# Aquifer Storage and Recovery

## Improving Water Supply Security in the Caribbean
## Opportunities and Challenges

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Water and Sanitation Division

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# Aquifer Storage and Recovery: Improving Water Supply Security in the Caribbean Opportunities and Challenges


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# PREFACE

*As part of the recommendations emanating from the Caribbean Water and Wastewater Association (CWWA), the importance of preserving and restoring groundwater aquifers was highlighted and identified as a priority intervention in the Caribbean.*

Climate change is impacting the water regime in Latin America and the Caribbean (LAC), with many countries experiencing severe droughts and floods, both in frequency and duration. Drought hazards have increased significantly, affecting over 60 million people over the last several decades. Sea level rise associated with climate change is also increasing the salinity of coastal aquifers, while urbanization has reduced the volume of rainwater infiltration, with associated increased impact of floods, degraded surface water quality, loss of ecological habitat, and limited recharge of the aquifers often already depleted by overexploitation.

Aquifer storage and recovery (ASR) is one method to increase water supply using subsurface reservoirs. Groundwater replenishment or increased groundwater stored in aquifers during wet periods can contribute to improved water supply, security, and sustainability. The recovered water can be used for drinking water supply, irrigation, and ecosystem restoration projects, often supplementing the surface water supply. Economically, ASR can be considerably cheaper and easier to implement than other storage methods, and is very cost effective if compared to developing alternative sources of water needed for development.

The IDB's Water and Sanitation Division (WSA), recognizing the potential benefits of ASR, has engaged technical experts in analyzing the various methods, advantages, and disadvantages of ASR use, especially in countries facing multiannual droughts. In the Caribbean, an IDB loan in Jamaica has incorporated technical analysis on ASR, and the concept has received attention in the wider Caribbean. The "Caribbean Regional Framework for Investment in Water Security and Climate Resilient Development" (GWP-C, 2017) calls for regional engagement to address impacts of droughts as part of its broader objective of supporting water utilities to manage drought events and reducing disruption to essential services. As part of the recommendations emanating from the Caribbean Water and Wastewater Association (CWWA), the importance of preserving and restoring groundwater aquifers was highlighted and identified as a priority intervention in the

Caribbean.[2] This is especially relevant where the main source of water comes from very costly desalination methods.

This technical document is the result of a technical consultancy addressing two main objectives: a) review the technical and socio-economic dimensions of ASR applications, using concrete examples around the world and in LAC, documenting the costs and benefits of ASR projects, and assessing conditions considered critical for implementation, including local planning and management, economic and financial constraints, and social and environmental factors; and b) develop a set of strategic/practical guidelines and evaluation criteria to assist Bank staff and national and sub-national counterparts and stakeholders in considering and incorporating ASR into their water policy.

The final results of this consultancy were presented and discussed in a Bank workshop in December 2018, with presentations of the overall conclusions and the case studies of Jamaica, Southern California and Barcelona. We extend our gratitude to IDB´s Knowledge, Innovations and Communications Sector (KIC) for supporting this product and the execution of the workshop.

The Water and Sanitation Division (INE/WSA)

2 White Paper on Governance and Climate Resilience in the Water Sector in the Caribbean (Prepared by James Fletcher for the 13th High-Level Forum of the 26th Conference of the CWWA).

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| | |
|---|---|
| **AGSR** | Artificial Groundwater Storage and Recovery |
| **ASCE** | American Society of Civil Engineers |
| **ASR** | Aquifer Storage and Recovery |
| **ASTM** | American Society of Testing and Materials |
| **BMP** | Best Management Practice |
| **CBA** | Cost Benefit Analysis |
| **CDWR** | California Department of Water Resources |
| **CWWA** | Caribbean Water and Wastewater Association |
| **EPA** | Environmental Protection Agency |
| **FEMA** | Federal Emergency Management Agency |
| **Flood-MAR** | Flood-Managed Aquifer Recharge |
| **HLF** | High Level Forum |
| **IDB** | InterAmerican Development Bank |
| **IRWM** | Integrated Regional Water Management |
| **LID** | Low Impact Development |
| **m3** | Cubic meters |
| **MAR** | Managed Aquifer Recharge |
| **MIT** | Massachusetts Institute of Technology |
| **OCWD** | Orange County Water District |
| **O&M** | Operations and Maintenance |
| **SEMARNAT** | Secretary of Environment and Natural Resources |
| **SLRC** | San Luís Rio Colorado |
| **TDS** | Total Dissolved Solids |
| **USD** | US Dollars |
| **USGS** | United States Geologic Survey |
| **WRD** | Water Replenishment District |
| **WSA** | Water and Sanitation Division |
| **WWTP** | Wastewater Treatment Plant |

# Aquifer Storage Recovery: Improving Water Supply Security in the Caribbean. Opportunities and Challenges

*"Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land."*

*Luna Leopold*

## EXECUTIVE SUMMARY

Water supply security is becoming an increasingly critical issue worldwide with expanding populations and impacts of climate change. The Caribbean region is particularly susceptible to drinking water supply concerns due to rising sea levels, changing precipitation patterns, and water quality degradation. Aquifer storage and recovery (ASR) and managed aquifer recharge (MAR) offer important tools to increase freshwater storage at a nominal cost. However, for these types of projects to be successful, proper physical, social, and economic conditions must be present. This report provides an overview of various ASR and MAR schemes, and discusses key factors to consider when evaluating the siting, design, and funding of these water supply projects. A decision tree with a step-by-step process is provided that will assist the project manager in assessing the viability of specific projects.

# 1.0 INTRODUCTION

In October 2012, a high-level forum for ministers in charge of water (HLF 8) in the Caribbean (Figure 1) was held during the 21st Annual Caribbean Water and Wastewater Association (CWWA) Conference and Exhibition in Nassau, Bahamas. At that meeting, key concerns were identified by meeting participants. These concerns included the "impacts of climate change, tariffs and financial sustainability of service provision, the need to upgrade existing water infrastructure and improve resource use efficiency, the prevention of pollution of water sources, and the management of resources and services in the face of natural hazards" (Cashman, 2014). These Caribbean water leaders "agreed on seven (7) critical concerns toward achieving national and regional water security. These areas include water as a national development issue; Integrated Water Resources Management (IRWM)[3]; climate change and water; wastewater; regional cooperation; capacity building; and public awareness" (Global Water Partnership and CWWA, 2012).


**Figure 1: The Caribbean Region (Wikipedia, 2018)**

3 "IRWM is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (UNEP-DHI Centre for Water and Environment, 2009, Integrated water resources management in action, WWAP).

*ASR is a water resource management tool applied widely around the globe, particularly in areas with critical water supply fragility.*

More recently, in their 2018 paper, Taylor, et al. stated that climate change poses a major threat to the Caribbean region due to its extreme "sensitivity due to (among other things) 1) the small size of the countries; 2) a near-exclusive reliance on climate sensitive economic activities such as agriculture and tourism; 3) an overwhelming dependence on rainfall for the water [supply]; 4) high public debt; 5) and limited hazard forecasting capabilities". The precariousness of secure high-quality water supplies is apparent and of strategic interest throughout the region. Aquifer storage and recovery (ASR), where applicable, is one proven method to improve both water supply and quality.

ASR is a water resource management tool applied widely around the globe, particularly in areas with critical water supply fragility. For this report, ASR is defined as the process of storing surface water supplies in aquifers when water is abundant and extracting that water during times of need or peak demand.[4] This definition has been expanded to include several other types of Managed Aquifer Recharge (MAR) schemes that can be useful in sustaining or enhancing freshwater supplies or mitigating poor surface water quality. ASR and MAR are common conjunctive water management tools. Conjunctive management is the "coordinated and planned use and management of both surface water and groundwater resources to maximize the availability and reliability of water supplies in a region to meet various water management objectives" (California Department of Water Resources, 2016).

ASR/MAR technologies are often a foundational element of an any IWRM, and offer an important set of tools for water managers in addressing the security of water supplies in the face of uncertainty precipitated by climate change. These techniques have been used for a variety of purposes, including, but not limited to:

- **Hedging water supplies against climate change and attendant extreme weather (FEMA, 2015)**
- **Recharging depleted aquifers (California Department of Water Resources, 2016)**
- **Reducing the impacts of flooding (California Department of Water Resources, 2016)**

4 ASR is often defined as the scheme whereby potable water is injected in the aquifer using wells. These same wells are then used to extract a significant portion of the water when needed. The aquifer into which the potable water is injected may be of lower water quality, creating a reservoir of higher quality water around the ASR well (Brown, 2006).

- **Increasing potable water supply in a cost-effective manner (Maliva, 2014)**

- **Mitigating the impact of saltwater intrusion into coastal aquifers and salinization of brackish water supplies (Pyne, R. D., 2014; Hartog, N., et al, 2017)**

- **Reversing salinization of brackish water used for desalination (Hartog, 2017; Scalley, 2012)**

- **Improving surface water and coastal water quality (https://www.waterboards.ca.gov/water_issues/programs/stormwater/; Scalley, 2012)**

ASR/MAR in the Caribbean region, as well as throughout Latin America, can offer similar benefits where conditions are amenable, and the technology is implemented and managed appropriately. The methods and tools presented in this report have broad applicability in nearly any country facing water supply security issues.

# 1.1 PROJECT OBJECTIVES AND REPORT ORGANIZATION

The objectives of this project are to provide a framework that the Inter-American Development Bank, (hereafter referred to as IDB or "the Bank") can use to evaluate: 1) the potential implementation and funding of stand-alone ASR/MAR projects, and 2) incorporating ASR/MAR schemes into future Bank-funded projects.

The results of the project are provided in this report, which is roughly divided into four parts. The first part consists of an analytical review of ASR/MAR techniques and technologies and how they are applied, regulatory and management considerations, and typical costs of implementation, as well as limitations. The focus in this section is on potential Caribbean-related applications.

The second part of this report consists of development of a high-level guidance document and decision tool that can be applied by the Bank to assess potential applications of ASR/MAR technologies. Useful references are identified and summarized. The guidelines and decision tool can be used to assist with:

- **Assessing proposed ASR/MAR projects**
- **Evaluating whether incorporating ASR/MAR technologies into existing projects is appropriate**
- **Providing guidance on technology selection considerations**
- **Identifying key factors for successful ASR/MAR implementation**
- **Assessing the incorporation of ASR/MAR into future IDB Water and Sanitation Division (WSA) loans.**

The third part of this report presents selected case studies highlighting the application of different ASR/MAR technologies and, where appropriate, lessons learned. Case studies for projects that represent a spectrum or sizes and applications are provided.

Key reports that may provide analysts with additional insight regarding ASR/MAR project evaluation and/or development are briefly summarized, and these summaries are provided in the fourth part of this document.

Reference materials that describe or highlight ASR/MAR applications or best management practices (BMPs) are provided in an extensive bibliography.

# 2.0 WATER RESOURCES IN THE CARIBBEAN

*Climate change exacerbates the problems associated with freshwater supply as rainfall patterns change, temperatures increase, droughts become longer and more intense, and sea levels rise (Calle, 2017).*

The Caribbean region presents special challenges in developing an integrated approach to managing water resources due to climate change and the role of sea level rise, the distribution and nature of freshwater resources, and the broad range in geologic/hydrologic conditions. On many islands, tourism has become the primary economic sector, with agriculture focused on domestic markets, necessitating a shift to higher quality water supplies. Given these factors and the small size of most Caribbean islands, a holistic and integrated approach to manage water resources is appropriate and necessary.

Water resource management (both the freshwater supply and beach/near shore marine water quality) is critical to economic growth given the high reliance on tourism and the relative scarcity of freshwater in many Caribbean countries (GWP, 2010; Scalley, 2012). Climate change exacerbates the problems associated with freshwater supply as rainfall patterns change, temperatures increase, droughts become longer and more intense, and sea levels rise (Calle, 2017). Combined with water quality degradation from inadequate sanitation treatment and agricultural runoff and seawater intrusion, the need for comprehensive, integrated water management is acute.

Typically, the most sustainable source of naturally occurring freshwater in the Caribbean is groundwater, as surface water resources are often limited because of: 1) seasonal rainfall patterns resulting in a distinct wet and dry season; 2) the distribution of rainfall across islands is often uneven due to orogenic effects (dry and wet parts of islands); and 3) "flashy" nature of runoff for most streams and rivers (GWP, 2010; Calle, 2017).[5] This runoff often carries pollutants, such as suspended solids and nutrients, to the ocean, affecting beach water quality and biological resources, such as coral reefs. Capturing and storing runoff for later use provides a measurable way to improve the supply and mitigate degraded surface water quality. However, the ability to store the water in reservoirs on many islands is often problematic due to the

5 Flashy runoff is typically characterized as short duration with a high volume of flow. These types of flows are typically difficult to manage with respect to water supply.

limited suitable geographic areas to build surface water reservoirs (Scalley, 2012; Calle, 2017) and construction costs (Choi, 2018), making subsurface storage an attractive option.

Where the hydrologic and subsurface conditions are suitable, aquifer storage via ASR/MAR offers a less expensive alternative to surface storage (Choi, 2018).

The success of ASR/MAR schemes is very dependent on local hydrogeologic conditions that must be evaluated during the feasibility analysis. Hydrogeologic conditions vary widely across the Caribbean, reflecting the geologic history of the islands and how the islands have developed over time. Aquifers in the Caribbean range from porous limestones and fractured volcanic and igneous bedrock, to sedimentary aquifers consisting of layered sands and clays. Salinity varies from fresh (less than 1,000 mg/L total dissolved solids, or TDS) to brackish (between 1,000 and 15,000 mg/L TDS), with saltwater intrusion common when aquifers are over-exploited (extraction exceeds replenishment).

A survey of water resources in the Caribbean indicates that historically, many islands once had a viable fresh groundwater supply but that these supplies deteriorated over time due to saltwater intrusion, over-use, and/or neglect. A brief overview of groundwater supply conditions at various Caribbean islands and countries is provided in Appendix A.

# 3.0 SUCCESSFUL ASR/MAR PROJECTS

The success of an ASR or MAR project is dependent upon numerous factors, many of which are site- specific. Key factors can be divided into project feasibility and project development. ASR has the added complexity of requiring that the recharged water can be effectively recovered at a later time, while MAR may be installed and operated for non-recovery purposes, such as mitigating saltwater intrusion and environmental mitigation.

