



Web-based global inventory of managed aquifer recharge applications

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Abstract

Managed aquifer recharge (MAR) is being successfully implemented worldwide for various purposes: to increase groundwater storage, improve water quality, restore groundwater levels, prevent salt water intrusion, manage water distribution systems, and enhance ecological benefits. To better understand the role of MAR in sustainable water management and adaptation to climate and land use change, about 1200 case studies from 62 countries were collected and analyzed with respect to historical development, site characterization, operational scheme, objectives and methods used, as well as quantitative and qualitative characterization of in- and outflow of water. The data harvested was used for the compilation of a global inventory of MAR schemes, whose main goal is to provide access to existing MAR projects and techniques and demonstrate their benefits. To increase the availability and facilitate continuous update of the MAR inventory, an MAR web-based portal was developed and integrated into IGRAC's Global Groundwater Information System. The MAR portal contains a "data layer catalog" containing the data arranged in a systematic way, a "map viewer" to visualize the selected data on a geographic location, and a "features panel" providing tabular output of the selected data. By facilitating access and promoting international sharing of information and knowledge on MAR, the web-based MAR portal aims to increase awareness of MAR as a viable solution for sustainable groundwater resources development and management, and to provide a new tool for better planning of MAR at regional and global scale.

Keywords Managed aquifer recharge · MAR · Web-GIS · Global Groundwater Information System

Abbreviations

| | | | |
|--------|---|--------|--|
| ASR | Aquifer storage and recovery | DSS | Decision support system |
| AS(TR) | Aquifer storage, transfer, and recovery | GGIS | Global Groundwater Information System |
| BMBF | German Federal Ministry of Education and Research | GIS | Geographic Information System |
| DDDM | Data-driven decision making | IAH | International Association of Hydrogeologists |
| DEMEAU | Demonstration of promising technologies to address emerging pollutants in water and waste water | IGRAC | International Groundwater Resources Assessment Centre |
| | | INOWAS | Innovative web-based decision support system for water sustainability under a changing climate |
| | | MAR | Managed aquifer recharge |
| | | OGC | Open Geospatial Consortium |
| | | WMS | Web Map Services |

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Introduction

Managed aquifer recharge (MAR) represents the intentional recharge of aquifers with surface water, mostly harvested runoff and river water but lately also treated municipal wastewater (Dillon 2005). Despite its obvious economic and ecological benefits acknowledged by water resources

specialists, MAR is often regarded by the decision makers as a rather costly, and potentially risky solution applied predominantly in arid and semi-arid countries with water scarcity problems. With some exceptions [e.g., in Europe, where about 200 MAR schemes, specifically riverbank filtration, are used for the production of drinking water (Sprenger et al. 2017)], the contribution of MAR to drinking water supply systems is still rather low. The main reasons for the low acceptability rates are the poor awareness on MAR in general and the lack of access to information (demonstration projects), which make water supply operators to adopt often much costlier, but considered ‘safe’ solutions (Sheehan 2009).

Under these circumstances, it is safe to consider that a better dissemination of results from successful projects could help stakeholders to understand the benefits of MAR and adopt the methodology on a larger scale. In response to this demand, numerous international initiatives aimed over the past years to make MAR technology widely accessible by demonstrating the quantitative and qualitative long-term positive effects on groundwater resources (Miret et al. 2013; Escalante 2014; DINA-MAR 2016; MARSOL 2016).

One such initiative was promoted by the International Association of Hydrogeologists (IAH), a scientific and educational organization founded in 1956 that aims “to further the understanding, wise use and protection of groundwater resources throughout the world” (IAH 2016). Over the years, IAH awarded MAR a special focus through the establishment of a special Commission on Managed Aquifer Recharge (IAH-MAR Commission). The main objective of the IAH-MAR Commission is to promote MAR through encouraging “research, development and adoption of improved practices for management of aquifer recharge and improving knowledge, skills and capabilities of practitioners, water resources managers and regulators” (IAH-MAR 2012). To further encourage the general acceptance of MAR as valuable element of integrated water resources management and to assist in the facilitation of MAR adoption to address effects of climate and land use change, the IAH-MAR Commission established in 2015 the MAR Inventory Working Group with the aim to collect and analyze data for the compilation of the first global inventory of MAR schemes.

