Economic Considerations of Managed aquifer recharge

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Managed aquifer recharge (MAR) is a technique for improving groundwater recharge and maintaining aquifer levels. It represents an effective buffer against future fluctuations in water demand, drought, and changing climate. In this section, we provide a brief overview of MARs across the world and in the US. Next, we draw on the existing literature to analyze the different types of economic analysis MAR assessment.

Review of MAR systems

Groundwater represents an important water resource. In the United States, groundwater serves as a source for more than 75 percent of the community water systems and almost all rural water supplies (NGWA:Managed Aquifer Recharge -A water supply management tool[1]). Groundwater serves a variety of needs, such as agriculture, industry, household needs, and the environment. For example, in the US, groundwater represents 42 percent of the irrigation sources. Moreover, groundwater feeds streams and rivers, providing environmental, and ecosystem services.

MAR umbrella includes a diversity of technologies to store and treat water, including aquifer storage and recovery (ASR), infiltration basins, river filtration, soil aquifer treatment, and salinity barriers (Maliva, 2014). In the US, MARs have been used to increase drought resilience, flood mitigation, aquatic ecosystem restoration, and constructed wetlands, reduce salt intrusion, etc (NGWA:Managed Aquifer Recharge -A water supply management tool).

There are a multitude of MAR schemes that are used across the world for water management purposes. These schemes are being used at various scales for multiple purposes. IGRAC MAR Portal – The *MAR Portal* contains detailed information on *Managed Aquifer Recharge* sites around the world (Figure 1). The IGRAC project collected data for 1,200 MAR projects around the world. The portal summarizes data on MARs by type, objective, influent sources, and final use. For example, the portal contains information on 255 ASR/ASTR projects, with 136 being located in the United States. In the US, the recent US Army Corps of Engineers' report shows the growing interest in understanding the opportunities and the needs for different MARs schemes.

[1] https://www.ngwa.org/docs/default-source/default-document-library/publications/information-briefs/managed-aquifer-recharge-a-water-supply-management-tool.pdf

Figure 1. MARs inventory across the world. Source: IGRAC, accessed October 2020.

Broadly, MAR systems have five major technical components: the source of water used for recharge, the recharge method, the storage method and the management approach, the recovery method, and the end-use of recovery. Using data collected by IGRAC MAR Portal, Table 1 summarizes MAR schemes by type, objectives, effluent sources, and final uses.

Type	Specific MAR Type	Objective	Influent	Final Use
Spreading	Infiltration ponds and basins Flooding Ditch and furrow Excess irrigation Reverse drainage	Ecological benefits Management of water distributor Maximize natural storage Physical aquifer management Water quality management Other benefits	Brackish water Distilled water Groundwater Lake water Physical aquifer management Reclaimed wastewater River water Stormwater Tap water	Agriculture Domestic Ecological Industrial Research Environmental River Water
Induced bank filtration	Induced bank filtration			
Well, Shaft & Borehole Recharge	ASR/ASTR Dug/Well/Shaft/Pit			
In-Channel Modification	Recharge dam Sand storage dams Subsurface dam Channel spreading			
Rainwater & Run-off Harvesting	Barriers and bunds Recharge bam Rooftop rainwater Harvesting trenches			

Table 1. MAR schemes by type, objectives, influent source, and final use

MARs Economic Analysis

Regardless of their purpose, investment projects need to be justified in terms of the project's monetary benefits being at least as large as the financial costs (construction and operation costs). However, despite their demonstrated benefits and advantages for water resource management, MAR schemes have not been implemented to their full capacity. The number of studies that thoroughly assess these projects' economic feasibility is limited (Maliva 2014).

Economic assessments of MAR systems are characteristic for each project and depend on the type of system, performance objectives, local physical and hydrological conditions, end uses of the recovered and storage water, and alternative water supply and treatment options. Any economics assessment should consider soil characteristics, aquifer storage capacity, the water resource location and source, and land-use constraints specific to the MAR location (Maliva 2014, Marechal et al. 2020).

The most robust and comprehensive economic analysis is the cost-benefit analysis based on assessing the market and non-market economic benefits and costs. However, considering the full extent of the benefits is not always possible. Alternative types of economic analysis include cost-effectiveness analysis and lifecycle analysis, where only costs to achieve a pre-set objective are considered (Maliva, 2014). Each of these types of analysis has its limitations. When possible, the economic analysis should be enhanced by a sensitivity analysis that considers the risk and uncertainty via Monte Carlo analysis (Maliva, 2014). Alternatively, a benchmark analysis can be implemented to determine the break-even point of a project.