To this end, each project needs to be evaluated independently with respect to technical, institutional, and economic factors, as well as overall project objectives. However, there are certain general characteristics that can be summarized into several broad categories, which include:

- **Technical**
- **Project construction and operation**
- **Funding construction and ongoing management**
- **Institutional structures**
- **Stakeholder involvement**
- **Organizational capacity**

Each is described in more detail below.

## 3.1 TECHNICAL

The importance of ASR/MAR to water managers in sustainably managing freshwater resources around the world is growing. Recently, the State of California enacted legislation that requires all groundwater basins to be managed sustainably.[6] Conjunctive

6 The California legislation is referred to as the Sustainable Groundwater Management Act of 2014 or SGMA. SGMA requires governments and water agencies to bring sensitive groundwater supplies into balanced levels of pumping and recharge.

use projects such as ASR/MAR have been identified by California as one of the keys to aquifer sustainability. Other states, particularly those in the southern U.S. sunbelt, such as Arizona, Texas, and Florida, have aggressively implemented similar water management programs to increase and secure future water supplies. Water agencies, utilities, and professional organizations throughout the U.S. and internationally have prepared various documents that summarize the technical considerations when planning and implementing ASR/MAR projects (California Department of Water Resources, 2016; Texas Water Development Board, 2015; Federal Emergency Management Agency (FEMA), 2015; GWP, 2010; American Society of Civil Engineers, 2001). Salient elements from each of these documents were used in preparing the technical considerations summarized briefly below.

**SUITABLE AVAILABLE LAND:** ASR/MAR projects often involve acquisition of property parcels, particularly near existing water infrastructure (e.g. canals, storm sewers, water treatment facilities, or pipelines for delivery of water to be recharged); water distribution systems (delivery of recovered groundwater); and natural surface water features, such as gullies, washes, and streams in areas with suitable hydrogeologic conditions (e.g. surface soils, available subsurface storage, and permeable subsurface conditions). Land acquisition, particularly in urbanized areas, can be one of the highest capital costs associated with the project, particularly if ASR/MAR consists of larger-scale features, such as recharge or spreading basins.

***Key Point:*** Ideal sites include undeveloped land parcels near existing water infrastructure that have suitable hydrogeologic conditions (hydrogeologically feasible).

**HYDROGEOLOGIC FEASIBILITY:** Hydrogeologic feasibility is determined by assessing soil characteristics (e.g. percolation rate at a spreading basin, Figure 2); subsurface characteristics such as porosity and permeability; subsurface layering; surface water and groundwater quality; and interconnection of the recharge zone and the extraction zone to ensure that recharged water can be appropriately recovered if that is an intended purpose.

This analysis usually requires an initial feasibility study to document that appropriate hydrogeologic conditions are present in the subsurface to fulfill the intended purpose, and is sometimes referred to as a Hydrogeologic Conceptual Model (California

Department of Water Resources, 2016; GWP Consultants, 2010). During this hydrogeologic feasibility analysis, typical tasks include assembling and analyzing existing soil, geologic, hydrogeologic, and hydrologic data; testing percolation rates; and drilling borings to assess subsurface geologic conditions (sand and clay thicknesses and depth to groundwater), groundwater storage capacity, permeability of subsurface geologic strata; and background water quality.[7] DEMEAU (2016) identified 10 essential aquifer characteristics required to be addressed as part of the hydrogeologic feasibility analysis. These include aquifer type (confined or unconfined), aquifer permeability, aquifer thickness, depth to water (available storage), aquifer pore type (porous alluvium, fractured, karst), aquifer uniformity, groundwater redox state (aerobic or anaerobic), and native groundwater chemistry.

**Figure 2: Spreading Basin at a Water Bank (From author's archive)**

A numerical model is often useful to evaluate the ASR/MAR project on water supply reliability.

One of the key tasks is to develop a preliminary water budget or water balance for the project, which is updated as project data are

7 A cost-effective step is to gather existing studies and other data regarding subsurface conditions. This can include geotechnical reports, historical records regarding groundwater use, and publications/academic research.

developed.[8] The budget should include an assessment of the fate of the recharged water and its impact on groundwater elevations. For example, the height and extent of mounding under a recharge basin can be estimated using equations presented by Bouwer (2002), or by using the simple USGS spreadsheet (USGS, 2010).

***Key Point:*** Hydrogeologic feasibility is paramount to developing a successful ASR/MAR project. Unless water can be effectively recharged, stored, and recovered in most cases, the ASR/MAR project is not feasible.

**AVAILABLE GROUNDWATER STORAGE CAPACITY:** Available groundwater capacity is the amount of unused subsurface storage that is available to store recharged water. In simple terms, unused storage is the volume of unsaturated earth between the water table and the ground surface. Often, the entire unsaturated zone cannot be completely filled, so a target depth is established. This available capacity can be manmade or natural. For example, at many ASR/MAR projects, additional storage can be created by pumping down the water table to allow for recharge during the rainy season. For some ASR applications in confined aquifers, storage is often significantly less and requires that the aquifer is pressurized.

***Key Point:*** Storage capacity in certain unconfined aquifers can be increased through pumping, thereby depressing the water table.

**WATER SOURCES:** A source of recharge water must be secured and can include local runoff, stormwater, desalinated seawater, treated wastewater (secondary, tertiary, or advanced), potable water, and imported water (water from outside the watershed) (DWP, 2016; Hartog, 2017). Depending on the source of water, engineering analysis (volume of water available for recharge or whether pretreatment is necessary prior to recharge), permitting (surface water diversions are often governed by local water laws), and legal agreements will likely be required to secure the water source for ASR/MAR projects.

***Key Point:*** Poor source water quality may require extensive treatment before recharge at considerable cost. For many projects, the blending of the recharge water with native water and the interaction between recharged water and aquifer sediments

8 A water budget is similar to financial accounting budgeting in that it tracks the amount of groundwater in storage, the change in groundwater storage, and groundwater inflows (recharge) and outflows (discharge). Surface water is comparable to a water "checking" account due to its transient nature, while groundwater is often regarded as a water savings account. A water budget is a fundamental water management tool used widely in many countries.

can also lead to unintended groundwater quality degradation or clogging of recharge wells or geologic media.

**PILOT TESTING:** Prior to finalizing an ASR/MAR project, pilot testing should be completed to evaluate the feasibility, time, and cost, and to improve the preliminary engineering design prior to development of the full-scale application. Often, previously unidentified adverse conditions can be identified during the pilot test that were unforeseen or underestimated (e.g. subsurface barriers to deep infiltration) and mitigated in the final design.

***Key Point:*** Even with the benefit of the pilot test, it is advisable to allow some flexibility in the final design to accommodate potential modification of the ASR/MAR system for unexpected conditions, particularly in subsurface conditions.

**CONVEYANCE:** Conveyance is often required to transmit source water to the recharge facility and to deliver recovered groundwater to the point of demand. Typical conveyance facilities are pipelines and canals (lined and unlined), but can also include streams and natural water courses.

**RECHARGE AND RECOVERY FACILITIES:** Recharge facilities can include injection wells, surface water spreading, and recharge basins, fallow agricultural fields, karst sinkholes in limestone aquifers, and other natural and manmade features that allow augmentation of the underlying groundwater supply. Attendant equipment can include measuring flumes and weirs, flow meters, pumps, and monitoring equipment. Recovery facilities typically include pumping wells. In some cases, recharge is done not to store water, but rather to address an environmental condition, such as poor surface water quality or to inhibit seawater intrusion.

***Key Point:*** Accurate water metering and accounting (inflows, outflows, and storage) are fundamental to a successful project.

**WATER TREATMENT FACILITIES:** Water pre-treatment facilities are required if there are high total suspended solids or chemical contaminants in recharge water that must be removed prior to infiltration. In some cases, water pre-treatment can be a passive treatment methodology (e.g. a settling basin and engineered wetland). Recent studies have shown that most common surface contaminants, whether dissolved or suspended, are effectively removed through the infiltration process (The Los Angeles and San Gabriel Watershed Council, 2008).

Post water treatment may be required before point-of-use delivery. These facilities are typically needed to meet existing water quality standards. For example, recharge of water with a

low total dissolved solids content or that is depleted in certain anions or cations may mobilize contaminants such as arsenic that are present in the aquifer as a solid (Fakhreddine, S., et al, 2015).

***Key Point:*** The need for pre- and post-water treatment is typically determined by the source water quality, native groundwater quality, the intended end use of the produced water, and local water quality regulations.

**REPORTING:** Reports are prepared at various phases of project selection, feasibility, and design. Certain reports can be combined into a single document. Typical reports that are common to many ASR/MAR projects include the following:

- **Preliminary Site Selection –** A document is typically prepared that includes an overview of the attributes of the sites considered for the location of the ASR/MAR facilities. This report includes a discussion of the source water (e.g. excess stream flows or treated wastewater), land availability, local infrastructure, and preliminary analysis of hydrogeologic conditions (based on existing information/reports). This report typically identifies data gaps and next steps.

- **Hydrogeologic Feasibility Report –** A hydrogeologic feasibility report includes a detailed discussion of subsurface conditions, including soil conditions, geologic strata, depth to groundwater, hydrogeologic parameters (porosity, hydraulic conductivity, water quality), hydrology and surface water supply, meteorological data, and a project water balance. This is sometimes referred to as a Hydrogeologic Conceptual Model. If a pilot test is performed, a description of the test and results may be included. An analysis of the suitability of the site for its intended ASR/MAR use is provided. If the project is not hydrogeologically feasible, it is usually no longer considered.

- ***Project Feasibility Study –*** A project feasibility report is typically prepared if the Hydrogeologic Baseline Report indicates that the site has appropriate subsurface attributes. Rough order of magnitude costs to design, build, and operate the project are developed with an appropriate level of uncertainty.

# 3.2 PROJECT CONSTRUCTION AND OPERATION

Project construction and operation may include construction and operation of treatment facilities, conveyance facilities, or spreading basins, as well as installation and operation of monitoring, production, and injection wells, and drilling of test holes. Certain construction capabilities in some Caribbean countries may be limited or expensive to import. For example, large diameter injection or recovery wells may require trained personnel and specialized drilling rigs for installation that may be costly to mobilize for a project (Figure 3).

**Figure 3: Recovery Well Installation (From author's archive)**

Two of the most significant challenges associated with operation of ASR/MAR projects are 1) physical plugging of the pore space in and around the spreading basins or ASR wells, and 2) treatment of recharged or recovered water.

Plugging pore spaces can be addressed using settling basins or other water treatment technologies prior to recharge. The operation and maintenance program should be designed to measure rate of infiltration and routinely restore infiltration capacity by removing debris, fine grained particulate matter, mineralization, and biological buildup (algae and biological slimes often form during recharge).

Mixing recharge water and native water can result in chemical reactions, such as the formation of precipitates or leaching of trace metals detrimental to overall project success. These can be identified a priori through baseline water quality testing. While recent studies have shown that infiltration of surface water serves to greatly improve overall water quality for many water sources, political and regulatory hurdles may still exist in permitting direct recharge into the aquifer based on surface water quality.

# 3.3 FUNDING AND ECONOMICS

Financial analysis for ASR/MAR projects should be conducted using a cost-benefit analysis (CBA) basis or similar evaluation. Costs generally fall into two general categories: 1) capital costs for project analysis, permitting, and construction, and 2) long-term operations and maintenance costs.

In many water districts in the U.S., capital costs can be a significant barrier to implement an ASR/MAR project. State and local government grants can be used to reduce barriers for project design and construction. Long-term funding for project operations and maintenance (O&M) is typically supported by the increase in available water for potable and irrigation purposes and the ability to charge the user for this water. This may require a tax or fee for this new water source.[9] Projects involving high value end points, such as potable supply, tend to be economically feasible, provided that local hydrogeologic conditions are favorable. Projects in developing countries may be economically viable, but external support is often required because of limited local financial resources (Maliva, 2014).

Ross and Hasnain (2018) evaluated 21 separate MAR schemes in the Netherlands, United States, Australia and New Zealand that included different types of source water, infiltration methods, and project objectives (water security, irrigation supplies, drinking water, and ecological benefit). Projects were segregated into one of four ASR/MAR schemes: recharge wells using recycled (treated) water; infiltration basins using recycled water; recharge wells using natural water; and infiltration basins using natural water. The researchers compiled capital cost and operating and maintenance (O&M) costs and developed "levelized" costs for each scheme. Levelized costs refer to the constant level of revenue needed each year to fund capital and operation costs through the life of the project, divided by the annual volume of water supply. The cost in U. S. dollars (USD) per cubic meter ($m^3$) of water recharged per year for each MAR scheme is provided in Table 2 and is used as a cost metric in this report. While the number of projects included in the analysis is relatively small (21), the data provide a suitable benchmark with which to compare project costs cited by other authors.



9 Stormwater management systems in the U.S. and Europe are often funded through a property tax based on property size and amount of impervious cover.

| MAR Scheme/ Water Source (projects per scheme) | Capital Cost/ $m^3$ Recharge Water | O&M Cost/$m^3$ Recharged Water | Levelized Cost/$m^3$ Recharged Water |
|---|---|---|---|
| Recharge wells/recycled water (5) | *$10.33* | *$0.65* | *$1.46* |
| Infiltration basins/recycled water (2) | *$7.44* | *$0.92* | *$1.50* |
| Recharge wells/natural water (5) | *$3.29* | *$0.19* | *$0.45* |
| Infiltration basins/natural water (8)[10] | *$0.77* | *$0.13* | *$0.19* |

**Table 1: Average MAR Scheme Costs (Ross & Adnain, 2018)**

As expected, the results of the researchers' analysis indicated that infiltration basins using natural water were the least expensive scheme by a wide margin, while recharge using recycled water was most expensive. The higher cost of recharging recycled water using infiltration basins rather than recharge wells may reflect the small population of example projects in the infiltration basins/ recycled water category.

In his review of 50 ASR well projects from four continents, Brown (2006) reported that costs in USD for water recharged and recovered ranged from $0.34 to $9.27/$m^3$. Costs to recover water from brackish aquifers was generally more than double that for non-brackish aquifers. This typically reflects higher operations and maintenance costs associated with brackish aquifer ASR projects.