The activities of the group are based on the previous works conducted within the European project DEMEAU (“Demonstration of promising technologies to address emerging pollutants in water and waste water”, <http://www.demeau-fp7.eu>). Under this project, a catalog was compiled with data harvested from over 280 European MAR schemes (Sprenger et al. 2017), the database being the first of its kind in Europe and, in this extent, one of the very few inventories of MAR projects worldwide. Following a similar approach, the Research Group INOWAS (“Innovative

web-based decision support system for water sustainability under a changing climate”, <http://tu-dresden.de/uw/inowas>) continued the previous efforts and collected data from about 1200 case studies in 62 countries worldwide (including the European examples and extended worldwide). To increase the availability and facilitate continuous update of the MAR inventory, the International Groundwater Resources Assessment Centre (IGRAC) setup a web-based GIS platform (<http://marportal.un-igrac.org>) where the locations and project-relevant data can be accessed, visualized and downloaded.

The aim of this paper is to present the framework for the global MAR inventory and the first outcomes of the activities of IAH-MAR Inventory Working Group and to introduce the web-based GIS inventory of MAR applications.

Data collection

Sources of information

For the compilation of the MAR inventory, a comprehensive survey on MAR case studies was conducted over a period of about 12 months. The data were extracted from freely available publications, including journal articles (22%), reports (31%), conference papers (10%), presentations (5%), books and book sections (9%), academic theses (5%), and partially websites (10%), newspaper articles (1%), and other documents (7%). The first attempts of online search using specific evident keywords gave very discouraging results, indicating that most case studies are not readily available via common search engines. In addition, the search in specialized databases such as Web of Science, Academic Search Complete, ScienceDirect and similar was not giving satisfactory results due to very different terminology used in articles’ metadata. The most efficient search method was proven to be the manual screening of references listed in already available papers. This led to a systematical search with results either geographically localized or grouped by similar technologies and objectives. Once a certain case study was geographically localized, further sources were identified in available databases using the location’s name as keyword. This led to a cross verification and validation of the original paper and often enabled the harvesting of additional information about the site.

Given the international scale of the survey, it was obvious that a search in local languages might reveal supplementary information. Using the same methodology as described above, the screening was thus continued, beside English, in German, Spanish, Portuguese, French, and Chinese by MAR experts fluent in these languages. In addition, the search for European case studies was conducted by DEMEAU project team also in Polish and Dutch.

All the papers collected were stored in Zotero (2016), a reference management software that allows to easily collect, manage, and organize bibliographic information (metadata).

Criteria for site selection

A set of criteria was formulated for the selection of suitable references for the review. The first condition was that the MAR scheme is either in the advanced planning phase with clear perspectives for implementation or at different construction or operational stages. The category included projects that were shut down by the time of publication but operated in the past, as well as pilot projects followed or not by full-scale implementation. Not included were simulation studies conducted for the estimation of feasibility of MAR schemes and optimisation of existing applications. If at one site, more infiltration tests were conducted and at least one parameter was different (MAR type, objectives, influent type or end use of effluent), then multiple entries were assigned to the site following the number of distinct infiltrations. A second criterion was the description of either main or specific MAR types in the paper analyzed, with papers only mentioning aquifer recharge but without description of the method being excluded. Further criteria included public availability of the reference, either as direct web reference or through institutional subscription at local university and state library.

A special situation was created by the identification of very large amounts of case studies concentrated in small regions such as the “Catalog of recharge basins on Long island, New York, in 1969” published by the U.S. Geological Survey in its 70th Bulletin in 1973 (Seaburn and Aronson 1973). The catalog contains descriptions of 2162 recharge basins in Long island, New York, constructed between 1923 and 1969. Another example is the personal communication received from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística) with technical data and locations of 3914 subsurface dams constructed between 2008 and 2015 in nine federal states of north eastern Brazil. These kinds of bulk data sets were not included in the present edition of the inventory, but they might be included in future updates after a more consistent review.

Database structure

Data collected was structured in four main categories, following the general structure of the DEMEAU catalog with minor modifications and extensions (Table 1): (1) general information (18 parameters); (2) operational parameters (18); (3) hydrogeological properties (9); and (4) water quality parameters (water quality monitoring with 6 fields and hydrochemical data with 106 fields). Mostly, general information about the site was available in the collected

references with some relevant aspects remaining unclear. For example, the exact number of MAR schemes in operation is currently unknown, same for the operational capacity of the schemes, existing monitoring programs or pre- and post-treatment measures. Nevertheless, more parameters are planned to be added in the future but these must be extracted from other sources (e.g., national hydrogeological maps, climate databases, etc.).

Due to data inconsistency (values within brackets indicate the number of sites where the parameter was reported, as percent from the total number of sites), the web-based portal contains at this stage mostly general information about the MAR sites (parameters marked with “*” in Table 1), including the original reference. In future updates, additional parameters are planned to be added, including financial and economic data from selected MAR schemes.

