Evaluating Karst Drywells for Urban Stormwater Management and Aquifer Recharge

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Drywells are extremely useful for coping with excess surface water in areas where drainage and diversion of storm flows are limited, facilitating stormwater infiltration and groundwater recharge. Drywells have been used for stormwater management in locations that receive high precipitation volumes, naturally or due to climate change; however, to date, they have not been developed in urban areas overlying karst landscapes. To test the performance of karst drywells, we constructed a pilot system for collecting, filtering, and recharging urban stormwater through drywells in karst rock. The study site is in the Judaean Mountains, an urban residential area in Jerusalem, Israel. The infiltration capacity of the drywells was evaluated using continuous and graduated water injection tests, and its effective hydraulic conductivity (*K*) was estimated. Drywells' infiltration capacity was up to 22 m_3/hour (the maximum discharge delivered by a nearby fire hydrant), while monitored water levels in the drywells were relatively stable. Calculated hydraulic conductivities were in the range of *K*=0.1-100 m/day, and generally, *K* was inversely proportional to the rock quality designation (RQD) index (obtained from rock cores during the drilling of the drywells). The pilot system performance was tested in the recent winter: during 9 days with a total rainfall of 295 mm, a cumulative volume of 45 m_3 was recharged through the drywell, with a maximum discharge of 13 m_3/ hour. High-conductivity karst drywells and adequate pre-treatment filtration can be valuable techniques for urban flood mitigation and stormwater recharge.

Keywords: Drywell, Karst, MAR, RQD, Unsaturated zone

Optimizing managed aquifer recharge in coastal dunes by extracting brackish groundwater: results of a field pilot in the Netherlands

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Faced with climate change and population growth, Dutch drinking water company Dunea is looking for additional water resources to secure the drinking water supply for the coastal city of The Hague. One of the options is to enhance the existing managed aquifer recharge (MAR) system in the coastal dunes by extracting brackish groundwater. Extracting brackish groundwater provides an additional drinking water source, can protect existing production wells from salinization, and can effectively stabilise or even grow the freshwater reserves in the coastal dunes, according to numerical groundwater modelling. To test this concept in the field, a three-year pilot commenced in January 2022 at Dunea's primary drinking water production site, Scheveningen. Brackish groundwater is extracted at a rate of 50 m_3/h with multiple well screens placed in a single borehole within the brackish transition zone (85-105 meters below sea level). The extracted groundwater is desalinated by reverse osmosis, whilst the flow rate and quality of extracted groundwater are continuously monitored. The hydraulic effects and the dynamic interfaces between fresh, brackish and saline groundwater are monitored with a dense network of piezometers, hydraulic head loggers and geo-electrical measurement techniques. At the IAH conference, the monitoring results of the pilot will be presented. Based on the results of the field pilot and additional numerical modelling, the feasibility of upscaling and replicating the concept of brackish groundwater extraction to optimize MAR and increase the availability of fresh groundwater in coastal areas is reflected.

Keywords: Brackish groundwater extraction, managed aquifer recharge (MAR), drinking water production, field pilot, coastal dunes

Managed Aquifer Recharge as a strategy for increased water supply security in Eastern Botswana

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The joint application of water supply system security, groundwater modelling, and multicriteria analysis (MCA) indicated the potential of Managed Aquifer Recharge (MAR) to increase water supply security in Eastern Botswana substantially. Botswana faces increased water stress due to decreased water availability as climate change exacerbates variability in rainfall and increases evaporation losses and water demand. The water supply for Eastern Botswana is based on the bulk water supply system of the North-South Carrier (NSC) connecting dams in the northeast to the main demand centres, including Gaborone. The potential of MAR to increase the water security of the NSC by storing water that otherwise would have been lost to spillover and evaporation and contribute to the provision of water during droughts was studied. Large-scale MAR in the Ntane sandstone aquifer at a wellfield by the NSC was evaluated in terms of hydrogeology and national water supply perspective. Comprehensive hydrogeological surveys and assessments included borehole injection tests and hydrogeological and geochemical modelling to evaluate risks of losing recharged water and clogging of boreholes. Probabilistic water supply system modelling analysed the impact of different MAR scenarios on the water supply security of the NSC, and an MCA tool assessed the sustainability of the different scenarios. The analysis showed that large-scale MAR is feasible, and a scheme with a capacity of 40,000 m_3/d is the most sustainable from technical, social, economic and environmental perspectives and could potentially reduce the number of months with water shortage by 50% in Gaborone.
Keywords: Botswana, MAR, groundwater modelling, multi-criteria analysis, probabilistic water supply system modelling, water security