When compared with typical desalination costs, the value of ASR/MAR is typically significantly lower, although the cost of desalination is decreasing due to technology advances and scale. In Israel, the Sorek project, the largest desalination plant in the world, came on-line in 2013 and is producing potable water and selling it at a cost of $0.58/$m^3$ while the cost typically cited for desalination is around $0.80/$m^3$ (Talbot, 2015). This megascale plant also requires less power than traditional desalination

10 Capital costs were in line with those cited by Scanlon, et al (2016). In that paper, typical capital costs for MAR systems using natural water ranged from $0.07 to $0.80/m3 based on grant applications in California.

operations. However, the size of the project (627,000 $m^3$/day), energy demands, and associated large capital cost ($500M) make these types of efficient, megascale desalination projects impractical in many Caribbean communities.

A chart comparing costs of potable water metered and delivered to domestic and commercial end users in the Caribbean shows variability in the price of delivered drinking water (See Appendix B). The cost per cubic meter of potable water to the domestic or commercial end user ranges from under $1 to approximately $12 for domestic, to approximately $2 to a little more than $20 for commercial. These figures also provide an indication of where ASR/MAR may be more attractive (higher cost water usually correlates with a greater local incentive to invest in ASR/MAR projects). While actual capital and operations and maintenance costs are going to be project-specific and sensitive to site conditions, this simple comparison suggests that MAR schemes could be economical to undertake in most Caribbean communities.

The value and overall benefit of ASR/MAR projects often include indirect benefits such as economic growth, environmental impact mitigation, improvements in public health, and improved public perception of organizations and agencies associated with the project. These indirect benefits can be a challenge to capture and monetize using traditional accounting methods. Decision analysis is a tool that can be useful for framing project benefits and quantifying the overall value of an ASR/MAR project. Where multiple projects are being considered, it can be used to capture and monetize indirect benefits and prioritize those projects with respect to the project objectives.

## 3.4 INSTITUTIONAL STRUCTURES



Water supply projects, particularly if they are intended for drinking water, must comply with local regulations and should be planned and constructed in concert with local customs, regulatory authorities, legal frameworks, and utilities (California Department of Water Resources, 2016). For example, it may be necessary in some areas to develop a tariff structure to fund the capital and/or ongoing operations and maintenance of ASR/MAR facilities and associated activities. This is sometimes referred to as a “pay to pump” scheme and is often referred to as a water replenishment fee.

**Institutional Structures:**

- Laws, regulations and ordinances
- Contracts and agreements
- Political support
- Public-private partnerships
- Governance

Public-private partnerships (PPPs) have become increasingly attractive in many countries as a way to accomplish specific projects, such as developing a new water source or increasing efficiency in water delivery while minimizing risk to the agency. Current trends are more focused on performance-based contracting with payment schemes tied to measurable metrics such as reducing non-revenue water. PPPs can be customized to meet the challenges of a particular country and can often be structured to increase technology transfer and improve local public sector expertise.

## 3.5 STAKEHOLDER ENGAGEMENT



The importance and convergence of water security, environmental protection, and tourism in the Caribbean requires that IWRM programs bring together applicable stakeholders. Given the importance of effective ASR/MAR projects to IWRM programs, stakeholder involvement should start early in the project and continue through its implementation. This is particularly critical in countries that suffer from periods of serious drought, severe climate change impacts, and have a fragile water supply. A strong stakeholder outreach program can bring together ministerial and private entities that benefit directly (e.g. utilities) and indirectly (e.g. beach water quality and public health) from ASR/MAR projects. This integrated approach to water resources management helps to secure the quantity and quality of future water supplies, protect the environment, foster economic growth, promote sustainable agricultural development, generate local interest in governance of water supplies, and promote water awareness.

## 3.6 ORGANIZATION CAPACITY BUILDING

Organizational capacity building is the process of equipping entities, usually public agencies, with certain skills or competencies, or upgrading performance capability by providing assistance, funding, resources, and training. Capacity building in this manner is important for the continued operation and long-term success of ASR/MAR projects.

# 4.0 ASR/MAR SCHEMES

There are a variety of ASR/MAR schemes, most of which have unique characteristics suited to fit a particular application. These schemes are often scalable technologies to accommodate a variety of expected flow rates. While MAR projects can be implemented from a single-family home to a watershed scale, ASR/MAR projects are typically at a larger sub-watershed and watershed scale to accommodate the higher costs typically associated with these facilities. The focus of this analysis will be at the community, sub-watershed and watershed scales, projects of a size that are larger in scale and requiring more significant investment (GWP, 2010; Pacific Institute, 2010; California Department of Water Resources, 2016; Bonilla Valverde, 2018).

## 4.1 LOW-IMPACT DEVELOPMENT (LID)

Stormwater collection and recharge is viewed as an important element of improving groundwater storage and surface water quality. In the City of Los Angeles, plans are to recharge more than 250,000,000 $m^3/yr$ of stormwater (New York Times, 2016). LID systems are an integral part of these plans. In fact, in the City of Los Angeles, the Department of Water and Power, the primary water supplier, is providing free engineering services to individual homeowners considering stormwater infiltration for their property.


**Figure 4: Stormwater Infiltration Swale, City of Paso Robles (Paso Robles Daily News, 2014)**

LID can be employed at scales ranging from single family homes through larger multi-hectare developments, and are often used when projects include a large area of impervious surfaces (such as

parking lots and roadways). In aggregate and when applied over a large area that directly recharges an unconfined aquifer, LID can have a significant impact on local water resources through the percolation of impaired or clean surface water to increase local groundwater supplies. Typical LID features include swales as shown in Figure 4 (dry, gravel or vegetated), drywells, permeable pavement systems, infiltration basins, and infiltration trenches (City of Los Angeles, 2016). While LID typically does not have a component of groundwater extraction, the benefits to the overall water supply are well established where the recharge directly recharges an unconfined aquifer.

In the U.S., LID systems are typically implemented through the permitting process as part of the construction of a new development, facility or building. While it is important to recognize the importance of LID in the IWRM program, this report focuses primarily on larger, stand-alone ASR/MAR schemes.

***Key Point:*** LID has become an integral part of IRWM plans in the U.S. as well as in other countries, to increase groundwater supply and improve surface water quality.

## 4.2 FLOOD-MANAGED AQUIFER RECHARGE (FLOOD-MAR)

Flood-MAR is a water management strategy that utilizes seasonal high flows in streams and rivers to recharge aquifers. It can be implemented at scales ranging from individual farmers diverting floodwater with existing infrastructure to using existing flood management infrastructure (See Figure 5) (California Department of Water Resources, 2018). This is a relatively new method to recharge aquifers and offers an array of benefits, in addition to aquifer replenishment and improved water supply. These benefits include flood risk reduction, water quality improvement, and climate change adaptation. The use of existing water conveyance infrastructure to take advantage of seasonal high flows can make this a low-cost recharge alternative. Clogging of the pore space from repeated percolation events over time can be alleviated through routine plowing/tilling of the fields.

Barriers to implementation include education of farmers/landowners, coordination between utilities and private parties, hydrogeological feasibility (shallow impervious clay zones), and recovery of recharged water (California Department of Water Resources, 2018). The rights to use recharged water should be considered during the feasibility phase of the project.

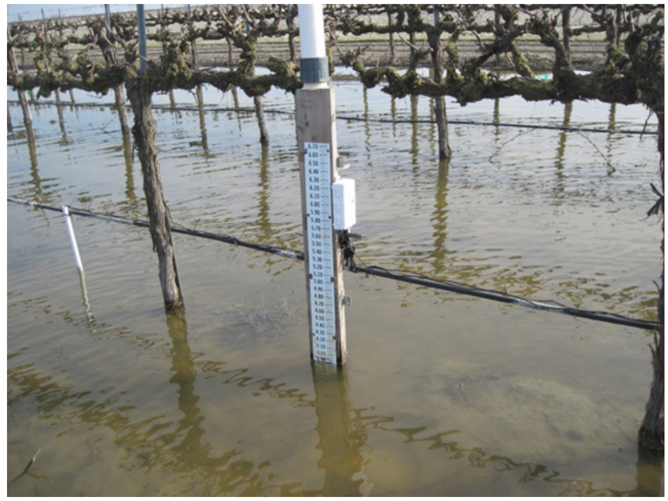

**Figure 5: Flood-MAR project in Central California (Kings Basin) Surface Water Staff Gauge (Banchard, et al, 2016)**

***Key Point:*** Flood-MAR requires strong public-private partnership coordination to be effective, but can be used to recharge large volumes of surface water.

## 4.3 INDUCED RIVER BANK FILTRATION

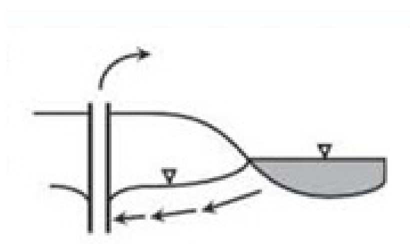

**Figure 6: River Bank Filtration (Farnsworth, 2011)**

Induced river bank filtration describes the enhanced infiltration of surface water because of pumping from a nearby well or gallery of wells (Figure 6). This type of MAR scheme is typically utilized along perennial streams or lakes as a method to improve the quality of delivered drinking water. As surface water infiltrates through the streambed and aquifer materials, it undergoes a degree of purification through the filtering process (this is sometimes referred to as geopurification). This results in a pumped water quality that is better than that of the surface water source (DEMEAU, 2018). This technique can also improve water security by reducing the pumping stress on the underlying aquifer as the extracted water is preferentially drawn from the nearby surface water source.

There are several important considerations with respect to utilizing induced river bank filtration:

- There needs to be a direct connection between the aquifer and the surface water body so that infiltration can be induced.
- The surface water body should be a perennial stream (flows year-round).
- The pumped water may still require further treatment depending on the quality of source water and the resi dence time in the aquifer.

***Key Point:*** Applicability of induced river bank filtration may be limited in the Caribbean and in many arid locations due to the lack of perennial streams and lakes.

# 4.4 INFILTRATION OR SPREADING BASINS

Infiltration or spreading basins are the most common form of ASR/MAR, and have been in use in many countries for decades (Figure 7). As such, the technology's limitations, design, construction, and operation are well understood (Bower, 2002). The source of water for spreading basins can range from routine stormwater overland drainage to seasonal high flows from streams and rivers, to treated wastewater from municipalities and industries. Geopurification of the recharged surface water is often realized during the infiltration process, depending on the chemical constituent.

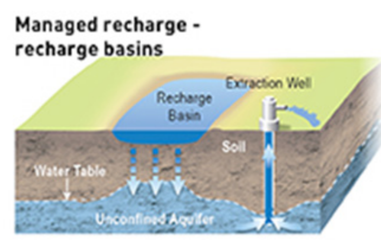


**Figure 7: Recharge (Spreading) Basins (California Department of Water Resources, 2016)**

Spreading basins are a relatively low technology, low cost option. Operations and maintenance of spreading basins are relatively straightforward, as they typically involve maintaining relatively high percolation rates by reducing soil pore clogging. One of the biggest obstacles for implementation is often the availability of suitable land in areas where the technology is feasible. Like Flood-MAR, these systems typically require adequate percolation rates, relatively thick layers of unsaturated coarse-grained sediments (unused aquifer storage), and unconfined aquifers (no overlying clay layer above the aquifer to impede percolation).

***Key Point:*** The use of infiltration or spreading basins is a well-established technology, but requires permeable shallow soils and a deeper water table (available storage) for optimal success.

# 4.5 DRYWELLS

Drywells can be part of an LID system or can be standalone structures to promote aquifer recharge in urban areas with limited space. They can also be used to promote infiltration in areas where there are near-surface impediments to percolation (low permeability soils or clay layers). Drywells are passive in that they rely on gravity rather than pumps to replenish the subsurface and usually require minimal maintenance. As such, they have a low energy footprint.

Concern has been raised regarding the potential for drywells to act as conduits to allow contaminated surface water to migrate to underlying drinking water aquifers. The placement and design of the drywell, as well as the control/treatment of fluids that enter the drywell, can alleviate many of these concerns (Edwards, 2016). This includes incorporating a suitable separation distance in the design to allow for geopurification (Figure 8).

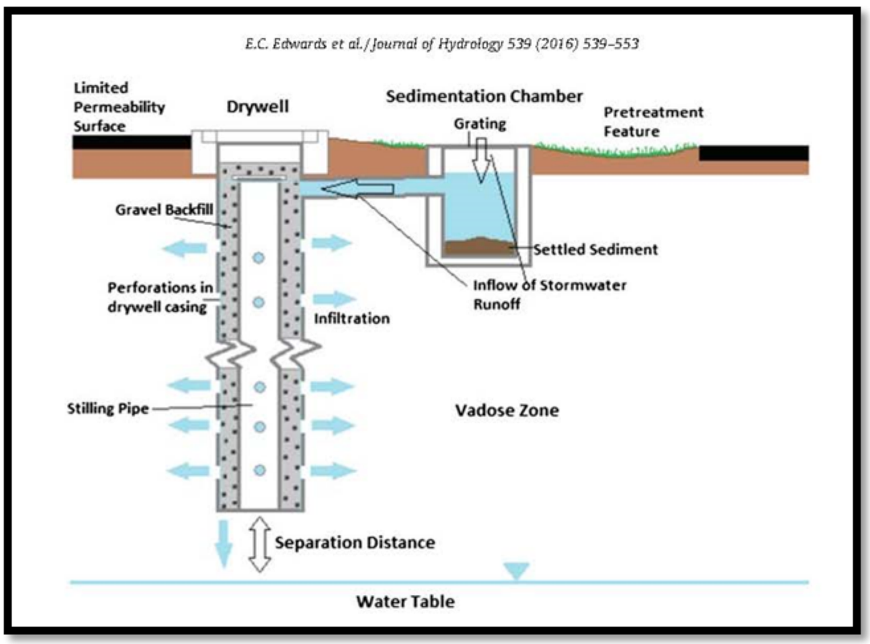


**Figure 8: Typical Drywell Design (Edwards, 2016)**

A typical drywell design consists of a large diameter borehole extending to depths up to 50 feet or more and is completed above the water table. The borehole is often cased or lined in a way to allow the passage of water laterally from the borehole into the formation. The boreholes can be mechanically drilled, or hand dug and are typically filled with gravel or crushed rock.

Stormwater pretreatment can consist of a settling basin that allows suspended sediment and fines to settle out of the water. This process can also remove metals or other contaminants that have an affinity for the fine-grained suspended solids.

***Key point:*** Dry wells can be used to enhance infiltration when shallow soils do not allow effective percolation or when there is insufficient space to accommodate the construction of infiltration basins.