MAR web-based portal

Setup of a web-based portal for data visualization

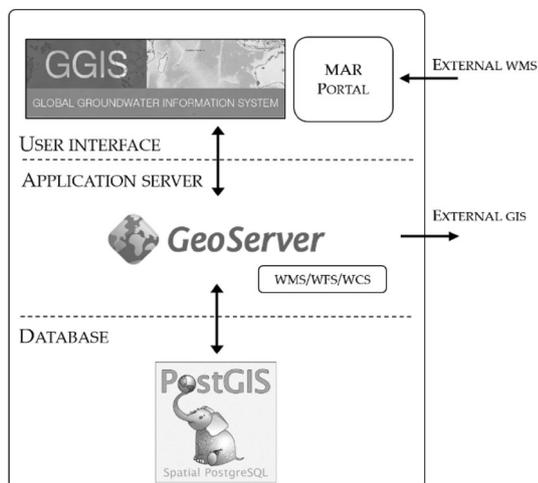
To increase the availability and facilitate continuous update of the MAR inventory, an MAR web-based portal was developed and integrated into IGRAC’s Global Groundwater Information System (GGIS). The GGIS is an interactive, web-GIS portal to groundwater-related information and knowledge. The main purpose of the GGIS is to assist in collection and analysis of information on groundwater resources and its sharing among water experts, decision makers and public. The GGIS consists of several modules structured around six themes, including a theme on Managed Aquifer Recharge. The MAR theme has its own portal (<http://marportal.un-igrac.org>) with underlying database to allow storing and visualizing the global MAR data in a systematic way. By facilitating access and promoting international sharing of information and knowledge on MAR, the web-based MAR portal aims to increase awareness of MAR as a viable solution for sustainable groundwater resources development and management, and to provide a new tool for better planning of MAR at regional and global scale.

The system was developed based on cloud solutions to enable processing of large data sets, including excel files, raster and shapefiles. The IT architecture of the system consists of a PostGIS database, a map server (GeoServer) and the user interface (Fig. 1). The mapserver follows the international standards for geospatial data of the Open Geospatial Consortium (OGC). Information in the MAR Portal can therefore be shared and easily integrated with external Geographic Information Systems (GIS) using web map services (WMS).

Table 1 List of entries in the MAR inventory database

| | | | |
|-------------------------------|---|----|---|
| 1. General information | | | |
| 1 | Site name ^a (100%) | 7 | Operator contact (14%) |
| 2 | Country ^a (100%) | 8 | Year operation start ^a (66%) |
| 3 | City (56%) | 9 | Year of publication (99%) |
| 4 | Latitude ^a (98%) | 10 | Year shut down (2%) |
| 5 | Longitude ^a (98%) | 11 | Main MAR type ^a (100%) |
| 6 | Operator name (33%) | 12 | Specific MAR type ^a (100%) |
| 2. Operational parameters | | | |
| 19 | No. of infiltration structures (15%) | 25 | Annual recharged volume (21%) |
| 20 | No. of infiltration wells (27%) | 26 | Volume rainwater harvested (2%) |
| 21 | Average filter depth (7%) | 27 | Average infiltration rate (3%) |
| 22 | Reservoir storage capacity (12%) | 28 | Number observation wells (5%) |
| 23 | Reservoir surface area (13%) | 29 | Number recovery wells (18%) |
| 24 | Recharge efficiency (2%) | 30 | Average filter depth (15%) |
| 3. Hydrogeological properties | | | |
| 37 | Aquifer hydraulic conductivity (16%) | 40 | Aquifer name (7%) |
| 38 | Aquifer transmissivity (5%) | 41 | Aquifer confinement (28%) |
| 39 | Aquifer thickness (21%) | 42 | Aquifer type (15%) |
| 4. Water quality parameters | | | |
| 46 | Water quality monitoring (6 parameters) (<1%) | 47 | Hydrochemical parameters (109 parameters) (<1%) |
| 13 | Influent source ^a (96%) | 14 | Effluent final use ^a (73%) |
| 15 | Main objective ^a (82%) | 16 | Specific objective (n.a.) |
| 17 | Mean annual rainfall (n.a.) | 18 | Mean annual evaporation rate (n.a.) |
| 31 | Average extracted volume (7%) | 32 | Recovery efficiency (3%) |
| 33 | Residence time (11%) | 34 | Distance horizontal passage (12%) |
| 35 | Pre-treatment (17%) | 36 | Post-treatment (7%) |
| 43 | Development water table (3%) | 44 | Water table depth before (8%) |
| 45 | Water table depth after (1%) | | |