Assessment of Water Supply Security and Sustainability of Managed Aquifer Recharge in Botswana

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An approach for evaluating the sustainability of managed aquifer recharge (MAR) has been developed and applied in Botswana. Numerical groundwater modelling, water supply security modelling (SWWM) and multi-criteria decision analysis (MCDA) are combined to thoroughly assess hydrogeological conditions, supply and demand over time and identify the most sustainable options. Botswana is experiencing water stress due to natural conditions, climate change and increasing water demand. MAR has been identified as a potential solution to increase water supply security, and the Palla Road aquifer, located 150 km northeast of the capital, Gaborone, has been identified as a potential site. To evaluate the potential of MAR and if it is suitable for improving water supply security, three full-scale MAR scenarios were evaluated based on their technical, economic, social and environmental performance relative to a scenario without MAR. The numerical groundwater model and the WSSM were used iteratively to provide necessary input data. The WSSM is a probabilistic and dynamic water balance model used to simulate the magnitude and probability of water shortages based on source water availability, dynamic storage in dams and aquifers, reliability of infrastructure components, and water demand. The modelling results were used as input to the MCDA to determine the sustainability of alternative MAR scenarios. The results provide useful decision support and show that MAR can increase water supply security. For the Palla Road aquifer, storage and recovery with a capacity of 40 000 m_3/d is the most sustainable option.
Keywords: managed aquifer recharge, multi-criteria decision analysis, sustainability assessment, water supply security model

The impact of storage and hydrogeological conditions on the design and recovery performance of small-scale urban ASR systems

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Aquifer storage and recovery (ASR) can play a vital role in sustaining water availability to cope with increasing weather extremes. In urban areas, ASR systems may provide flooding risk mitigation and support urban greenery. However, such systems are often relatively small and therefore, their recovery performance depends more strongly on site-specific storage conditions such as dispersion and displacement by ambient groundwater flow. In this study, we evaluated the impact of these factors by adapting and developing analytical solutions and numerical modelling, with recently established Urban ASR systems as a reference for a wide range of realistic field conditions. We validated the accuracy and usefulness of the analytical solutions for performance anticipation. Results showed that a simple, analytically derived formula describing dispersion losses solely based on the dispersion coefficient (α) and the hydraulic radius of the injected volume (Rh) provided a very good match for all conditions tested where $\alpha/Rh<0.2$. An expansion of the formula to include the development of recovery efficiency with subsequent cycles (i) was also derived and in keeping with simulation results.
Also, displacement losses were found to be significant at groundwater flow velocities that are typically considered negligible, particularly as displacement and dispersion losses disproportionally enforced each other. For specific conditions where the displacement losses are dominant, using a downgradient abstraction well, effectively resulting in an ASTR system, might be beneficial to increase recovery efficiencies despite increased construction costs and design uncertainty.
Keywords: Urban groundwater, Managed Aquifer Recharge, Aquifer Storage and Recovery, MAR, ASR

Managed Aquifer Recharge within the Greater Kruger National Park and Implementation of Recharge Scheme.

