MANAGED AQUIFER RECHARGE (MAR): PRACTICAL TECHNIQUES FOR THE CARIBBEAN

under the project

Promoting Rainwater Harvesting in the Caribbean Region - Phase 2

A collaborative effort between the

Caribbean Environmental Health Institute (CEHI), the Antigua Public Utilities Authority (APUA), the United Nations Environment Programme (UNEP), and GWP Consultants

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About CEHI

The Caribbean Environmental Health Institute (CEHI), an agency under CARICOM, was established in 1989 with the broad mandate to provide technical assistance on matters of environmental management to Member States. The Institute is headquartered in St. Lucia. For more information on the Institute please visit www.cehi.org.lc.

1. Introduction

1.1 Managed Aquifer Recharge

Managed Aquifer Recharge (MAR), or enhanced recharge, previously known as 'artificial recharge' is the intentional diversion of surface water to the groundwater reservoir by modifying, through a variety of techniques, the natural movement of surface water. The adverse connotations of 'artificial' in a society where community participation in water resources management is becoming increasingly prevalent and important resulted in the development of a more appropriate title: Managed Aquifer Recharge (UNESCO-IHP, 2005).

The main purpose of Managed Aquifer Recharge is to augment groundwater resources by storing excess surface water for later use and restore groundwater levels which may have been depleted due to over-abstraction (UNEP, 1998a), thus enhancing the sustainability of groundwater development. On its own, MAR is not a cure for over exploitation of aquifers and it could merely enhance the rates of abstraction. Consequently, successful and sustainable implementation of MAR projects requires good planning and operation as an integral part of a catchment wide, or national (in SIDS), water management strategy which encourages rainwater harvesting and re-use.

MAR is also employed to address water quality issues, notably rising salinity, by improving the quality of existing groundwater through dilution, as well as removing bacteriological and other impurities from poorer quality surface waters (*e.g.* treated waste water) through geo-purification and natural attenuation so that it is suitable for re-use (Balke and Zhu, 2008). Groundwater is traditionally preferred as a drinking water over surface water, and so employing MAR techniques to store and then recover poorer quality waters may improve the public perception of recycled water.

1.2 Scope of Study

The overall aim of this study is to produce a useful and practical guideline for the capture and management of surface water for aquifer recharge in the Caribbean Region, with a particular case study focus on Antigua and Barbuda. The structure of the report is intended to address the below objectives.

1.2.1 Objectives

i. Introduce the nature of water scarcity and security in the Caribbean by using Antigua and Barbuda as a case study. Illustrate current water supply, demand and resource trends and issues with reference to climate change.

ii. Evaluate the benefits of investment in MAR in addressing water scarcity and security issues and their associated socio-economic benefits as well as any potential direct and indirect environmental health benefits.

iii. Summarise concisely the range of techniques available for MAR and discuss the important influencing factors on the selection of appropriate practical methods for MAR implementation.

iv. Establish the most suitable 'best practise' MAR techniques for Antigua and Barbuda and illustrate through a range of appropriate examples and case studies the selected techniques. Provide descriptions and schematics of the required civil works and recommendations on maintenance and monitoring.

v. Provide guidance on the planning and implementation of MAR schemes at a strategic level. This will consist of practical guidance to facilitate development of a MAR plan which may be integrated within national water resources/drought management (IWRM) plans.

1.3 Antigua and Barbuda: A Case Study

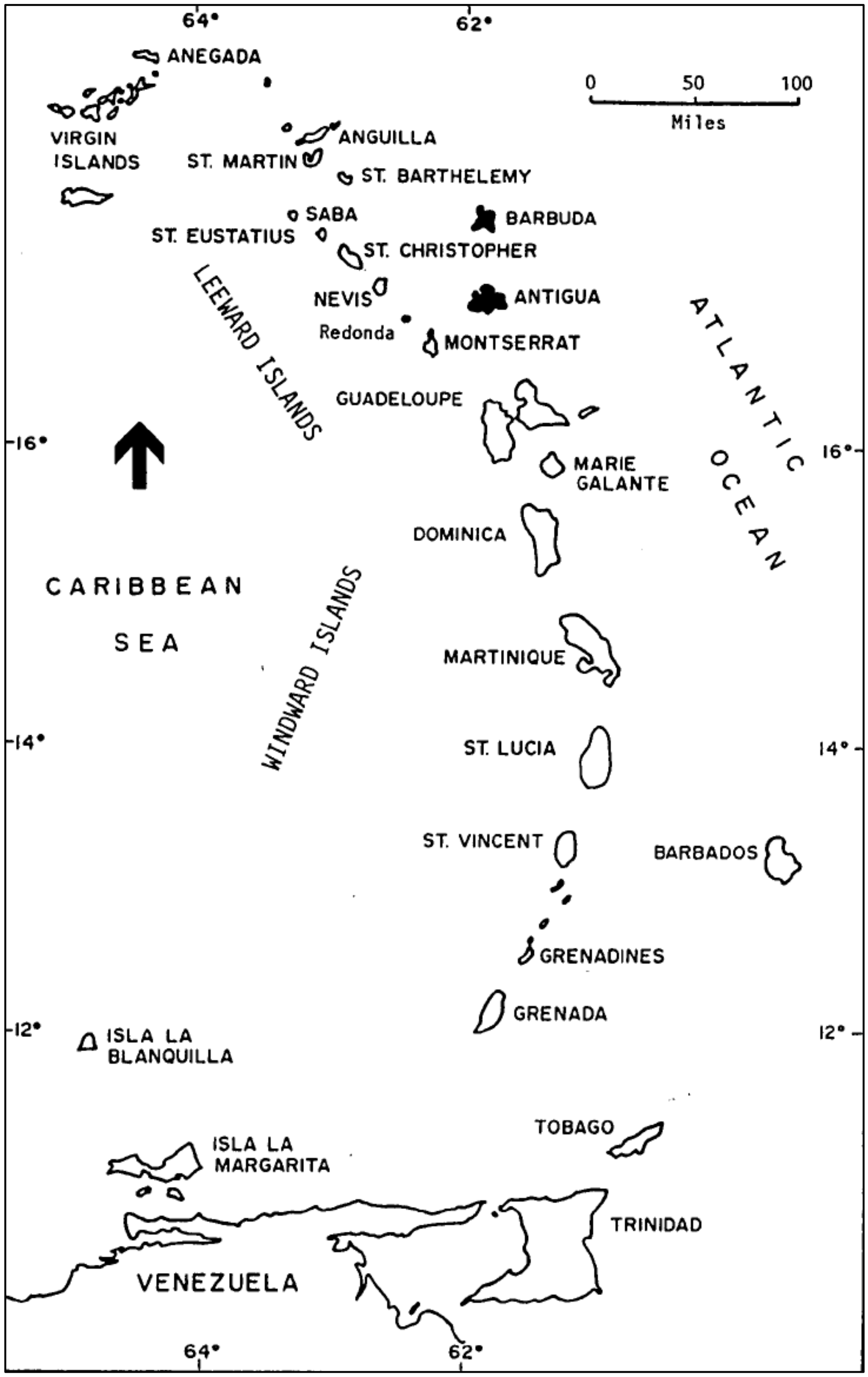


Figure 1: Location of Antigua and Barbuda in Eastern Caribbean. Source: Antigua and Barbuda, Ministry of Public Works and Environment, 2005

By providing a summary of some of the issues relating to water resources in Antigua and Barbuda (See Figure 1 & 2), many of the issues which relate to the Caribbean Islands more generally will be illustrated, due to similar factors (climate, geology, society *etc*) which are influencing them.

The topography of Antigua is generally low lying with volcanic areas in the south and west, the highest point rises to 470m AMSL (above mean sea level). The north and east is composed of limestone with elevations up to 120m AMSL. The low lying central area consists of alluvium with elevations less than 15m AMSL.

Barbuda is composed of limestone and is relatively flat with a maximum elevation of 63m AMSL. There are no permanent (perennial) rivers on Antigua or Barbuda.

1.3.1 Socio-economic issues

Antigua and Barbuda has a combined population of 84,000. Tourism, which tends to be 'high–end', has seen rapid growth in recent years and currently accounts for 65% of the GDP of Antigua and Barbuda (USACE, 2004); it has overtaken agriculture (in the form of sugar production) as the largest sector of the economy. Presently, agricultural production is directed at the domestic market only, with international markets (including the tourism industry) apprehensive of produce quality due to unreliable freshwater supply and excessive pricing due to a shortage of labour as a result of higher wages in construction and tourism.

Water resources management is critical to continued growth of the economy whose GDP is so heavily reliant on tourism. Water supply and sanitation are critical to public and environmental health, particularly in the rapidly urbanising areas. Antigua and Barbuda rely on the quality of their near shore environment as a source of national revenue, and as such good watershed management is essential to long term marine habitat health.

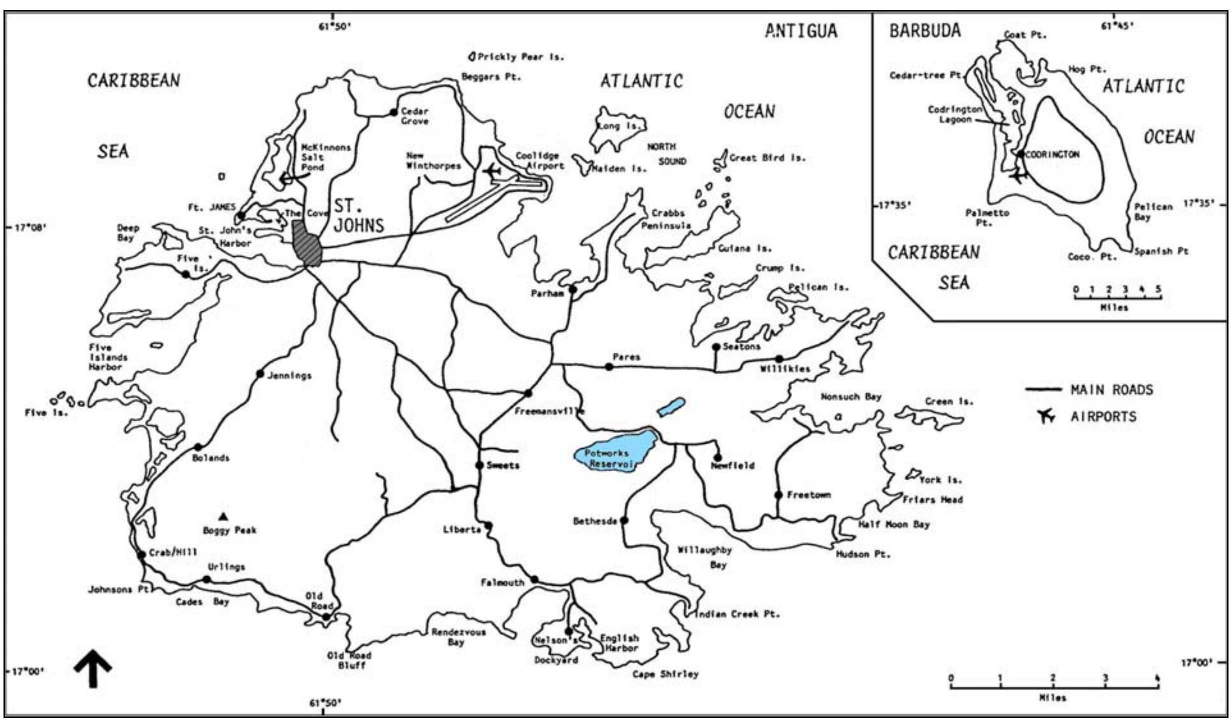


Figure 2: Map of Antigua and Barbuda. Source: Antigua and Barbuda, Ministry of Public Works and Environment, 2005

1.3.2 Water Resources

Freshwater is a scarce resource on Antigua and Barbuda. Both islands have a history of drought. This can be attributed to the seasonal and interannual variability of rainfall over the islands, as well as the spatial distribution of rainfall; Figure 3 which depicts the isohyetal distribution of annual average rainfall in Antigua, in inches. Surface fresh water is only available in streams for a few months after significant rain events. Demand is increasing due to population growth and the expanding tourist industry. This demand is presently expected to be met through a combination of surface water, groundwater, and desalination of seawater.

At present Antigua has some 10 medium to small municipal reservoirs (see Figure 4) with a combined capacity of approximately 5 million m^3. There are also numerous agricultural ponds and earth dams with an estimated capacity of approximately 1 million m^3 (Antigua and Barbuda Ministry of Public Works and Environment, 2005). Groundwater development consists of approximately 50 active wells located at 5 major well fields. During periods of drought, wells near coastal areas stop pumping to avoid saltwater intrusion (USACE, 2004).

The Potworks Reservoir (see Figure 2), which was constructed in 1968, is by far the most significant surface water reservoir representing over 83% of the total surface storage capacity. It receives runoff from a drainage area of 430 hectares of low lying land which is sparsely covered with vegetation, the majority of which is pasture and agricultural land. The watershed land uses create concerns relating to silting and organic, chemical and bacterial contamination. The maximum surface area of the reservoir is about 192 hectares and has extensive shallow zones and high evaporation rates exaggerated by exposure to the trade winds (Antigua and Barbuda Ministry of Public Works and Environment, 2005).

There are two desalination systems in Antigua, and due to the unreliable reservoir storage and supply of surface water and groundwater, the country has become more dependant on desalinated water as a primary water source, despite the increased costs. Table 1 describes the seasonal variation in water supply on Antigua.

Source	Dry season %	Wet season %
Surface water	5	25
Groundwater	20	15
Desalination	75	60

Table 1: Antigua's Seasonal Water Supply (After USACE, 2004).

In Barbuda the primary source of freshwater is from shallow aquifers that underlie the 650 hectares of sands in the Palmetto Point area. Elsewhere groundwater is saline and unsuitable even for agriculture (Cooper and Bowen, 2001).

A reverse osmosis desalination plant has recently been installed in Barbuda to augment water resources and meet the needs of the residents (Antigua and Barbuda Ministry of Public Works and Environment, 2005). Some private resorts on the island meet their own water demands through desalination techniques. However, private desalination at resorts across Antigua and Barbuda, though producing relatively significant volumes of water, meets little of the public water demand.