^aSelected for visualization in the web-GIS portal. The recharge efficiency (parameter #24) was defined as percentage of water harvested and infiltrated from the total amount of water potentially available. Development of water table (#43) has the following values reported: “rising”, “initial rise, continued decline”, “initial rise but returning to old state”, “decline slowed down”, “stable”, “stable through recharge otherwise declining” while the parameters #44 and #45 refer only to the initial and final groundwater stage. Parameter #46 refers to periodical monitoring campaigns for water quality. The data recorded include the frequency at which different groups of parameters were monitored and not the concentration of the respective compounds. Parameter #47 includes the concentrations of a group of hydrochemical parameters, each reported only once for native groundwater (before infiltration), influent, and recovered water

**Fig. 1** IT architecture of the web-GIS MAR portal

Implementation of web-based MAR portal

The MAR portal consists of a data layer catalog, a map viewer to visualize the selected data on a geographic location

and a features panel to provide tabular output of the selected data. Additional information for each (point) location, such as references, can be displayed in the feature info. The portal can be used to generate new pieces of information by creating overlays of map layers (MAR suitability maps, or other overlays) and to build queries on the data. Users can export the global MAR inventory data in excel format via download functionalities in the system or by making use of the web services. Users can provide new data via an online submission form. Data is reviewed before including it into the web-based MAR portal. The MAR portal is available online and can be accessed without the prerequisites of any GIS knowledge or software licenses.

MAR sites

Among the four categories described in Table 1, almost 100% data coverage was found only in the first category (general information) while information about water quality was extremely scarce (either no water quality monitoring program was available or this kind of data was simply not published). For this reason, only the following parameters were selected for the web-based MAR portal: site name,

country, location (latitude/longitude), MAR type, year of scheme deployment, the source of infiltration water, the final use of abstracted water, as well as the main objectives of the project (Fig. 2):

Due to the high diversity of data sources, the terminology used in various papers was highly heterogeneous, which led to the creation of very long lists of thematic layers. For simplicity, a standardized classification system was needed so that data could be easily visualized and understood. The classification system selected was based on the methodology created within the DEMEAU project, which includes 15 MAR subtypes (Table 2), 7 project objectives, 8 types of infiltration water and 4 final uses of abstracted water

(Table 3). The detailed description of the respective categories is very well documented elsewhere (Hannappel et al. 2014) and was therefore not included in this paper.

MAR suitability maps

The identification of suitable locations for the implementation of MAR interventions is another tool to improve planning of MAR at regional scale (Bonilla et al. 2016). Existing regional MAR suitability maps are collected and made available within the portal to improve accessibility to this information and provide guidance for MAR suitability

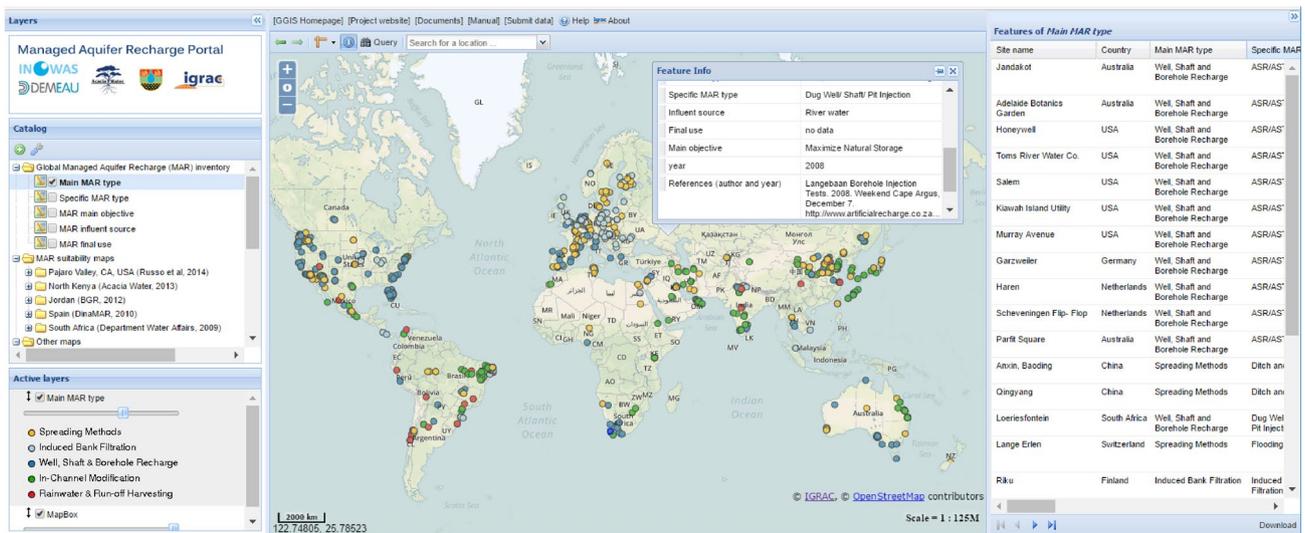


Fig. 2 Interface of the MAR portal displaying the MAR sites (marportal.un-igrac.org)