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West of the world-renowned conservation site, Kruger National Park, lies the larger extent of the Greater Kruger National Park within the Limpopo province. Boreholes have been drilled for decades to provide water to game lodges, large resorts, and watering holes for game viewing and livestock. The area contains both primary and secondary aquifers classified as having yields between 0.5 and 5.0 l/s, based on the geological setting, which consists of gneiss intruded by dolerite dyke swarms. A geohydrological assessment revealed that groundwater quality within the project area has an EC of 100 - 350 mS/m, linked to borehole proximity to surface water systems. The Makhutswi Gneiss and Doleritic Dyke swarms are the major controlling geology of the area, with higher-yielding boreholes close to dykes and major structural lineaments (faulted / weathered zones). A concern identified through geohydrological assessment observations is that boreholes frequently dry up after a few years, requiring deeper drilling/redrilling or drilling a new borehole. Aggressive calcium hardness in the water frequently damages equipment and increases maintenance costs. This project investigated the feasibility of increasing recharge to the aquifer with seasonal flooding/rainfall events by constructing artificially enhanced recharge locations overlaying doleritic dykes. This is expected to decrease the groundwater's salinity and hardness, reducing operational costs.
This pre-feasibility assessment has been completed, and the project has continued through a gradual implementation phase.
Keywords: Aquifer, Dolerite, Feasibility, Gneiss, Increased, Managed, Recharge

Electrical Hydrogeology of Managed Aquifer Recharge from Meter to Kilometer Scales

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While traditional well and spring sampling are limited to the integration of point data and the interpolation of the data across large scales. Electrical measurements of aquifers can be extended across a range of scales and integrated to provide an improved quantitative understanding of groundwater systems. At a site in Oklahoma, USA, a karst-managed aquifer recharge research site is being used to test electrical techniques for aquifer characterization on the kilometer scale and monitoring the aquifer on the meter scale. At the kilometer scale, the data illustrate fault locations, siphons in flow paths, and previously uncharacterized conduits.

At the metre scale, the monitoring data illustrate porosity structure, flow paths, and potential biological changes in the subsurface. The results indicate that electrical approaches can significantly change aquifer conceptual models and provide targeted sampling locations in karstic bedrock aquifers.

Keywords: Byrds Mill Spring, carbonate, electrical resistivity imaging, enhanced aquifer recharge, karst

Evaluation of the impact of artificial recharge of groundwater by river replenishment in the North China Plain using a numerical model

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Since 2018, the North China Plain has started a large-scale ecological water replenishment project for rivers and lakes, with 17.5 billion cubic meters total from the South–North Water Transfer Project and other water sources. It is a key question of how much water infiltration into aquifers will affect groundwater and how to characterize and evaluate this effect quantitatively. The groundwater numerical model of the Beijing-Tianjin- Hebei region as the main part of the North China Plain was established using a numerical simulation method, and the groundwater level variation under the replenishment condition was simulated and predicted.

By comparing the two scenarios, the relative rise method of groundwater level was proposed to characterize the influence of river water infiltration on groundwater level, and the unstructured grid method was used to refine cells near the river to improve simulation accuracy. Simulation results show that the groundwater level around some rivers has risen significantly in the past four years, especially in the alluvial fan regions with better infiltration properties.

Accordingly, at the Piedmont alluvial fan region, there is also a large influence range on groundwater level. The maximum influence distance is more than 10km (0.1m relative rise of groundwater level was taken as the influential boundary). According to the prediction, if the water replenishment project continues, the range of influence can continue to expand, but the expansion rate will slow down due to the reduction of the hydraulic gradient.

