geochemical models as well as water balance models are also frequently applied and often coupled. As each planning step to setup a new MAR facility requires cost and time investment, modeling is used to minimize hazard risks and assess possible constraints of the system such as low recovery efficiency, clogging and geochemical processes.

1. Introduction

The rising water demand worldwide, caused by climate change, urbanization and population growth, poses increasing stress on groundwater as a resource [1,2]. Especially in arid or semi-arid regions the natural recharge is often not enough to meet the local water demand leading to over-exploitation of the groundwater resource and as a consequence to decreasing water tables and increasing salinization [3]. The storage of water in surface reservoirs is widespread but it has several disadvantages such as high evaporation losses, high land area requirements, sediment accumulation, the possibility of structural failure and high vulnerability to contamination [1,4,5]. An alternative to surface storage is storing excess water underground during periods of low demand or high availability to use it later in times of shortages [4,6,7]. In contrast to other recharge types such as natural or incidental recharge, managed aquifer recharge (MAR) is the intentional recharge of water into aquifers for future recovery or environmental benefits [1,3]. Incidental or unintentional recharge implies recharging the aquifer coincidentally by undertaking activities not directly designed to enhance recharge such as excess irrigation or leakage from water systems [1,8]. The main objective of MAR is to increase groundwater storage to overcome the temporal imbalance between local water demand and availability thus securing drinking or irrigation water supply at any time of the year [1,3]. Other objectives include the reduction of saltwater intrusion in coastal aquifers, prevention of land subsidence, improvement of the source water quality through Soil Aquifer Treatment (SAT) and avoidance of direct potable reuse of treated wastewater by an underground passage [1,3]. Water sources include surface water from rivers or lakes, stormwater runoff and reclaimed water [1,9,10].

Before this water is recharged to an aquifer a pretreatment might be necessary depending on the source water quality, the contaminant attenuation through the soil passage, the native groundwater quality and the intended use of the recovered water.

Subject to the local conditions, a wide range of MAR methods can be used to recharge an aquifer [8]. Usually five main MAR techniques are distinguished: well, shaft and borehole recharge; spreading methods; induced bank filtration; in-channel modifications; and rainwater and runoff harvesting [11,12] (Table 1). Recharge by well, shaft and borehole includes MAR methods that recharge directly into the aquifer which is often overlain by low permeability surface structures [11]. Spreading methods are applied at ground level where the water is infiltrated through permeable surface into the unsaturated zone. Induced bank filtration covers infiltration of surface water through river, lake or dune sediments caused by well pumping [8,11]. In-channel modifications are obstructions built directly in the stream network to temporarily store stormwater and enhance infiltration into river sediments [8]. Rainwater and runoff harvesting comprises the gathering and infiltration of surface or roof runoff by barriers, bunds and trenches [9,11]. It should not be confused with other MAR methods which often use stormwater as a water source. For detailed descriptions of the aforementioned MAR techniques see Dillon [3], Gale [8] or Hannappel et al. [11]. The classification of MAR techniques in this paper is based on the classification system developed by the International Groundwater Resources Assessment Centre [13], with the exception that ASR and ASTR are joint. In addition to these established MAR methods, there is a rising interest in new strategies for water banking which includes using agricultural land for surface spreading methods outside the irrigation season [14].

Table 1. Managed Aquifer Recharge (MAR) classification system stating five main methods and associated specific MAR methods, adapted from International Groundwater Resources Assessment Centre [13].

	Main MAR Methods	Specific MAR Methods
Techniques referring primarily to getting water infiltrated	Well, shaft and borehole recharge	Aquifer Storage and Recovery (ASR)/Aquifer Storage, Transfer and Recovery (ASTR) Shallow well/shaft/pit infiltration
	Spreading methods	Infiltration ponds & basins Flooding Ditch, furrow, drains Irrigation
	Induced bank infiltration	River/lake bank filtration Dune filtration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams Subsurface dams Sand dams Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting Barriers and bunds Trenches

Despite the apparent simplicity of MAR approaches and their large implementation worldwide [15], the complexity of site-specific hydrogeological conditions and the processes occurring at various scales combined with different objectives require a very good understanding of the system's response to the proposed measures. The characterization of the system including heterogeneities such as preferential flow paths is best investigated by field experiments, e.g., [16,17]. Laboratory experiments are used to investigate occurring processes in detail but are limited in representing boundary conditions and scale-related issues may occur. On the other hand, modeling can be used for scenario analysis and future predictions to compare different MAR techniques and operational schemes. Despite adaptive approaches for example using trial and error, modeling is a valuable tool

to estimate the feasibility of a MAR method at a given location. Given its flexibility, a model-based preliminary assessment is often recommended prior to pilot field experiments [17,18]. Even though building up a calibrated model takes up time and requires a detailed data set, the variety of possible applications such as scenario and sensitivity analyses can make the efforts worthwhile. However, modeling does not always lead to success and despite that fact, failures are hardly ever published. Some countries including Australia and the USA implemented guidelines that specifically regulate the requirements for risk assessment of new MAR facilities and advise the application of modeling during the planning phase [19,20].

So far, only Kloppmann et al. [18] published a summary of the application of groundwater models for the estimation and optimization of the performance of MAR schemes. They focus on different planning phases of a MAR system including site selection, design and operation and give an overview of data requirements and model selection.