Table 2 Classification of specific MAR types

| | Main MAR type | Specific MAR type | |
|---|-----------------------------------|---|-------------|
| Techniques referring primarily to getting water infiltrated | Spreading methods | Infiltration ponds and basins Flooding Ditch and furrow Excess irrigation Reverse drainage method | |
| | Induced bank infiltration | | |
| | Well, shaft and borehole recharge | Deep well injection Dug well/shaft/pit injection | ASTR ASR |
| Techniques referring primarily to intercepting the water | In-channel modifications | Recharge dams Subsurface dams Sand dams Channel spreading | |
| | Runoff and rainwater harvesting | Barriers and bunds Trenches Rooftop rainwater harvesting | |

Table 3 Classification of other MAR parameters used in the web-GIS portal

| Primary objective | Type of infiltration water | Final use of abstracted water |
|--|----------------------------|-------------------------------|
| Ecological benefits | Brackish water | Agricultural |
| Management of water distribution systems | Distilled water | Domestic |
| Maximize natural storage | Groundwater | Ecological |
| Physical aquifer management | Lake water | Industrial |
| Water quality management | River water | |
| Other benefits | Storm water | |
| | Tap water | |
| | Wastewater | |

ASTR aquifer storage, transfer and recovery, *ASR* aquifer storage and recovery

(Fig. 3). References and reports of MAR suitability mapping are available via the portal.

Other overlays

Additional data layers and information, such as climate zones, population density, global groundwater stress, and the hydrogeological map of the world are available to understand the location of presented MAR sites in a broader water-related context.

Discussion

Quality assurance

Difficulties in the compilation of a global MAR inventory

The major impediment in the compilation of the global inventory was given by the poor availability of written documentation of MAR projects. The authors assume that much more case studies exist worldwide but their technical documentation is not easily available via common search engines and academic databases. Further impediments include the language barrier: although the survey was conducted in eight languages, much more results would be expected if the list will be extended to more languages (for example, a large