Rainwater harvesting at the household level contributes an important source of safe drinking water for the majority of the population provided the collection and storage systems are kept in an hygienic condition. By law, all new houses must be equipped with rainwater harvesting systems. The average size of this storage is reportedly $19m^3$ (Antigua and Barbuda Ministry of Public Works and Environment, 2005). Such measures should also be enforced on all communal buildings such as churches and

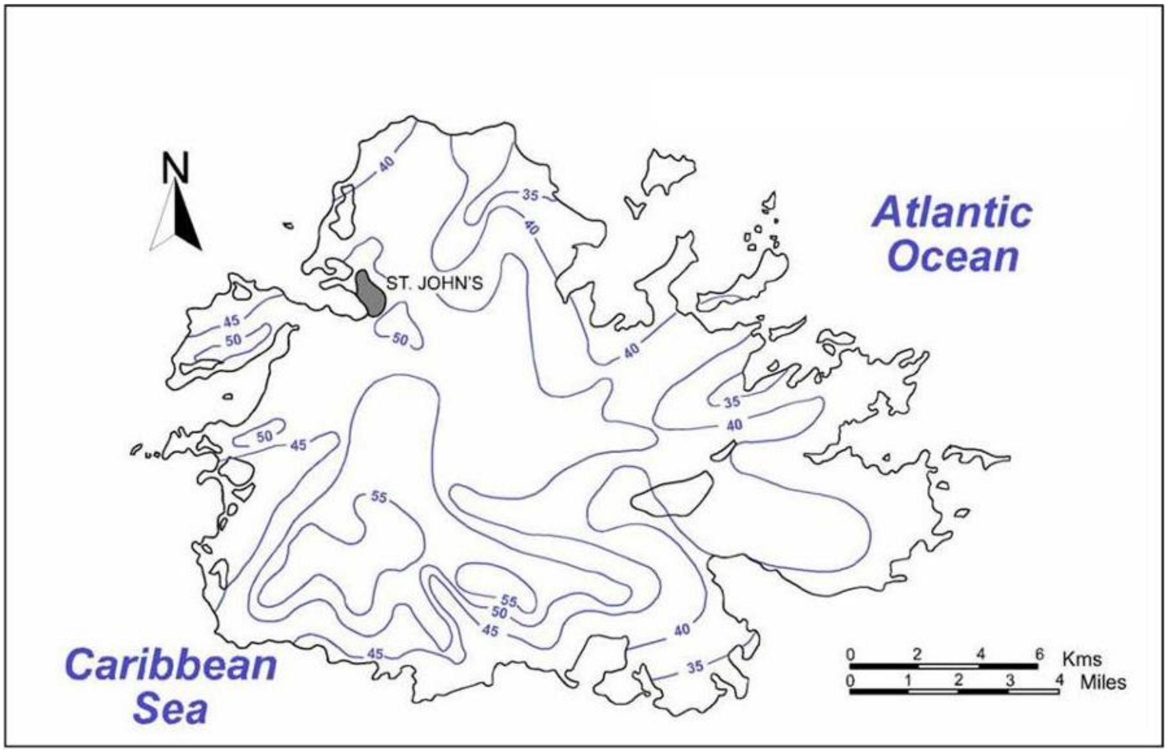


Figure 3: Isohyetal distribution of rainfall in Antigua, in inches. Source: Cooper and Bowen, 2001.

schools, where significantly more water can be collected, cost-effectively, due to the larger roof catchment areas. Reserve communal water supplies can be extremely important in drought periods.

1.3.3 Sanitation

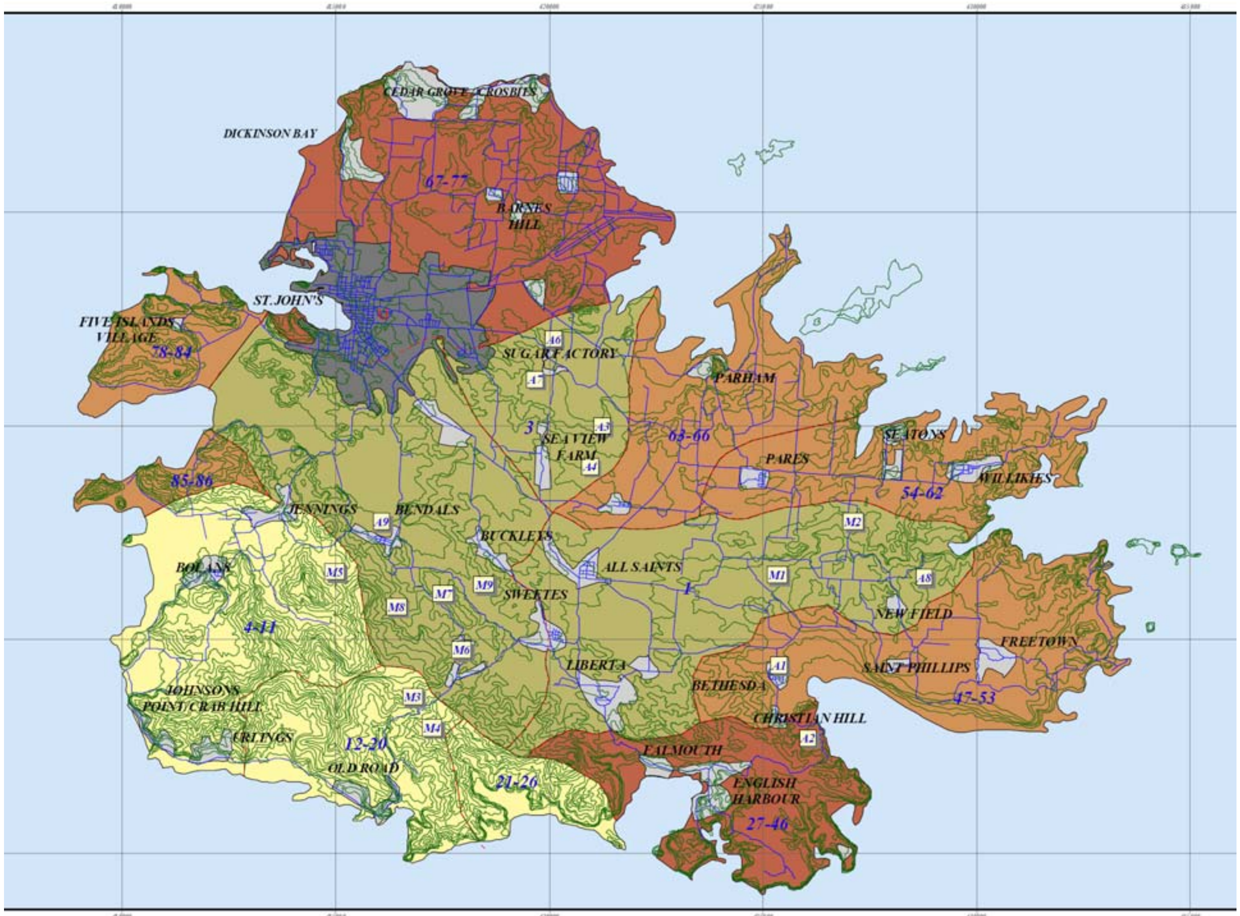
There is reportedly a serious problem with inadequate sewage handling and treatment in the urban areas of Antigua, particularly in the capital St. John's, which has a growing population of 45,000 (60% of the country's total). A small percentage of properties have individual sewage treatment systems and a similar percentage discharge untreated effluent directly into the open drainage system, while the majority use septic tanks which vary in efficiency (GEF, 2008). Generally, the septic tanks are not pumped frequently enough resulting in failure of the systems and overflow of low-quality effluent to surface water, coastal water and groundwater.

In addition, the septic bio-solid waste is disposed of at a municipal landfill site and it is now recognised that this presents a threat to nearby groundwater quality. The result has been severe degradation of groundwater quality through leaching of pollutants, and marine pollution of St John's Harbour which threaten both public and environmental health.

1.3.4 Climate

The annual rainfall in Antigua ranges from about 890 – 1400mm. Barbuda has a lower rainfall average ranging from 508 – 991mm, one of the lowest in the Caribbean.

Typically there is a dry season that extends from January to March or April when less than 10% of annual rainfall occurs. May is a wetter month before the wet season in August to November when typically over 50% of the annual rainfall can be expected to fall. Notwithstanding the seasonal patterns, the most significant feature of the rainfall regime is its variability.



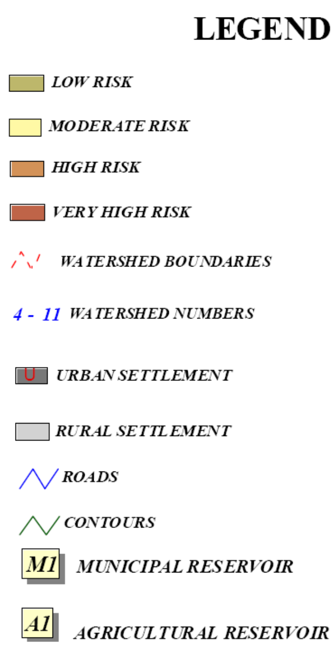


Figure 4: Drought risk map of Antigua, including municipal and agricultural reservoirs, watershed boundaries, and topography. Source: USAID/OAS Post-Georges Disaster Mitigation Project http://www.oas.org/pgdm

Antigua and Barbuda are prone to drought. In Antigua drought generally implies that less than 826mm of precipitation fall annually. In 1983, annual rainfall was 566mm (the lowest since 1874) and the drought left all the ponds and most of the reservoirs empty. Interestingly, in the severe drought of 1993, an average rainfall of 1016mm was recorded (a figure which is not a great deal lower than the long term average), however approximately a third of this rain fell in May, thus during the following the dry season, much of the precipitation was already lost as runoff (USACE, 2004).

Both Antigua and Barbuda are affected by hurricanes which can produce 250-750mm of rain in a few days. These hurricanes and tropical storms remove topsoil through runoff, by forming and deepening gullies. This effect is greatest where land has been cleared for farming, landscaping or construction (USACE, 2004). Storm surges associated with tropical storms and hurricanes can increase saline intrusion and contamination of coastal aquifers.

The unreliability and variability in climate is predicted to worsen. The climate change scenarios suggested for the Caribbean and Antigua and Barbuda consist of increased hurricane/tropical storm activity and more intensified drought conditions. These synthetic scenarios have been suggested in the Antigua & Barbuda Initial National Communication on Climate Change (Office of the Prime Minister, 2001) and are based on the IPCC and other projections of the likely impacts of anthropogenic climate change on the islands of the Caribbean.

1.3.5 Flooding

Flooding on Antigua and Barbuda is caused by high intensity rainfall events which often result from tropical storms. Apart from the usual negative impacts of flooding (such as disruption to services and agriculture and damage to infrastructure), on small islands such as Antigua and Barbuda water resources can be severely impacted: contaminated overland flow has entered water wells on Antigua and Barbuda in recent years, presenting a risk to the security of the underground water resources. The main factors exacerbating flood risk are:

- Expanding urbanisation which replaces pervious areas with impermeable surfaces such as roofs and roadways;
- Widespread grazing by goats and cattle that compacts soils (reducing infiltration capacity) and removes vegetative cover, increasing runoff and leaving the surface vulnerable to soil erosion;
- Relatively low capacity ephemeral streams, possibly reducing due to silting; and
- Widespread deforestation (burning, clearing and overgrazing) reducing concentration times (ie the time to peak flood flow) of catchments as interception by vegetation and catchment storage is reduced and overland flow is enhanced. This results in increased flood peaks ('flashier' hydrographs).

1.3.6 Water Sector Issues

The points below summarise the main issues facing the water sector:

- High seasonal and interannual rainfall variability: most of the rainfall is received in tropical storms (very high intensity events) during the rainy season (July – December).
- High and increasing risk and vulnerability to floods and droughts, given reported climate projections.
- Inadequate reservoir design or construction: many of the water storage structures are not holding water effectively due to their design or construction (embankment, lining, spillway etc) (Antigua and Barbuda Ministry of Public Works and Environment, 2005).
- Reliance on desalination: Water production is expensive and has to be highly subsidised.
- Inadequate catchment management: increased urbanisation, poor sanitation, expansion of tourism, increase in construction, and intensification of farming has led to a change in land use and a rise in diffuse and point source pollution and soil erosion rates.
- Need for integrated water resources management policy and strategy.

1.4 The suitability of investment in Managed Aquifer Recharge to meet Antigua and Barbuda water sector issues

The key issue in terms of water resources faced by Antigua and Barbuda, much of the Caribbean, and other SIDS, is the annual variability in rainfall (which is dictated by the climate), combined with a lack of natural hydrological cycle water storage. In terms of Antigua and Barbuda, this issue is compounded by relatively recent land use changes which generate high runoff rates and loss of valuable fresh water to the sea. In the past this problem has been partially mitigated through storage of freshwater behind dams on the land surface and groundwater development. More recently, desalination has been used to supply the majority of freshwater on Antigua.

The reliance on desalination (which is relatively more expensive than surface water or groundwater supply) in supplying the majority of the freshwater is currently sustainable due to the national revenue developed by tourism. However, the proportion of water supply met by desalination is growing, and if the tourism economy declines this may become prohibitively expensive. Continued tourism is therefore crucial to the water sector, as it provides the economic stability necessary to finance and thus sustain desalination for public consumption. Protection of the marine environment in particular (notably from land based pollution – including sediment erosion) is important for sustaining this source of revenue.

To reduce over-reliance on desalination, increased quantities of freshwater (as rainfall or runoff) could be captured and stored during the wet season. This would help to balance the gap between water demand and available stored water for supply in the dry season, thus reducing the risk of water scarcity and increasing water security in times of drought.

Surface water storage has its benefits, such as providing a reliable water resource which is easily monitored and controlled; attenuating flood peaks and usually surface retention structures are long lasting. However, increasing surface water storage generally requires large engineering projects and a large land inundation area which may be hard to procure, especially on small islands (although individually small but abundant rainwater harvesting units are an example of an extremely cost effective solution to surface storage of rainfall, which provides dry season freshwater supply). Additionally, open surface water storage is subject to evaporation losses, siltation and water quality degradation issues associated with the existence of agriculture, livestock and other potentially polluting activities within the catchment.

With increasing freshwater demand in Antigua and Barbuda and the seasonal availability (or non-availability) of fresh surface water, which may be further exaggerated according to current climate change projections, in the absence of appropriate dam sites and without heavier reliance on desalination, groundwater resources will have to be further exploited.

Groundwater resources on both islands are already becoming depleted and current abstraction rates may be unsustainable, as the salinity of water obtained from supply wells is reportedly increasing. MAR affords the opportunity for strategic replenishment of aquifers to re-establish groundwater levels, to reverse saline intrusion, and to augment national water supply by providing a means of storing wet-season freshwater for re-abstraction when necessary.

Aquifer recharge, if correctly implemented, will reduce evapotranspiration and runoff to the sea, two major losses within the island hydrological system. It is also considered that innovative and varied approaches to water resource management will improve the preparedness and the ability for adaptation to meet future scenarios for water availability.

GEF (2007) suggest, in their main findings and recommendations; that aquifers in SIDS are an important, but sometimes forgotten component of the SIDS ecosystems. Besides the direct socio-economic benefits associated with improving the sustainability of water resources, MAR potentially provides many environmental benefits including:

- Improved groundwater quality: beneficial to the health of groundwater dependent environments and coastal ecosystems, also has positive impacts on public health in urban areas.
- Raising or stabilising groundwater levels: beneficial to groundwater dependent environments (e.g. wetlands).
- Control of surface runoff: benefits to watershed management and prevention or reduction of flooding, land degradation and desertification, surface water quality degradation and sedimentation of water courses and the near shore environment.

Given an appropriate geological setting, the available techniques for MAR are relatively straightforward, cost-effective (particularly when compared with desalination) and generally sustainable in the long term, with appropriate management and maintenance. Many of these can be adopted by communities at a small scale with locally available materials and manpower. Techniques can also be applied at much larger scales. Generally the source for water is harvested rainfall and harnessed surface water runoff. However, there is an increasing trend globally, particularly prevalent in Australia (Australia EPA, 2005; Foster *et al*, 2003), for storing and recycling treated sewage effluent (grey and black water) within aquifers, and exploiting the natural physical, chemical and biological processes which occur in the soil and rock matrix to attenuate the transport of pollutants and break them down, thus providing a higher quality water resource.