Nevertheless, no review paper is published yet which analyzes model applications specifically focusing on each MAR method and comprises past areas of application and the choice of modeling software for each technique. Focus is not only restricted to groundwater models but also regards analytical and numerical flow and transport models considering, besides groundwater, also other components of the hydrological cycle. For this reason, case studies were collected from reviewed articles, scientific reports and conference proceedings, all written in English language. The search for publications was carried out via search engines and online databases but also reference lists of already located publications were screened. The search was restricted to MAR and artificial recharge. Only flow and transport models were included. Despite the scrupulous search, it was difficult to track all publications in the field and further relevant modeling studies likely exist. Data was analyzed regarding the evaluated main and specific MAR techniques, the model tools applied and the modeling objectives. Furthermore, the country of the field site or whether the publication covers a laboratory experiment or theoretical analysis was noted. The analysis helps to identify general trends in the utilization of models for MAR assessment. The overview on the presented software tools and their classification by model and MAR type can further ease the search of a suitable computer code and can thus be used as a general reference. Furthermore, modeling studies were reviewed regarding the different MAR methods to allow a more detailed look into modeling objectives and applications in the various fields of MAR. Elaborative information is given on what kind of model approaches and software tools can be applied during the planning stage, the first pilot experiments or the optimization of existing facilities depending on the site-specific issues. The review covers most processes occurring during MAR applications and discusses the influence of various operation and site-specific parameters on the overall system efficiency. While this is comprehensively discussed in the literature, the added value of the review is that it provides the reader also with the adequate tools for the quantitative and qualitative assessment.

The overall objective of the present paper is thus the introduction and evaluation of different modeling approaches which are used to assess MAR schemes dependent on site-specific conditions and applied MAR method through a structured review of most commonly used software codes and tools.

2. Analysis of Managed Aquifer Recharge Modeling Case Studies

Overall, 216 studies dealing with flow and transport modeling of MAR from 37 countries were collected from widely available literature published between 1985 and 2015 (Table S1). The papers included 188 modeling studies which evaluate field-scale MAR schemes or sites, 10 modeling studies which evaluate laboratory experiments and 18 assessing theoretical issues. Most studies were carried out in the USA (45 literature studies), Australia (39), The Netherlands (20) and India (13).

2.1. Modeled Managed Aquifer Recharge Methods

The majority of modeling studies were performed for well, shaft and borehole recharge (57%) and spreading methods (29%) (Figure 1). A recently published global MAR inventory shows that these are also the two most common MAR techniques applied worldwide [15,21]. However, the comparison of the global MAR inventory with this study reveals that spreading methods are the most common MAR techniques worldwide whereas most of the modeling studies identified were conducted for well, shaft and borehole recharge. As this method is technically demanding and there is a high need for information during the planning of the system, it is often accompanied by modeling. Only a few case studies are published which deal with modeling of rainwater and runoff harvesting facilities [22,23]. This method is frequently used in rural areas and is not technically demanding. Thus, it is regularly not accompanied by scientific or monitoring studies (in contrast to harvesting stormwater which is injected into wells or infiltrated via infiltration ponds) [22]. Models are mostly applied for the MAR subtypes ASR/ASTR (52%), infiltration ponds and basins (23%) and induced bank filtration (6%).
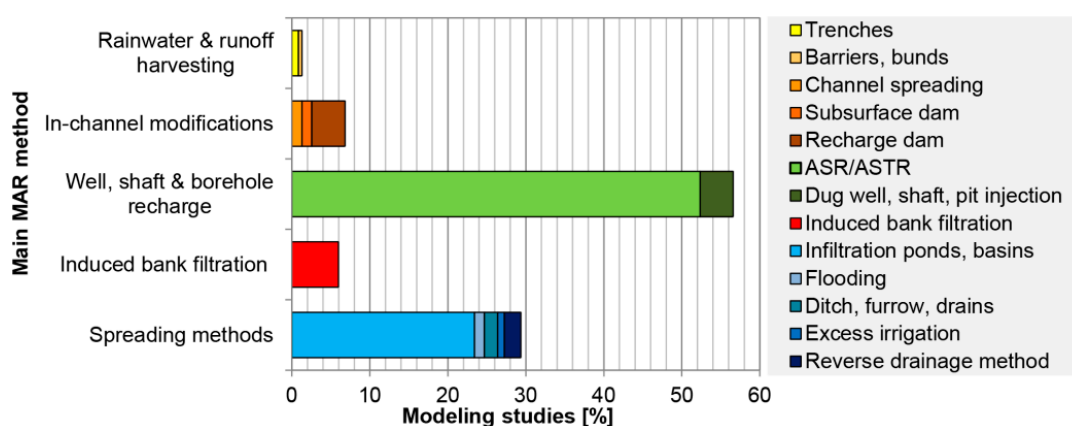

Figure 1. Distribution of modeling studies (%) for the main MAR techniques and MAR subtypes used (literature studies may involve multiple MAR techniques).

2.2. Survey of Applied Models

Various models are applied to evaluate MAR. For this analysis models were grouped into five categories namely groundwater flow, unsaturated flow, solute transport, reactive transport and watershed or water balance models. Groundwater flow models depict the saturated soil zone and are mainly based on Darcy's law [24] whereas unsaturated flow models mostly apply the Richards' equation [25]. Non-reactive or solute transport models include solute transport codes where advection, dispersion, diffusion, sorption and decay are considered. Reactive transport models are more complex and include geochemical and biogeochemical reactions. Watershed or water balance models include the surface water and partly apply an integrated water resource management approach.