Benefits of MAR systems

As water supplies shortages caused by an increasing population and changing climate conditions are becoming more prevalent, MARs offer a feasible solution to mitigating the associated socio-economic and environmental impacts. MARs projects can improve overall well-being by adding water to an aquifer, stabilizing or even increasing water levels for later uses, reducing groundwater pumping costs, preventing seawater intrusion, maintaining environmental flows, protecting structures from land subsistence, controlling contaminant plumes, enhancing wellfield productions, etc. (Damigos et al. 2017)

Assessing a MAR project's economic feasibility requires quantifying total benefits and total costs accrued by the project. Since the primary purpose of MAR is ensuing groundwater sustainability, quantifying their benefits translates into quantifying the value of water stored in the managed aquifer. The fundamental challenges in quantifying the benefits of any water projects reside in the fact that the observed prices for water do not reflect the social value, which is driven by the unique characteristics of water as an economic good.

Water as an economic good has special characteristics (Weebley, The Economics of Water)[2]:

- Water is essential to life, economic production, and environment.
- Water is scarce; not all the water can be used.

[2] https://economicsofwater.weebly.com/water-a-normal-economic-good.html, accessed October 2020

- The availability of water varies over time. While water can be stored artificially, there is a need for available water for this purpose.
- Water is a system with water flowing in one direction. The upstream actions impact the downstream, creating externalities. Using river water for aquifer recharge can impact volume of downstream water, affecting the water temperature, with implication for fish habitat.
- Water is bulky and difficult to transport over large distances. Furthermore, different users have different willingness to pay for its use. For example, agriculture users are willing to pay only a fraction of domestic and industrial users' desire to pay.
- Unlike other natural resources, water has no other substitutes.
- Water is a public good. Since water is essential and has no substitutes, it creates a government's responsibility to make sure that every type of user has access to safe water.

To sum up, water's value varies greatly and depends on time, circumstances, and water preferences. Furthermore, since water is provided by non-competitive markets, the emerging price might not reflect the true value. Its price might not reflect the social (non-use) or environmental values associated with water provision.

Given the importance of water to the total economy, the MAR's benefits should rely on the total economic value, which includes: use and non-use (passive) uses (Figure 2). The use values include (Damigos et al. 2017): direct use (the actual use of groundwater for commercial purposes), indirect use (the benefits from using ecosystem services provided by groundwater), and option value(the value ensuring the option of using groundwater in the future). The non-use values are derived from the knowledge that the environment is maintained. The non-use values include: altruistic values (the use of environmental goods provided by others), bequest values (the values people derive when ensuring that future generations will be able to enjoy the environment), and existence values (people may value resources for moral reasons, not related to current and future use) (Damigos et al. 2017).

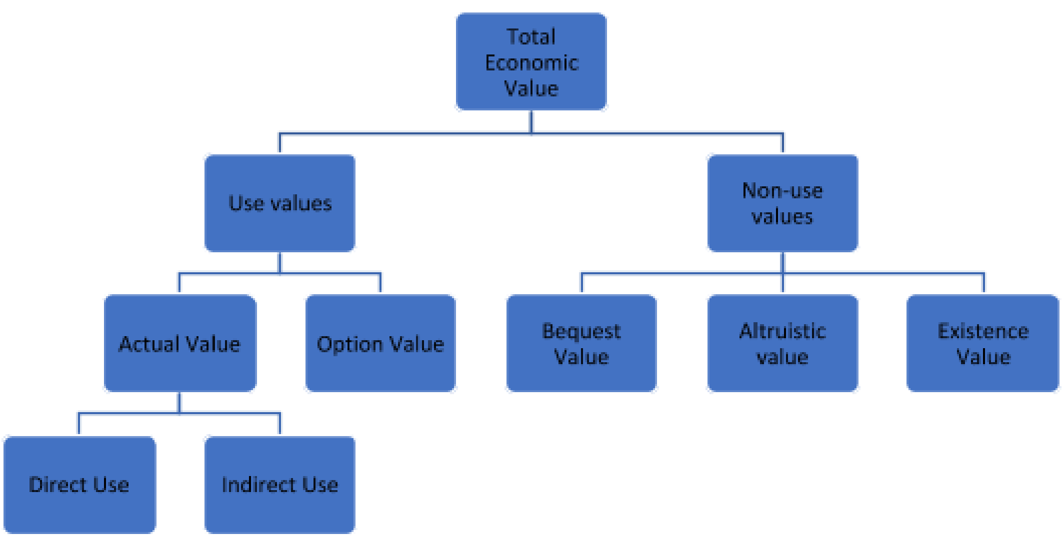

Figure 2. Values from the total economic value approach (adapted from Damigos et al. 2016)