MAR, however, must not be seen as a single solution to water resources problems, and integrated management is crucial. MAR could potentially provide a false confidence in the security of groundwater resources, leading to increased abstraction rates, an unwanted outcome. Demand management is therefore an important part of any water resources strategy, particularly when MAR is involved.

Implementation of large scale MAR projects requires detailed investigations and monitoring systems which produce a variety of data to inform the choice of MAR technique, its specific design considerations, its operation and maintenance.

1.4.1 Summary of Advantages

- The ability to store water in aquifers for later use.
- Balancing out supply and demand fluctuations.
- Stabilising or raising groundwater levels where currently over-exploited.
- Stabilising or freshening of brackish or rising salinity groundwater;
- Reducing losses to evaporation and runoff.
- Improving groundwater quality though dilution and natural treatment of recharged surface water.
- Potential disposal and reuse of waste and storm water, avoiding pollution of water courses and the near-shore marine environment.
- Area footprint is smaller than surface water reservoirs which require inundation of large areas. The structures which are therefore required are small which generally makes them cost effective.
- Use of more appropriate technology: most aquifer recharge systems are relatively easy to construct and operate and can facilitate community involvement in water resources.
- Environmental benefits, including raised or stable groundwater levels for wetlands, enhanced water quality for groundwater dependent ecosystems, control of surface runoff and associated land degradation and desertification.

1.4.2 Summary of Disadvantages

- Not always applicable: needs a suitable water source and the appropriate hydrogeological conditions.
- ‘Clogging’ (physical, chemical and/or micro-biological) of infiltration/percolation surfaces (due to recharging poor quality water), can reduce recharge rates drastically and is often the major limiting factor to infiltration, as well as main long term maintenance issue. Measures to reduce clogging through pre-treatment of MAR or maintenance of the systems are well documented.
- Potential for contamination of the groundwater from surface water runoff, especially from agricultural fields and road surfaces. In most cases, the surface water runoff is not pre-treated (apart from settling of suspended sediment) before infiltration or injection.
- In the absence of financial incentives, laws, or other regulations to encourage landowners to maintain private infiltration systems adequately, the diversion and recharge infrastructure may fall into disrepair and ultimately become sources of groundwater contamination.
- Before large-scale recharge projects are fully implemented, a wide range of information is required (monitoring, hydrogeological investigation etc) and feasibility/pilot projects are often necessary: they may not always be economically feasible (see Section 3.5).
- At larger scales, where water is stored on the surface before infiltration and recharge, similar drawbacks to those associated with surface storage will prevail, such as evaporation losses and the large required land area.

2. Managed Aquifer Recharge Techniques

This section provides a brief introduction to the range of techniques for MAR available to the water resources engineer. All of the techniques outlined below may not be specifically 'practical' for use in the Caribbean, however given the correct hydrological, hydrogeological and economic circumstances they could be. Further detailed investigation is necessary to determine the most cost effective methods for MAR; this will be discussed further in Chapter 3. Chapter 4 will then select a number of the **most** applicable of these techniques to Antigua and Barbuda to provide further information on generic design and implementation of selected schemes.

2.1 Infiltration Techniques

Infiltration techniques are used to infiltrate water into the vadose (unsaturated) zone, above the water table. From here water percolates to the water table through the soil and rock, which can provide a degree of natural treatment of pollution. These methods are generally simple and applicable but require appropriate ground and hydrogeological conditions.

Clogging, or silting of the infiltration surface and the shallow soil/rock matrix reduces infiltration capacity and depends on the quality, particularly the turbidity, of recharge water. Turbid water, with high suspended sediment loads, can be treated through settlement before entry into the system, or maintenance (de-silting) of schemes can be periodically provided, when required, to increase their longevity and effectiveness.

2.1.1 Soakaway/Trench

Soakaways are a traditional way of disposing of surface water from buildings and other hardstanding areas remote from a suitable public sewer or watercourse. A soakaway must have capacity to store immediate storm runoff or harvested rainwater and provide sufficient infiltration into the surrounding soil for the soakaway to be able to cope with the runoff from a subsequent storm. Soakaways are generally formed from square or circular pits, filled with rubble, rock or gravel or lined with dry jointed masonry or perforated concrete ring units to provide structure. Soakaways serving larger areas are generally trench type soakaways.

The maintenance requirements of soakaways are generally low, as long as the surface water is of a relatively high quality on entry. If clogging of the soakaway reduces recharge rates significantly, thus creating a greater risk of failure, they will require cleaning and clearing. This involves removing and cleaning the fill material and the infiltration surfaces of the soakaway. If clogging is anticipated, cleaning should be allowed for in the structure design.

2.1.2 Swale

Swales are linear depressions formed in the ground to receive runoff and slowly allow the flow of water to a discharge point. The sides and longitudinal slopes are very shallow. The slow movement of water along the swale aided by grass and small check dams/weirs, encourages deposition of solids, helps to remove nutrients (such as phosphorous) and promotes infiltration. Lightly contaminated drainage *e.g.* from yard areas can be treated by means of swales. Swales will have to be regularly cleaned and cleared of accumulated debris, but this is a straight forward and cheap activity to undertake.

2.1.3 Infiltration Gallery

Infiltration galleries are generally constructed from a series of relatively large diameter horizontal perforated (about 10% of the surface area) pipes situated in a gravel pack which are connected to vertical inflow pipes from the surface. Ideally the top and side of the galleries are covered in geotextile material to prevent topsoil from entering the galleries, while the base is open to the in situ soil or bedrock, although impermeable plastic sheeting has also been used on the top side of the gravel to reduce unwanted direct percolation within the disturbed ground and prevent soil and other fine particle entry.

An infiltration gallery works in a similar way to a trench soakaway in that it has the ability to temporarily store water within the pipes and surrounding gravel whilst the stored water infiltrates into the soil/strata beneath. The advantage of infiltration galleries over most other infiltration systems is that they are buried and therefore have minimal land surface footprint, making them attractive in semi-urban or sensitive land use environments.

Infiltration galleries is a term also used to describe horizontal groundwater abstraction systems from shallow or sensitive aquifers, or thin freshwater lenses on small SIDS. Within the context of this report, the term is used to recharge aquifers rather than abstract from them.

Maintenance of infiltration galleries is similar to the maintenance of soakaways. Inspection manholes must be provided to help maintenance of the systems.

2.1.4 Pervious Paving

Pervious paving is widely used in developed countries, generally to manage storm water runoff for flood control. The concept is to promote infiltration which can be instrumental in enhancing recharge in urban areas otherwise characterised by large areas of impermeable hard standing. The major advantage of pervious (or permeable or porous) paving is that it does not require any drainage or water collection and storage systems, as it permits rainfall to pass through it, assuming that the soil/strata below has adequate infiltration capacity. However it is relatively expensive and the intensity of rainfall in the Caribbean may mean that infiltration is limited by the permeability of the paving and not the soil/strata, and thus may not be an appropriate recharge technique in the Caribbean.

2.1.5 Infiltration Basin

Infiltration basins are often employed to manage storm water runoff to prevent flooding, however their use in artificial recharge of aquifers is also significant. An infiltration basin is essentially a shallow impoundment, generally with a deliberately designed flood event overflow (to prevent uncontrolled over-topping which could cause erosion and bank failure), which is designed to infiltrate water through the soil into the aquifer.

Infiltration basins are believed to have a high pollutant removal efficiency, particularly if the depth to the water table, beneath the basin is significant. Clogging, or silting of the surface, due to deposition of suspended solids can reduce efficiency, however due to their design de-silting is relatively straightforward. Removal by scraping or digging (with anything from a spade to a bulldozer – depending on size) of the clogging layer in the system will restore infiltration rates. They are also subject to evaporation losses and their effectiveness as recharge structures primarily depends on the infiltration potential of the underlying soil/strata.

Recharge wells and shafts can also be constructed within the infiltration basins to augment infiltration and recharge in situations with lower permeability superficial formations or soil structure close to ground surface. Infiltration basins can accept water from a variety of sources, such as storm water runoff of small urban/rural catchments or surface water diverted from a stream or pumped/diverted from surface water body such as a reservoir.

In the Middle East, where spate or storm flows are occasional, and there is no inter-storm flow within the wadis/canyons, sediment loads within the storm flows are high. In this situation to prevent immediate clogging of the infiltration basin, infiltration basins have been excavated down gradient of check dams (see Section 2.3 below), with the check dam being used to hold back the storm flow, reduce its velocity and encourage settlement of sediment within the flood waters. 1-2 weeks after the dam water retention, the water is then released through the dam into the infiltration basin, using high level intakes to prevent re-scouring and remobilisation of the sediment upstream of the dam. These dam-infiltration basin combinations are known as Recharge Dams.

2.1.6 *Ditch and Furrow System*

Ditch and furrow systems are a method for spreading surface water (generally from high stream flows) over an area of land with irregular topography to provide maximum water-ground contact area for recharge. The rate of flow through the ditches from the feeding channel can be controlled by gates. The excess water is returned through a return ditch along with the residual silt. The technique requires less soil preparation than an infiltration basin and is less sensitive to silting as a uniform flow is maintained through the system to prevent settlement of solids. Ditches should be shallow, flat bottomed, and closely spaced to obtain maximum water contact area. This recharge method can be costly as it requires a high level of supervision and maintenance. The ditch and furrow system is a method of 'controlled flooding', which essentially diverts high flows over agricultural land and which causes recharge *via* infiltration. Over agricultural areas on flatter land it also provides regeneration of soils with sediments; clogging is not usually an issue due to the large surface area over which water is spread, furthermore agricultural practices can break up clogging layers.

2.2 Direct Recharge Techniques

Direct recharge techniques are used to recharge water directly into the phreatic (saturated) zone of the aquifer, below the water table. The advantages of direct recharge are that they generally require less land surface area, easing procurement and reducing cost; they may improve control over the ultimate location of water within the aquifer and thus improve the chance of subsequent abstraction recovery; they are useful in areas where either the aquifer is overlain by less permeable strata or soil infiltration rates may be low; they reduce the normal soil moisture losses (induced by percolation through the vadose zone) and evaporative losses associated with other recharge techniques; or in areas where structures for direct aquifer recharge are already in place (dug wells or boreholes) thus reducing capital cost.

Direct recharge schemes are often subject to clogging by bacterial growth, chemical precipitation and/or deposition of silt within the borehole screens as well as the rock interstices surrounding the well or borehole. Hence, the chemical/biological composition of direct recharge water is often required to be of better quality than when employing infiltration techniques as there is little opportunity for natural treatment, thus posing a greater risk to aquifer pollution, whilst also increasing operation and maintenance (cleaning) costs.

2.2.1 *Open Well/Borehole*

Specifically designed recharge wells, as well as existing groundwater abstraction wells and boreholes can be used to recharge aquifers directly if deep enough to penetrate the water table. Water from a range of sources (storm water, river water, treated water) can be diverted into these structures. Inflow pipe-work can be used to direct inflows below the water table to try to reduce entrapment of air bubbles and prevent scouring and re-mobilisation of sediment and other debris within the borehole, which can clog the aquifer. The quality of the source water (including the silt content) should be compatible with the aquifer, so that the quality of the groundwater reservoir is not deteriorated.

2.2.2 *Recharge Shaft*

Recharge shafts are reportedly very efficient and cost effective structures for direct recharge and are recommended in areas with seasonal availability of source water. They typically consist of a vertical shaft of at least 2 m diameter, which penetrates below the water table. This implies that they may not be practical (in terms of construction) if the water table is very deep. The large diameter allows storage of water and avoids eddies in the well. The shaft should ideally be filled with boulder gravel with a near surface coarse sand filter layer, to form an inverted filter. The uppermost sandy layer has to be removed and cleaned periodically. This filter within the shaft provides some treatment of the water and hence precludes the necessity of pre-treatment before direct recharge unless the water is heavily polluted. Even so, water should ideally be pre-screened to remove organic flotsam and jetsam and, if turbid, pre-settlement of fines may be necessary. This method is well suited to reasonably permeable formations as the storage within the shaft is limited, unlike a recharge basin or similar. If the aquifer is highly permeable, such as a karstic limestone, a large quantity of recharge can be achieved rapidly and effectively.

2.2.3 Injection Bore

Injection wells are generally used where aquifers are confined. Treated surface water is pumped under pressure (hence 'injection') directly into the aquifer. The recharge is instantaneous and there are minimal transit and evaporation losses. The method is also very effective in fractured rocks or karstic limestones. However, if the aquifer is too permeable it may be hard to recover the injected water when required. It is essential that water is treated before injection to avoid regular clogging of the well-aquifer interface with sediment or bio-fouling (the accumulation of bacterial growth – see Section 3.4) and to protect the quality of the groundwater in the aquifer; water used for well injection is usually treated to drinking-water quality standards. Pre-treatment, pumping and maintenance requirements mean greater operational costs and specialised technologies but if the good quality injected water can be readily recovered it may be a valuable method, given the correct aquifer characteristics.

2.3 Channel Modification Techniques

Channel modification techniques refer to ways of minimising excess surface water runoff, providing additional channel storage and increasing the wetted area generally through use of dams. Infiltration through the streambed either upstream or downstream of the dam structures is maximised. Channel modification schemes must be located upstream of a well field or in a position where the recharged groundwater and augmented water table can be developed.

2.3.1 Check Dams

Check dams vary considerably in size and construction depending on the catchment size, topography and available resources for construction. As a result they have many names in different regions of the world. They can be constructed from earth, rocks, boulders concrete, steel, rock gabions, sandbags, wood, bamboo, and even rubber inflatables filled with water or air. Essentially all these structures are provided to do a similar job, arresting surface runoff within the confines of the stream and facilitating infiltration upstream of the dam.

They can be constructed in ephemeral (seasonal) gullies or streams and must be underlain by permeable river bed and a permeable rock or alluvium. They are designed based on channel cross-section (usually no more than 3m in height) and excess water is allowed to spill over. In order to avoid scouring and stream incision resulting from hydraulic shear stresses, the streambed must be protected on the downstream side of the dam. To harness maximum runoff in the stream a series of such dams can be constructed to provide recharge on a regional scale.

Providing a series of dams will achieve some downstream attenuation of the suspended sediment load as sediments will be deposited upstream of dams during infiltration after the flood peak. Attenuating the sediment load should therefore increase infiltration efficiency in subsequent check dams. Check dams do suffer from silting and therefore are best in conjunction with catchment management strategies especially in deforested, arid degrading areas such as areas of the Caribbean including Antigua and Barbuda.

Check dams can also be applied at a larger scale in larger streams to submerge a greater land area, which must have adequate permeability to facilitate sufficient recharge of the impounded surface runoff. In the larger structures a spillway must be provided, with adequate freeboard such that the structure is not overtopped in an uncontrolled manner. Uncontrolled overflows are the main cause of dam and embankment failure.

A specific type of check dam is known as a 'Leaky Dam'. These can be constructed from gabions, made from locally sourced boulders bound in wire mesh into rectangular blocks. These structures are intended to allow some flow through the structure and provide some retention of floodwater. Infiltration then occurs upstream in the pond created as well as downstream as the flow through the leaky dam controls stream flow. The silt content of the stream water is deposited in the gabion interstices, reducing silting of the stream bed upstream (as a low velocity is maintained and the silt doesn't fall out of suspension) and downstream. Over time the dam will become more impermeable as further deposition of silt occurs within the gabion structure.