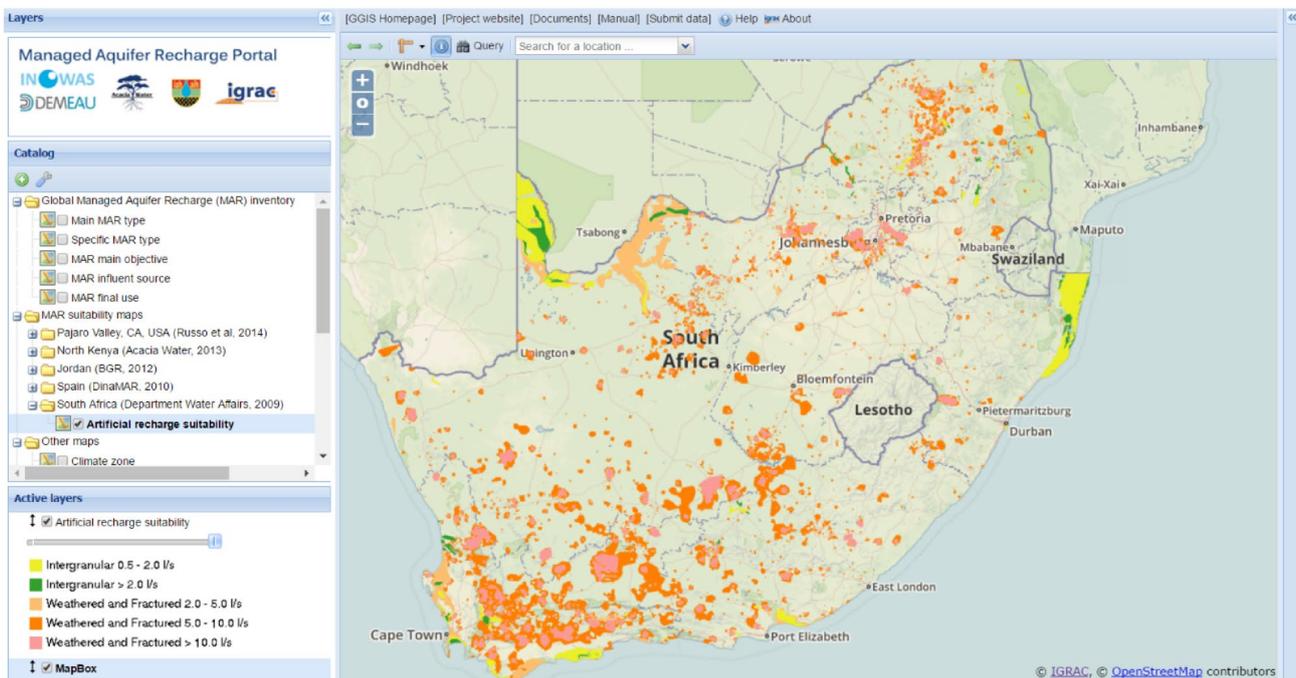


Fig. 3 Interface of the MAR portal displaying the MAR suitability map for South Africa. Data have been made available by Department of Water Affairs, South Africa (Department of Water Affairs 2009)

number of studies were published in Arabic and Japanese but couldn't be analyzed within the framework of the present study). In several cases, different approaches used for romanization of non-Latin based languages may lead to zero results when submitting a query to the MAR portal database, especially for the field "site name". Searching on geographical location could assist in this regard.

Concerning data quality, the MAR inventory relies on freely available data. Given its global scale, no field surveys could be done to verify the existence of MAR schemes and no interviews were conducted. In most cases, a cross check in more than one paper (when available) was considered sufficient for data validation. When not available in the reference, the location of MAR schemes was manually identified by querying online mapping services. Nevertheless, not all schemes are visible on online maps, some may already be shut down or, for infiltration wells, more than a single location was identified (in this case, a location in the center of the well field was considered). In very few particular cases when the location couldn't be identified, the center of the nearby town or city was considered.

Data quality and limitations of collected MAR suitability maps

A large variety of methodologies exist to develop an MAR suitability map. Some may focus on landscape characteristics to present the suitability, while others assign more importance on excess water to present its suitability. This large variety of methods, where different parameters are considered and assumptions taken, results in different types of MAR suitability maps. The MAR portal does not aim to harmonize MAR suitability maps at a global scale, its purpose is to improve accessibility of this information and increase awareness of this 'tool' to identify suitable MAR locations. The collection of regional MAR suitability maps started in 2016 and is still in its early stages. Only maps with permission of corresponding author and institutes are made available in the system. The references and reports on these suitability maps are available via the portal to provide additional information on data quality, applied methodology and clear limitations for each study. Based on careful review of the MAR suitability maps and considerations that relate to applied methodology, data quality and scale, maps may or may not be added to the portal.

Database updates

The MAR portal is integrated in the Global Groundwater Information System to ensure long-term online availability of the data. Specialists are encouraged to share information on (new) MAR sites and MAR suitability maps that are not yet included in the portal. New MAR sites and suitability

maps will be uploaded to the portal as they come available. In addition, the IAH-MAR Inventory Working Group envisions a major update of the global MAR inventory every 3 years to keep the database timely. A similar approach will be used for data collection. Developments are underway to integrate outcomes of other IAH-MAR working groups on economic and financial performance of MAR and factsheets on successful MAR projects. By assembling the work done by various IAH-MAR working groups, the MAR portal could encourage stakeholders to regard MAR as a viable solution for sustainable groundwater resources development and management.

Perspectives for using the global MAR inventory and web-based portal

Data-driven decision making (DDDM)

The data collected for the MAR inventory was analyzed in respect to MAR historical development, geographical distribution, hydrogeological site characterization, technical description of the operational scheme, objectives and MAR technologies used, modeling approach, or quantitative and qualitative characterization of both infiltration and abstraction water (Ringleb and Stefan 2015; Stefan 2015). The preliminary data analysis revealed interesting patterns in MAR utilization in different countries and continents (see examples in Figs. 4 and 5) as well as correlations between technical and site-specific parameters. Further data extracted from the inventory such as volumes of water infiltrated or recovery efficiencies could lead for example to valuable information about the costs of MAR worldwide and help assess its impact on local and national economies.