Groundwater and water have social and environmental values that are difficult to measure in terms of the market. Over the last decades, the research proposed and successfully tested several non-market valuation techniques that capture different aspects of the total economic value in general. Table 2 (Maliva, 2014) summarizes some of these methods:

Method	Description
Market prices	Value of water determined by actual prices set by willing buyers and sellers in a competitive market.
Alternative cost	Value of water storage or treatment is determined from the cost of the least expensive alternative that provides comparable benefits.
Value marginal product	The value of water is quantified from the marginal productivity of water, i.e., the extra value of output that can be obtained from additional applications of water.
Contingent value	Survey-based methods to determine an individual's willingness to pay or willingness to accept compensation for a good or service.
Hedonic property value	Value of water is inferred from market transactions (e.g., real estate sales) that are linked to the value of water.
Defensive behavior	Value of a safe and reliable water supply can be estimated from expenditures to avoid exposure to unsafe water.
Damage cost	Value of water is estimated from damage costs avoided, such as health impacts of drought damage.
In-situ groundwater value	MAR system value is estimated from costs avoided resulting from groundwater being in place, such as pumping and land subsidence costs.

Table 2. Methods to monetize the benefits of managed aquifer recharge (MAR) systems. (Source: Maliva 2014)

However, the number of studies directly related to the social costs and benefits of MAR technologies is limited, with the existing studies addressing the natural groundwater recharge or hypothetical schemes (Damigos et al. 2016). Nevertheless, using the non-market approaches for monetizing the environmental and social costs and benefits can improve the decision-making process by: enriching the cost-benefit analysis, raising awareness regarding the environmental impacts, finding the optimal alternative among competing options, support and justify the decision taken by stakeholders involved in the project (Bonnieux and Rainelli, 1999).

Costs of MARs

Capital or investment costs can include (Marechal et al. 2020, Maliva ,2014):

- Cost of preliminary studies- all preliminary characterization studies of the recharge site (geological and hydrological characterization, technical-economic study, impact study).
- Water abstraction cost: cost of civil engineering works for the pumping of water out of the river/canal, as well as pumping equipment (in the case where gravity supply is not possible)
- Cost of the recharge water pre-treatment units: the quality of the recharge water must meet regulations standards. Additional treatment may be required.
- Cost related to land acquisition: the costs of purchasing land for the construction of MAR

- Construction costs (e.g., roads, piping, instrumentation, controls, and pretreatment systems)
- Testing costs, feasibility analyses.
- Other costs (cost of monitoring equipment and ancillary works-protection and development of the recharge site)

Operation and maintenance costs include (Maréchal et al. 2020):

- Water purchase cost: if applicable, includes the purchase cost in the case of withdrawal from a water canal or network, as well as charges, levies, or other taxes.
- Maintenance costs of the water intake (e.g., parts replacement, well and basin rehabilitation)
- Energy cost: electricity consumption of the equipment and pumping system used to supply the recharge water to the recharge site (if not gravity-fed). It will depend on the flow rate and the price of energy.
- Pre-treatment operational cost: the operational and maintenance costs of the infrastructure for pre-treatment of groundwater (excluding investment). They include, for example, the cost of maintaining and cleaning settling tanks, the cost of chlorination products)
- Cost of maintenance and upkeep of injection wells (e.g. cleaning of injection wells) and surroundings
- Monitoring costs: all the costs related to the control and periodic monitoring of groundwater or recharge water quality
- Other annual expenses: administrative and personnel management expenses, financial expenses on investment and insurance loans etc.

Other factors that influence MAR scheme costs (Ross and Hasnain, 2018):

- Source of end-user of water and water treatment costs
- The range of objectives that a scheme has to meet
- Scale of the scheme and economies of scale (large schemes might benefit from economies of scale, leading to lower unit costs of water recharged and recovered)..
- Scheme operating periods and frequency utilization
- Hydrogeological setting; soil and aquifer characteristics (infiltration rates, well yields)
- The percentage recovery rate from storage

Types of economic analysis for MAR

Economic analysis of MARs system depends on an array of factors such as: type of system, performance objective, physical, hydrological, and soil conditions, end uses of the recovered and storage water, alternative water supply and treatment options (Maliva 2014). Depending on data availability, different approaches can be used to evaluate the economics of MAR projects. The costs are highly MAR system specific and influenced by a multitude of factors as mentioned above. The benefits of MARs are related either to the value of water (an economic good with idiosyncratic characteristics) or to environmental benefits that require non-market valuation methods for evaluation. Moreover, due the uncertainty associated with its different inputs, the economic analysis should be extended by a sensitivity analysis. Figure 3 summarizes the different types of economic analysis for MARs.