One of the earliest applications of modeling for the assessment of MAR dates back to 1985 [26,27]. An increase in the number of model applications is observed from 1996 to 2000 reflecting amongst others the fast development and public availability of computer capacities and the increasing use of MAR worldwide [21] (Figure 2). The total number of publications continues to increase till the end of the study period (2015), with groundwater flow models being the most frequently applied model type during the entire investigated period. Since 2006, the number of publications of groundwater flow, unsaturated flow as well as water balance and watershed models keeps increasing.
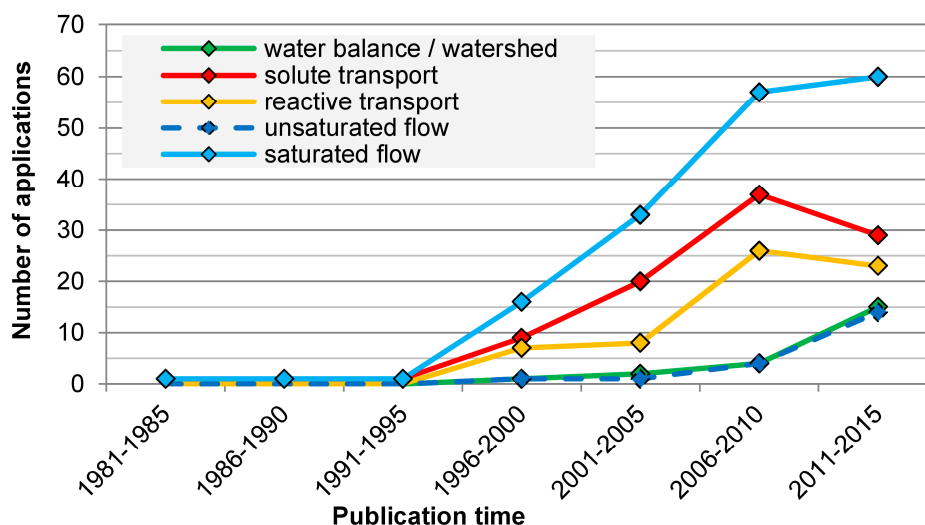
Figure 2. Historical development of different model types (literature studies may involve multiple or combine different model types).

In the reviewed literature studies various software tools were applied which model flow and transport (Table 2). A number of software tools were specifically developed for MAR applications while others are also used in general hydrogeological studies. Within the first category, the NASRI-BF Simulator assists in the design and operation of bank filtration sites and allows for a first assessment of the feasibility and conditions of a proposed site [28]. EL-ASR is an ASR adjusted derivative of the transport model EASY-LEACHER and able to account for various water quality issues which can arise during ASR [29]. Five major clogging mechanisms namely physical, biological, chemical clogging as well as the formation of gas and compaction were implemented into a numerical three-dimensional finite element code called CLOG [30]. It can assist in the design and operation of a MAR facility helping to prevent clogging and consequently improving the efficiency of the system [30]. Besides analytical and numerical models, simple empirical tools were developed particularly for the utilization as screening tools, e.g., ASRRI and the ASR Performance Index. The software ASRRI (ASR Risk Index) is a screening tool to predict the potential for contaminant attenuation during ASR and ASTR [31]. The ASR Performance Index evaluates whether lateral flow, density effects and dispersive mixing have negative effects on the recovery efficiency in saline or brackish aquifers [32].

The majority of models applied are not specifically developed for MAR applications. The most commonly used groundwater flow model is MODFLOW [33]. Further frequently applied codes for saturated flow modeling include FEFLOW [34], SEAWAT [35], HST3D [36] and PHAST [37]. Frequently applied unsaturated flow models include MARTHE [38], HYDRUS [39] and MIKE-SHE [40]. For solute transport modeling FEFLOW, MT3DMS [41], SEAWAT and CXTFIT [42] are used repeatedly. Reactive transport modeling is conducted mainly by using PHREEQC [43], MT3DMS, PHT3D [44] and EASY-LEACHER [45]. For the category water balance and watershed models only WaterCress [46] was applied in more than one case study.

Table 2. List of modeling software tools which were applied more than once in literature studies arranged in alphabetical order including the number of applications. The main MAR methods analyzed and the model types covered by the listed software tools are marked with "x" (note that some software tools can also be feasible for other MAR methods and might be applicable to further model types).

Software	Number of Applications	Model Type					MAR Method				
		Saturated Flow	Unsaturated Flow	Water Balance/ Watershed	Solute Transport	Reactive Transport	Well, Shaft and Borehole Recharge	Spreading Methods	In-Channel Modifications	Induced Bank Filtration	Rainwater and Runoff Harvesting
CFEST [47]	2	x			x		x				
COMSOL [48]	2	x	x		x		x	x			
CXTFIT [42]	6				x		x	x		x	
EASY-LEACHER [45]	5				x	x	x	x			
Eclipse [49]	3	x			x		x				
FEFLOW [34]	17	x	x		x		x			x	x
HST3D [36]	3	x			x		x				
HYDRUS [39]	3	x	x				x				
MARTHE [38]	4	x	x		x		x	x			
MIKE-11 [50]	2			x			x		x		
MIKE-SHE [40]	3	x	x				x	x	x		
MOCDENS3D [51]	2	x			x			x			
MODFLOW [33]	73	x					x	x	x		x
MT3DMS (MT3D) [41]	16				x	x	x	x			x
NASRI-BF Simulator [28]	3	x									x
PHAST [37]	2	x			x	x	x				
PHREEQC [43]	30					x	x	x			x
PHT3D [44]	13				x	x	x	x			
SEAWAT [35]	11	x			x		x	x			
SUTRA [52]	5	x			x		x	x		x	
SWIFT [53]	2	x			x		x				
TOUGH2 [54]	2	x	x		x	x		x			
WaterCress [46]	2			x			x	x			