Keywords: Artificial recharge, groundwater management, river water replenishment, the North China Plain

Aquifer storage and recovery (ASR) applications to enhance drinking water supply security in the Sultanate of Oman

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Water scarcity has driven many countries in arid regions, such as Oman, to desalinate seawater for freshwater supply. Episodic problems with seawater quality (e.g., harmful algae), extreme weather events that affect energy supply and hence the desalination process have nurtured the urgent need to store desalinated seawater (DSW) in the aquifers for use during emergency and peak demand time. Aquifer Storage and Recovery (ASR) using injection wells is a possible strategic option for Oman Water and Wastewater Services Company (OWWSC) to augment aquifer storage using excess desalinated water during low demand times. ASR strategically serves as a water supply backup to optimize production capacities against seasonal demand patterns. The technical-economic feasibility of implementing ASR schemes was investigated in Jaalan, Oman, using hydrogeological and geophysical field measurements, groundwater flow and hydraulic modelling, and economic analysis. Analysis of modelled scenarios results revealed that the Jaalan aquifer is suitable for storing and recovering about 4,000 m_3/hr in 2045. Various well field designs have been tested and optimized numerically using MODFLOW 6, showing that with 160 dual-purpose wells, 7.9 Mm_3 can be injected and abstracted within the constraints defined for a robust and sustainable ASR system. Simulations with the density-dependent flow model (MF6 BUY) show that the injected volume can be fully recovered considering the drinking water quality standard. Other sites were also studied. ASR capacity was found to be site-specific, and the groundwater developments near the ASR site governed its feasibility.
Keywords: Aquifer Storage and Recovery (ASR), Oman, desalinated seawater, drinking water supply, groundwater flow modelling, hydrogeology,recovery efficiency

Benefits and costs of managed aquifer recharge: An integrated water governance solution

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Managed Aquifer Recharge (MAR) provides an integrated water governance solution that improves water security for communities and farmers by storing water in aquifers and managing groundwater extractions to ensure water supplies are available during droughts. Quantitative analysis of levelised costs and benefit-cost ratios (BCRs) of 21 MAR schemes from 15 countries and qualitative assessment of additional social and environmental benefits demonstrates the benefits of MAR compared to water supply alternatives. Cost-benefit analysis provides a systematic method for comparing alternative water infrastructure options. Levelised cost is a widely accepted method of comparing MAR with alternative water infrastructure solutions when market valuations of water are unavailable. The benefits of MAR can be estimated by the cost of the cheapest alternative source of supply or the production value using water recovered from aquifer storage. MAR schemes recharging aquifers with natural water using infiltration basins or riverbank filtration are relatively cheap with high BCRs.
Schemes using recycled water and/or requiring wells with substantial drilling infrastructure and or water treatment are more expensive while offering positive BCRs. Most MAR schemes have positive or neutral effects on aquifer conditions, water levels, water quality, and environmental flows. Energy requirements are competitive with alternative sources of supply. This analysis demonstrates strong returns to investment in the reported MAR schemes. MAR provides valuable social and environmental benefits and contributes to sustaining groundwater resources where extraction is managed.
Keywords: Managed aquifer recharge; aquifer storage; water infrastructure; cost-benefit analysis; levelized cost; benefit-cost ratio

The Atlantis Water Resource Management Scheme – Lessons in Resilience

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The Atlantis Water Resource Management Scheme (AWRMS) has operated since the 1970s. It demonstrates cost-effective and wise water use and recycling through visionary town planning and Managed Aquifer Recharge (MAR), offering water security to Atlantis's residential and industrial sectors. For the AWRMS to succeed, it required integrating its water supply, wastewater and stormwater systems. Each of these water systems is complex and requires a multidisciplinary management approach. Adding to the challenges of inter-departmental co-operation and communication within a municipal system is the complexity and vulnerability of the coastal, primary Atlantis Aquifer. A combination of operational difficulties, biofouling, vandalism and readily available surplus surface water (leading to scheme augmentation from surface water) were negative drivers to decrease the reliance on groundwater supply from the scheme's two wellfields. In response to the 2015-2018 drought experienced in the Western Cape of South Africa, the City of Cape Town has improved assurance of supply from the scheme and successfully built resilience by upgrading knowledge and insight through improved investigative techniques, monitoring, modelling and adaptive management of the various water resources and associated infrastructure systems. An integrated and adaptive management approach is essential to ensure continued water security and resilience to the effects of on-going urban expansion, population growth and climate change. Resilience is assured by institutions, individuals and communities taking timely and appropriate decisions, while the long-term sustainability of the AWRMS depends on proper management of all actors coupled with a high level of scientific confidence.
Keywords: adaptive management, drought, managed aquifer recharge, resilience