2.3.2 Recharge Dams

Recharge dams (already referred to briefly in Section. 2.1.5) are generally large scale structures designed to intercept flows in ephemeral channels and store water during a flood. They are best applied in areas with high suspended sediment loads, as they promote settlement and silting upstream of the dam. The stored and clarified water is then released at a reduced flow rate, often through culverts in the dam, so it can infiltrate and recharge the downstream alluvium. Contrary to the check dam concept, recharge mainly occurs downstream of the dam and not in the upstream reservoir/ponding area itself as the bed generally becomes clogged with silt, although infiltration will occur upstream of the dam if silt content of the water is kept low.

The objective is to spread the whole of the stored flood spatially and temporally, to the benefit of the aquifer in the downstream infiltration channels by infiltrating for as long as possible in a small wetted area (to reduce evaporation). This generally means that the culvert discharge is kept as low as possible. The dams are designed in such way that the maximum discharge of outlets ensures that the total storage volume of the dam can infiltrate through the wetted contact area in the channel downstream subsequent to a flood event.

Recharge dams require a greater storage than check dams and thus a greater inundation area and appropriate topography.

2.3.3 Streambed Modification

When channels have small slopes and water depths, small bunds about 1m high can be constructed within a stream channel, often in a 'T' or 'L' shape to increase the flowpath of water, the time for infiltration and the contact area with the streambed. This method enhances the natural recharge through a stream bed. Streambed modification is useful when a small flowing channel flows through a relatively wide valley. Where streams are prone to flash floods this may not be a preferable technique as bunds will be destroyed, however downstream of 'leaky' dams or recharge dams where flow is controlled and peak flows are significantly attenuated it is potentially a good method for enhancing natural infiltration. Construction costs are low for such schemes but may need to be regularly maintained (by reconstruction).

2.4 Catchment Management

Within the context of this study, the objectives of catchment or watershed management are to reduce soil erosion and land degradation, augment soil moisture and infiltration and retard rapid runoff of rainwater. If these objectives are met, groundwater levels will be raised down the hydraulic gradient as a consequence of enhanced aquifer recharge; a reduction in suspended sediment loads in downstream runoff will occur; and flood peaks will be reduced as a consequence of longer catchment residence time thus resulting in less 'flashy', flatter, broader hydrographs in ephemeral streams. There are a range of techniques for such watershed management. These systems are generally very cheap to build and involve little detail in design but they may need to be applied over large areas for the benefits to be evident. Some maintenance is required with such schemes involving clearing of sediment and rebuilding when structures may occasionally fail.

2.4.1 Contour Bunding

Small earth or boulder bunds constructed perpendicular to land slope act as barriers to overland flow. Water is impounded resulting in increased infiltration and soil moisture storage. Bunds must be sufficiently closely spaced to intercept overland flow before it reaches velocities great enough to produce shear stresses capable of eroding and entraining sediments.

2.4.2 Contour Trenching

Shallow intermittent trenches are excavated perpendicular to land slope and a small earth bund (best stabilised by planting) on the downstream side is constructed with the cut material. Such trenches are capable of accepting and infiltrating (if soil and geological conditions permit) up to 50% of peak rainfall in semi-arid regions. Trenches may need cleaning and desilting regularly.

2.4.3 Gully Plugging

Gullies are a symptom of land degradation; they are a result of concentrated soil erosion. Gully plugging aims to reduce flow velocities in gullies to reduce further erosion, promote infiltration, promote settlement of sediment, and re-establish soils and soil moisture within gullies. Gully plugs are essentially small check dams (typically at vertical intervals of 2-3m) created from locally sourced materials such as earth, boulders and brush wood. Planting of vegetation in gullies will also reduce flow velocities, and improve soil development.

2.4.4 Afforestation

Re-vegetation, where possible, of catchments with local species of specifically low-transpiring trees and shrubs will reduce surface runoff and promote interception and infiltration.

2.4.5 Controlled Grazing

Grazing by livestock denudes vegetation cover and accelerates soil erosion. Control of this on hill slopes, particularly by keeping livestock away from water bodies and thus providing a buffer of vegetative cover, will reduce the detrimental impacts. Stall-feeding should be encouraged, as well as reducing the numbers of livestock held.

2.5 Indirect Recharge Techniques

Indirect recharge techniques promote aquifer recharge, whether intentionally or not, as a result of some other human activity.

2.5.1 Induced Recharge

Induced recharge generally refers to water supply wells located a short distance from the bank of a surface water body (stream/river). Pumped abstraction from the wells lowers the water table adjacent to the water body, thus steepening hydraulic gradients in the vicinity and inducing river water to enter the aquifer system. This type of scheme has been applied in many places in Europe within alluvial valleys, so as not to deplete groundwater resources inland and to purify the surface water by inducing flow through the stream bank, soil and aquifer to provide a better quality water than would occur through direct abstraction from the same river.

2.5.2 *Over Irrigation*

Excess irrigation water from canals and fields have historically caused water logging and salinisation problems. However, over-irrigation of crops will also result in groundwater recharge by infiltration and percolation, and when properly managed this incidental recharge could be an asset. For example, approximately 60% of the water applied to rice paddies is utilised, the balance evaporating or percolating to groundwater.

2.5.3 *Leaking Water and Wastewater Pipe Networks*

In urban areas with a dense potable water supply, effluent discharge, and stormwater network, leakage from pipes can form a significant component of the water balance of a catchment. Leakage from such pipe networks can contribute significantly to groundwater recharge, in some cases resulting in rising groundwater levels and flooding. The impact of leakage reduction schemes on both the quantity and quality of groundwater could be considered, as part of any integrated groundwater augmentation strategy.

2.5.4 *Sewage Disposal By Septic Tank*

Septic tanks are widely used in areas where no connection to mains sewerage is available and can be very effective in treating wastewater and providing some indirect groundwater recharge if well maintained. They treat a limited amount of effluent within an anaerobic bacterial environment, retain indigestible solids and greases, and discharge a partially treated effluent into a 'leach field' which further treats the water through natural purification processes. Subsequently, the water percolates to groundwater or is lost to soil moisture, evaporation, or transpiration. The treatment of effluent can be made more effective by combining septic tanks with biofilters or aerating components, which speed up the oxidation and break down of organic matter.

Solid, inorganic, waste which cannot be decomposed within the tank eventually has to be removed. If the tank is not 'pumped' regularly enough, undecomposed waste water could discharge straight to the leach field. This has obvious environmental consequences for groundwater quality and if the sludge (retained solids) also overflows, it may clog the leach field, reducing the efficiency of the system and the ability of the system to treat effluent, even once the tank has been pumped.

2.6 MAR Synopsis

A matrix (See Table 4 – p43) of 5 **scales** of implementation and 5 **water sources** has been developed to provide a concise summary of the range of techniques available for MAR and the scales of their application, and to enable selection of the most appropriate technique for MAR in a given situation.

Table 4 is presented at the end of chapter 4, which gives case studies and greater explanation of MAR techniques and their application.

Scales:

- Dwelling
- Building (e.g. large municipal building/area of hardstanding)
- Complex - group of buildings and hardstanding areas (e.g. hotel)
- Sub-catchment (e.g. town/farm/hydrological sub-catchment)
- Catchment

Water Sources:

- Direct rainfall harvesting
- Overland flow surface runoff
- Confined surface runoff (e.g. stream/river)
- Grey water (non-industrial, domestic waste water form processes such as washing and laundry)
- Black water (Wastewater containing faecal matter)

As the scale increases from dwelling up to catchment, with it the construction and operational costs of the recharge schemes increase, as does the scheme investigation requirements as well as the range of considerations in planning and design of recharge and diversion infrastructure. This is discussed further in the next chapter.

3. MAR Method Selection: Criteria and Considerations

To develop, operate and maintain an economic and efficient recharge project, proper planning, including selection of the most appropriate method, is necessary. The existing conditions (namely the hydrological and hydrogeological setting) may limit the methods of MAR to be considered and will affect the design, operation and maintenance of the project. The nature, scale and distribution of benefits also depend on such site specific factors - it cannot be assumed that MAR will always lead to an improvement in groundwater availability. Therefore, the selection of an appropriate method for MAR requires detailed investigation of the appropriate site specific factors.

The basic requirements for MAR are:

i. Identify a suitable aquifer for storing water or where water table recovery is desirable and procure land for recharge.
ii. Identify available non-committed surplus wet season runoff, or water from another potential source.
iii. Identify the most cost effective recharge technique given the site specific conditions.

These requirements need to be met through geological, hydrological and hydrogeological investigation. Locating schemes (*i.e.* the first two stages above) can generally be met through mapping relevant topographical geological, hydrological, climatological, and land use parameters.

3.1 Geology and Hydrogeology

The success of a MAR scheme depends largely on the local and the regional sub-surface conditions. These determine the ability of the recharging water to percolate through the unsaturated zone, the ability of the aquifer to store the recharge water, the efficiency of the recovery of stored water and/or the effectiveness of reducing saline intrusion (if this is an objective).

Knowledge of the regional geology is important for selecting an aquifer for recharge and a method of recharge. Geological maps and/or an exploratory programme can help to identify the physical parameters and hydraulic boundaries of the aquifer and the degree of confinement. Physical properties of the strata (permeability and porosity) determine the infiltration and percolation rates that can be sustained and the volumes of water that can be recharged to the groundwater body.

Hydrogeological investigations need to establish the sustained percolation rates, maximum storage capacity, and effective transmission rates of groundwater away from the recharge site. Important factors requiring evaluation are:

- The physical character and permeability of the subsurface deposits above the water table. This determines the sustained infiltration and percolation capacity;
- The depth to the water table (Thompson et al, 2010) which determines the mounding which will occur;
- The porosity, specific yield and thickness of the deposits, and position of the maximum permitted fluctuation of the water table. These factors establish the subsurface storage capacity at the chosen location;
- The transmissivity (that is permeability) of the aquifer and the hydraulic gradient of the water table. These factors determine the spreading or mounding of groundwater at the recharge site (aquifers with a high transmissivity can permit rapid dispersal of recharge water and, as a

result, only limited quantities of water might be recovered. This may not always be a problem if the aim of the recharge scheme is to supplement groundwater flows on a regional basis (possibly to gain environmental benefits eg protect brackish coastal wetlands); and

- The chemistry of the native groundwater and the aquifer mineralogy must be considered in relation to the recharge water to minimize problems associated with chemical transfer.

(After, ASCE, 1996)

3.2 Hydrology

By harnessing water, particularly surface runoff, to recharge aquifers, water is being removed from the natural (or current) hydrological regime. MAR is a very suitable technique for augmenting water resources as long as the potential source water is currently wasted through runoff (especially to the sea) or evaporation. If the source water is not wasted, it is likely that this water is being utilised elsewhere, for irrigation, as recharge water through streambeds, for filling up surface reservoirs *etc*. The relocation of water resources through implementing MAR schemes needs careful consideration within the context of natural recharge and discharge, abstraction, and current water uses (Gale *et al*, 2006).

Considering water users within any hydrological assessment is therefore essential. The location of a MAR scheme within the catchment is important. If located in the area of origin of the water, benefits such as maintaining water resources by inducing recharge, elevating water tables, reducing soil erosion *etc*. can be gained. However, this may be detrimental to downstream users who rely on the flow of water from the source.

Conversely, if located downstream within the catchment a problem faced when designing a MAR scheme may be providing enough storage to capture the flood peak before infiltration. Also, water quality is potentially worse as more pollutant pathways and contaminant sources will lie within the enlarged catchment. However, the flow of water through the entire catchment before being harnessed for recharge allows replenishment of surface reservoirs and other essential water uses such as abstraction from streams for agriculture.

As in the Caribbean, MAR is useful in climates with a pronounced wet season to store surface water for use in the dry season which would otherwise runoff. Evaluation of hydrological and meteorological data is needed to ascertain an estimate of the quantity of water available for MAR. The quantity of water available for recharge has direct bearing on the need for, and size of, a project.

Timing of water supply is also important. The water supply available may vary widely within a short period of time or remain almost constant over a long period. The availability usually can be ascertained from a review of recorded flow (or rainfall for direct rainfall as a water source) for the selected supply source. Generally the more extreme fluctuating storm runoff becomes the more it causes problems related to inefficient project operation, as large volumes of water containing high concentrations of silt and debris must be handled within a relatively short period of time – consider trying to capture and store hurricane related rainfall events for example !

The surface infiltration methods are recommended when the source is a fluctuating flow and excessive fluctuations necessitate increasing the storage capacity of the project (ASCE, 1996). The basin and pit techniques have the advantage of providing temporary storage capacity, depending on the area covered and the depth of water. At the other extreme, injection wells have very little storage capacity and require a fairly uniform supply of high quality water.

Hydrological investigations for recharge schemes require the following information:

- The quantity of water available for artificial recharge;
- The time for which the source water will be available;

- Current demand and water use; and
- Engineering designs required to convey water to the recharge site.

3.3 Soil Infiltration Capacity

Where ever possible, surface infiltration systems are preferred. They offer the best opportunity for reducing clogging and the best soil-aquifer treatment if quality improvement of the water is of importance (Bouwer, 2002). Surface infiltration systems are dependent on permeable soils and a relatively shallow (to reduce soil moisture losses) unconfined aquifer which is sufficiently transmissive to promote lateral flow from the infiltration system without significant mounding, which reduces infiltration efficiency.

The soil infiltration capacity is often the limiting factor to the ability to recharge water and therefore dictates the method and size of the recharge site and the maintenance and operational techniques to be utilised. Infiltration is generally dependent on the relative amounts of clay, silt and sand in the soil composition (although moisture content, vegetative cover, air entrapment *etc* all affect infiltration). Maps of soil type as well as field reconnaissance supplemented by hand auger borings can be used to locate potentially viable sites for surface infiltration systems, assuming the underlying geological conditions are favourable.

Individual soil infiltration tests should be carried out for detailed designs of important, large, recharge schemes as long term infiltration capacities are inherently site specific. The most reliable tests use large infiltration areas, for example a 5m × 5m bermed area, where the divergence or 'edge' effects are less significant (Bouwer, 2002). However, these tests are laborious as they require large volumes of water, and take a long time to conduct.

If surface infiltration rates are so low that large surface storage volumes would be required, direct recharge techniques should be considered or another potential site located.

3.4 Water Quality and Clogging

MAR can be used as an effective treatment method for water, and the rock and soil matrix, as well as acting as a physical filter, can effectively attenuate pollutants through biological and chemical processes. However, the result of this treatment of water over time is clogging of the soil matrix, particularly at the infiltration surface (basin bottoms, walls of trenches, well screens and gravel pack - aquifer interfaces *etc*). Clogging is caused by physical, biological and chemical processes and results in a marked reduction of recharge rates (Pavelic *et al*, 2007).

Physical clogging generally occurs at the surface as a result of the accumulation of suspended solids (inorganic and organic) in the recharge water, however clogging layers can also form at depth where soil is denser or finer. Biological clogging occurs as a result of growth of micro-organisms (generally a result of high nutrient loading) on and in the soil which form biofilms and thus reduces aquifer porosity. Chemical processes include the precipitation of calcium carbonate, gypsum, phosphate, and other chemicals on and in the soil, aquifer and well screen infrastructure (Bouwer, 2002).