## 4.6 INJECTION AND ASR WELLS

A common ASR scheme is the installation of injection wells to recharge aquifers at depth, often below low permeability clays or soils that limit downward percolation (Figure 9). These wells can be used in areas where there is limited space and can consist of one well that both injects and recovers injected water (typically called ASR wells) or stand-alone injection well that is used solely to recharge the aquifer to prevent seawater intrusion. ASR wells are often used to inject potable water into native groundwater of poor quality such as brackish water to create a zone of stored water, a significant portion (not all) of which can be extracted when needed. This can be an important source of water during emergencies or during peak water supply demand.

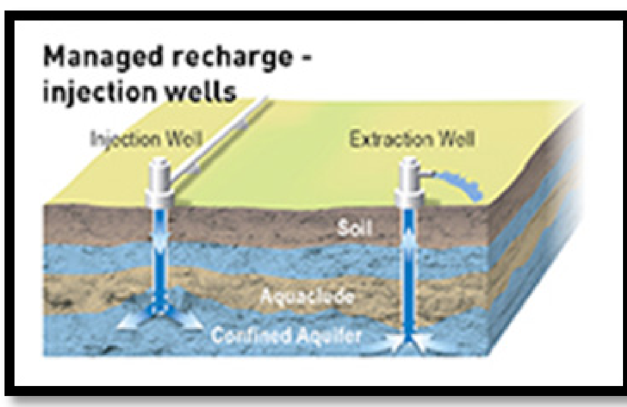


**Figure 9: Separate Injection and Extraction Wells (California Department of Water Resources, 2016)**

ASR and injection wells for enhancing or protecting the water supply have been used where geologic and/or hydrogeologic conditions do not allow surface infiltration. For example, in Figure 10, a confining layer (typically a lower permeability stratum such as clay)

would prohibit the use of spreading basins. ASR wells overcome this challenge by injecting water below the low-permeability layer.

Injection wells, including ASR wells, are subject to clogging and typically require careful monitoring and periodic cleaning to remove particulate matter (e.g., clays and fine-grained mineral precipitates), microbial biofilms, and mineralization. Reasons for clogging and the various methods to rehabilitate the plugged wells are well-understood, and pre-treatment of source water can significantly alleviate the severity of clogging. These rehabilitation methods include mechanical cleaning, chemical treatment, and disinfection, often applied in combination. Prior to selecting a rehabilitation method, proper diagnosis is necessary.

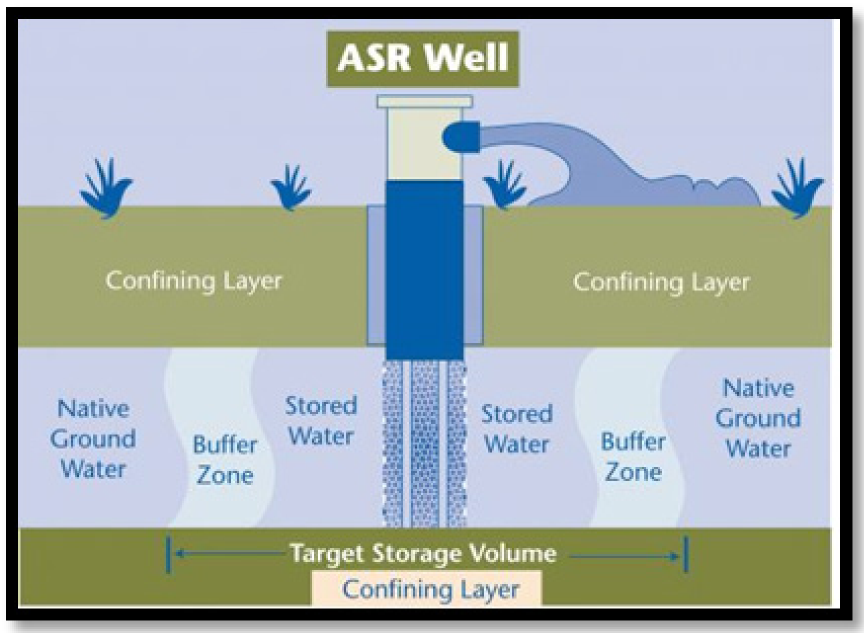


**Figure 10: ASR Wells (City of Tulatin, 2018)**

Interactions between the injected water and aquifer matrix can lead to water quality problems with recovered water. Brown (2006) reports in his review of ASR projects that multiple sites experienced water quality challenges, ranging from formation of disinfection by-products (e.g. haloacetic acids and trihalomethanes), to mobilization of heavy metals (e.g. arsenic, manganese, and nickel).

It is important to establish and maintain a buffer zone between native water and stored water (Figure 10). This reduces operations and maintenance costs, improves extraction efficiency, and

reduces water treatment costs. Creating this buffer zone usually requires a one-time addition of stored water that is left in-place (Pyne, 2015). Augmentation of this buffer zone may be required over time as the water quality in the zone declines. Finally, it is important to understand the lateral movement of groundwater in the target zone. If the injected water migrates away from the ASR well during the storage period, the project may not be feasible.

Historically, ASR has been used extensively in coastal areas such as southern Florida, a region with hydrogeologic conditions similar to part of the Caribbean (e.g. coastal limestone aquifers). ASR wells have been used to provide an alternative to surface water supplies and help restore the Everglades ecosystem and reduce saltwater intrusion (Reese, 2002). Similarly, injection wells using highly treated wastewater have been used to limit seawater intrusion, protect coastal freshwater sources, and replenish depleted aquifers for decades in areas such as Southern California and Barcelona (Orange County Water District, 2015; Water Replenishment District of Southern California, 2016); Martion-Alonso, J. (2016).

***Key Point:*** ASR wells have been used successfully to store potable water in brackish or saline aquifers. However, they require careful management to optimize the benefit and overall efficiency (ratio of abstracted volume over recharged volume).

## 4.7 STREAMBED MODIFICATION

Streambed modification includes a variety of technologies that are employed to promote seepage of surface water from natural water courses into the subsurface to replenish the groundwater supply. These methods fall into two general categories: 1) regulating the volume, slowing or otherwise controlling the surface water flow to promote residence time and maintain the infiltration wetting front in the soil, and 2) enhancing streambed seepage rates (California Department of Water Resources, 2016). These are some of the oldest methods to promote groundwater recharge and have been used worldwide.

Regulating or controlling surface water flow can be achieved using a variety of methods, including: 1) regulating dam releases to maximize seepage and 2) installation and operation of rubber dams (Figure 11), check dams or weirs to slow and pool surface water along reaches of rivers amenable to percolation (Figure 12). Streambed seepage rates are enhanced by routinely removing fine grained sediments and biological buildup from the streambed. This is sometimes referred to as scarifying the streambed.

**Figure 11: A Rubber Dam Fully Inflated (Orange County Water District, 2016)**

**Figure 12: Streambed Modification in New Mexico to Promote Groundwater Recharge (US Water Alliance, 2016)**

Advantages of this method include ready access to surface water supplies and the ability to infiltrate large volumes of water at a low capital cost. Disadvantages include the need for routine scraping, cleaning and tilling of the streambed to remove fine-grained material and biological buildup, downstream stakeholder concerns, and potential environmental impacts. This method is most practical where access to the stream bed is routinely available, such as in arid landscapes with ephemeral streams or channels/canals that can be periodically emptied and percolation rates restored.

***Key Point:*** Streambed modification can often be the most effective method to infiltrate the largest volumes of surface water but may require extensive permitting and stakeholder engagement.

# 5.0 ASR/MAR PROJECT DECISION TOOL

The site selection, feasibility, and development of ASR/MAR projects requires the consideration of a large number of technical elements. A systematic, hierarchical decision flowchart has been developed to assist with this process (Figure 13). The basis for this flowchart was developed from published conceptual flow/decision diagrams (GWP, 2010) and the decision framework provided in the code of practice for ASR projects (EPA, 2004), both of which have their basis in the work done by Dillon and Pavelic (1996). The flowchart identifies important questions and decision points that should be addressed during the project planning phase and when reviewing a project for potential approval.

This decision tool does not explicitly consider institutional structures, stakeholder involvement, or organizational capacity building. These can be addressed outside the project decision analysis task. For example, a stakeholder communication plan is often prepared, sometimes as a stand-alone document. It may include a formal process for stakeholder outreach and involvement in the decision-making process.

Figure 1 has been divided into two parts for ease of discussion. The first part, Figure 14, provides the decision flowchart from project inception (determine demand for stored water) through MAR technology selection. This is often regarded as the Hydrogeologic Feasibility phase. Key project decision points are indicated where the project feasibility cannot be assured (a hard stop), or where additional data needs to be gathered and analyzed to assess project feasibility (data gap analysis). The second part, Figure 15, provides the decision flowchart through the engineering evaluation phase and is regarded as the Engineering Feasibility phase. The project moves forward to Engineering Feasibility only if it passes Hydrogeologic Feasibility.

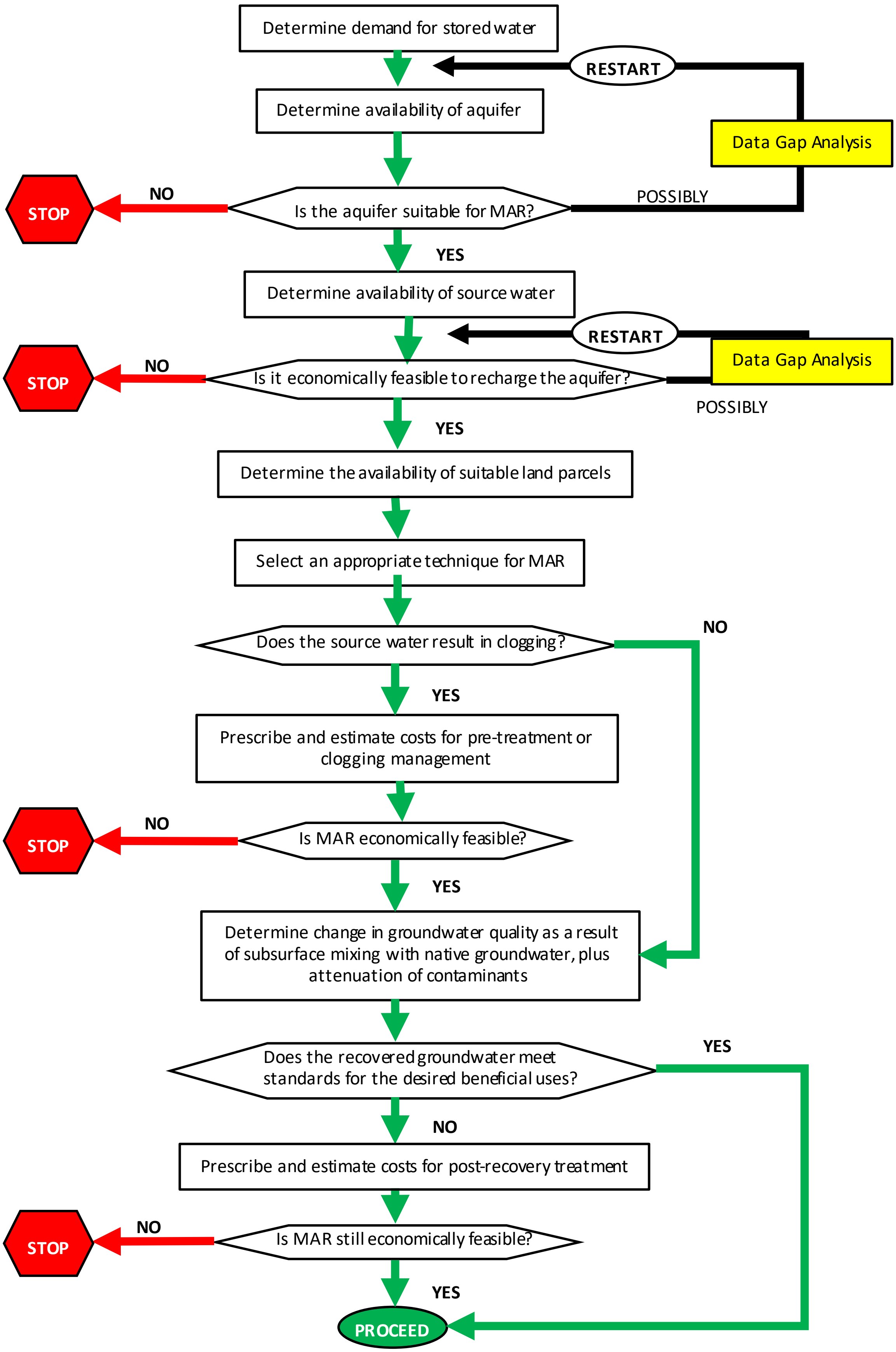


**Figure 13: Decision Flowchart**

# 5.1 HYDROGEOLOGIC FEASIBILITY

Hydrogeologic Feasibility analysis establishes that the subsurface conditions are appropriate for the intended project, that a suitable surface water source is available, that a MAR scheme can likely be successfully applied, and that the project can move forward to the engineering analysis phase. Two key decision points are identified in the Hydrogeologic Feasibility process (Figure 14).