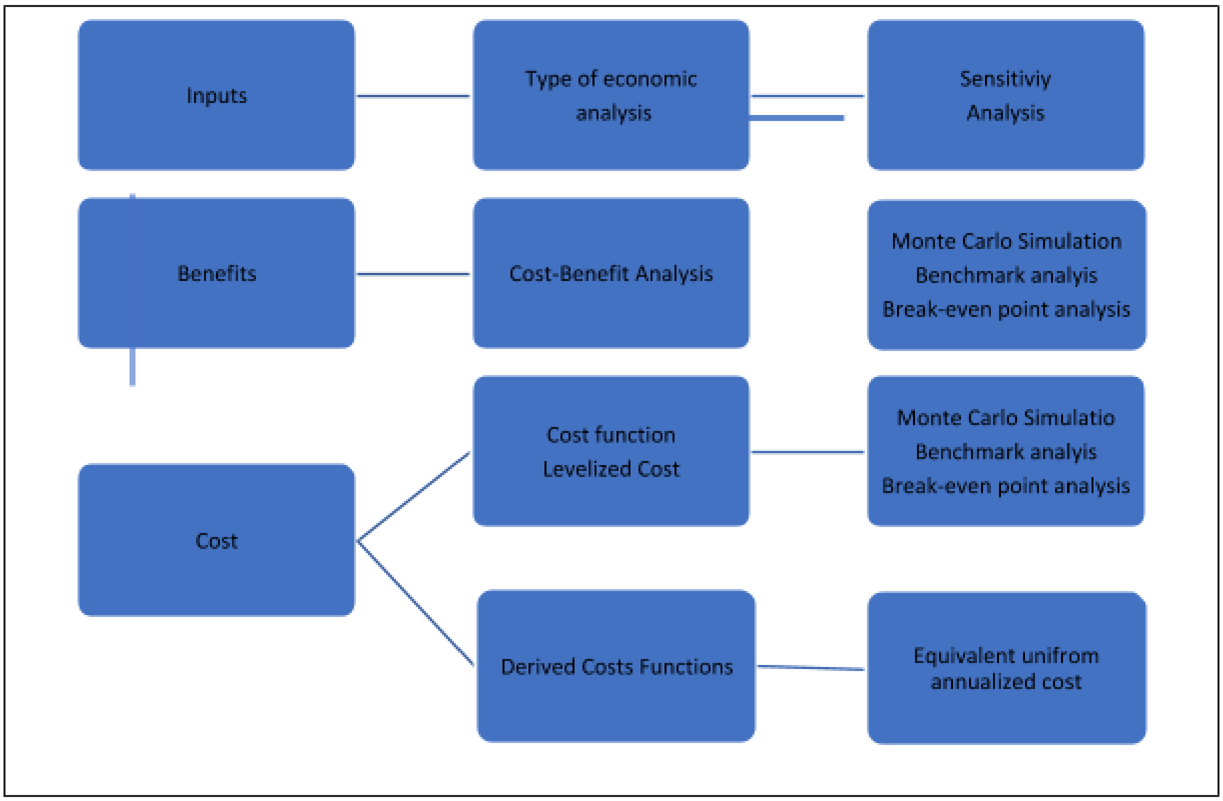

Figure 3. Types of economic analysis

Cost-Benefit Analysis

Cost-benefit analysis (CBA) is a broadly used decision-making tool for obtaining the economic and/or social profitability of a public investment, policy or initiative. It compares the benefits and the cost associated with the proposed measure. CBA is performed using the net present value (NPV) method, which considers both the initial investment and the benefits and costs expected to be incurred over the project's lifetime, with both costs and benefits being discounted at an appropriate rate. The discount rate represents the time preference individuals have for benefits and costs.

The basic NPV equation is:

$$NPV = -C_0 + \sum_{t}^{T} \frac{B_t - C_t}{(1+r)^t}$$

Where C_0 is the initial capital costs in year 0, Bt and Ct are the benefits and the costs in year t, and r is the discount rate.