The global MAR inventory was compiled as part of INO-WAS-DSS, an integrated web-based decision support system for planning and assessment of managed aquifer recharge applications (Stefan et al. 2016). By making use of the large load of information provided by the MAR inventory, the system can enable a preliminary reduction of the search intervals for an optimal planning parameter based on the case similarities and distribution of probabilities. In some cases, this can generate a ready solution without employing modeling and optimization instrumentation. For example, by knowing the influent source, final effluent use, and main objectives of a new MAR scheme, a statistical evaluation of the database can provide suggestions for the main MAR type as output parameter of a data-driven model.

Overlay to other information

To promote international sharing of information and knowledge on MAR, the web-GIS portal allows to import the full database as WFS file into external applications.

Fig. 4 Example of statistical data analysis: MAR primary objectives by continent

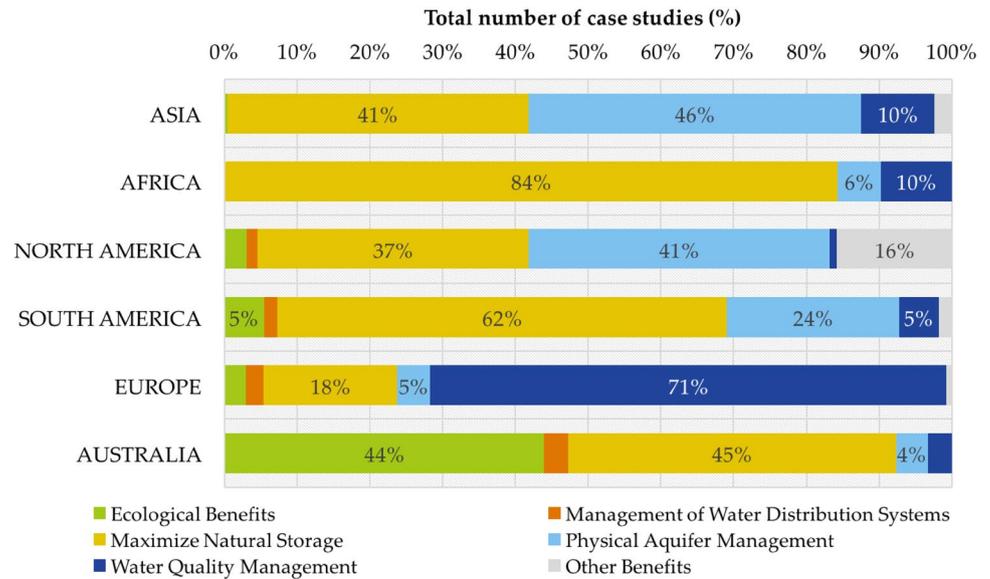
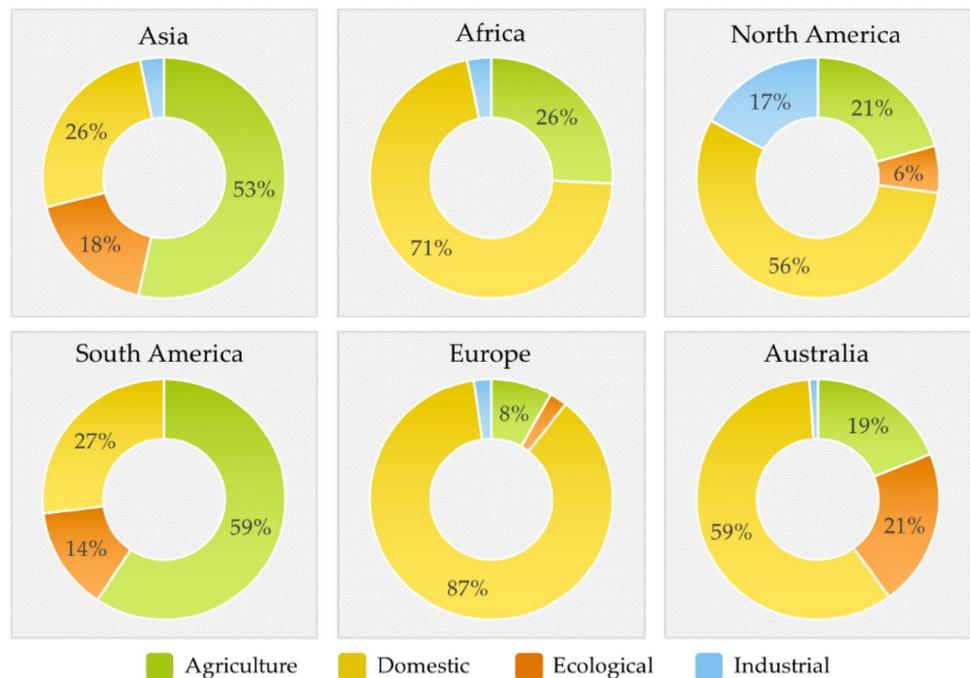


Fig. 5 Example of statistical data analysis: final use of abstracted water by continent



Researchers who would like to extract information for further analysis are invited to use this option. WFS functionality makes it possible to include MAR data in external (desktop) GIS to continue analysis or give the data a new meaning by overlaying the MAR inventory on top of other relevant maps such as groundwater potential maps, MAR suitability maps, climate zones, water scarcity index, population growth, etc. (see an example in Fig. 6).