2.3. Modeling Objectives

The objectives for conducting a modeling study are manifold and for this paper they were classified into 13 categories. Literature studies comparing different proposed recharge methods as well as sites show that flow modeling can help to select a MAR method and evaluate its advantages and disadvantages at a proposed location [6,55,56]. Modeling is usually performed during the approval or planning phase of a MAR system to evaluate its feasibility at a suggested site (*Feasibility*). Further investigations may assess the optimal design of the system (*Design*) and whether it will meet performance objectives prior to the construction of field-scale systems [4,17]. The optimization of MAR systems (*Optimization*) which includes assessing optimal infiltration and recovery schedules is another aspect of MAR planning. Modeling studies are also conducted to quantify the recovery efficiency (*Recovery efficiency*) which is the amount of water that can be recovered with desired water quality and the residence time (*Residence time*) of infiltrated water. The migration of injected water and the mixing with natural groundwater are thus calculated to quantify the storage or infiltration capacity of a MAR site.

Modeling studies focusing on geochemical processes (*Geochemical processes*) during the MAR application mainly analyze the quality of recovered water. Metal release and mobilization, nutrient removal and micropollutant breakthrough are the main issues evaluated. The fate of pathogens, nutrients and chemicals such as disinfection-by-products during the soil passage are examined. Another significant aspect is clogging which decreases the infiltration capacity of a MAR scheme (*Clogging*). Studies on general assessment of water quality (*Water quality*) might consider water quality changes of the injected water, the ambient groundwater or the recovered water. Soil aquifer treatment specifically focuses on water quality improvements due to the oxidation and microbial degradation of organic matter during the soil passage through the unsaturated zone (*Soil aquifer treatment*).

Modeling the impact on groundwater generally depicts the resulting groundwater level changes and the area of impact when MAR is applied (*Groundwater management*). In addition, sustainable river discharge due to economic or environmental restrictions is evaluated (*River flows*). Risk Assessment is a method to evaluate possible hazards and associated risks such as pathogen breakthrough which can arise during MAR (*Risk assessment*). In coastal areas, modeling is also used to assess the effect of applying MAR against saltwater intrusion (*Saltwater intrusion*).

The reasons for model applications cannot be generalized for the individual MAR types. However, some application trends can be derived from the survey and are more closely discussed in the Sections 2.3.1–2.3.5. The different MAR methods are described separately as each method poses diverse requirements on the modeling study and various objectives are pursued.

2.3.1. Well, Shaft and Borehole Recharge

During well, shaft and borehole recharge water is injected either directly into the aquifer or infiltrated by gravity into the unsaturated soil zone. Various hydrogeological and operational parameters such as the groundwater gradient, the aquifer heterogeneity and the recharged water volume influence the success of the system. Thus, injecting water into an aquifer is quite complex and its general feasibility is often investigated by applying a numerical groundwater flow model [7,57–64] (Figure 3).

Not only various design scenarios such as well locations and well spacing but also operational management options such as pumping and injections rates are being tested and optimized with the help of simulations [7,17,57,63–68]. Water management models are applied to assist in the cost-effective planning and design of reliable subsurface infiltration systems [7,69]. Scenario analysis incorporating projections of climate change and effects of urbanization into MAR scheme design was also addressed by modeling [46].
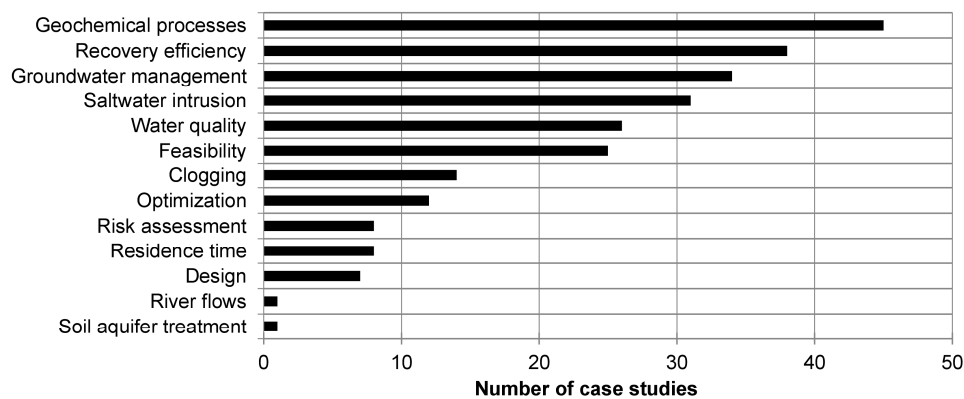
Figure 3. Distribution of well, shaft and borehole recharge modeling studies by objective (literature studies may involve multiple modeling objectives).

Quantifying the resulting groundwater levels and the spreading of injected water in the aquifer is a task often solved by groundwater flow modeling [7,55,70–74]. In addition, a groundwater flow model can help to estimate the quantity of water which can be stored underground [71,75–77], the impact of ASR on nearby production wells [72,78,79] and the impact of ASR on possible land subsidence [80]. When infiltrating into coastal aquifers the extent of seawater intrusion and the location of the freshwater-saltwater interface is of special interest and requires the application of density-dependent groundwater flow models [58,81–83].

Groundwater flow and solute transport models were also widely used to examine the influence of hydrogeological and operational parameters on the recovery efficiency [4,26,27,84–90] (Figure 3). Key parameters that have been modeled and that influence the recovery rate are the dispersity of the aquifer [32,86,88,91] and the aquifer heterogeneity [4,92,93] which can be characterized by high variations of permeability or the presence of dual-porosity zones. Modeling these parameters may help to understand the aquifer system and thus adapt the MAR operation scheme. Dual-porosity flow [4,92–94] and density-driven or buoyancy-induced flow [4,32,83,89,93–99] were incorporated into models in order to depict those complex processes. A simple screening tool developed by Ward et al. [32] can help to assess ASR performance in brackish and saline aquifers prior to numerical modeling.