Since MAR projects can impact the environment, in addition to the net private cash-flows (revenues minus costs), a CBA for a MAR project should incorporate the associated social costs and benefits. Non-market evaluations methods are needed to evaluate the non-use values. Furthermore, a distinction must be made between the discount rate (private) used for the financial costs and the discount rate (social) used for the water project's social benefits. The social discount rate is lower than the private discount rate because private decision makers are concerned with their own short-term welfare and are risk-averse, while society as a whole is concerned with long-term outcomes.

When, social costs and benefits are considered, the NPV value equation can be rewritten as:

$$NPV = - C_0 + \sum_t^T \frac{B_t - C_t}{(1+r)^t} + \sum_t^T \frac{Be_t - Ce_t}{(1+r_e)^t}$$

Where, Bet and Cet are the social benefits and the costs in year t, and r_e is the social/environmental discount rate

The NPV is one of the profitability indicators used in CBA analysis. An economically feasible MAR project requires a positive NPV. Another indicator is the internal rate of return (IRR), or the discount rate at which NPV is zero (investment costs are equal to the benefits); the higher the IRR the higher profitability of the project. The IRR of projects that considers the social costs and benefits is determined by keeping the social discount rate constant.

The steps in the design of a CBA for a MAR project are (Rupérez-Moreno et al. 2017):

- Identify and monetize all costs and benefits of the project.
- Determine the lifetime of the project.
- Determine the discount rate (private and social).
- Define profitability indicators (NPV, IRR).
- Analyze the most uncertain variables (sensitivity analysis).

Maliva (2014) summarizes some important issues related to CBA applied to MARs:

- Marginal costs and not average costs should be used in the CBA analysis.
- Sunk costs (costs already incurred such as previously performed hydrological investigations, existing wells that are no longer used, and existing intakes and piping) should not be included in the analysis.
- Avoid the appraisal optimism: overestimating the benefits and underestimating the costs of the project
- Not all costs and benefits of a MAR project are borne and accrued by the owner
- The value of the discount rate(s) being used in the analysis

- The difference between financial CBA that measures only the direct financial implications, and a social cost-benefit analysis.
- Opportunity costs (i.e. the benefits one could have received by taking an alternative action) should be incorporated in the analysis. For example, the land corresponding to a MAR project can generate revenue via alternative uses (renting, agriculture production, etc.)
- The cost of water stored in a potable water ASR system is the marginal cost to abstract and treat the additional recharged water by a water treatment plant. It is not the average production cost or the price charged to customers.
- Addressing the risk and uncertainty

Levelized cost analysis

Levelized costs of MAR represents an alternative to the cost benefit analysis when information of MARs benefits is not readily available. Levelized costs analysis is frequently used to determine the average net present cost of electricity generation for a generating plant over its lifetime. For MAR, the levelized cost divides the capital, operating and maintenance costs over the life span of the project to the annual volume of recharge. Similarly, to the levelized cost of energy, the levelized cost of a MAR project is an effective way to compare the costs of the project with alternative water projects.

Alternative Metrics for Cost-effectiveness

Cost functions based on the capital and operating costs can be estimated for computing alternative metrics for comparing the costs of MAR. Ross and Hasnain (2018) summarized data on three of the main classes of MAR schemes included in the global MAR inventory; spreading methods/infiltration basins (10 schemes), recharge wells (10 schemes) and bank filtration (1 scheme), and computed a set of three metrics to compare the cost effectiveness of these MAR schemes. Table 3 summarizes the costs data collected, Table 4 describes the cost-effectiveness metrics, and Table 5 summarizes the Average MAR scheme costs, by MAR type.

Capital Costs	**Operating Costs**
Land cost	Labor
Feasibility Analysis	Electricity
Consulting services	Water
Construction costs	Consulting services
Construction: water conveyance	Maintenance costs
Construction: pre treatment facilities	Pre-treatment costs
Construction: post treatment facilities	Post-treatment costs
Pre-operational testing	Depreciation allowance
Regulatory and operational testing	

Table 3. MAR costs data (Source: Ross and Hasnain, 2018)

Ross and Hasnain (2018) findings show that MAR projects using natural water have much lower costs than schemes using recycled water, and infiltration/spreading basins have the lowest recharge costs.