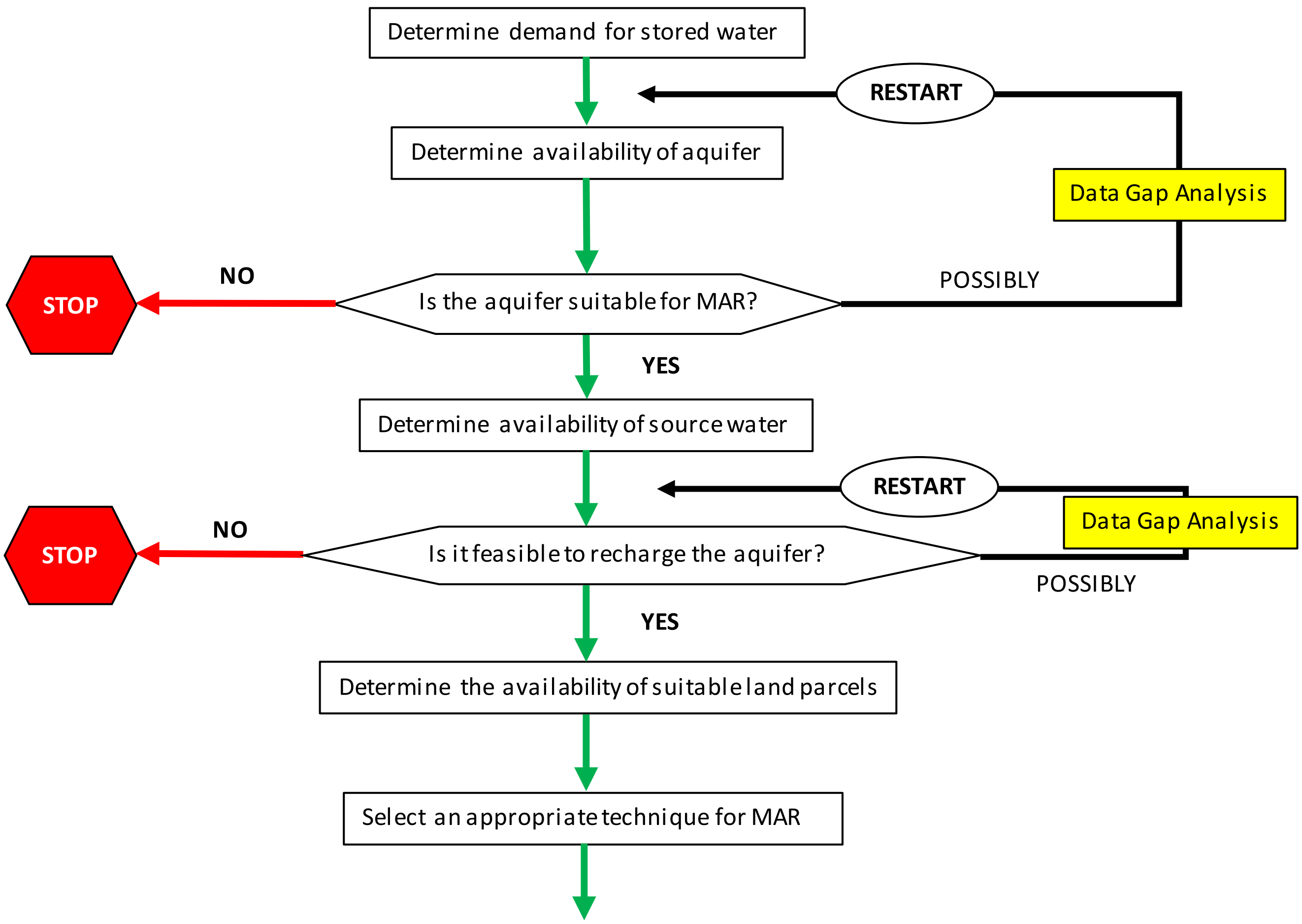


**Figure 14: Hydrogeologic Feasibility and MAR Scheme Selection**

The first decision point is a determination regarding whether there is a suitable aquifer available for subsurface water storage. If there is not a suitable subsurface reservoir, the MAR project will not be successful. Factors considered in this decision include the nature of the subsurface conditions (e.g. aquifer porosity, permeability) and whether storage is available or whether it can be created by pumping and drawing down the aquifer.

The second decision point is whether there is a sufficient quantity of recharge water available, when it is available, its quality, whether that water can be successfully recharged, whether the recharge will achieve project objectives (e.g. improve the drinking water supply, mitigate seawater intrusion), and whether the recharge will result in any detrimental outcomes (such as flooding, excessively high groundwater elevations, or groundwater degradation). A pilot test is recommended to evaluate field conditions. If project objectives include extraction of stored groundwater to meet an agricultural or domestic need, an evaluation of groundwater extraction should be included. Typically, the analysis outlined in Figure 14 is provided in a hydrogeologic feasibility analysis report.

At two points in the decision flowchart, a possible outcome is that the existing dataset doesn't fully address whether MAR is hydrogeologically feasible. Additional data, testing, and/or analyses may be needed to address the uncertainties in a Data Gap Analysis. For example, it may be unclear how high the water table will rise under recharge conditions and whether the increase in the groundwater elevation could result in excessive flooding. Pilot testing and a groundwater model may be required to address this issue.

Often, there is limited publicly available information regarding subsurface hydrogeologic conditions, making the development of a hydrogeologic feasibility analysis challenging without an expensive drilling and investigation program. Local or regional universities may be a source of useful information in such a scenario. In addition, a variety of techniques, such as surface geophysics, are available that can be used to characterize subsurface conditions while minimizing drilling and investigation costs. Finally, many islands historically enjoyed a local groundwater supply that became unusable over the years due to seawater intrusion, pollution, and/or neglect. This indicates that an aquifer exists, and that ASR/MAR may be useful in rehabilitating this historical resource.

Costs of implementing a hydrogeologic feasibility study are site specific and depend on the ASR/MAR scheme, the project objectives, and the availability of historical information regarding the soils, geology, and aquifer. For a simple spreading basin project using natural water in an area where subsurface data is available, the hydrogeologic feasibility analysis and report can be under $100K.

# 5.2 ENGINEERING AND FINANCIAL FEASIBILITY



The second part of the decision flowchart, Figure 15, consists of the project engineering and financial analysis. This phase of the analysis identifies the likely costs, constructability of the project, and whether the project is financially feasible. Financial feasibility focuses on: 1) the costs to treat the water before it is recharged to remove contaminants, meet regulatory requirements, or to prevent clogging; and, 2) the cost to treat the water after it is recovered to meet drinking water requirements or other project objectives.

Project benefits should include the direct benefits, such as an increase in the domestic or agricultural water supply or mitigation of

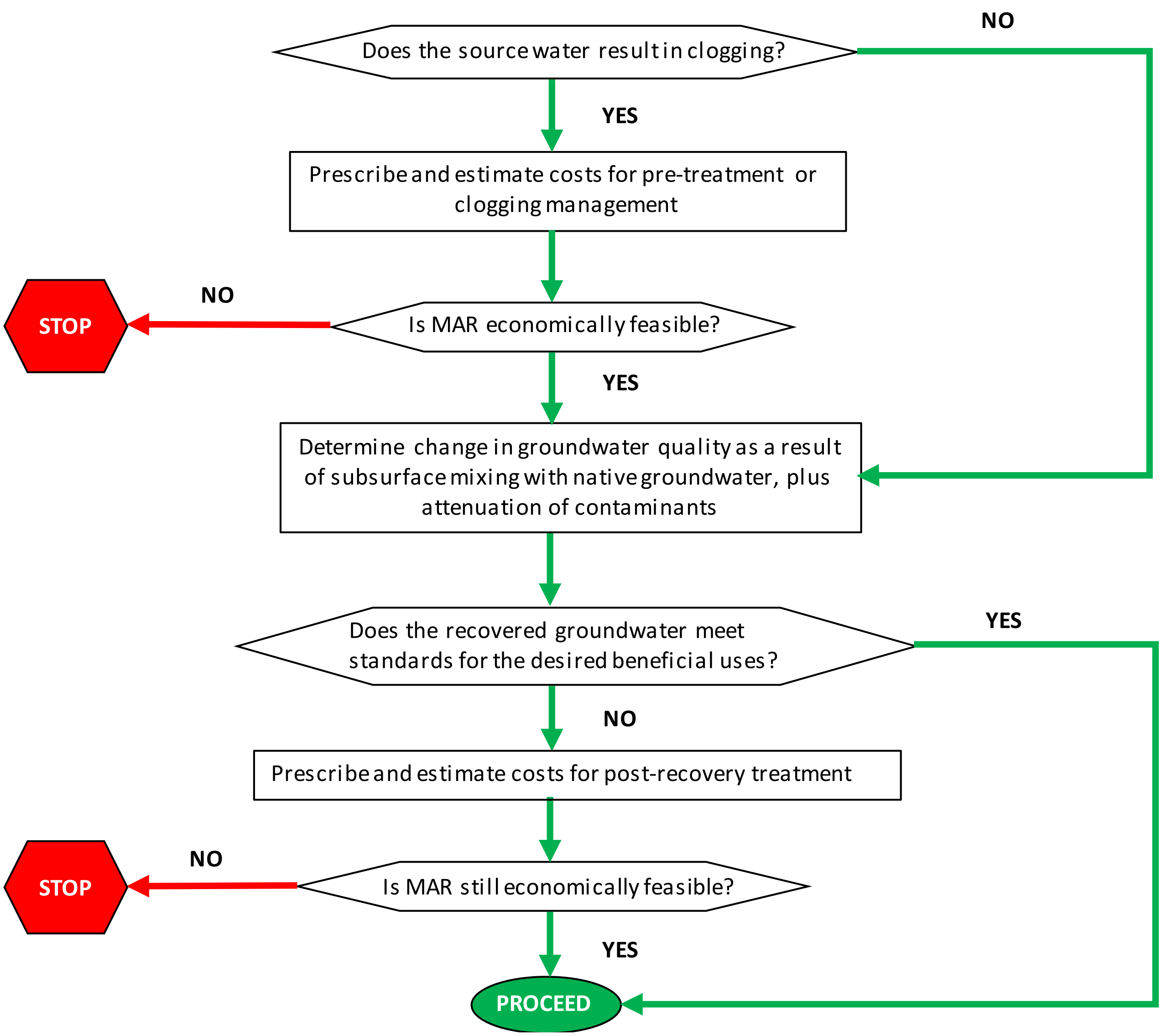


**Figure 15: Engineering and Financial Feasibility**

saltwater intrusion. Secondary project benefits, such as improved public health, disaster response (alternative water supply), and economic growth may also be considered quantitatively as part of the cost analysis or qualitatively. Stakeholder outreach and involvement can help identify these secondary benefits and establish their value. The use of multi-criteria decision analysis is a growing area and several papers provide an overview of the technique (Schloten, et. al, 2017; Moglia, et al, 2012).

## 5.3 CLIMATE CHANGE

Climate change presents a challenge in the planning and execution of long-range IRWMs in that the degree of uncertainty in climate-related factors such as precipitation patterns and amounts and drought frequency increases significantly with time (Larson, et al, 2015). A typical climate change predictive analysis is shown in Figure 16. The figure depicts the increasing range in response outcomes and uncertainty with time.

For individual ASR/MAR projects, the impact of climate change uncertainty makes the need for robust conjunctive use projects more acute. With respect to the future impact of climate change on a project, an adaptive management approach in the design and operation of a ASR/MAR may be appropriate given the uncertainty in forecasting future hydrologic conditions. When presented with choosing a limited number of projects from a portfolio of possible projects, a priority may be placed on those projects that present the greatest opportunity to mitigate effects of climate change.



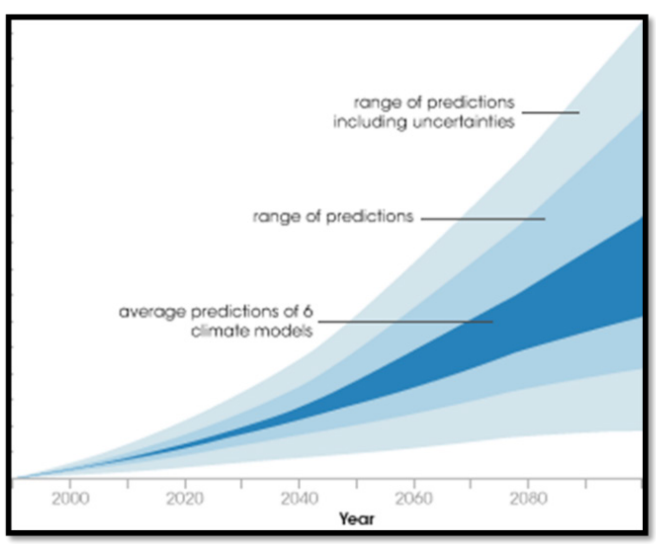


**Figure 16: Climate Change Predicive Uncertainty (NASA, 2005)**

# 6.0 CASE STUDIES

A summary of case studies covering a range of technologies and applications can provide insights on the ASR/MAR systems, as well as their positive impacts and challenges. Where available, cost summary information is included.

Numerous references to ASR/MAR projects were identified in the literature; however, detailed technical and cost information was not available through public sources. For example, injection wells and a recharge dam are reportedly used in Cuba to recharge run-off and prevent seawater intrusion into a karstic (limestone) aquifer; however, little detailed information was available for review. Other projects were noted in Costa Rica, Colombia, Mexico, and Brazil.

Example projects highlighting various technologies and applications are described to provide a range in the technical issues encountered. Several summary papers are presented that reviewed a larger suite of projects and provided a discussion of lessons learned.

## 6.1 JAMAICA – AGRS INNSWOOD (IDB FUNDED CONSTRUCTION)

Water resources in Jamaica are provided from both surface water and groundwater. The domestic supply is equally provided by groundwater and surface water, while irrigation water is about 60% surface water and 40% groundwater. Jamaica is susceptible to severe droughts and, as the whole of the Caribbean, recently experienced an extremely dry period between 2015 and 2017. In addition, overall groundwater supply has diminished by approximately 5%. The Jamaican government identified the need to invest in their water systems to improve resiliency and make the supply less susceptible to climate change and drought.

In mid-2014, Jamaica constructed its first MAR project and has been operating the Artificial Groundwater Storage and Recovery (AGSR) facility at Innswood, Jamaica since 2016 (Figure 17).

**Figure 17: AGSR, Innswood, Jamaica (Google Earth, 2018)**

AGSR project objectives include reversing seawater intrusion, increasing aquifer storage, helping sustain the extraction of 73,000 $m^3$/day, and alleviating potable water restrictions during drought. The 68-acre project is in a rural area approximately 22 km west of Kingston's city center. Site selection was based on underlying aquifer characteristics, availability of source water, ability to recharge and extract large volumes of water, and overall potential risk. Operations include an intake structure, control structures and flow meters, settling (sedimentation) basins, and wetland beds to treat the water, pipelines and recovery wells. Source water consists of excess surface water delivered via an irrigation canal. Construction costs for the project were approximately $8.2M, with about $393K in consulting and project management costs (total roughly $8.6M).

The facility is designed to treat and recharge a maximum of 36,000 $m^3$/day but on average treats and recharges about 23,000 $m^3$/day at an annual operational cost of $70K/yr. Normalized capital costs are $\$8.6M/(23,000 \times 365) = \$1.02/m^3$. This compares reasonably well with the costs in Table 2 ($0.77/$m^3$ for recharge basins with natural water). AGSR O&M costs are very low ($0.01/$m^3$) and more than an order of magnitude lower than those cited in Table 2 ($0.17/$m^3$); however, the MAR is relatively new and O&M costs should be regarded as preliminary.