Geochemical processes represent a major challenge as they influence not only the quality of the recovered water but also clogging. Their occurrence is caused by the differences in the chemical composition of injection water and ambient groundwater or water-rock interactions. Therefore, the modeling objective assessed the most for well, shaft and borehole recharge is geochemical processes (Figure 3). Reactive transport models are applied to identify the geochemical processes that take place during well injection and recovery [2,100–105]. Besides complex numerical codes, analytical transport models like EASY-LEACHER can be used to evaluate geochemical processes during deep well injection [29,45,106]. Pyrite oxidation is one of the key geochemical reactions identified [107–112] which often leads to mobilization of trace metals or metalloids [107–115]. Other geochemical reactions that could be identified by modeling are the dissolution of fluoride minerals [116] and the acidification in the aquifer [114,115]. Furthermore, scenario simulations were done to test how the dissolution of metals can be controlled [114].

Not only the dissolution of minerals but also their precipitation has been studied by modeling as it can affect the performance of an artificial recharge system by causing chemical clogging [117–123]. The numerical code CLOG has been used to assess different aspects of clogging taking into account the accumulation of suspended solids, bacterial growth, chemical reactions and the generation of gas and compaction [30,124].

Risk assessment tools were used to evaluate the fate of possible organic contaminant hazards during ASR [31,125–130]. Incorporation of biogeochemical reactions can help to quantify bacterial

influence on the local geochemistry [131,132] and show the removal efficiencies of organic contaminants during successive ASR cycles [133].

About two third of the compiled studies combined several objectives in their modeling study. An overview about the models used more than once for the specific objectives is given in Table 3. It can be stated that MODFLOW (33 applications) and PHREEQC (21 applications) are the most commonly used simulation tools for modeling of well, shaft and borehole recharge.

Table 3. List of models which were applied more than once for the different modeling objectives for the MAR technique well, shaft and borehole recharge.

Modeling Objective	Model Used	References
Clogging	PHREEQC	[118–120,123,134,135]
	PHT3D	[103,132,136]
	CLOG	[30,124]
Design	FEFLOW	[63,64,121]
	MODFLOW	[76,77]
Optimization	MODFLOW	[7,68,71]
	WaterCress	[46,137]
	FEFLOW	[82,138]
Feasibility	MODFLOW	[55,57,59,61,65,71,84,139–143]
	PHREEQC	[2,114,144]
	SEAWAT	[83,84]
Water quality	PHREEQC	[2,7,100,101,110,111,116,134,145]
	PHT3D	[103,104,107–109,126,132,136,144,146]
	EASY-LEACHER (EL-ASR)	[29,45,126]
	MODFLOW	[103,108,132,136]
	MT3DMS	[103,132,136]
Geochemical processes	PHREEQC	[2,7,100,101,110–112,114,116–121,123,134, 135,144,145,147–149]
	MODFLOW	[103,108,132,136,148,150–152]
	PHAST	[102,149,153]
	PHT3D	[103,104,107–109,126,132,136,146]
	EASY-LEACHER (EL-ASR)	[29,45,126]
	MT3DMS	[103,132,136,148]
	CLOG	[30,124]
Groundwater management	MODFLOW	[55,60,61,72–78,122,154,155]
	FEFLOW	[63,64,82,99,138]
	HYDRUS 2D	[156,157]
	SEAWAT	[83,98]
	SUTRA	[81,158]
Recovery efficiency	FEFLOW	[32,63,64,95,99,135,159,160]
	MODFLOW	[57,76–78,84,86,92,155,161]
	SEAWAT	[4,7,84,96–98]
	HST3D	[7,89,90]
	MT3DMS/MT3D	[78,84,86,92,161]
	INTERA	[26,27]
	SUTRA	[87,162]
	PHAST	[102,153]
Saltwater intrusion	FEFLOW	[32,63,64,82,91,95,96,99,121,135,138,159]
	SEAWAT	[4,82–84,92,97,98]
	SUTRA	[81,87,158,162]
	HST3D	[7,89,90]
	ECLIPSE	[66,93]
	MODFLOW	[57,84,155]
Residence time	PHT3D	[104,126,146]
	FEFLOW	[63,64,96]
	MODFLOW	[152,155]