Planning for increased water security and preventing salinisation in coastal areas of the Netherlands: A study on the suitability for managed aquifer recharge and extraction of brackish water, including quantification of potential extractable volumes

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Year-round water security is at risk as socio-economic developments lead to increasing water demands, while climate change affects water availability through higher-intensity rainfall and prolonged periods of drought. Coastal zones and deltas with often high population densities experience additional risks of salinisation and land subsidence. These developments ask for creative solutions to secure sustainable and year-round access to fresh water. The subsurface provides storage capacity to actively infiltrate freshwater, bridging the time-gap between demand and supply. Combining infiltration with extraction and desalination of brackish water prevents the salinisation of aquifers whilst providing an additional water source. We call this COASTAR. A Dutch research consortium with partners like water companies and water boards develops COASTAR. Among COASTAR results are suitability maps for Aquifer Storage and Recovery (ASR) and Brackish Water Extraction (BWE) in the coastal zone of the Netherlands.
The maps are based on geohydrological factors. A quick-scan analysis was also performed to quantify the nation-wide potential extractable ASR and BWE volumes. COASTAR develops case study models and local scale pilots on ASR and BWE. For two water supply regions, an analysis has been made to geographically match development in water demand with suitability for ASR and BWE as a step in the search for strategic locations to develop ASR and BWE. The suitability maps provide guidance for initiatives' development and practical experiences from pilot projects; this provides important information for further upscaling of COASTAR approaches.
Keywords: Aquifer Storage and Recovery (ASR), Managed Aquifer Recharge (MAR), aquifer salinisation, brackish water extraction, suitability maps, water supply

Tracer applications in an urban MAR (Rhine) scheme: Identifying the presence of regional groundwater in a complex geological setting

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Managed aquifer recharge (MAR) has become increasingly popular in Central Europe as a sustainable, clean, and efficient method for managing domestic water supply. In these schemes, river water is artificially infiltrated into shallow aquifers for storage and natural purification of domestic water supply, while the resulting groundwater mound can simultaneously be designed to suppress the inflow of regional groundwater from contaminated areas.
MAR schemes are typically not managed based on automated optimization algorithms, especially in complex urban and geological settings. However, such automated managing procedures are critical to guarantee safe drinking water. With (seasonal) water scarcity predicted to increase in Central Europe, improving the efficiency of MAR schemes will contribute to achieving several of the UN SDGs and EU agendas. Physico-chemical and isotope data has been collected over the last 3-4 decades around Switzerland's largest MAR scheme in Basel, Switzerland, where 100 km^3/d of Rhine river water is infiltrated, and 40 km^3/d is extracted for drinking water. The other 60 km^3/d is used to maintain the groundwater mound that keeps locally contaminated groundwater from industrial heritage sites out of the drinking water.
The hydrochemical/isotope data from past and ongoing studies were consolidated to contextualize all the contributing water sources of the scheme before online noble gas and regular tritium monitoring commenced in the region. The historical and the new continuous tracer monitoring data is now used to inform new sampling protocols and create tracer-enabled/assimilated groundwater-surface water flow models, vastly helping algorithm-supported MAR optimization.
Keywords: Isotopes, MAR, Online monitoring, Urban groundwater