Method/use Description Comments	Description	Comments
Capital cost, operating cost per m3 of water recharged	$/m3 charged	Does not combine capital and operating costs and amortize them
Capital cost, operating cost per m3 water recovered	$/m3 recovered	Does not combine capital and operating costs and amortize them
Levelized cost of water supply	Amortizes capital costs and operating costs over volume supplied through the life of scheme $/m3 supplied	Accounts for expected regular utilization of supply.
Water supply security insurance cost	Capital cost divided by supply capacity $m3per day	Does not include operating costs, does not account for amount of utilization of scheme and is primarily used for water banking for water security.

Table 4. Metrics for Cost-effectiveness (Source: Ross and Hasnain, 2018)

MAR Scheme Type/ Water Source	**Capital cost/ m^3 recharged**	**O&M cost/ m^3 recharged**	**Levelised cost (US$/$m^3$ recharged)**
Recharged wells / recycled water (4 projects)	$ 8.07	$ 0.53	$ 1.16
Infiltration basins / recycled water (3 projects)	$11.41	$ 0.84	$ 1.89
Recharge Wells/ natural water (5 projects)	$ 3.29	$ 0.19	$ 0.45
Infiltration Basin / natural water (8 projects)	$ 0.77	$ 0.13	$ 0.19

Table 5. Average MAR scheme costs, by MAR type (Source: Ross and Hasnain, 2018)

Risk and uncertainty in the MARs financial-economic analysis

The goal of economic analysis of a MAR scheme is to evaluate whether the project is financially sound. However, there are risks and uncertainties associated with MARs that arise from Maliva 2014):

- Recharge may not meet the anticipated aquifer water levels.
- The system has a poor recovery efficiency, and the water is not available when needed
- Unexpected water quality changes (arsenic contamination)
- Excessive clogging
- Water treatment goals are not achieved
- Anticipated future demand for water (hence associated revenues) may not be realized.

These risks and uncertainty can impact the accuracy of economic analysis. A risk or sensitivity analysis of MAR schemes should allow for the identification of the main natural characteristics (i.e. water quality and availability), technical specifications (i.e. system duration, recharge volume objective), economic parameters (i.e. energy price, discount rate, water demand), and uncertainties associated with the estimation of social benefits if applicable. Sensitivity analysis can be performed via Monte Carlo simulations, probability analysis or break-even analysis (cross even points.)

Maliva (2014) describes a three step Monte Carlos analysis:

1. Specify the probability distributions for all important uncertain quantitative assumptions for MAR projects such as natural site characteristics, technical characteristics, economic costs and factors.
2. Execute a trial by taking random values drawn from the distribution for each parameter to arrive at a set of specific values for computing realized net benefits; and
3. Repeat the trial numerous times to produce a large number of realizations of net benefits.

Another method to assess the financial feasibility of MAR under uncertainty consists in identification of the cross-over points in break-even analysis (Arshad et al., 2014). Cross-over points are the thresholds where MAR and an MAR alternative such as surface storage have equal financial returns. These thresholds can be viewed as a minimum requirement beyond a MAR scheme is not financially feasible. The cross-over point analysis is also known as the break-even point or switch even point analysis. Its complexity increases with the number of variables taken into consideration. Arshad et al. (2014) suggest the following benefits of a cross-over points analysis:

- It can determine minimum hydrogeological and cost requirements under which MAR can be financially feasible
- It increases the confidence in decision making for MAR investment, by assessing the factors and conditions that make a MAR investment less feasible when compared to alternative methods (surface water storage)

- By targeting only areas that satisfy the minimum requirements, it can reduce the cost of geophysical and hydrogeological assessments.

Conclusions and Discussions

Managed aquifer recharge (MAR) includes a multitude of groundwater managing tools for recharging and maintaining aquifers levels. Various MAR technologies are currently used across the world and in the US. Typically, a MAR system is characterized by five technical components: the source of water used for recharge, the recharge method, the storage method, and the management approach.

Like any other investment project, a MAR project needs to be economically feasible, with monetary benefits being at least as large as the total costs. Economic assessments of MAR schemes are project-specific and depend on the local physical and hydrological conditions, the recovered and storage water uses, and alternative water supply and treatment options.

In standard economic analysis, markets dictate the monetary value (i.e. price) of the provided goods. However, MAR projects provide water for later use. Water is an economic good with atypical characteristics derived from the fact that water is essential and doesn't have close substitutes. Moreover, MARs projects can have social and environmental benefits (non-market benefits) whose monetary values are not provided by the existing markets. Costs of MARs include capital, operation, and maintenance costs, and finance costs.