2.3.2. Spreading Methods

In contrast to other MAR methods, spreading methods require large areas of land as well as certain land use types and geology. Hence, modeling is used to select and evaluate suitable sites for the application of infiltration ponds and basins and to optimize their design [163–169] (Figure 4). The planning of recharge basins as well as the evaluation of different management options is done by modeling [170–174]. Modeling can be used in particular as a supporting tool to design the groundwater monitoring network for infiltration basins and ponds [171,175–179].
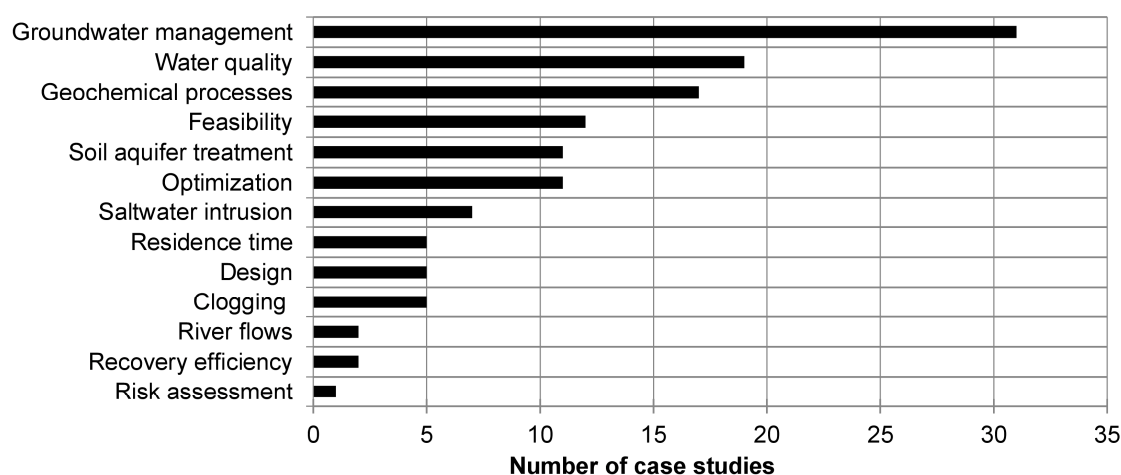

Figure 4. Distribution of spreading methods modeling studies by objective (literature studies may involve multiple modeling objectives).

The impact of the infiltrated water on the groundwater is of interest, especially with regard to the resulting groundwater levels [71,169,174,180–182]. Flow paths and travel times of the infiltrated water in basins and ponds and capture zones of the abstraction wells were often estimated by using groundwater flow models [171,175,180,183–187]. Reactive transport modeling helps to identify the occurring geochemical processes, e.g., the interaction of the infiltrated water with the ambient groundwater can be simulated [188,189]. Physical, chemical and biological processes occurring during the infiltration of treated wastewater into the unsaturated soil zone are of special interest as further water purification can be achieved through the soil passage [190–195]. The transport and degradation of organic pollutants like pharmaceuticals or pathogens are studied with transport models [18,131,168,176,196–198]. Consequently, understanding the biogeochemical reactions which occur in the unsaturated and saturated zone is necessary for a thorough risk assessment of complex SAT systems [18]. Modeling can moreover help to predict clogging of surface infiltration systems [30,199–203].

The groundwater flow model MODFLOW is most commonly applied and used to solve almost all identified modeling objectives (Table 4). To evaluate and identify geochemical processes and water quality changes during spreading methods application, PHREEQC, MARTHE, CXTFIT, MT3DMS and EASY-LEACHER are used.

Table 4. List of models which were applied more than once for the different modeling objectives for the MAR technique spreading methods.

Modeling Objective	Model Used	References
Design	MODFLOW	[163,204]
Optimization	MODFLOW	[71,168,174,205,206]
	MT3DMS	[168,174]
Feasibility	MODFLOW	[57,71,163,164,169,182,207]
	VS2DI	[178,179,208]
	FEMWATER	[178,179]
Water quality	PHREEQC	[188,193,209,210]
	MODFLOW	[131,177,196–198,211,212]
	MARTHE	[18,188,193]
	MT3DMS	[177,197,198]
	CXTFIT	[202,211,213]
	PHT3D	[130,196]
	MOCDENS3D/MOC3D	[18,212]
Geochemical processes	PHREEQC	[18,188,189,193,210]
	MODFLOW	[196,202,212]
	MARTHE	[18,188,193]
	EASY-LEACHER	[45,200,214]
	PHT3D	[191,196]
Groundwater management	MODFLOW	[71,142,163,164,169–171,174,180, 182,205,212,215–217]
	MOCDENS3D/MOC3D	[185,212]
	SEAWAT	[186,187]
	TOUGH2	[181,218]
	FEMWATER, VS2DI	[178,179]
SAT	PHREEQC	[193,209,210]
	MODFLOW	[177,197,211]
	MARTHE	[18,193]
	MT3DMS	[177,197]
Saltwater intrusion	MODFLOW	[57,170,171,207]
Residence time	SEAWAT	[186,191]
River flows	MODFLOW	[142,163]

2.3.3. Induced Bank Filtration

Pumping well induced infiltration from a surface water body is commonly conducted to improve the surface water quality by an underground passage. Hence, matters of particular interest in the course of induced bank filtration are to separate flow paths, to determine sources of the bank filtrate and to quantify the leakage water.

Those issues are mainly evaluated by groundwater flow modeling, especially with the help of MODFLOW [219–224] (Table 5). Solute transport modeling is also important but applied models are more diverse, with CTXFIT [42,225], MT3D(MS) [219,220] and PHREEQC [226,227] being the most commonly applied ones.

The NASRI-BF Simulator, a tool specifically designed for induced bank infiltration, allows a first rough estimate of the feasibility of bank filtration and to define the optimal position and number of wells [28,121]. Optimization of well design has been also conducted by Schafer [224].

As the improvement of water quality is the main objective of induced bank filtration, most modeling studies found focused on transport modeling. Clogging and its evolution during long-term operation have been modeled and the reduction of hydraulic conductivity was simulated [219,224]. Governing biogeochemical processes and redox conditions have been simulated for conceptual column studies [227] as well as field studies [226]. Further studies were undertaken to investigate the fate and transport behavior of contaminants [220,223], organic contaminants [220] as well as pharmaceutics

and algae toxins [42,202,225] during riverbank filtration. The influence of microbiological activity on the recovered water quality was also modeled [226]. With the evolution of simulation codes, very complex chemical interactions can be studied now such as multispecies biochemical reactions [223]. Being able to simulate complex bio- and geochemical reactions holds great potential for understanding the transport and degradation processes of solutes in the subsurface passage. This will enable MAR scheme operators to manage their sites in a more sustainable and efficient way as they are able to determine flow paths, infiltration sources and travel times of the bank filtrate. The identification of geochemical processes during filtration is especially important as the quality of the abstracted water defines the need for further treatment.