The physical, chemical and biological properties of the water to be recharged are thus particularly important in the success of MAR (as well as the degree of purification to be achieved) and often dictate the choice of technique, in combination with the geological setting. (Balke and Zhu, 2008). For example, injection wells require very high quality water for recharge and the quality of water used in deep pits or shafts must be nearly as good. Relatively good water quality, which can be achieved through pre-settlement of sediment is desired for basin projects (ASCE, 1996). Conversely, properly designed ditch and furrow projects have been used advantageously with waters of high silt and clay content. Also, groundwater flow in karstic limestone, for example, which may have high flow rates and little contact with rock surfaces relative to other hydrogeological conditions, may not receive the same level of bioremediation as in other hydrogeological settings.

As a consequence, the composition of the surface water available for recharge needs monitoring to prescribe the appropriate method, necessary pre-treatment of the recharge water, and/or maintenance of structures, to enable high operational capacity and longevity. The suspended solids is generally the most crucial quality parameter, particularly for infiltration schemes, and this must be sampled (and evaluated in mg/l by filtering and drying) during the peak flows which provide the source water for recharge to provide estimates of the sediment load and thus how quickly a clogging layer will form.

Clogging is best controlled by prevention (Bouwer, 1999); by removing the components that cause clogging. For surface water, especially flood runoff which may be highly turbid, this typically involves pre-sedimentation for infiltration methods. For direct recharge, if biological and chemical quality of water is poor further treatment will be necessary, techniques such as activated carbon filtration and disinfection with chlorine will produce required quality.

For surface infiltration systems, clogging is controlled by periodically (generally decided upon by inspection) removing clogging layers or breaking them up after a drying period. Where the water is extremely muddy, drying and cleaning may be necessary after each flood event. If surface water quality is good, maintenance of basins may be required annually or even less frequently.

3.5 Effective Technical Design and Specification for MAR schemes

The detailed design and maintenance of MAR schemes requires knowledge of a wide range of factors as outlined above. Because soils and underlying geological units are inherently heterogeneous, and water quantity and quality highly variable, planning, design, and construction of groundwater recharge schemes must be progressive and responsive. The first stage is to test for critical flaws and general feasibility and subsequently proceeding with pilot and small scale systems so that the benefits can be observed (Bouwer, 2002). These steps should be carried out before designing the complete system. This staged approach is especially valid for large systems where scale effects are significant and large amounts of money are commonly involved.

The level of study necessary to inform final designs depends on the scale and cost of the proposed project, and the risks associated with failure. Five scales have been developed (see Table 1) for which the necessary level of scientific investigation (largely based on monitoring networks) and feasibility/pilot study (largely relating to infiltration testing and water table monitoring) is wide ranging.

For the smallest scale, ‘dwelling’, it may not be necessary for any testing or monitoring if soil type and geology is known to be favourable for infiltration. On the largest ‘catchment’ scale however, full monitoring networks and large-scale investigations will likely be necessary including: streamflow monitoring and analysis; surface water quality trends and fluctuations (particularly during and after flood events); groundwater level fluctuations, trends and contours; groundwater quality monitoring (most importantly during pilot studies); aquifer hydrogeology, such as permeability testing and possibly tracer testing (in karst formations); geological investigation; and geophysical investigations.

Additionally post project evaluation and appraisal is necessary, which will involve a level of monitoring analysis and investigation, to inform future projects and optimise current operation and maintenance.

3.6 Cost-Effective Design and Specification of MAR Schemes

Table 2 illustrates rough indicative costs for MAR schemes at different scales. Without estimating the total water recovered, which is difficult to quantify generically, it suggests that larger schemes are most cost effective. However, they may have greater environmental and social impacts; whereas smaller schemes with community involvement and ownership can be more easily operated, maintained, and produce less negative impacts.

STORAGE RESERVOIR SCALE		ROOF	PLOT	SUB-DIVISION	MINI-	SMALL	MEDIUM	LARGE	VERY LARGE
Rainwater Harvesting Infrastructure Description		Small Household Rainwater Tank	Large HH Tank and foundations; minor hill slope channelling	Multi-building water management improvements; small retention structures eg road drainage storage	Medium SIDS Earthworks Dam &/or Infiltration Basin	Large SIDS Earthworks Dam &/or Infiltration Basin	SIDS Concrete Dam &/or Stormwater Diversion Structures	Large Continental Concrete Dam & Stormwater Diversion Structures	Mega Continental Concrete Dam & Stormwater Diversion Structures
Antiguan Scale Examples (not specifally designed for managed aquifer recharge)					Brecknocks #1 20,500 m^3 or Bendalls 23,000 m^3	Collins 342,000 m^3 or Bethesda 537,000 m^3	Potsworks 5 Million m^3	N/A	N/A
% of Build	Generic Total Construction Cost (US$ 2009) (+/-30%)	300	3,000	30,000	300,000	3,000,000	30,000,000	300,000,000	3,000,000,000
3%	Site Investigation (SI) in US$	9	90	900	9,000	90,000	900,000	n/a	n/a
6%	SI & Assessment in US$	18	180	1,800	18,000	180,000	1,800,000	n/a	n/a
10%	SI, Assess, Planning, Permitting in US$	30	300	3,000	30,000	300,000	3,000,000	n/a	n/a
m^3	Typical Volume (+/- 30%) (m^3)	1	20	300	25,000	500,000	10,000,000	1,000,000,000	100,000,000,000
$/$m^3$	Construction Cost/Vol Ratio	**300**	**150**	**100**	**12**	**6**	**3**	**0.3**	**0.03**
Potential losses (evap & unrecovered ground water)		very low	low	medium	medium	high	very high	n/a	n/a
Cost of recovery (of water)		nil	low	medium	medium	high	high	n/a	n/a
Operation and maintenance		low	low	medium	medium	high	high	n/a	n/a
Potential environmental benefits (including flooding)		low	low	medium	medium	high	high	n/a	n/a
Potential environmental impacts		very low	low	medium	medium	high	very high	n/a	n/a

Table 2: Indicative costs of MAR at different scales

To identify the most cost effective way of implementing a large-scale MAR scheme, detailed investigation of the site specific conditions discussed above must be carried out and an appropriate method, possibly in conjunction with appropriate pre-treatment, selected based on the conditions encountered. Figure 5 has been developed to summarise this process of investigation and method selection for a large-scale MAR scheme.

The cost of this pre-design and construction site investigation and study is necessary as it should prevent over or under design, reduce construction costs and risks, improve efficiency and longevity of the recharge schemes, and also potentially reduce maintenance costs by enabling more sustainable and applicable scheme design. In the construction industry, it is suggested that good site investigation can reduce construction costs by up to 30% (Latham, 1994) and reduce the risk of failure (Staveren and Seters, 2004).

Research in the USA recommends that spending up to 3% of a projects' total cost on site investigation can be worthwhile. This is a useful 'yardstick' when establishing the effort to put into design and investigation for any MAR scheme, from household roof soakaway to municipal flood basins to catchment dams.

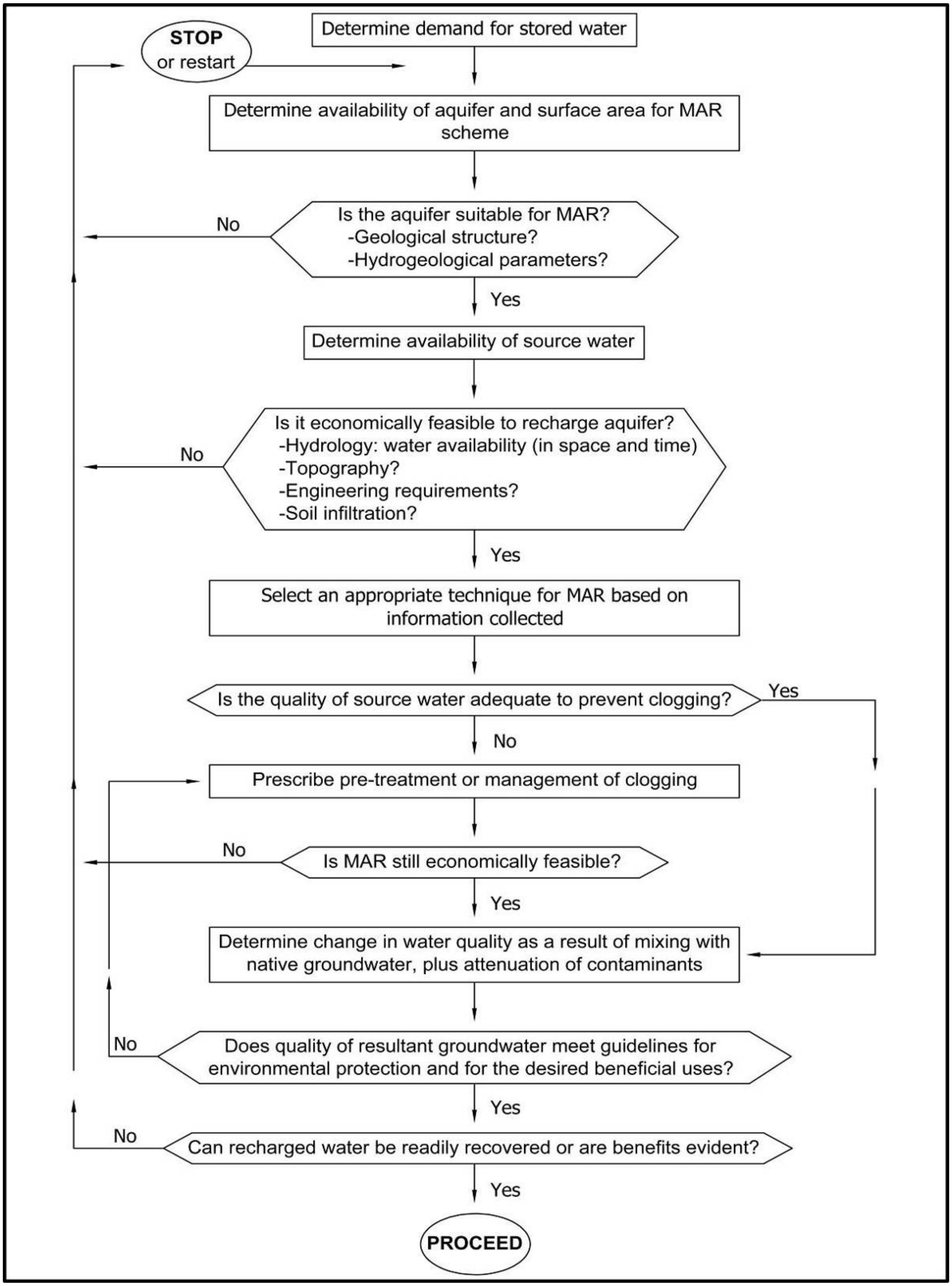


Figure 5: Conceptual Flow/Decision Diagram for MAR Feasibility

4. MAR Best Practice Techniques

The review of the available techniques for MAR (Chapter 2) and the conditions which influence selection and implementation of recharge schemes (Chapter 3) has enabled selection of the types of recharge schemes which will best help to resolve the Antigua and Barbuda water sector issues. This chapter presents practical guidance for implementing MAR schemes at all 5 of the scales identified in Section 2.6. As the water sector issues faced in Antigua and Barbuda are similar across the Caribbean, and as many of the Caribbean Islands possess similar existing conditions in terms of hydrology, geology, topography and environmental and socio-economic factors, this guidance will be applicable to many Caribbean SIDS.

The issues facing the Antigua and Barbuda water sector are repeated below for reference (see Section 1.3.6). These issues are the reasons for implementing MAR schemes and they help to define the choice of techniques:

- High seasonal and interannual rainfall variability: most of the rainfall is received in tropical storms (very high intensity events) during the rainy season (July – December);
- High and increasing risk and vulnerability to floods and droughts, especially given reported climate projections;
- Inadequate reservoir design: many of the water storage structures are not holding water effectively due to their design (embankment, lining, spillway etc);
- Reliance on desalination: Water production is expensive and has to be highly subsidised;
- Inadequate catchment management: increased urbanisation, poor sanitation, the expansion of tourism, the increase in construction and the intensification of farming has led to a change in land use and a rise in diffuse and point source pollution and soil erosion rates; and
- Need for integrated water resources management policy and strategy.

This chapter provides guidance for recharge techniques at each scale and for different water sources; the guidance is comprised of descriptions of schemes and schematic drawings depicting generic designs. These designs will have to be adapted as required to suit each individual scheme and specific site; they give an indication of the engineering works that will be required and the level of detail involved in design and construction. Construction techniques available on SIDS may also require the suggested designs to be amended.

The investigative, monitoring and maintenance requirements of implementing and planning the schemes at the range of scales are addressed. To reinforce the selected methods in the guidance, evidence in the form of brief case studies and examples of similar successful schemes in similar environments is provided, where possible from Caribbean Islands.

4.1 Individual Dwelling Scale

Direct rainfall at this scale is an important water resource throughout the Caribbean. Antigua and Barbuda currently has well developed rainwater harvesting practices for domestic use. There is reported evidence to suggest that village/dwelling-scale rainwater harvesting will yield much more water for consumptive use than large or medium dams (Cortesi *et* al, 2009) contrary to the indicative cost calculations presented in Table 2. Notwithstanding this, enforcing the bylaws which ensure rainwater harvesting, potentially including small scale MAR, at households is crucial in IWRM.

Due to the high variability in rainfall (much of the annual rainfall can fall in the wet period of 5 months) and the typically inadequate storage capacity (due to space requirements and cost of large tanks) of rainwater harvesting tanks, overflows will be common during the wet season as a result of consecutive rainfall events. Currently, overflows from rainwater harvesting are generally lost to overland flow and evaporation. This potentially increases downstream (urban) flooding problems and the risk of surface water entraining contaminants thus posing a risk to public health.

Accordingly, where conditions permit, overflows from rainwater harvesting tanks should be routed and infiltrate directly to the ground. This will reduce the loss of clean harvested rainfall that currently overflows from tanks, increase groundwater recharge, reduce flood risk and the overland flow of contaminated surface water, and potentially improve groundwater quality (through dilution) in aquifers underlying urban centres.

It is possible this could have a beneficial effect in larger urban areas on Caribbean SIDS, such as St John's (in Antigua), where indirect groundwater recharge with poorly treated effluent from inadequately maintained septic tanks is a common problem. This diluting effect of promoting recharge does not negate the need for better maintenance of septic tanks. Steps to reduce effluent discharges to groundwater, through enforcing better maintenance of septic tanks, are necessary.

In Bermuda, recharge of groundwater in unsewered urbanised areas appears to be about twice that occurring under naturally vegetated areas. The additional, artificial recharge is reportedly due to inputs from excess roof drainage and effluent from cesspits. The recharge in high density, unsewered areas is estimated to be 740 mm/yr compared with about 365mm/yr in areas of grassland and woodland. These recharge estimates represent respectively, about 50 and 25 % of the annual average rainfall of 1460mm (Thomson and Foster, 1986, cited in: Falkland, 1991). Although water quality was not considered in this study, it provides evidence of effective recharge (although indirect) of a limestone aquifer in Bermuda. If conditions permit, and this type of recharge is promoted and controlled through MAR techniques at a range of scales in the urban environment, groundwater levels and quality could potentially be improved across the Caribbean.