The most robust and complete economic analysis of a MAR project assesses both the market and non-market benefits and costs when possible. Cost-benefit analysis (CBA) is performed using the net present value methods, where the lifetime project's monetary benefits and costs are discounted to reflect the individuals' time preference. The CBA should be extended by a risk or sensitivity analysis that considers the risk and uncertainties related to the CBA inputs.

Some of these uncertainties are derived from the project's physical and technical aspects (i.e., the recharge source is not sufficient to meet the anticipated aquifer levels, the system has a low recovery efficiency, there is a high contamination risk). Other uncertainties are reflected on the benefits side when the anticipated future demand for water is not realized.

The projected climate change and the population growth create increasing pressure on the water demand (either drinking or irrigation) that will further strain our nation's water resources. Although MARs have been successfully used in areas where water is scarce in the US, they have a reduced scope and scale in the Midwest. Future adoption of MAR schemes in the Midwest should consider both the hydrological and technical aspects and their socio-economic-ecological impacts. A successful economic analysis that incorporates the socio-economic and environmental aspects can be achieved by carefully understanding the extent of water demand and its uses, possible environmental implications, and the cost efficiency relative to alternative water resource projects that have similar goals.

Aquifer storage and recovery

Aquifer storage and recovery (ASR) is the process of injecting or pumping water into an underground aquifer, where it is stored to be used later. Pyne (1995) defines ASR as "the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed". The influent ASR source can be surface water from rivers, treated wastewater, groundwater from aquifers, or captured storm runoff. IGRAC MAR Portal finds 276 ASR projects in 22 countries, with 136 projects located in the US. The existing projects showed that ASR could enhance water availability with a minimal environmental impact when carefully done.

Pavlic et al. (2006), research from South Australia EPA (2004) and evidence from Texas[3], highlight the following benefits for ASR:

- It allows for a continuity to water supplies during periods of prolonged drought and substantial reductions in water supply
- It requires less habitat disruption than alternative water supply projects such as reservoirs or infiltration basins.
- It is reliable storage with reduced evaporation potential, hence leaving more water for consumption and habitat. Relative to other MARs, it prevents algal growth and mosquito breeding.
- By injecting water into aquifers (through increased hydraulic pressures), it can ameliorate salt intrusion, restore ground levels, and prevent land subsistence (sinking land).
- Aquifer storage offers more protection from contamination with pollutants. Also, it has potential for pathogen and contaminant improvements and natural disinfection during storage
- ASR could also be used in reverse by releasing water into rivers if the flows are too low to sustain a healthy ecosystem (fish and wildlife), although the costs might be very high.
- It can mitigate peak flows in flood events.

However, when using river water to recharge the aquifer, ASR can diminish the amount of water available to fish and wildlife, negatively impacting the local ecosystem. Also, there are high energy costs associated with injecting and retrieving the water.

Bloetscher and others (2014) review and summarize findings from a survey of ASRs in the United States, with the most schemes being located in Florida, followed by California, New Jersey, and Arizona. A careful analysis of both active and inactive schemes finds that 26% of the ASRs are inactive. The failure of ASR schemes is due to:

- physical and chemical clogging.
- low recovery rates for the injected water.

[3] https://texaslivingwaters.org/bestbets/ASR.html

- water quality changes (arsenic, metals mobilization and trihalomethanes).

ASR's initial costs include: constructing intake, transmission, and treatment facilities, either acquiring the land above the aquifer or ensuring the legal rights for the use of the water stored in the aquifer. For example, in Texas, an ASR facility purchased the land, but it leased it back to the previous owners to use it for different agricultural uses. Additional costs include operation and maintenance costs over the ASR's lifetime. Energy costs are high since ASR uses an injection/pumping process. Relative to other MAR projects, the lower evaporation rate of ASR projects can offset some of the energy costs. Also, ASR requires less land acquisition relative to other projects.

In the US, there is an increasing interest in ASR. The Federal Emergency Management Agency (FEMA) encourages communities to consider ASR as a potential strategy for mitigating the increased risk of flood and drought caused by climate change. FEMA describes ASR as a method of capturing water when it's abundant (rainy season, spring snow melts), and storing water in the subsurface in brackish aquifers to be recovered at a later use. Two types of ASR as considered: confined and unconfined. A confined aquifer can be recharged only through injection wells. A buffer zone will be maintained between the original aquifer and the injected water. An unconfined aquifer can also be recharged via natural infiltration processes. The method of recharge and the treatment of the effluent source should be based on specific site conditions.