Table 5. Induced bank filtration modeling studies. The following abbreviations are used for the covered modeling objectives: Groundwater management (GM), Residence time (RT), Design (D), Feasibility (F), Recovery efficiency (RE), Water quality (WQ), Geochemical processes (GP), Clogging (C), Optimization (O).

Country *	Publication Year	Model Used	Modeling Objectives	Reference
Austria	2006	MODFLOW, MT3D	GP, C	[219]
Germany	2006	PHREEQC	WQ, GP	[226]
Germany	2006	MODFLOW-MT3DMS, CXTFIT	GP, C	[202]
Germany	2002	FEFLOW	RT, RE, C	[228]
Germany	2014	MODFLOW, MT3DMS	WQ	[220]
Germany	2006	MODFLOW	RT, GM	[221]
Kenya	2012	MODFLOW, NASRI Bank Filtration Simulator	F, WQ, GM	[222]
L. E.	2006	PHREEQC	GP	[227]
L. E.	2006	CXTFIT	WQ, GP	[225]
L. E.	2006	CXTFIT	GP	[42]
Malawi	2012	MODFLOW, NASRI Bank Filtration Simulator	F, WQ, GM	[222]
T. A.	2008	NASRI Bank Filtration Simulator	F, D, O	[28]
USA	2006	MODFLOW, PHT3D	GP, C	[223]
USA	2006	MODFLOW	RE	[224]

Notes: * L. E. = laboratory experiment, T. A. = theoretical analysis.

2.3.4. In-Channel Modifications

Recharge and check dams are built in a river bed to enhance recharge from streams whereas subsurface dams are designed to contain the underground flow raising the water table [13]. In general, the prolongation of the flow length and the residence time achieved by channel spreading increases the recharge to the groundwater.

Groundwater management is the focus of the retrieved case studies for in-channel modifications and MODFLOW is the dominating numerical model used [217,229–231] (Table 6). It has been utilized to test planned recharge structures [230] as well as to adjust existing structures [55] regarding their effect on artificial recharge rates. Simulating the movement of recharged water through the underground helped to increase the knowledge about the overall MAR system [231]. Studies testing different in-channel modification techniques regarding their impact on the groundwater have been conducted for Japan [56] and India [217,229] and showed the potential of modeling for scenario analyses and MAR method selection.

Assessment and prevention of seawater intrusion is another issue that has been studied with the help of modeling [138,158,232]. The two-dimensional variable-density flow and solute transport model SUTRA was used in this context [158,233] as well as an integrated water resource management approach using a coupled groundwater and surface water model (FEFLOW and MIKE-11) [138,232]. Optimization of existing MAR facilities under various recharge conditions concerning the reduction of seawater intrusion has been studied in Australia [158,233], China [138] and India [232]. The latter study [232] also concerned the assessment and optimization of future structures.

Table 6. In-channel modifications modeling studies. The following abbreviations are used for the covered modeling objectives: Groundwater management (GM), seawater intrusion (SI), Optimization (O), Residence time (RT), Design (D), Feasibility (F), Recovery efficiency (RE).

Country	Publication Year	Specific MAR Type	Model Used	Modeling Objectives	References
Australia	2002, 2007	Channel spreading	SUTRA	GM, SI	[158,233]
China	2012	Recharge dam	FEFLOW, MIKE-SHE, SIWA, WBalMo, MIKE-11	GM, SI, O	[138]
China	2015	Recharge dam	FEFLOW	GM	[234]
India	2014	Recharge dam	FEFLOW, MIKE-11, NAM	GM, SI	[232]
India	1998	Recharge dam	MODFLOW	GM	[229]
India	2010	Recharge dam	MODFLOW	GM	[217]
India	2006	Recharge dam	MODFLOW, analytical spreadsheet model	RE	[235]
Italy	2006	Recharge dam	MODFLOW	RE	[55]
Japan	2006	Subsurface dam	2D FEM model	D	[56]
Namibia	2012	Recharge dam	MODFLOW	GM	[230]
Russia	2006	Channel spreading	hydrogeological model	RT, GM	[236]
Turkey	2012	Subsurface dam	SEEP/W (2D)	GM, D	[237]
USA	2012	Recharge dam	MODFLOW	GM	[231]
Uzbekistan	2010	Channel spreading	MODFLOW	F	[238]

2.3.5. Rainwater and Runoff Harvesting

Rainwater and runoff harvesting is a cost-effective and easy to apply method to artificially recharge an aquifer. It is widely implemented in rural areas but seldom accompanied by scientific studies to monitor and manage the structures [22]. Modeling studies using water balance models and rainfall-runoff models demonstrate that modeling can be valuable to estimate the contribution of rainwater and runoff harvesting to the local water balance and to evaluate further implementation of recharge structures in a catchment [22,23] (Table 7).

Table 7. Rainwater and Runoff Harvesting modeling studies. The following abbreviations are used for the covered modeling objectives: Groundwater management (GM), Optimization (O).