The project operates under gravity flow minimizing energy requirements and the carbon footprint. The Jamaican Water Resources Authority (the Authority) has recently put in place a groundwater monitoring program to track the measured increase in groundwater elevations and changes in water quality. The project benefits the water supply and the Authority indicated that it did not encounter any significant obstacles during planning or construction. The Authority has indicated that it would be interested in building and operating additional MAR projects.

# 6.2 SONORA, MEXICO – MAR WITH TREATED MUNICIPAL WASTEWATER

Like many countries with large arid regions, Mexico has a chronic shortage of groundwater, with an estimated 106 aquifers in serious depletion in 2013. Management of an integrated water supply is necessary to better achieve sustainability. This MAR project was undertaken to reduce the costs to dispose of treated wastewater and recharge the underlying aquifer, which was overexploited (overdrafted) by roughly 7,500,000 m$^3$ on an annual basis. Project funding was supported by the North American Development Bank (Humberto, 2017).

The project is in San Luís Rio Colorado (SLRC), located in the northwest corner of State of Sonora. SLRC has a population of nearly 200,000 and overlies a depleted aquifer. Rainfall averages about 55 mm/year, nearly 30 times less than the evaporation rate. The geology of the area appeared conducive to MAR, with a thick layer of intermingled gravels, sands, and silts. Groundwater underlying the project has a total dissolved solids (TDS) content of a little less than 1,000 mg/L.


Pilot tests were undertaken to estimate the infiltration capacity by constructing a pilot test infiltration basin, installing monitoring wells, and infiltrating clear water followed by treated wastewater (Figure 18). Infiltration rates in the pilot test decreased substantially in a short period of time when using reclaimed water due to pore clogging.

Following the pilot test, 115,200 m$^2$ of infiltration ponds were constructed, accommodating an average volumetric load of 5,200 m$^3$/day in winter and 8,600 m$^3$/day in summer. Routine monitoring of the underlying native groundwater is required by the environmental regulatory agency (SEMARNAT). Monitoring indicates an increase in TDS and several other parameters, likely as a result of recharge activities through saline soils (i.e. TDS of 1700 mg\L has been identified in shallow groundwater). The vadose zone appears to be effective in removing bacteria in the percolating surface water (geopurification).

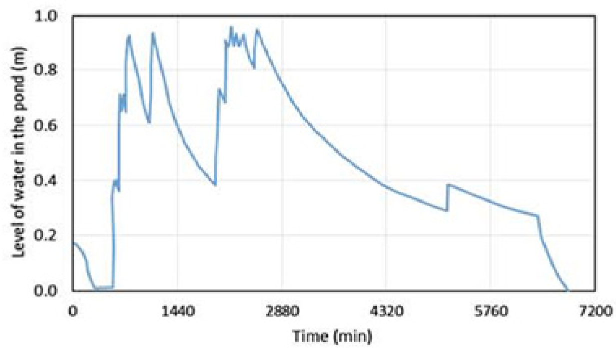


**Figure 18: Pilot Test Infiltration Rate Treated Wastewater (Humberto, et al, 2017)**

Maintenance is performed routinely as algae, dead algae, and sediments clog pore spaces, quickly reducing the infiltration rate. The pond is taken out of operation and upper crust (0.15 m) is physically removed from the infiltration pond and used as a soil amendment (Figure 19). Initially, the crust was not removed but simply tilled into underlying soil. This resulted in a substantial decrease in infiltration rates. Removal of the clogging layer has helped slow this decline in infiltration. Simply plowing the soils is not recommended.

**Figure 19: Soil Crust (Humberto, et al, 2017)**

The infiltration rates are closely monitored to identify when the ponds require rehabilitation. On average, ponds are scraped every two to three wetting/drying cycles. The ponds have been operating a total of 10 years and recharge on average 8,200,000 $m^3$ per year of secondary treated wastewater (accounting for evaporative losses of 1.5 m/year). This more than offsets the overexploitation of 7,500,000 $m^3$. Capital and operation and maintenance costs were not available for this project.

# 6.3 KINGS COUNTY, CALIFORNIA, USA – WATER BANKING USING EXCESS STREAM FLOWS

The Kings River groundwater basin in California's San Joaquin Valley is severely depleted due to over-pumping for agricultural use. This has led to chronic drops in the water table and significant subsidence. The Apex water bank near the Kings River was constructed between 2003 and 2009 to harvest excess flows in the Kings River, store them underground, and recover stored groundwater at a later date.

After an extensive investigation, this location along the Kings River was chosen for the APEX water bank based on its proximity to the water source, an existing nearby conveyance system, and suitable hydrogeologic conditions. A nearby abandoned river channel was selected as the recharge basin, which would be outfitted with low head dams to create recharge ponds. A hydrogeologic investigation, aquifer testing, and a pilot test were completed. A project design was developed based on their results, and groundwater extraction wells, dams, pipelines, flow meters and surface water weirs were installed. Routine maintenance includes cleaning the spreading ponds to maintain infiltration rates.

**Figure 20: Recovery Well and Construction of a Conveyance Pipeline (From Author's Archive)**

On average, 7,000,000 $m^3$ of surface water per year are recharged into the depleted aquifer and up to 90% of that recharge volume is extracted with recovery wells. Annual reports are prepared that account for water recharged and extracted and the groundwater in storage. River water quality is excellent, with an average TDS of less than 100 mg/L.

Two of the most significant lessons learned in building and operating this water bank included: 1) the value of good stakeholder communication during project design and implementation and 2) the importance of accurate accounting of groundwater in storage. Addressing these areas more directly and thoroughly would have likely improved acceptance of the project by the neighboring landowners. Finally, the system configuration and operations and maintenance have been modified over time to reflect performance data. An adaptive management strategy would have provided a better platform for managing stakeholder expectations.[11]

Capital costs to construct the water bank were approximately $8.2M, or $1.17/m$^3$ of water recharged ($8.2M/7,000,000).[12] Average normalized capital costs in Table 2 were $0.77/m$^3$ of water recharged. Annual costs to operate the water bank are $1.6M or $0.23/m$^3$ of water recharged ($1.6M/7,000,000). This is higher than the O&M costs cited in Table 2 for recharging natural water ($0.13/m$^3$ using infiltrations basins and $0.19/m$^3$ using recharge wells). These costs are off-set by the price of the water sold from the water bank, $0.45/m$^3$.

## 6.4 HILTON HEAD ISLAND, SOUTH CAROLINA, USA – ASR AND CONTROL OF SEAWATER INTRUSION

Hilton Head Island, off the coast of South Carolina, is approximately 19 km long and up to 6 km wide. The island is heavily developed, with a permanent population of 37,000 that can swell to 275,000 during peak tourist season. Drinking water is provided by 27 groundwater wells completed in an underlying limestone aquifer. The aquifer naturally discharges to the sea. Regional pumping has lowered the groundwater elevations and seawater intrusion has been advancing inland at a rate of about 60 meters/year. This has resulted in the loss of approximately 25% of the groundwater supply wells due to lateral advancement of the seawater front and upconing of brackish water. Water use restrictions were put in place to slow the progression of seawater intrusion.

11 Adaptive management includes monitoring performance, learning from decisions, and adjusting operations and expectations to optimize the result.

12 Capital costs are $0.15/m3 higher than those for the AGSR project in Jamaica ($1.02/m3).

However, the rate of intrusion has persisted. A pipeline has been installed from the mainland to the island and a desalination plant was constructed and began operating in 2009. ASR was evaluated as a potential source of water, particularly to meet seasonal peak demand (Pyne, 2015).

ASR wells were completed in an aquifer zone where lateral migration was limited, keeping the injected water in close proximity to the ASR well while the water was in storage. Testing was performed to evaluate the efficiency of the recharge extraction process (the efficiency in the percentage of injected and stored water that can be recovered). A key element of the success of this project was the development of a "buffer" zone around the ASR well (Figure 8). Maintaining this zone provided for higher rates of recovery of the stored water.


**Figure 21: Hilton Head Island (Pyne, 2015)**

Capital costs for the ASR facilities were $1.9M. The design recovery capacity is 8,000 $m^3$/day. This yields a normalized capital cost of $0.65/$m^3$. Brackish water desalination by comparison is typically 2.5 to six times the capital cost and seawater desalination is eight to 14 times the capital cost of ASR.

# 6.5 KINGS COUNTY, CALIFORNIA - FLOOD-MAR AT TERRANOVA RANCH

Flood Managed Aquifer Recharge (Flood-MAR) is a relatively new technology that is only recently being implemented, primarily in California's Central Valley. A new project is currently being implemented along the Kings River in the San Joaquin Valley to offset severe groundwater overexploitation in the underlying aquifer. The project consists of capturing seasonal high flows in the Kings River and flooding fallow or flood resistant crops (nut trees and vineyards) and allowing this water to percolate into the subsurface. This project also alleviates potential flooding damage to downstream communities.

Pilot tests were conducted on 1,000 acres of farmland by flooding the entire area to a depth of 15 to 30 centimeters. Pilot tests assessed infiltration rates, infrastructure requirements, logistics, crop effects, and costs. In total, nearly 4,000,000 $m^3$ of water were diverted onto 1,000 acres of farm fields between January and April. The amount of water that could be diverted during this period was limited by the conveyance infrastructure. No significant impact on crop yields were identified and none are expected over the long term.

**Figure 22: Pilot Testing (California Department of Water Resources, 2018)**

Costs to capture and apply the flood flows were approximately \$0.02/$m^3$ compared to dedicated recharge basins, which cost up to about \$0.90/$m^3$. Costs to pump groundwater are typically on the order of \$0.05 to \$0.10/$m^3$ (depth to water is around 65-70 meters below the ground surface) (Banchard, 2016).

# 6.6 ORANGE COUNTY, CALIFORNIA – ASR AND SEAWATER INTRUSION CONTROL USING RECYCLED WASTEWATER

Orange County Water District (OCWD) in Southern California manages the water supply for approximately 2.4 million people. The water supply consists of approximately two-thirds groundwater and one-third imported water. The cost of groundwater is approximately 50% of that of imported water. Imported water is water that originates from outside the groundwater basin and is provided by a third party.

The primary source of recharge to the Orange County groundwater is the Santa Ana River, whose flows consist of stormwater and treated wastewater from upstream municipalities. OCWD captures and recharges approximately 185 million $m^3$/year of river

water through its array of recharge basins and 57 million $m^3$/year of recycled water is recharged through 109 injection wells used to control seawater intrusion and replenish the aquifer. This was the first facility in California allowed to inject recycled water into a potable aquifer. The barrier injection wells have been effective in preventing further seawater intrusion.

Wastewater is treated using a combination of treatment technologies prior to injection. These technologies include microfiltration, reverse osmosis, and advanced oxidation using ultraviolet light and hydrogen peroxide.

Due to the advanced treatment of the wastewater, resulting water was depleted in mineral content, which in turn resulted in deterioration of the concrete conveyance pipeline and mobilization of arsenic in the soil underlying the recharge basins. Effluents from the advanced water treatment plant are conditioned prior to conveyance to the recharge facilities to mitigate this impact.

The capital cost to build the advance wastewater treatment system was $481M ($8.4/$m^3$ of recharge capacity).[13] The unit cost of producing water from the advanced treatment system is $0.72/$m^3$. These costs are comparable to those identified in Table 1. The cost to treat the wastewater is equivalent to the cost of importing water (Herndon, 2014).

**Figure 23: Recharge Spreading Basins, Orange County, California (Orange County Water District, 2015)**

13 Building the treatment plant avoided the need for a new sanitary sewer ocean outfall ($200M) by reducing the flow to the outfall. These flows replenished the groundwater supply.

# 6.7 BARCELONA, SPAIN – LLOBREGAT AQUIFER, BASIN INFILTRATION AND DEEP WELL INJECTION

The Llobregat aquifer in Barcelona is an important source of agricultural, industrial, and drinking water, particularly during dry periods. Overexploitation of the aquifer has led to decreasing groundwater levels and seawater intrusion. Over the last several decades, a variety of projects have been installed to improve the sustainability of this important resource. These projects include routine scarifying of the riverbed at specific locations to encourage recharge, spreading basins (ponds), ASR wells, and a seawater hydraulic barrier.

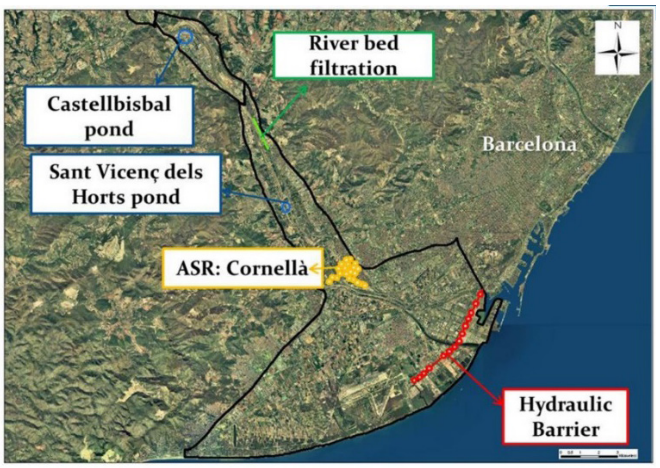


**Figure 24: MAR Features in the Llobregat River and Delta (Martin-Alonso, 2016)**

Spreading basins have been constructed and operated along the Llobregat River to recharge river water and treated effluent from the tertiary wastewater treatment plant (WWTP). River water is treated using sedimentation basins to reduce potential clogging and water quality is monitored for turbidity, conductivity, and ammonia. The estimated recharge to the aquifer from these basins is 6M to 10M $m^3$/year.

ASR wells are also used to inject, store, and extract pre-potable water. Source water is derived from the intermediate stage of a drinking water treatment plant after sand filtration. Injection rates are 2.2 $m^3$/min and extraction rates are 13.2 $m^3$/min.

Various studies have been implemented to assess the impact of using the partially treated water, including clogging potential, on well screens and aquifer water quality.

Deep well injection is also used in the Llobregat aquifer in an effort to control seawater intrusion. Tertiary treated wastewater from the WWTP undergoes further treatment at the hydraulic barrier prior to injection using reverse osmosis (reduce TDS), UV disinfection, and ultrafiltration (reduce fouling and clogging potential). After treatment, the effluents are injected using a 15-well linear array approximately 1 km inland of the sea and paralleling the shoreline. Injection rates of 2,400 to 10,000 $m^3$/day were utilized during testing of the barrier system. This water is pumped and used for industrial and domestic supply. The project has resulted in increased groundwater elevations and reduced salinity. Treatment has minimized clogging of the injection wells (DEMEAU, 2014).