Providing **soakaways** (see Drawing No. 1 – p44) for new rainwater tank overflows and retro-fitting soakaways in dwellings which already have rainwater harvesting schemes is relatively simple and inexpensive although it is likely to require some kind of incentive.

Rainfall data, regional soil maps and geological maps should be used to indicate suitable locations for soakaways attached to rainwater harvesting overflows. An estimation of infiltration capacity would be useful for designing soakaways, however it seems unnecessary to carry out infiltration tests at all dwellings where such schemes may be applicable.

It is suggested to size the soakaways to be able to store half of the mean annual daily maximum rainfall based on the area of the roof and a runoff coefficient of 0.85 (SOPAC, 2004). The void space in the fill material must also be accounted for (*e.g.* use 0.4 for uniform gravel).

For example if the roof area is 10m², and the mean annual daily maximum rainfall event is 150mm, assuming a runoff coefficient of 0.85 and a void space of 0.4, the required volume of the soakaway would be $10 \times 0.15 \div 2 \times 0.85 \div 0.4 = 1.59 m^3$*, assuming that the tank has the capacity to store half of the roof runoff (which may not be the case in a prolonged wet period), and that over the duration of the storm event that infiltration was negligible.*

Based on these assumptions, the design soakaway system will overflow every other year. More realistically it is likely that it will fail less than this as there will often be enough storage in the tank to accommodate most of a large rainfall event, and infiltration rates will be greater than zero.

However, it must be realised that sizing the soakaways will depend on practicalities such as the amount of space available, the ability to dig the soakaway, and the amount of gravel (or other fill material) which can be obtained. If the soakaways are under-sized, the worst result will be some overflow running off, this is an improvement on all rainwater which overflows from a rainwater harvesting tank running off to waste.

Sizing tanks for rainwater harvesting is usually based upon storing the difference between water availability and demand. There are a range of techniques to calculate necessary storage from very simple calculations based on the longest expected dry period and the daily demand to more sophisticated computer aided analysis (*e.g.* SimTanka2, 2009). There is already much literature and practical guidance on sizing rainwater harvesting tanks for domestic use on SIDS, this is not repeated within this report: See SOPAC (2004); UNEP (1998b). First flush systems, which remove the sediments that accumulate between rain events on roof/hardstanding catchments, need to be operating well so as not to contaminate tanks.

In areas where underlying sediments are highly permeable and reach ground surface, such as near shore coral sands, soakways may not even be necessary and direct routing of the rainwater harvesting overflow pipe into the sand may be adequate (Carpenter, 2006). This technique is well practiced in low-lying coral atoll countries, notably the Maldives, where rainwater overflow pipes are frequently either routed directly into the household well or into the ground adjacent to the well, to enable the sand to provide a degree of filtration. The increase in freshness in these wells compared to others on the island was tangible.

4.2 Building Scale

At this scale such as a church or village hall and associated communal infrastructure, such as car parks etc, larger volumes of water can potentially be harvested. Constructing tanks for this water can be costly, but greatly enhances water security for communities. If tanks are not available, the water should be routed to the ground to mitigate the problems associated with urban runoff discussed in Sections 4.1 and 1.3.3. Larger soakaways will be necessary to store and infiltrate the volumes of water associated with the larger catchments. All areas of hardstanding can be used to collect rainwater, such as cemented or asphalted car parks and rooftops. Runoff can be routed *via* gutters and downpipes to larger drains (or grassed swales which provide some treatment and infiltration) to infiltration systems.

Generally **infiltration trenches** (see Drawing No. 2 - p45) are used for larger MAR systems as they provide more opportunity for infiltration for a given land footprint. During large rainfall events, significant volumes of water will be routed to the infiltration system and, except for the most permeable of soils, the inflow to the infiltration system *via* runoff will exceed the outflow *via* infiltration. Hence, provision of sufficient storage capacity is essential for an infiltration system to perform properly. If the infiltration system is incorrectly designed, the outflow rate may not be enough to allow the system to empty sufficiently before the next rainfall event. The system will then overflow, causing localised flooding among other negative effects and the scheme will be deemed a failure. In-situ infiltration tests are therefore required for systems draining more than $100m^2$.

There are a range of techniques for infiltration testing, see Bouwer (1999; 2002). A simple, applicable method has been outlined in Box 4.**1**, which give infiltration in meters per hour (m/h), is widely used in the UK and largely avoids overestimation by divergence or 'edge' effects, a common problem with infiltration testing.

Infiltration systems are normally designed to accommodate and discharge a specific Return Period (or probability) rainfall event. The design return period should be selected appropriate to the risk and the consequences of failure.

Where rainfall data is inadequate this kind of approach may not be viable. However as the scale of infrastructure investment becomes more substantial, the need for it to operate effectively and have an intended design life and performance becomes more relevant.

***Box 4.1: Infiltration Testing** (photograph, Figure 6)*

A test pit should be dug at the proposed site of infiltration to the same approximate depth of the anticipated system. If the area to be drained is less than $100m^2$ the volume of water used in the test should be at least $0.5m^3$ and if greater than $100m^2$ the volume of water should be at least $1m^3$.

Procedure:

1. Excavate trial pit of appropriate size.
2. Record the wetted area of the internal surface of the pit when the pit would be half full including all sides and base.
3. Fill the pit to expected invert level of the inflow pipe.
4. Record the water level (depth) at frequent time intervals.
5. Repeat the test twice more in succession, preferably on the same day.

Infiltration rate (*q*) m/h:

$$q = \frac{V_{75-25}}{a_{50} \times t_{75-25}}$$

Where:

V_{75-25} = Storage volume between 75% and 25% of the depth to maximum water level (m^3).

t_{75-25} = Time taken for pit to empty from 75% to 25% of depth (h).

a_{50} = Area of the base and sides of pit at 50% of the depth (m^2).

The smallest value of *q* should be used to size the soakaway.

After, Bettess (1996)

Figure 6: Undertaking an infiltration test in alluvial soils, UK.

In the UK and many other developed nations, infiltration drainage systems are used to control rapid runoff as a result of urbanisation, primarily for flood risk reduction. Consequently, systems are often designed to be capable of storing and infiltrating the 100 Year Return Period storm event (particularly on new developments where 'green field' runoff rates – ie pre-development runoff rates – must not be exceeded).

As flood control may not be the primary reason for infiltration drainage on Caribbean SIDS, and recharge is the principal objective, the systems could be sized for a lower probability event: the volumes necessary to attenuate and infiltrate the 100 Year Event may be impractical in terms of space, resources, and cost. Given a design rainfall return period, the scheme can be designed using relatively simple hydrological/hydraulic analysis.

Historic rainfall data must be evaluated to provide the relationship between rainfall intensity and duration for the design return period rainfall event. This may require analysis from an experienced hydrologist. The method varies depending on the quality and resolution of historic rainfall data.

Assuming that infiltration only occurs through the base of an infiltration system, then for a given rainfall event discharging to an infiltration system of a particular area, a mass balance equation can be solved to estimate the maximum depth of water generated, h_{max}, which therefore equates to the minimum required depth of the system. The equation for h_{max} is given by:

$$h_{\max} = \frac{D}{n}\left(ri\frac{A_D}{A_b} - q \right) \tag{1}$$

Where:

D=	Storm duration (h)	
i	=	Rainfall intensity (m/h)
r	=	Runoff coefficient (0.85 for impervious urban surfaces)
A_D	=	Catchment area (m^2)
A_b	=	Infiltration surface area (m^2)
q	=	Infiltration rate (m/h)
n	=	Porosity of fill (decimal) (1 for infiltration basin without fill)

This equation can be solved for h_{max} using a calculator or spreadsheet for a range of rainfall durations and intensities. The largest h_{max} determines the required depth of the system (and the critical storm duration for the catchment and specific infiltration system). An example of the necessary calculations is presented in Table 3.

A small settlement tank or first flush device which stores and releases the initial runoff from each storm will reduce clogging of the soakaway-soil/strata interface. The settlement prior to entry into the system prevents large (or an excessive amount of) solids entering the system and reducing infiltration. A screen, to retain larger debris, may be adequate if catchment surfaces are kept relatively clean. The water will be treated to a certain extent by the filtering effect of the vadose zone of the soil matrix and aquifer.

In and around the urban areas where recharge is being enhanced, ground levels and water quality trends should monitored through observation wells in the underlying aquifer. This will afford the ability to assess the success of the cumulative effect of promoting recharge at the dwelling and building scale.

From rainfall analysis		Total runoff volume m^3	Total infiltration m^3	Storage required m^3	Maximum water depth **(H_{max})**		Constants	
Storm duration (D)	Rainfall intensity (i)							
0.5	0.12	1020	25	995	0.995		Storm return period	1 year
1	0.08	1360	50	1310	1.310		Catchment area (A_D)	20000
2	0.048	1632	100	1532	1.532		Infiltration area (A_b)	1000
4	0.0288	1958.4	200	1758.4	1.7584		Infiltration rate (q)	0.05
8	0.0168	2284.8	400	1884	1.884		Runoff Coefficient (r)	0.85
12	0.0124	2529.6	600	1929.6	**1.9296**		Porosity of fill (n)	1
16	0.0100	2720	800	1920	1.920			
24	0.0072	2937.6	1200	1737.6	1.7376			

Table 3: Example of calculating soakaway or infiltration basin without fill. h_{max} = 1.93m, so design depth = 2m.

4.3 Complex (Multi-Building) Scale

This scale of groundwater recharge scheme considers a cluster or group of buildings, which either are or can be managed as a single water recharge system. Examples might include school and university campuses, shopping malls, government buildings, hospital sites and resorts.

4.3.1 Storm Runoff as a Water Source

Because the cost of implementation is greater at this larger scale, evaluation of the benefits of MAR should be made before implementation (to optimise design) and after implementation (to evaluate success). Whether the intended benefits are to augment groundwater resources through recharge or to mitigate the negative effects of surface runoff (flooding and pollution) in the surrounding environment, monitoring and investigation to prove the effectiveness of the scheme is necessary to justify the expenditure.

Pre-implementation monitoring of groundwater levels and their seasonal fluctuations is important to understand some of the hydrogeological regime. For example, for a larger scale infiltration trench/basin, the base should be at least 2m above the peak wet season water table levels: if the water table rises to the base of the infiltration system infiltration rates will be reduced and the opportunity for water treatment obtained through percolation of water through the unsaturated soil and aquifer matrix in the vadose zone will be limited. This is not so critical for smaller dwelling scale systems, as the consequences of failure are negligible in comparison, and the solutions – a larger soakaway more obvious and achievable.

Many designs of infiltration system are feasible, from large open vegetated **infiltration basins** (see Drawing No. 3 – p46) for larger catchments, to small discrete soakaways (Bettess, 1996) as well as the use of permeable hard surfaces. Topography, land use and available space determine the techniques to use, and different techniques can be integrated into one system, to promote recharge at this scale. Runoff can be captured from roads, car parks, roofs, and other surfaces, which individually may require differing amounts of pre-treatment. The cricket stadium in Barbados currently directs storm runoff to underground infiltration galleries consisting of a number of subsurface chambers (Figure 7).

Figure 7: Storm water retention and infiltration at the cricket stadium in Barbados.

Collecting and infiltrating water from a range of (and larger) catchments will create a higher probability of contamination and sediment entrainment. Direct rainfall has high water quality and can generally be routed straight to infiltration systems. However for runoff collected from areas likely to pick up contaminants including heavy metals, hydrocarbons and sediments, such as roads or car parks, simple treatment is generally necessary. If kept clean, **grassed swales** (see Drawing No. 4 – p47) can provide effective treatment and infiltration for yards, car parks and minor roads, whilst conveying and controlling the flow of excess water to larger infiltration systems or storm drainage.

Grassed filter strips, with a maximum acceptable slope of 5%, located upstream of the drainage infrastructure, can also be employed to slow down and partially infiltrate laminar runoff from impervious urban surfaces. They should be as flat as possible to avoid concentration of storm runoff. Generally, this technique will reduce runoff speed but will not greatly reduce peak runoff, the main benefit is the removal of pollutants such as fine sediment, organic matter and trace metals (they are not effective at removing soluble pollutants), hence they are particularly useful upstream of infiltrating MAR schemes. Both grass filter strips and swales should have as shallow slopes as possible and grass should be dense to avoid concentrated runoffs and erosion (Tucci, 2001).

Infiltration systems located near roads or car parks with heavy traffic may require hydrocarbon interceptors, sediment traps and/or sand filter beds to meet the water quality necessary for infiltration to groundwater, many designs are available for such systems (Tucci, 2001) depending on capacity and water quality required. Highly polluted flows must be diverted to convenient treatment or disposal. If open vegetated infiltration basins are provided which add aesthetic value to urban areas, inflow water quality is required to be good, because if such systems accumulate greases and sediment their value will diminish.

The volume of infiltration basins for storm water storage and infiltration are sized with the same equation as for soakaways, however are generally not infilled with boulder/rock, which allows greater storage volumes to be dealt with, and hence are feasible for larger catchments. They can be created by digging out topsoil, or by constructing embankments around the area designated for infiltration. The construction method depends upon topography and available resources.

An innovative recharge scheme has recently been completed at a waste management centre in Barbados which has 7.2 hectares of impermeable hardstanding, comprised mainly of rooftops and yards, which is underlain by limestone (Smikle and Yokon, 2008). Infiltration basins were provided to recharge the aquifer; it is thought that the basin would be capable of infiltrating the seasonal rainfall events. However, to ensure post-development runoff rates do not exceed pre-development rates in more rare intense rainfall events, increased infiltration rates were deemed necessary. To augment infiltration (and recharge) recharge wells 12m deep were dug in the basins. To reduce sedimentation of the wells, they were surrounded by stone and riprap bunds to reduce flow velocities and retain sediment (Smikle and Yokon, 2008). This is a technique used locally on Barbados in conjunction with recharge wells. By keeping runoff below pre-development levels the benefits include reduced flood risk and reduced surface water contamination as well as recharging the limestone aquifer upon which the island's public water supply is dependent.

Recharge wells (see Drawing No. 5 – p48), known locally as 'suckwells' are used widely in Barbados to reduce runoff by disposing of drainage and to promote aquifer recharge, often in conjunction with infiltration basins (see Figure 8). The underlying geology is conducive in facilitating their construction and allowing recharge, as a result, significant experience in their design and construction has been developed. The depth of the drainage wells ranges from about 10m to 30m and is determined based on reaching an adequate "suck" or fissure in the rock (Mwansa, John: pers. comm.). Road drainage is also a source water for suckwells in Barbados; these roadside wells are built and maintained by the government (UNEP, 1998a). Maintenance of suckwells is labour intensive, involving the removal of silt which accumulates at the bottom of the well which plugs the 'suck'.


Figure 8: Suckwells located in an infiltration basin for storm runoff, Barbados. Source, Smikle and Yokon, 2008.