Country	Publication Year	Specific MAR Type	Model Used	Modeling Objectives	Reference
India	2011	Trenches	water balance model	GM	[22]
India	2012	Trenches	rainfall-runoff model	GM, O	[23]

3. Discussion

For this survey, 216 studies published over the past 30 years addressing modeling of MAR have been collected and evaluated. Most modeling studies were conducted in the USA, Australia, The Netherlands and India. A few countries implemented guidelines that regulate the requirements for risk assessment of new MAR facilities [19,20,239,240]. The Australian guidelines explicitly advise the application of groundwater flow, transport and geochemical models on a hazard-specific basis during the investigation and trial phase of a new MAR facility [19]. The standard guidelines published by the American Society of Civil Engineering (ASCE) also propose the use of modeling during the preliminary design or feasibility study [20]. The Mexican regulations for the artificial recharge of treated wastewater require the application of numerical models for determining physical-chemical

reactions in the unsaturated and saturated zone and the system impact on wellfields as well as phreatic levels [240].

Most modeling studies were conducted for well, shaft and borehole recharge and spreading methods, which are also the most frequently applied methods to recharge an aquifer worldwide. Planning and establishing a MAR scheme at a proposed location includes studying the often complex hydrogeology at the site in order to mitigate hazard risks, such as low recovery efficiencies and clogging that can lead to the failure of the facility. Typical objectives for conducting a modeling study are therefore to optimize and plan the design and operation of MAR facilities and to quantify their impact on the groundwater. The achievable recovery efficiency and possible geochemical processes can be assessed using models to analyze scenarios and minimize the failure risk of a facility. Modeling is further used to predict possible long-term impacts regarding the geochemical processes, the recovery efficiency and the impact on the local groundwater. A specific issue often analyzed by modeling includes the prevention of seawater intrusion through MAR. Modeling studies can reduce laboratory and field work that is otherwise needed. Comparative studies may help to select a MAR method and evaluate its advantages and disadvantages at a proposed location. Modeling of different scenarios may also include: site selection, well-field and monitoring network design and the adjustment of operational parameters. Furthermore, a sensitivity analysis can assist to identify the most important hydrogeological and operational parameters influencing the performance of a MAR system. Best-case and worst-case scenarios can be simulated whose reproduction in field and laboratory experiments can be difficult. Having said this, modeling provides the distinctive possibility to include future climate change, water use and management scenarios into the feasibility study.

Depending on the specific objective and data availability, various models are applied. As this study confirmed, groundwater flow models, which are often combined with solute or reactive transport models, are most widely used for MAR assessment. Furthermore, the publications on unsaturated flow, water balance and watershed models keep increasing. Even though some software tools have been specifically developed for MAR [28–32], mostly non MAR-specific models are being utilized. The reviewed modeling studies show that commonly known modeling tools are mostly sufficient to meet the general needs observed for MAR modeling. These include unsaturated and saturated flow modeling, density-driven modeling and also geochemical modeling. Using well-established tools for MAR modeling such as MODFLOW and PHREEQC is generally of advantage due to their existing wide field of past applications and their comprehensive documentation. Developing MAR specific simulation tools has been driven forwards with regard to processes that are not yet well depicted in the common simulation tools. As clogging is a major concern during MAR application, focus has been set on better representation of clogging processes in simulation tools [30]. Other modeling tools have been developed to aid in the detailed MAR operation design for river bank filtration [28] or ASR [29]. Despite that, sophisticated models which include dual-porosity, account for aquifer heterogeneity or accurately simulate reactive geochemical reactions are required to predict MAR performance more reliable at complex sites [4,17,88]. There is a need for holistic model systems integrating not only groundwater but also the unsaturated zone and surface water in order to represent intricate MAR systems such as in-channel modifications. Supplementary studies should be conducted to incorporate biological enhanced reactions into biogeochemical modeling as they occur in complex systems with treated wastewater or stormwater [18].

However, with rising complexity of applied models additional hydrogeological parameters and therefore a more detailed characterization of the study site is required. An accurate determination of site-specific parameters and an uncertainty analysis is important to predict the performance, design and operation of a MAR system more reliably by modeling [241]. As models are only a simplified representation of a complex natural system, many sources of error and uncertainty exist. Sources of uncertainty include the conceptual model, model parameters and uncertainties in observation data [242]. As a result, setting up a modeling study is not always crowned by success. Although hardly any failure in MAR modeling is communicated, some general reasons can be inferred from modeling

studies not dealing with MAR. Insufficient data availability, incorrect interpretation of available data, wrong conceptualization or oversimplification of a complex system and unsuccessful calibration can lead to the fact, that a modeling study is not further pursued. Especially model calibration, which includes sensitivity analysis, can be very demanding. Models with a high number of parameters often need to be calibrated with the help of inverse modeling and specific tools, such as PEST [243] or UCODE [244]. These tools not only require a reliable calibration dataset but also thorough knowledge about the incorporated mechanisms. Thus, calibration is one of the most time-consuming and complex parts of the modeling approach. Emphasis on this modeling step is, however, of importance as it defines the quality and reliability of the modeling results. Furthermore, calibration helps to evaluate if the representation of the system sufficiently meets the study objectives.

Information required for management decisions like the granting of permissions can be derived from modeling. The California Department of Drinking Water recently published a guideline comparing different approaches for the determination of underground residence time at MAR sites using treated wastewater [245]. Numerical groundwater flow modeling was ranked less reliable than geochemical field approaches such as intrinsic or added tracers [245]. This reflects that it often can be difficult to create reliable models considering the frequently insufficient knowledge about aquifer properties and especially preferential flow paths. In addition, the uncertainties inherent in modeling results and limitations of the model need to be properly communicated so that water managers can interpret the results correctly.

Overall, MAR is a valuable method for the sustainable management of groundwater and is widely applied to restore groundwater resources. Modeling is nowadays integrated into MAR feasibility studies and offers the unique possibility to predict the performance and to decrease the risk of failure of a facility.

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