## 6.8 LOS ANGELES, CALIFORNIA – WATER REPLENISHMENT DISTRICT (WRD)

The WRD of Southern California has many ongoing programs intended to increase sustainability of fresh water resources in their 420-square-mile region of southern Los Angeles County. The 43 municipalities in their service area use about 310M $m^3$/yr. The WRD is currently working on its Water Independence Now (WIN) program to become independent from imported water for recharge operations.

**Figure 25: Tertiary Wastewater Treatment Plant, Recharge Basin, and Water Inlet Structure** (Water Replenishment District of Southern California, 2016)

WRD projects range from advanced treatment of recycled water for injection into seawater intrusion barriers to groundwater replenishment using stormwater at several large spreading (recharge) areas.

WRD has well-established data collection, engineering, water conservation and community outreach programs. They have developed groundwater computer models to routinely test how changes in replenishment operations, climate, demand, or other factors impact their operations.

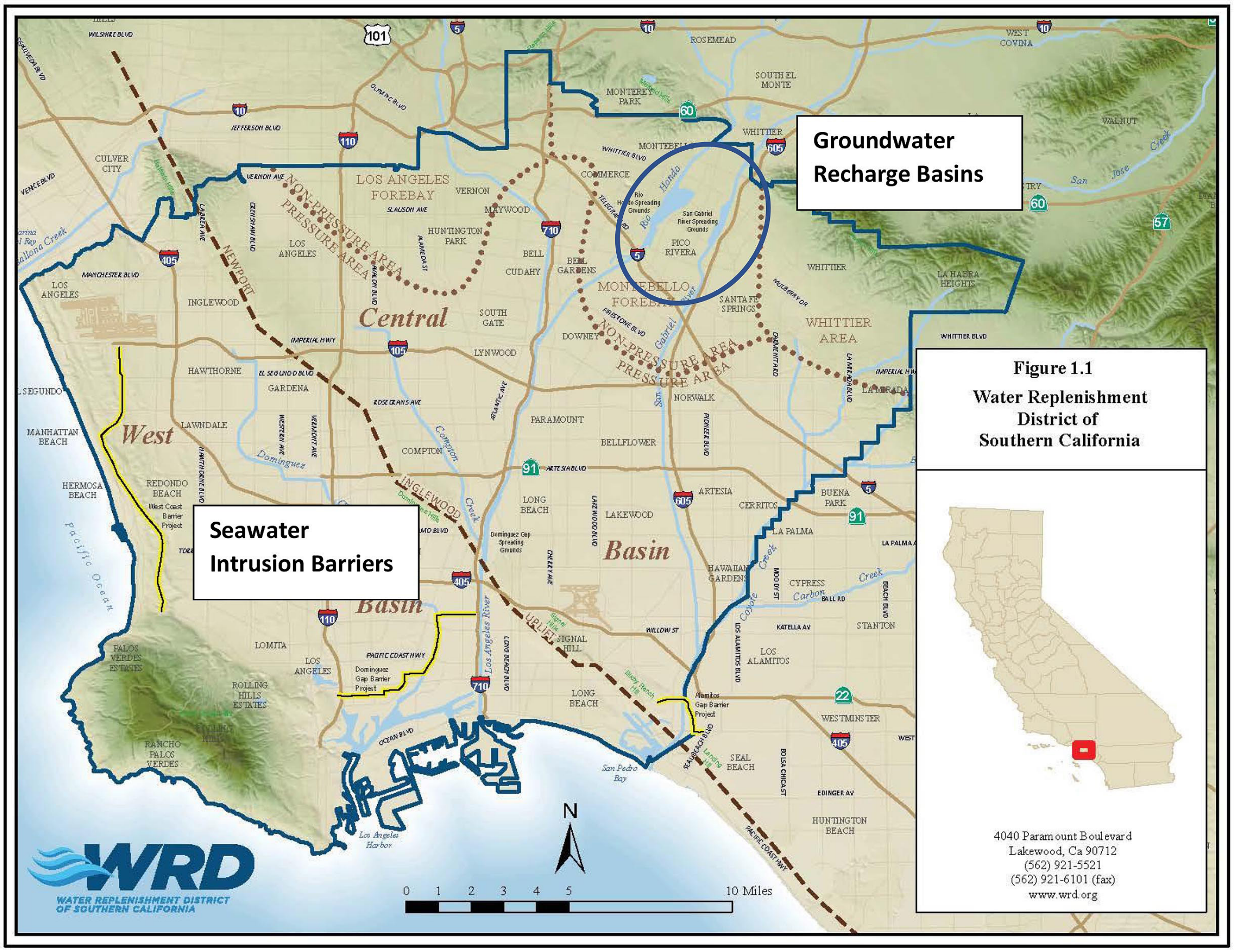


**Figure 26: Water Replenishment District Service Area and MAR Features Water Replenishment District of Southern California, 2016)**

# 6.9 PUERTO RICO, MAR OF THE SALINAS AQUIFER

The Salinas Aquifer in southern Puerto Rico has been heavily exploited for domestic and agricultural use for many years, resulting in groundwater overdraft, seawater intrusion, and impacts to nearby sensitive environmental receptors. A drought in 2015 exacerbated conditions.

The U.S. federal government under FEMA subsidized a successful MAR project to replenish the aquifer by regulating the releases from a nearby reservoir and promoting recharge through existing irrigation canals. The project coordinators involved local stakeholders to develop and implement the project. The project cost effectively utilized existing water infrastructure and required minimal new construction.

A video prepared by FEMA provides an overview of the project from inception to implementation. The video can be found at:

https://www.youtube.com/watch?v=EpmMXbuv2Go.

# 6.10 USA, ENGLAND, AUSTRALIA, INDIA, AND AFRICA – ASR LESSONS LEARNED

A total of 50 ASR projects located in the USA, England, Australia, India, and Africa were reviewed by the University of Florida and U.S. Army Corps of Engineers to compile performance information on different applications of ASR technology (Brown, 2006). Projects reviewed included ASR applications in 30 brackish water sites (freshwater injected into a brackish aquifer) and 20 freshwater sites (freshwater injected into a freshwater aquifer). Of the 30 brackish sites reviewed, 21 were in Florida. Receiving aquifers ranged from fractured rock (basalt, chalk, and limestone) to sandstone, sands, and gravels.

The authors draw four major lessons learned from their review of the 50 individual projects. These are summarized below:

***Well Clogging:*** Well clogging was identified at 65% of the fresh water sites. Clogging can be ameliorated by back flushing (pumping) the well to remove particulate matter. Sand aquifers may require frequent (nearly daily) back flushing, while fractured or limestone aquifers may require infrequent back flushing. Air entrainment can plug the well. Air can be introduced into the aquifer if water free falls in the well or if dissolved gases are released due to changes in pressure and temperature of the receiving aquifer. Removal of air in the aquifer can be difficult. The need to backflush is typically identified by closely monitoring injection pressures (injection pressures increase with clogging) or decreasing specific capacity of the well (injection rates divided by the water elevation in the injection well).

***Mixing of Different Water Quality:*** The injection of oxygenated water into an aquifer of depleted oxygen (a common occurrence) or with a significantly different water quality can result in reactions with the aquifer matrix that can release metals such as arsenic, iron, and manganese into the water. A chemical profile of the water being injected and receiving water should be done to assess potential impact of the injection on water quality of the mixed waters.

***Well Interference and Well Hydraulics:*** Well interference occurs when multiple wells are located in the same general proximity. Injecting or recovery from one well may impact the performance of the other well or wells in the well field. Similarly, if there are other groundwater users in the area the injected water may be drawn into non-ASR project wells. Sometimes the injection can lead to unwanted increases in the area's groundwater elevation, as well as potential impacts to third parties. High volume ASR project recovery wells may also have unintended impacts on other nearby groundwater users, drawing their water levels down and increasing their pumping costs, reducing their yields, or worse, causing their wells to go dry. Placement and monitoring of observation wells can be an early warning indicator of unintended ASR operation consequences.

***Develop and Implement a Robust ASR Monitoring Program:*** Allow for sufficient monitoring points in the subsurface and for above-ground facilities so potential problems can be identified and accurately diagnosed as early as possible. Develop a monitoring program that routinely checks different system components for pressure and chemical indicators of potential problems.

# 7.0 ASR/MAR GUIDANCE DOCUMENTS

Several key guidance documents developed in the United States, Europe, and Australia are available and may be useful resources when evaluating or implementing ASR/MAR projects. While this is not an exhaustive list, consultation of these documents will provide a foundation for project developers or analysts.[14]

Standard Guidelines for Artificial Recharge of Ground Water (American Society of Civil Engineers, 2001)

The American Society of Civil Engineers (ASCE)'s Standard Guidelines for Artificial Recharge of Groundwater prepared their guidelines to provide a comprehensive description of the individual steps required to plan, develop, design, operate, and maintain ASR/MAR projects. It includes a discussion of the regulatory and water rights issues, typical institutional constraints, economic considerations, and financial analysis. The guidance was developed by a panel whose members are well-known for their expertise in managed aquifer recharge.

This robust set of guidelines can be applied to any size project and describes the typical investigation and testing procedures that may be applicable to most aspects of a ASR/MAR project. A detailed discussion of potential problems typically encountered when implementing ASR/MAR projects is provided along with a description of the possible solutions. The document provides a definition of terms and a listing of American Society of Testing and Materials (ASTM) methods for field testing procedures (e.g. well installation, borehole testing, and aquifer testing), data analysis techniques, and groundwater modeling analysis.

Code of Practice for Aquifer Storage and Recovery (Environmental Protection Authority, 2004)

The Code of Practice for ASR was developed by the Australian Environmental Protection Agency (EPA) specifically for ASR wells. It provides a brief description of key issues to address in ASR systems and a list of best practices to ensure the ASR

14 Additional notable documents include the Federal Emergency Management Agency's (FEMA) Aquifer Storage and Recovery Checklist (2016) and the Best Suggested Practices for Aquifer Storage and Recovery (2014).

system is sustainable. Although it was prepared primarily for ASR implementation in Australia, the document is relevant to ASR applications in other countries.

Strategies for Managed Aquifer Recharge (MAR) in Semi-Arid Areas (UNESCO/International Association of Hydrogeologists, 2005)

This manual was prepared to summarize practical experience and lessons learned regarding the implementation of ASR/ MAR strategies. It provides a description of typical MAR systems and a summary of best practices that should be considered in implementing MAR systems.[15]

Managed Aquifer Recharge (MAR): Practical Techniques for the Caribbean (GWP, 2010)

This document presents a summary of typical MAR applications (including ASR), MAR selection considerations, best practices, and strategy guidance, and was prepared with the Caribbean region in mind. Aquifer storage applications were focused on Barbuda and Antigua in the Leeward Islands.

D12.2 Pre-requisites and design criteria for the new MAR systems in compliance with EU WFD and GWD (including pre-treatment) (DEMEAU, 2014)

This study and report were funded by the European Commission and provide a detailed review of hydrogeologic prerequisites for surface spreading and injection, procedures for field investigation, and an overview of recharge water pretreatment options. Several tables are provided that summarize decision criteria, particularly for hydrogeologic feasibility and recharge water pretreatment options.

Evaluation of the Methodology to Present and Evaluate Artificial Aquifer Recharge Projects (AMPHOS 21 Consulting, Chile, 2014)

The report was prepared by AMPHOS 21 on behalf of Chile's General Water Directorate to develop a guidance document to present, evaluate, and analyze artificial aquifer recharge projects in Chile. The scope of work included a bibliographical review of local and international aquifer recharge projects, a technical and legal evaluation of the artificial recharge framework in Chile, development of the guideline, and application of the proposed methodology to three basins, thereby validating the suggested approach.

15 Traditional ASR (injection and extraction from the same well) is considered as one type of MAR technology in this document.

The guideline was validated by applying the methodology to the Choapa, Quilimarí, and Aconcagua basins. The results of the validation indicate that the same opportunities for improvement exist across the three basins: (i) water demand and availability have not been calculated; (ii) impacts to groundwater, surface water, and ecosystems were not evaluated; (iii) development of the conceptual model is incomplete; (iv) the evaluation and design phase does not include an economic evaluation; and (v) there are no contingency sentinel monitoring plans related to potential contamination scenarios.

Conjunctive Management and Groundwater Storage (California Department of Water Resources, 2016)

This document focuses on MAR projects and describes project feasibility, development, and implementation considerations. While the report is centered on applications in California, where hundreds of ASR/MAR systems have been installed and operated, the tools and techniques described are germane to projects in the Caribbean.

Planning and Land Development Handbook for Low Impact Development (LID) (City of Los Angeles, 2016)

This City of Los Angeles publication provides review of LID technologies and discusses best management practices. The handbook was prepared as part of implementation of the city-wide stormwater management program.

# 8.0 CONCLUSIONS

*Direct benefits of implementing ASR/MAR projects in the Caribbean can include reduced reliance on more expensive water sources such as seawater desalination. Indirect benefits include improved public health and economic growth.*

ASR/MAR technologies are an integral part of any IWRM program focused on improved water supply security and sustainability where groundwater resources are either an existing or proposed part of the water supply. The technologies are well understood, widely applied, and typically cost effective when compared to developing other sources of water, such as building surface water reservoirs or seawater desalination. With proper monitoring and operations management, the ASR/MAR systems can function successfully for many years. While ASR/MAR may not provide the only solution to vexing water supply shortages, it can be an important part of the solution.

Proper application of ASR/MAR requires an appropriate physical setting with an ASR/MAR scheme that is engineered to accommodate local conditions. This includes a supply of potential recharge water or, in the case of ASR wells, drinking water, an appropriate hydrogeological setting, and water conveyance features. It requires engineering design and support to construct the infrastructure necessary to recharge, store, recover, and convey extracted groundwater. Successful implementation and operation require appropriate local control, oversight, and monitoring with a strong stakeholder outreach program that builds community support.

Direct benefits of implementing ASR/MAR projects in the Caribbean can include reduced reliance on more expensive water sources such as seawater desalination; minimizing seawater intrusion; developing a water supply hedge against natural disasters; utilizing existing subsurface reservoirs for storage; promoting more sustainable agricultural production; and improving surface water quality. Indirect benefits include improved public health and economic growth.