Recharge wells may alternatively be filled with a uniform rock and a sand filter (0.5-1m thick) at the top to provide some pre-treatment before direct recharge, thus essentially acting as a deep soakaway and improving the quality of water for recharge. This may facilitate easier (but more frequent) maintenance as the top layer of sand can be replaced easily. However, the storage volume will be dramatically reduced, resulting in a system which is less applicable to storm drainage, additionally, more wells would be needed or a large holding tank, thus increasing capital costs. Due to the nature of direct recharge schemes, such as recharge wells, their maintenance is more difficult than surface infiltration systems, this is the most likely reason, exacerbated by increased labour costs, that many of these suckwells are falling into disrepair in Barbados (UNEP, 1998a)

The use of recharge wells to directly recharge depleted aquifers with storm drainage from rooftops or terraces in groundwater dependent urban areas is practised with success in other regions, generally in urban India where soil is relatively impermeable and land area is at a premium. In Bangalore, from a complex with a roof area of 11,000m^2 a peak, direct recharge rate of 20,000 l/h has been accomplished through an open well of depth 7m and diameter 2m (Vishwanath, 2008). The water is recovered by nearby borewells. Due to the limited storage provided in wells, the recharge well must have a relatively large capacity (2m diameter) and large holding/attenuation/settling tanks often combined with sand filtration to produce the necessary high quality water for direct recharge. Close monitoring of water levels and quality in the nearby producing borewells is important, particularly, as in the case mentioned above, if water is used directly for drinking after softening. The increased complexity in design and management may dictate that such schemes are not feasible in the Caribbean, except on those 'complexes' where active and on-going maintenance protocols are already in place. In addition, open wells in flood prone areas or areas with a high water table will be susceptible to contamination. However, given appropriate aquifer conditions, which would permit the water to be effectively recovered, and large clean rooftops/catchments, such schemes are potentially very effective.

Integrated infiltration drainage systems and direct recharge systems can be applied to an agricultural setting, if infiltration rates and aquifer properties are conducive to MAR. For example, suckwells have been implemented on plantations in Barbados. However, the range of contaminants will be different, often comprising nutrients and faecal coliforms and pathogens. Attempts have to be made to prevent such pollutants entering recharge systems and consequently groundwater. As well as sediment traps and filters, another potential management strategy is to stop pollutants at source by encouraging the use of good management practice, such as applying agricultural nutrients and pesticides in the right quantities and during the dry season, providing vegetated buffers around water bodies and recharge systems and managing animal waste effectively, see USEPA (2009).

4.3.2 Treated Wastewater as the Source

Treated wastewater from a complex such as a hotel or resort, which would otherwise be disposed to the ocean, can potentially be used for MAR at this scale. Tertiary treatment of the effluent is provided through employing infiltration techniques, such as **infiltration galleries**, to recharge relatively shallow aquifers (see Drawing No. 6 – p49). Water can then be recovered from a nearby production well, re-used for irrigation, made potable through treatment, or used to reduce or prevent saline intrusion enabling existing well field yields to be sustained or increased.

Infiltration through the vadose zone potentially removes nutrients, such as phosphates and organics, degrades chemicals such as disinfection by-products and causes pathogen die off, as most pathogens will die within 50 days of infiltration (USEPA, 1992). This significantly reduces the health and environmental risks that may be associated with secondary treated wastewater, leaving the reclaimed water in similar quality to that of the surrounding groundwater. In addition, secondary treated wastewater should be of good enough quality to allow MAR without clogging as long as bacterial growth is contained (possibly through increased chlorine dosing). Operational monitoring of the treated effluent input and monitoring of groundwater quality upon abstraction for re-use are essential as well as water level trends so as not to deplete the aquifer by abstracting more than can be recovered from the infiltration system. Before implementing such schemes water quality standards for the recharged effluent must be set and strictly obeyed.

Such techniques are successfully employed in Australia (CSIRO, 2009) and could be applied to the Caribbean where hydrogeological and other conditions are appropriate, in particular in tourist resorts where irrigation is necessary (*e.g.* golf courses) and the money for implementation is more likely to be available. Large scale infiltration of primary sewage effluent has also been practised in the UK for decades, through simple shallow trenches in the chalk limestone.

Currently, treated wastewater is used for irrigation on a golf course in Bermuda (Thomas, 1987) and treated wastewater from a hotel is used for irrigation in Barbados (UNEP, 1998b), however no schemes are recharging through infiltration systems to aquifers. At the Sam Lord's Castle Hotel in Barbados (which closed in 2005), kitchen, laundry and domestic sewage was treated through aeration, clarification, aerated sludge tanks and chlorination to provide a 'secondary' effluent which was then used for irrigation which results in substantial savings in irrigation water costs, and may indirectly recharge underlying aquifers (UNEP, 1998b). Operational monitoring of treated effluent water quality in such schemes is of great importance as there are associated public health risks and ground and surface water contamination risks.

4.4 Sub-Catchment Scale

4.4.1 *Overland Flow as the Water Source*

In many Caribbean counties, in particular Antigua and Barbuda, recent land use changes have led to reduced vegetative cover, and are believed to have resulted in accelerated runoff, higher flood peaks, greater soil erosion rates and increased contaminant transfer. Since surface storage is limited, increasing recharge within sub/micro-catchments should increase water retention, thus reducing flood peaks (and associated erosion) and prolonging ephemeral streamflow.

Small watersheds provide an amount of water per hectare greater than that collected over larger watersheds because evaporation and losses of water from small puddles *etc* are avoided (Courtesi *et al*, 2009). This suggests that recharge of in-situ water (direct rainfall and overland flow) should be promoted at this sub-catchment scale. However, it is important to recognise that harvesting water for recharge within upstream sub-catchments can deplete downstream water resources. As a result sub-catchment management schemes should be gradually introduced over time and the hydrological regime of the catchment monitored (including groundwater levels and abstractions) to ensure the success of such schemes.

In Antigua and Barbuda, where land degradation is reportedly high, MAR methods could also provide benefits by retaining soils and soil moisture to improve land quality (thus intensifying crop production and improving food security and economic security), as well as reducing flood peaks. By taking an integrated approach to land and water management, recharge can effectively be increased without designing and constructing specific MAR structures.

Catchment management strategies aim to reduce the velocity of runoff and promote retention, which will result in greater infiltration. Additionally, less sediment is eroded and entrainment velocities are exceeded less frequently. Consequently siltation of downstream infiltration structures and reservoirs will be reduced. Additionally, the downstream transfer of chemical pollutants through adsorption to suspended solids will be reduced and in situ pollutant attenuation (within the soil matrix) will occur, which will help to address surface and groundwater quality issues.

An additional reason for the potential effectiveness of these methods in Antigua and Barbuda is that the design of existing surface water storage facilities is known to be poor, allowing high evaporation rates as well as high flow overflow losses as runoff to the ocean. Thus subsurface storage and attenuation of flood peaks should reduce surface water resource losses and provide augmented groundwater resources for dry season abstraction. It is important that the major reservoirs used for public water supply are still consistently filled up during the wet season, and surface water reservoir levels need to be monitored throughout the year.

Groundwater level monitoring around sub-catchment recharge schemes and at downstream well fields will provide the necessary information on the effectiveness of such schemes. The location should be suitable in terms of soil infiltration and geological structure, however in-situ infiltration tests over whole sub-catchments would not be appropriate and suitable locations could be inferred from soil and geological maps with occasional 'ground-truthing' regional infiltration tests.

MAR at this scale can be accomplished by a range of means. Planting, or afforestation, provides a vegetative canopy which promotes interception and retention whilst providing a humus covered topsoil and increasing soil stability through root structures (Cooper and Bowen, 2001). For this reason, in naturally forested areas catchment management and MAR schemes will not be applicable (Malmer, 2009).

Other than planting, **contour bunding and trenching** (see Drawing No. 7 – p50) provides effective rainwater harvesting retention and infiltration. The vertical spacing between trenches and the size of the trench bund are the controls on the water harvesting potential and hence the infiltration potential (Shinde *et al*, 2005). These techniques can capture approximately 50% of the rainfall. Over 7.5 hectares in rural India, 17,000m^3 of water was recharged in a year (annual rainfall = 870mm) using continuous contour trenching, producing a rise in local groundwater table height of 4m (Shinde *et al*, 2005). When recharge is intended to provide augmentation of groundwater at a regional level, it is preferable to be recharging to an aquifer with relatively high hydraulic conductivity so the water spreads across the aquifer and the benefits are appreciated regionally as opposed producing localised recharge mounds.

4.4.2 Confined Surface Runoff as the Water Source

At the sub-catchment scale, water can be retained and recharge promoted using confined surface runoff (ie stream/river flow, as opposed to overland flow) as the source water. Infiltration MAR schemes of this type and scale, can be off-line or on-line. Off-line systems are defined as where water, during peak flows, is diverted from the channel to a location where recharge is achieved through infiltration, using a range of techniques. On-line systems require construction of a dam across the channel to retard flow and promote recharge either upstream or downstream of the embankment, depending on construction. Using confined surface runoff as the source water implies that it may be of poorer quality than in-situ or direct harvesting of rainwater, including suspended sediment loads. Hence, catchment management practices should be used in conjunction with these recharge methods to reduce maintenance and treatment requirements.

The advantage of on-line recharge schemes is that no diversion and conveyance structures are necessary. On-line structures may however cause or contribute to substantial upstream deposition of sediment clogging the river bed, and reducing their upstream infiltration efficiency. On larger structures, it is essential overflow spillways are carefully designed requiring hydrological analysis. There is greater chance of catastrophic failure, which dictates the need for specialist engineering design and surveying; they also often have a larger inundation area.

The advantage of off-line structures is that they can be located in a position better suited for recharging the aquifer and are generally easier to maintain in terms of de-silting. Calculating elevation and size of stream off-takes able to provide reasonable quantities of water on a regular basis through the wet season without overloading the system can require hydrological and hydraulic analysis. Local experience however may be used in operating sluices or other measures to divert excess surface runoff to off-line structures. The appropriate topographic conditions are also required to route the water to the off-line recharge scheme *via* canals as gravity operated systems are easier to manage and less costly. In perennial (permanent) streams, pumping water to off-line infiltration basins is a feasible method.

For designing spillway or diversion (stream off-take) elevations and breadths and for monitoring the success of such schemes in promoting recharge, hydrological streamflow data is often necessary. Box 2 summarises some easily implemented systems for monitoring hydrological flows.

4.4.3 On-line Structures

In gullies and small ephemeral streams, where the consequences of failure of small dams are insignificant, simple, low tech, cost effective techniques can be adopted (Figure 9). Known as 'gully plugs', these structures are constructed across gullies and small valleys with locally available materials, generally boulders and earth. The height of the dam should be no greater than the bankfull height of the gully which should approximately equal the stage of the annual flood (1 year return period flow event), thus spanning the channel. Erosion protection measures (stones and boulders) are placed on the downstream river bed.

Gully plugs can involve local communities in construction as the land degradation benefits will be felt locally and they do not require detailed designs. Additionally, silt accumulated behind the small dams can be used in fields or for nursery plants. These structures can be applied across a whole sub-catchment for the same reasons as the overland flow watershed management techniques (contour trenching *etc*.): Flow will be retarded, runoff velocities reduced and as well as potential erosion rates, flood peaks attenuated, suspended solids retained and recharge of groundwater promoted at a regional scale.

UNEP (1998a) suggests that earthen **check dams** (see Drawing No. 8 – p51; Figure 10) of 1 to 3m in height constructed at downstream intervals of 70 to 100m with storage capacities between about 250 to 400m^3 are effective in Latin America and the Caribbean. Earth dams should be 'keyed' into the bedrock, and if the dam is on fractured bedrock cement grouting is necessary to make the foundation leakage free. The top of the dam should be erosion resistant and act as a spillway for larger floods. Concrete spillways may have to be provided on larger check dams to prevent overtopping and failure (UNESCO-IAH, 2005), and erosion protection measures downstream of spillways or weirs should be provided. Applied regionally, on-line check dams are used effectively in the Canary Islands, a group of volcanic islands in the east Atlantic. Flood waters stored by the small check dams replenish the soil water storage and produce recharge which can be reclaimed by shallow wells (Falkland, 1991).

Throughout arid regions of the world, where intermittent streams are incised into coastal aquifers, retention structures have been constructed to augment groundwater storage. This practice along the west coast of India has revolutionized agriculture by enhancing groundwater recharge and hence well levels and base flows in rivers (CSE-India, cited in: UNESCO, 2005).

In Rajasthan, India, a study by Stiefel et al (2009) reports direct evidence, using geochemical tracers, of recharged surface water in adjacent wells, providing confirmation that rainwater harvesting structures (in this case relatively large check dams,) can increase reliable access to groundwater. Due to the fractured nature of the underlying hard-rock aquifer, not all wells located in the nearby downstream vicinity were influenced by the recharge structure. However, according to the results of the study, the quality of water in wells which did receive recharge was improved through dilution of chemical constituents in the groundwater.

Figure 9: Gully plugs, India.

Figure 10: Masonry check dam in Rhajasthan, spillway elevation 2m.

Check dams or leaky dams should generally be located in valleys which produce a relatively high depth to surface area to minimise evaporation losses. Also, to justify their construction, check dams must be located on streams overlying suitable and also exploited aquifers. Streambeds and surrounding alluvial deposits will often provide the appropriate conditions for infiltration however can become clogged in which case they may need de-silting during dry seasons.

4.4.4 Off-line Structures

There are a range of structures to divert excess surface water from a stream to an off-line recharge structure (see; Oosterman, 1997); Drawing No. 9 (p52) gives simple examples of stream off-takes which use appropriate technology. If a dam or weir is constructed to promote lateral diversion of stream water, floods below the level of the spillway will be diverted laterally (to the canal/recharge structure), whereas during occasional large flood peaks, which would cause heavy sedimentation and possible damage to structures, the majority of water will pass over the weir and follow the river bed.

Off-line recharge techniques include i**nfiltration basins** (Figure, 11), **ditch and furrow systems** and **controlled flooding** (see Drawing No. 10 – p53). Controlled flooding, or spate irrigation (Steenbergen and Tuinof, 2009), and ditch and furrow systems are low-tech solutions and require little maintenance as clogging due to sedimentation is theoretically reduced to a manageable level by maintaining velocity through the structures. Infiltration basins require regular maintenance, particularly when accepting and infiltrating silt laden flood flows, this can be relatively easily carried out with bulldozers, or similar plant. If sediment loads are too high to sustain infiltration rates, pre-sedimentation in settlement ponds may be required or a different technique preferred. To increase settlement velocities in settlement ponds a coagulant, such as alum, can be added to inflows.

Figure 11: Example of an offline infiltration basin, Southern Africa.

This off-line recharge technology has been used extensively in the San Juan river basin of Argentina, where two artificial recharge experiments have been conducted (see; UNEP1998a). The first experiment involved construction of infiltration basins 200m by 90m and 1.2m deep. The second experiment was 9.3 hectares of infiltration canals (similar to the ditch furrow method). The canals were found to be more efficient as maintaining a velocity precludes the settling of sediment, thus sustaining infiltration rates.

In southern Cyprus, flood flows from the River Kouris have been diverted into infiltration basins within plantation well fields to recharge the over-exploited aquifer. At one pond (with a storage capacity of 54,000m^3 and a surface area of 17,500m^3) a total of 11 million m^3 of surface water was recharged between 1984 and 1992 at an average of 7700m^3/day. The infiltration rate varied over the period dropping from about 0.8m/d to 0.2m/d as the pond was not regularly cleared of vegetation and sediment (Iacovides, 1997). One such clearing operation occurred in 1986; figure 12 shows the change in the infiltration rate during 1986/7, indicating a steady decline from 1.4m/d at the start of operation after clearing the pond to 0.6m/d before recharge completion. This suggests that as a result of the flood water quality, that maintenance at this site through clearing sediment should occur annually.