Mitigating climate change with managed aquifer recharge: 5 Case Studies

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In the past decade, Southern Africa has experienced periods of extreme drought. This was especially true in the western Karoo in South Africa. Continuous drought and limited rainfall led to declining aquifer water levels that curtailed sustainable water supply for towns and livestock. The western Karoo is almost completely dependent on groundwater. Managed aquifer recharge (MAR) is being used to reduce the effects of droughts and mitigate climate change impacts. A good understanding of the geology and the behaviour of the aquifers is needed for implementing various MAR designs, including nature-based solutions, which are used to recharge aquifers with limited rainfall. This paper discusses 5 active MAR case studies in the Western Karoo. Here, site-specific MAR methods that use small rainfall events deliver reasonable results, whereas the implemented MAR options keep most aquifers functional.
Observations at the MAR sites also showed improved water quality and less bacterial clogging. This improves the environment around the managed aquifer recharge sites. The MAR methods and designs discussed in this paper can be used on a larger scale for a town or a smaller scale for a farm. Maintenance costs are low, which makes these options cost-effective for less wealthy areas.
Keywords: Climate change; drought; MAR; nature-based solution; case studies

Experiments of the artificial-recharge rate of sand and gravel aquifer through shallow recharge wells in the Chao Phraya River basin region

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The aquifers in the Chao Phraya River basin region were abundant in groundwater. Lately, the groundwater level has been declining due to agricultural activities. While in the wet season, these areas frequently suffered from flooding due to lower elevation than their surroundings. The Managed Aquifer Recharge (MAR) methods were applied to ease problems by constructing artificial recharge wells which can detain stormwater runoff and let it gradually infiltrate into the aquifer directly. For decades, the Department of Groundwater Resources started the MAR project to alleviate groundwater depletion and flooding over specific areas. However, most of the projects in the past lacked follow-up results and evaluation. Thus, later projects attempted to study recharge processes to evaluate the volume of recharged water through structures and calculate the infiltration rate through filter layers within the structures. Recently, the field experiments of artificial groundwater recharge were conducted as 8-hour and 20-day experiments with shallow recharge wells in the Chao Phraya River basin regions.

These two types of experiments provided similar results. The average recharge rates of 8-hour and 20-day experiments are 2.22 m3/hr and 2.57 m3/hr, respectively. Recharge rates of each well were independently distinct depending on sedimentation characteristics, aquifer thickness, and volume of dry voids. During the test, the recharge well continuously encountered the problem of sediment clogging due to using untreated water from neighboring streams and ponds. This clogging issue needed to be treated regularly to maintain the efficiency of the recharge well.

Keywords: MAR, Managed Aquifer Recharge, clogging, recharge rate

Managed aquifer recharge (MAR) suitability mapping Using GIS-MCDA: The South African perspective

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To increase the security of groundwater resources, managed aquifer recharge (MAR) programs have been developed and implemented globally. MAR is the intentional recharge and storage of water in an aquifer, which will be recovered later. It was previously known and implemented as Artificial Recharge (AR). In South Africa, the documented practice dates back 40 years. There are five main MAR methods: Well-Shaft-Borehole, Spreading-induced bank infiltration, In-channel modifications, and Runoff harvesting. Two regional-scale MAR suitability maps for the Spreading Method (SM) and the Well-Shaft-Borehole (WSB) Method were compiled for South Africa, using the Geographic Information System combined with Multi-Criteria Decision Analysis (GIS-MCDA) methodology. Parameters used to compute the maps included the nature of the different aquifers, groundwater level, water quality (EC), distance to river, terrain slope, mean annual rainfall, land cover, soil moisture availability and clogging (Fe-iron content). To create a suitability map, the parameters were combined using the weighted overlay method and the Analytic Hierarchy Process (AHP – specifically the pairwise comparison). The site suitability maps indicated that most areas in South Africa are suitable for the Spreading and Well-Shaft-Borehole methods. The results were verified with the location of existing MAR schemes and were found to agree. However, these maps are not applicable for siting projects at a local scale but can serve as a guide and screening tool for site-specific studies looking for highly suitable or target areas for MAR implementation.

Keywords: Managed Aquifer Recharge, Multi-Criteria Decision Analysis, Regional Scale, Suitability mapping