The Caribbean region offers opportunities to implement ASR/MAR projects at a variety of scales to improve water supply security. Successful projects in the region include the IDB-supported AGSR project in Jamaica and the FEMA-supported Salinas Aquifer in Puerto Rico. Both projects were built on existing water supply infrastructure, were innovative in their approach, and resulted in an overall improvement in water supply security. It is reasonable

to assume that new projects can be implemented successfully at many other locations in the region.

While the benefits of ASR/MAR can be substantial, and it is likely that there are numerous locations where application of these technologies can be implemented, projects can't be applied in a "cookie cutter" approach. A geologically, socially, and economically diverse region such as the Caribbean requires that projects must be tailored to accommodate regional and local variations in geologic conditions, recharge water supply availability, infrastructure, institutional controls, and economics. A decision tool that provides a stepwise framework to evaluating potential projects is provided to help identify those that have the greatest potential for successful implementation. This tool builds upon the fundamental elements of project siting, design, and implementation, providing project off-ramps where successful implementation is not feasible.

Climate change impacts are fundamentally changing the water supply security of the Caribbean. ASR/MAR offers a suite of tools that can be used to help address the challenges facing the region, provided they accommodate local conditions.

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# APPENDIX A: OVERVIEW OF GROUNDWATER SUPPLY IN THE CARIBBEAN REGION

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| *Anguilla* | Water scarcity is significant in Anguilla and the island is heavily dependent on rain and water storage for water supply. Groundwater is generally brackish and unfit to drink. In addition, groundwater yield has been deemed insufficient to meet the island's long-term needs.<br><br>Historically, a thin layer of fresh groundwater overlying a heavier saltwater zone. Groundwater was produced by the Anguilla Water Department from about 10 wells at a rate of approximately 1,000 $m^3$/day (1993). A desalination plant was built in 2010 and has subsequently been decommissioned. Various companies have imported water treatment equipment and sell that water to the public. Hotels have their own water treatment facilities (Safege, 2015). |
| *Antigua and Barbuda* | Antigua has approximately 43 active wells. The island has three RO desalination plants/systems with a total desalination capacity of approximately 7.1 million $m^3$/year. The Antigua Public Utilities Authority (APUA) tries to rely on surface water and groundwater as much as possible given the inexpensive nature of its production. As a drought-prone island, relying on surface water and groundwater often becomes difficult.<br><br>In Barbuda, with a population of less than 2,000 people, most of the water supplied to the population comes from shallow wells. In 2005, water obtained from wells in the Palmetto Point area was potable but other wells around the island have been found to be saline. APUA installed a Reverse Osmosis (RO) Plant in Barbuda that produces approximately 113.6 $m^3$/day, or 0.041 million $m^3$/year, to meet needs of Barbuda's residents. |
| *Aruba* | Drinking water is provided by desalination plants. Groundwater tends to be brackish due to seawater intrusion and the arid environment. Some groundwater is fresh enough for agricultural purposes. Historically, wells were used for drinking water supply but these wells became saline over time. |
| *The Bahamas* | Freshwater resources are finite and vulnerable in The Bahamas. Fresh surface water is essentially non-existent. There are no true rivers or streams on the islands due to the low relief of the country and to the high permeability of the limestone that permits rainwater to percolate quickly to the water table. The country's freshwater resources are limited to very fragile freshwater 'lenses' in the shallow karstic limestone aquifers. In 2000, total desalinated water produced was estimated at 7.4 million $m^3$ (20,300 m3/day) (AQUASTAT, 2015). |
| *Barbados* | The main water supply is from groundwater, with an increasing amount from desalination facilities. A brackish water desalination plant is operated by Barbados Water Authority and provides 40,000 $m^3$/day (Chase, 2008). The groundwater supply on Barbados has been extensively studied. |
| *Bonaire* | Drinking water is provided by desalination plant using a pipeline and trucks. Groundwater tends to be brackish due to seawater intrusion and the arid environment (Safege, 2015). |
| *British Virgin Islands* | The islands have limited natural fresh water resources except for a few seasonal streams and springs on Tortola. Households typically collect rainwater using individual cisterns. Piped water is supplied by the Water and Sewerage Department within the Ministry of Communications and Works, and is obtained from several groundwater sources and from a desalination plant. The entire water supply on the islands of Tortola and Jost Van Dyke is desalinated water, as is 95% of Virgin Gorda's public water supply (Safege, 2015). |

**Appendix A: Overview of Groundwater Supply in the Caribbean Region**

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| *Cayman Islands* | Freshwater resources are scarce on the Cayman Islands and manufactured water is produced on a large scale from desalination plants on Grand Cayman. Historically, freshwater was obtained from wells and cisterns. Small decentralized desalination plants serve individual properties and developments on Cayman Brac (Safege, 2015). |
| *Cuba* | Approximately 52% of the water resources are used for irrigation. Groundwater supplies are produced from limestone aquifers and are stressed, resulting in seawater intrusion near the coast (Chase 2008). |
| *Curacao* | Drinking water is provided by desalination plants. Groundwater tends to be brackish due to seawater mixing and the arid environment. The island once had reliable aquifers but urbanization has reduced infiltration. A series of dams, built by the Dutch around 1920, impeded runoff and allowed percolation into the ground to promote groundwater levels (Safege, 2015). |
| *Dominica* | Compared with other countries in the region, Dominica has an abundance of rivers and surface water. In 2004, the Dominica Water and Sewerage Company produced about 16.4M m3 of drinking water from 47 different river intakes. |
| *Dominican Republic* | In 2002, the Dominican Republic's domestic water demand was approximately 1,800M m3/yr and the industrial demand 8,000M m3/yr. About 67% of the water supply is surface water resources, with 33% from groundwater. The surface water and shallow ground water aquifers are increasingly polluted with biological and agricultural wastes near and downstream of population centers. Due to increasing migration of the population to urban centers, such as Santo Domingo and Santiago, biological contamination has been growing. Very little sewage is treated before being discharged into streams, unlined pits, and some wells. In areas with very permeable limestone, these wastes are carried a long distance from the source in the underlying aquifer. |
| *Grenada* | Water resources originate mainly from a system of permanent streams and rivers but there is some groundwater available from the limestone areas along the northwest coast. Most surface water originates from high rainfall areas in the central mountain ranges of Grenada island. Overall, there are 71 river basins on the island. All eight major rivers have perennial flows, though these are significantly reduced during the dry season (AQUASTAT, 2015). |
| *Haiti* | Groundwater resources in Haiti are considered abundant, with greater than 2B m3/yr of renewable resources and 56B m3 of reserves. However, groundwater is not available everywhere and many aquifers are often low yielding, discontinuous, or are at risk from saltwater intrusion, overexploitation, reduced recharge, and contamination. |
| *Jamaica* | Jamaica pumps approximately 26M m3 of groundwater annually. Approximately 50% of domestic demand and 40% of irrigation demand are provided by groundwater extraction.<br>Surface runoff predominates on outcrops of basement rocks and interior mountainous valleys, while groundwater is the dominant water resource associated with the karstic limestone and coastal alluvial valleys. Surface water resources are characterized by a marked seasonal variability in flow. Jamaica has one MAR project that utilizes passively treated surface water. |
| *Montserrat* | Freshwater demands of the entire island are met by potable supply from six productive springs on the flanks of the extinct volcanic complex of Centre Hills. In 2013, combined discharge from the six supply springs was in excess of 4,300 $m^3$/day (Montserrat Utilities Ltd.). Supply at this rate easily meets current demands of the population, (~1,600 $m^3$/day). However, consumption rates are expected to rise as population and agriculture production increase, during a period of relative volcanic quiescence. |

**Appendix A: Overview of Groundwater Supply in the Caribbean Region (cont.)**

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| *Puerto Rico* | Groundwater is plentiful in coastal Puerto Rico and is reasonably well-understood, having been the subject of numerous comprehensive studies. Seawater intrusion and industrial/sanitary contamination problems are numerous on the island. An ASR project is currently funded in southern Puerto Rico to offset groundwater supply shortages due to drought and over-exploitation. |
| *Saba & St. Eustatius* | Drinking water is provided by cisterns or groundwater wells. There are few surface water features. |
| *St. Maarten/ St. Martin* | Drinking water is provided by desalination plants. Groundwater tends to be brackish due to seawater mixing and the arid environment. |
| *St. Kitts & Nevis* | The main groundwater supply is from a coastal aquifer, with seven groundwater basins. The estimated safe yield is approximately 38,000 $m^3$/day. Roughly 40% of their potable supply comes from the Basseterre Valley aquifer. Groundwater aquifers are being impacted by sea level rise (seawater intrusion), pollution, and urban encroachment and will eventually be negatively impacted by further saline intrusion due to climate change (GWP, 2014). |
| *St. Lucia* | Water resources in Saint Lucia are extracted for municipal and agricultural purposes. In 2007, total water withdrawal was estimated at 42.9 million $m^3$ of which 12.5 million $m^3$ (29 percent) was by municipalities. Surface water accounted for 100 percent of total withdrawals. Attempts to develop groundwater for public supply have had very limited success on the island. A 1998 study on improved water supplies for the south of the island concluded that this source is unlikely to make a significant contribution except in small isolated rural communities (AQUASTAT, 2015). |
| *St. Vincent & Grenadines* | St. Vincent has an abundance of surface water from plentiful streams from which water supplies are drawn. The Grenadines use rainwater harvesting and desalination plants, which produce about 1,600 $m^3$/day. |
| *Trinidad and Tobago* | In 2011, total water withdrawal in the country was estimated at 383.2 million $m^3$ of which 237.6 M $m^3$ or 62 percent for municipal use, 128.9 M $m^3$ or 34 percent for industrial use, and 16.7 M $m^3$ or 4 percent for agricultural use. Of the total withdrawal, 228.4 M $m^3$ or 60 percent comes from surface water, 107.8 M $m^3$ or 28 percent from groundwater, and 47.0 M $m^3$ or 12 percent from desalinated water. Tobago produces about 20% of its domestic water supply from groundwater. |
| *Turks & Caicos* | Water is scarce in Turks & Caicos, with very limited natural freshwater resources. Potable water is typically sourced from reverse osmosis desalination of brackish, underground water on the populated islands of Providenciales and Salt Cay; while on the less populated islands, many homes have sizeable cisterns to store water (which have been required by law), and these may be replenished either from rainwater or via truck-borne water supplies. Non-potable water resources, including sea water and brackish groundwater, are also utilized for non-potable uses. Groundwater is not used for a freshwater supply in Grand Turk. Previous studies discarded the possibility of this source in Grand Turk and other islands off the Caicos. |
| *U.S. Virgin Islands* | Historically, rainwater harvesting has been a principal source of potable water for the residents of the U.S. Virgin Islands, with some reliance on groundwater. Surface water supplies are virtually non-existent. Desalination satisfies most of the water needs of the population of about 115,000 persons, and is the principal provider of water for the islands' limited public water distribution systems (USGS, 2011). |

**Appendix A: Overview of Groundwater Supply in the Caribbean Region (cont.)**

# APPENDIX B: WATER IN US DOLLARS/CUBIC METER DELIVERED

| Country/Island | Unit | To 1 USD | Domestic | Commercial | Source |
|---|---|---|---|---|---|
| Anguilla | XCD | 2.70 | 3.91 | 11.62 | http://gov.ai/water.php |
| Antigua & Barbuda | XCD | 2.70 | 2.05 | 4.89 | http://www.apua.ag/ |
| Aruba | AWG | 1.79 | 2.54 | 5.33 | https://www.webaruba.com/your-water-bill/water-rates |
| Bahamas | EUR | 0.86 | 5.11 | 8.52 | http://www.wsc.com.bs/Tariff.aspx |
| Barbados | BDD | 2.00 | 2.48 | 4.66 | http://barbadoswaterauthority.com/?p=393 |
| Bonaire | USD | 1.00 | 3.76 | Not Available | https://www.webbonaire.com/wp-content/uploads/rates/WEB_Water_tarieven_NL_2018_01-03-18.pdf |
| British Virgin Islands | USD | 1.00 | 4.90 | 5.56 | http://www.viwapa.vi/Customers/RatesFees/Water_Rate.aspx |
| Cayman Islands | KYD | 0.83 | 5.39 | 6.47 | http://www.waterauthority.ky/upimages/pagebox/WaterRatesRevJul2018_1531431139.pdf |
| Cuba | CUP | 25.50 | 0.04 | 1.00 | (Scalley, 2012) |
| Curaçao | NAF | 1.84 | 2.67 | 5.67 | https://www.aqualectra.com/en/rates/ |
| Dominica | XCD | 2.70 | 2.11 | 3.57 | http://www.dowasco.dm/index.php/tariffs |
| Dominican Republic | DOP | 50.08 | 1.67 | 1.85 | (Scalley, 2012) |
| Jamaica | JMD | 136.58 | 0.91 | 3.42 | https://www.nwcjamaica.com/Rates |
| Martinique | EUR | 0.86 | 6.32 | Not Available | http://www.observatoire-eau-martinique.fr/services-d-eau-potable-et-d-assainissement/prix-de-l-eau/prix-de-l-eau-martinique/commune/35?annee=2016 |
| Montserrat | XCD | 2.70 | 12.84 | 19.97 | (Scalley, 2012) |
| Puerto Rico | USD | 1.00 | 4.73 | 6.59 | http://www.acueductospr.com/TARIFA/estructuratarifaria.html |
| Saba & St. Eustatius | ANG | 1.84 | 5.55 | 14.16 | (Scalley, 2012) |
| St Maarten / St Martin | ANG | 1.84 | 5.55 | 14.22 | (Scalley, 2012) |
| St. Kitts & Nevis | XCD | 2.70 | 5.71 | 14.27 | (Scalley, 2012) |
| St. Vincent & The Grenadines | XCD | 2.70 | 6.34 | 11.62 | https://habgroup.com/water |
| Trinidad & Tobago | TTD | 6.74 | 11.01 | 22.02 | (Scalley, 2012) |
| Turks and Caicos Islands | USD | 1.00 | 4.02 | Not Available | https://habgroup.com/water |
| US Virgin Islands | USD | 1.00 | 4.90 | 5.56 | http://www.viwapa.vi/Customers/RatesFees/Water_Rate.aspx |

**Appendix B: Water in US Dollars/Cubic Meter Delivered**
(Costs are 2018 except where indicated)