Conclusions

The 1200 examples of MAR schemes constructed worldwide bring important evidence about the application of MAR as feasible method for the management of water resources under various climatic, geographic, and socio-economic conditions. A statistical analysis of the data

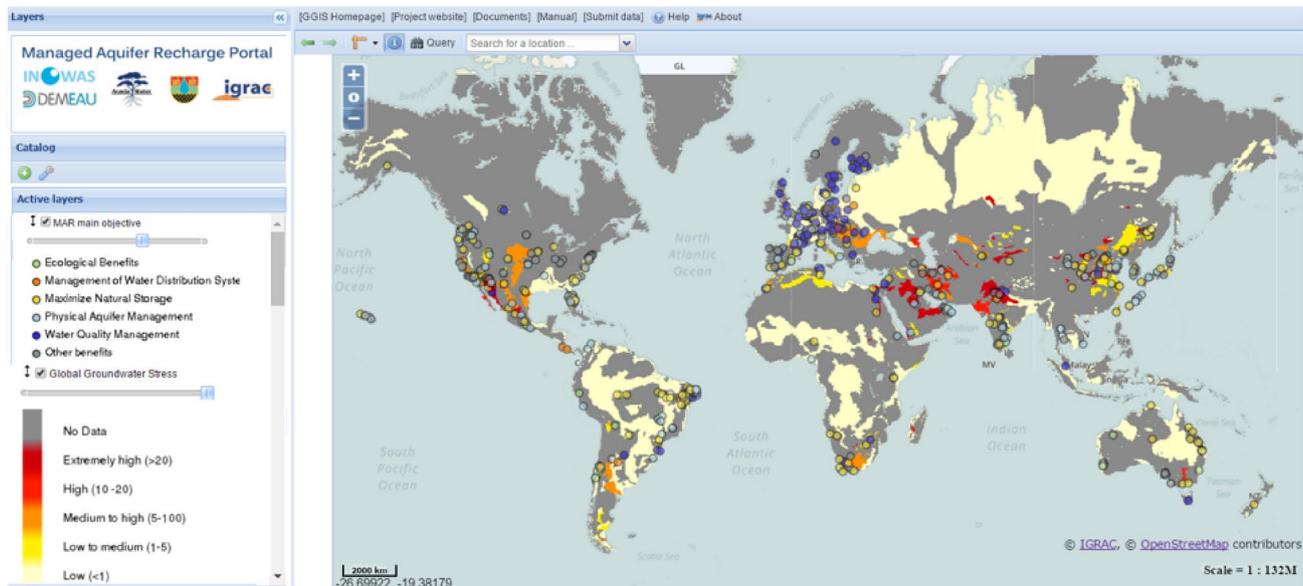


Fig. 6 Example of overlay of MAR objectives and global groundwater stress map (Gassert et al. 2014). In some groundwater stressed places MAR is opted to address security of water supply, but also in humid climates, MAR is used largely to improve drinking water

reveals regional differences that can be observed in the objectives of the project, type of MAR used, source of infiltrated water, final use of abstraction water, etc. On the one hand, this shows the wide applicability of MAR and its suitability for different site-specific conditions and, on the other hand, demonstrates that MAR has already been considered a valuable tool in many regions of the world.

For long-term storage and dissemination of results, the inventory can be visualized on a web-GIS MAR portal which aims facilitating access and promoting the international sharing of knowledge on MAR. The advanced functionalities of the portal (i.e., combined data query) allow for targeted and filtered display of specific data sub-sets, which makes the tool useful for planning specific MAR configurations.

Supplementary materials

The web-based MAR portal is available online at marportal.un-igrac.org.

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quality. However, there are large areas that are water stressed, where MAR is not currently reported as in use and could potentially be valuable

Author contributions CS collected the case studies, compiled the inventory, conducted statistical data analysis, wrote the chapters Introduction and Data collection and contributed to chapters MAR web-GIS portal and Discussions. NA set up the online portal, wrote the chapter Web-GIS MAR portal, and contributed to chapter Discussions.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest arising from writing the present paper. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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