Furthermore, FEMA commissioned a cost-benefit analysis tool for ASR projects (ASR BCA tool) that meet the agency's criteria for drought and flood mitigation[4]. It was built to provide the planners with a high-level tool to assess the cost-effectiveness of designing, constructing, and operating an ASR project[5].

The FEMA-ASR BCA tool is tailored for ASR projects intended for drought mitigation. Also, the tool performs a drought and mitigation analysis. The main inputs into this cost benefit analysis tool are: general project information such as population in the area covered by the ASR and the average water use rate, technical and cost information, and project's useful life and the discount rate. The technical input requires specific information related to infrastructure such as maximum depth and average depth to recoverable water. Cost information requires estimated capital costs for fixed costs such as land acquisition, feasibility analysis, design, permitting, construction and materials (pipping, pumps, instrumentation), construction oversight, other miscellaneous costs and annual operation and maintenance costs (labor, electricity, consulting services, regulatory testing, maintenance, treatment, raw water), and other miscellaneous costs.

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[4]https://www.fema.gov/media-library-data/1464288989120-5439c85896bf950c82009b95dbe2c16b/15_J_0051_ASR_BCA_Methodology_508.pdf

[5]https://www.fema.gov/media-library-data/1487160966426-3e774ec4315295499f45a25bc8915c90/ASR_Fact_Sheet_Feb2017_COMPLIANT.pdf

https://www.fema.gov/media-library-data/1464288989120-5439c85896bf950c82009b95dbe2c16b/15_J_0051_ASR_BCA_Methodology_508.pdf

Evidence of ASR cost effectiveness

Ross and Hassain give an overview of cost data on several MAR schemes (Table 6). Their analysis using a levelized cost function approach finds that schemes using wells and or advanced water treatment are relatively expensive when compared to infiltration basins. However, a number of socio-economic, environmental legal and institutional factors have been overlooked because of lack of data.

The same study shows that, for ASR schemes, well yields are an important driver for their performance. Citing a report from the Texas Water Development Board, well yields explain the range of capital cost per day of recovery capacity that vary from \$0.50 and \$2.00 per gallon per day.

Choi and others (2018) use an econometric approach to compare the unit water production cost (UWPC) for ASR schemes to other schemes using different water resources that secure water for later uses. The purpose of their study is to investigate ASR cost-effectiveness in South Korea. The authors collected data for 11 ASR well fields located elsewhere. The various uncertainties in their analysis are addressed through Monte Carlo simulations. Their findings show that, in general, ASRs are the lowest UWPC solutions to providing drinking water.

Conclusions and discussions

In the US, the recent MARs study conducted by the US Army Corps of Engineers and ASR cost-benefit analysis tool promoted by FEMA show the growing interest in exploring different opportunities to meet the growing demand for water needs in cost-effective ways. The main drivers of ASR have been economics, proven performance, and operational flexibility. Relative to other MAR schemes, ASR has a lower evaporation potential and a smaller footprint, requiring less land. However, ASRs might have higher operating (energy) cost. Also, by diverting water from rivers, an ASR scheme can affect the fish and wildlife habitat. Evidence shows that clogging, low recovery rates, and changes in water quality can impact the ASRs performance and impact benefit assumptions.

The cost-benefit analysis is the most comprehensive and robust assessment method, and it is the preferred method for state or federal agencies. Ideally, a cost-benefit analysis identifies all the economic benefits and costs to all the involved parties. It can incorporate market and non-market benefits and costs. The results of this analysis should be compared to a "no-project" situation. Furthermore, a sensitivity analysis should be performed regarding demand aspects, discount rate, capital, operating costs, or the benefits included in the analysis.

Recommendations

In Minnesota, given the lack of previous ASR projects across the state, we recommend a multi-step approach in determining the economic feasibility of a potential project:

Step 1. Determine the availability and suitability for the aquifer, the recharging source, and the demand for stored water and its uses.

Step 2. Determine the project's technical parameters that ensure that the injected and pumped water meets the environmental and health guidelines for native groundwater water and end-uses, respectively.

Step 3. Conduct a cost-benefit analysis by adapting the inputs required by the FEMA recommended ASR CBA (FEMA- Methodology for Aquifer Storage and Recovery Benefit Cost Analysis) tool to the specific project.

Step 4. The economic analysis should be revised and updated to consider any changes that might affect the original assumptions and inputs and hence overall economic outcomes.

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