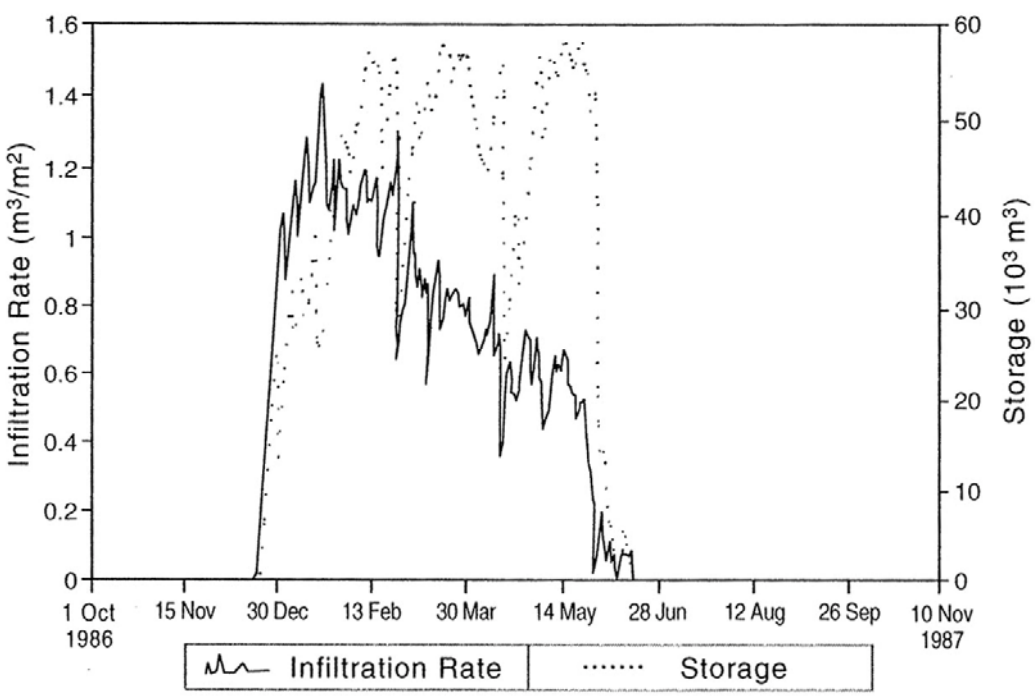


Figure 12: Infiltration rate and storage at infiltration Basin in Southern Cyprus. Source: Iacovides, 1997.

Box 4.2: Flow Gauging

Generally, flow data is estimated from river level. River level can be monitored by regularly checking stage boards at given locations. However, modern pressure transducers which are easily and cheaply obtained allow continuous monitoring of river or stream stage (for which it is necessary to subtract atmospheric pressure). This allows all flood peaks to be incorporated in the stage record. This is best accomplished by situating the pressure transducer in a stilling well to exclude waves and turbulence in main river flow.

Flow data is then estimated from the stage record through obtaining a rating curve. The rating curve is constructed by estimating flow at a range of stages usually by the velocity area method, for which velocity must be measured with a current meter, or using an open channel flow equation such as manning's equation (see a hydraulics text book, *e.g.* Simon, 1986). This can be time consuming, particularly given that natural channels are rarely stable for long periods meaning that the rating relationship must be checked with any changes in stream geometry.

The reliability of stage discharge relationships can be greatly improved if the river flow can be controlled by a rigid, indestructible structure of standardised shape (which creates critical flow conditions) for which there is a unique and stable relationship between depth of flow and discharge. This adds to the capital cost of gauging, however once installed, more accurate continuous flow data can be obtained easily.

Flumes are particularly useful for small streams carrying a considerable sediment load. Relating the discharge Q for a rectangular cross-section to the stage H, the general form of the equation is:

$$Q = KbH^{3/2}$$

Where b is the throat width and K is the discharge coefficient for that particular flume.

Weirs are more versatile structures and provide a restriction to height rather than width. For rectangular sharp-crested weirs (for smaller flows) or concrete broad-crested weirs (for larger rivers):

$$Q = KbH^{3/2}$$

For V-notch weirs, the discharge formula becomes:

$$Q = K\tan(\theta/2)H^{5/2}$$

Where θ is the angle of the notch. Tables for weir and flume coefficients (K) are derived by experiment and can be found in specialist hydraulic reference books.

Within small channels and conduits, such as urban drainage, recent developments in technology has introduced in-situ flow meters which use a range of techniques (such as ultrasonic and electromagnetic) to estimate discharge, and can provide continuous flow records. However, their reliability is not well documented.

4.5 Catchment Scale

Most of the techniques already suggested in this chapter can be applied at the catchment scale, either by widespread implementation of the smaller scale recharge systems, where they are applicable, or by up-scaling the schemes suggested for recharging confined surface waters or wastewater at the sub-catchment and complex scale.

Up-scaling the projects which harness excess surface runoff from confined channels to recharge water from a large catchment area requires more detailed design and investigation before construction of diversion, retention and pre-treatment infrastructure and greater capital expenditure and increased operational, monitoring and evaluation costs. This is particularly true for on-line structures, such as recharge dams or large check dams, as the flood peaks and necessary storage volumes at (or near) catchment outlets (ie the end of the catchment) will be far greater. The civil works and investigations involved in constructing such dams would be large, and the costs of failure (either catastrophic – by failure of embankment – or by failing to produce sufficient recharge and/or recovery opportunity relative to investment) are much greater.

Consequently large, catchment scale, on-line structures are seemingly less viable at this scale on SIDS, especially given the available space. Large scale recharge dams require significant areas of unfarmed or undeveloped land for inundation; hence, the extensive installation of such structures in the desert 'wadis' of the Middle East (UNEP, 2001).

Recharge Dams have received considerable investment in the Sultanate of Oman, with many structures built on both the coastal plain (to capture run-off otherwise lost to the sea) and internal plain (to capture run-off otherwise lost to the desert) being deployed (Figure 13). Similar structures in many thin (up to 50m thick) alluvial coastal aquifers in Cyprus have been studied in detail, with groundwater levels demonstrably rising as a consequence (Simmers, 1997; cited in, Periera, 2002). By releasing surface water almost continuously (in the order of 20,000m^3/day) from reservoirs upstream of the alluvial valleys, losses to the sea are minimised and the fresh-salt water interface is stabilised. Between 1982 and 1992 it was estimated that 51.70 million m^3 was recharged artificially through this method at the Yermasoyia aquifer, southern Cyprus, supplementing the abstraction, from the same aquifer, of 48.1 million m^3 of groundwater for consumption in nearby Limassol (Iacovides, 1997).

Given the location of many of the principle well fields in Antigua and Barbuda within the alluvial tracts, consideration should be given to this type of structure. For large projects, suitable budget needs to be able to provide appropriate and thorough investigation before implementation to maximise the probability of success of such a scheme and ensure that the recharged water is recoverable and the system can be properly managed to guarantee a long project-lifetime.

However, it is established by Barragne-Bigot and Yearwood (1991) that the reservoirs of Potworks and Collins, on Antigua, are leaking through the semi-pervious formations of the valley floor, thus recharging the underlying limestone aquifer. Whether this incidental recharge is recovered by the well fields exploiting this aquifer it is not known. This illustrates that there may be some scope for large dams for recharge in the Caribbean, if located above an aquifer with sufficient storage capacity. There are many detailed design considerations for dam construction which are not within the scope of this report and require experience in civil engineering, geotechnical engineering and dam construction. Also, detailed topographic surveys are necessary to evaluate the depth-capacity curve and the pond area-capacity curve enabling selection of embankment height and a specific location which will minimise the area of inundation and the cost per unit of storage.

At the catchment scale, Aquifer Storage and Recovery (ASR) through well injection is a possible recharge method. It is thought to be more environmentally friendly than surface storage. In the Caribbean, the flashiness of hydrographs resulting from intense storms does not lend itself to injection methods as a relatively constant water supply is necessary due to the limited storage within the injection infrastructure as well as the need for high water quality necessitating water treatment. This suggests that significant surface storage would still be necessary to capture flood peaks before injection. If surface water is already stored, this method becomes more feasible. In fact, water sourced in the Collins Reservoir on Antigua is being used to replenish the groundwater of the nearby Collins well field (Rodriguez, Ivan: Pers. Com.) presumably through pre-treatment and then injection because the water quality in surface reservoirs on Antigua is known to be poor. The reason for this MAR scheme is that the water would otherwise be lost to deep seepage due to poor reservoir design.

To directly recharge aquifers in the Caribbean with excess surface water from rivers and streams at the catchment scale, will likely require the MAR methods to be adapted to the situation and will be opportunistic. This requires understanding of the site specific conditions. For example, in Jamaica, a recharge experiment was conducted for two years in 1981-1982. During the wet season, when irrigation demand was low, excess runoff from irrigation canals was directed to settling basins and treated with Alum then routed by gravity to sinkholes in the limestone (Fernandez, Basil: pers. com.). The underlying aquifer was commonly associated with seawater intrusion and hence saline. The recharged water was monitored through a series of monitoring and production wells to measure changes in groundwater level and quality. A recharge mound of up to 6.7m was evident as well as declines in salinity (UNEP, 1998a). The scheme made use of local experience and circumstances and was simple to operate. A canal attendant would read flume gauges and open or close sluices accordingly. The irrigation canals were maintained to ensure maximum delivery of water, and the clearing of the settling basins ordered upon inspection, generally every 4-5 months.

This scheme appears to have worked because large flows of surface water could be treated and directed to sinkholes enabling rapid recharge of a deep saline aquifer. Without the treatment investment and the karstic sinkholes, the scheme may have failed. In short the scheme worked in a karstic aquifer in Jamaica. Whether it could operate elsewhere in different geology, on a smaller island with smaller operating budgets is debatable.

If surface infiltration systems are deemed applicable according to infiltration tests and hydrological and geological investigations, it is still a big step to then install multi-hectare recharge systems. Thus it is advisable to install a pilot or test basin of at least 50m × 50m, for several months to see what actual basin infiltration rates will be, how the water will move down to the groundwater (piezometers above restricting layers will indicate perched water), what the response of the groundwater level to recharge will be, and observe the groundwater mounding (Bouwer, 1999). This is also necessary to evaluate clogging effects, and how it can be remediated by drying and cleaning.

Figure 13: Large scale Wadi recharge dam, Oman.

TABLE 4.

MATRIX OF SCALES, MAR TECHNIQUES

WATER SOURCE	SCALE: DWELLING	LARGE BUILDING	COMPLEX (MULTI-BUILDING)	SUB-CATCHMENT	CATCHMENT
DIRECT RAINFALL	RAIN WATER HARVESTING AND INFILTRATION OF OVERFLOWS *VIA* SOAKAWAY/ PIT	RAIN WATER HARVESTING AND INFILTRATION *VIA*: • SOAKAWAY/PIT • TRENCH	RAIN WATER HARVESTING AND INFILTRATION *VIA*: • SOAKAWAY/PIT • TRENCH • SWALE PERVIOUS PAVING OR DIRECT RECHARGE (MAY REQUIRE TREATMENT)		
OVERLAND FLOW			OVERLAND FLOW COLLECTION AND INFILTRATION *VIA*: • SOAKAWAY/PIT • TRENCH • SWALE • BASIN PERVIOUS PAVING OR DIRECT RECHARGE (MAY REQUIRE TREATMENT)	<u>RURAL (AGRICULTURAL):</u> • CONTOUR BUNDING • CONTOUR TRENCHING • BENCH TERRACING • GULLY PLUGGING <u>URBAN:</u> (SETTLEMENT OF SOLIDS AND SEPARATION OF OILS PROBABLY ESSENTIAL) OVERLAND FLOW COLLECTION AND INFILTRATION OR INJECTION *VIA*: • SOAKAWAY/PIT • TRENCH • SWALE • BASIN PERVIOUS PAVING OR DIRECT RECHARGE (REQUIRING HIGHER QUALITY WATER)	
CONFINED SURFACE RUNOFF				<u>ONLINE:</u> • STREAMBED MODIFICATION • GULLY PLUG • CHECK DAM • LEAKY DAM <u>OFFLINE:</u> • INFILTRATION BASIN • CONTROLLED FLOODING • DITCH AND FURROW METHOD	• STREAMBED MODIFICATION • CHECK DAM • RECHARGE DAM • INDUCED RECHARGE (INDIRECT) • INFILTRATION BASIN • CONTROLLED FLOODING • DITCH AND FURROW METHOD • DIRECT RECHARGE THROUGH WELL/SINKHOLE
GREY WATER	SEPTIC TANK	SEPTIC TANK	DEPENDING ON WATER QUALITY, PRIMARY AND/OR SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT)	DEPENDING ON WATER QUALITY, PRIMARY AND/OR SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT) OFTEN *VIA* INFILTRATION GALLERY	DEPENDING ON WATER QUALITY, PRIMARY AND/OR SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT) OFTEN *VIA* INFILTRATION GALLERY
BLACK WATER	SEPTIC TANK	SEPTIC TANK	PRIMARY AND SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT)	PRIMARY AND SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT) OFTEN *VIA* INFILTRATION GALLERY OR DIRECT RECHARGE IF WATER MEETS DRINKING WATER STANDARDS	PRIMARY AND SECONDARY TREATMENT THEN INFILTRATION (TERTIARY TREATMENT) OFTEN *VIA* INFILTRATION GALLERY OR DIRECT RECHARGE IF WATER MEETS DRINKING WATER STANDARDS

5. Managed Aquifer Recharge (MAR) Strategy Guidance

In attempting to introduce Managed Aquifer Recharge practices into the Caribbean it is important to recognise the role MAR can play in delivering sustainable water sector management as well as how MAR can be planned for rather than adopted in a piece meal fashion. Indeed understanding how to plan strategically for MAR at both the policy level and the resources level will be significant in determining its take-up and its recognisable contribution.

5.1 Strategic Planning of Managed Aquifer Recharge

Strategic planning of MAR at a national and island scale will form the basis for preparing the appropriate spatial plans for MAR. The location and assessment of appropriate sites for MAR through 'spatial mapping' of the various selection criteria parameters, underpins the strategic planning process as it directs MAR to areas where the benefits - including abstraction for drinking or irrigation; water table level recovery; reduction of saltwater intrusion; and environmental benefits - will be tangible; where water is available and of the quality required or can be treated; and where the prevailing hydrogeological, geological, soil and topographical conditions are conducive to effective MAR schemes.

This can be achieved with relative ease by overlaying maps, ideally using GIS techniques (however this is not necessary), of the important factors which facilitate or impede MAR (most of which will have some datasets already available), inclusive of a combination of:

i	Topographic map	Including detailed land relief contours
ii	Hydrographic map	Including drainage pattern, catchment boundaries and other surface water features
iii	Climatic Map	Including average annual rainfall, or effective rainfall distribution
iv	Geological map	Including underlying strata and dimensions, for locating aquifers
v	Hydrogeological map	Including groundwater table contours (inferred from baseline information collected)
vi	Soil map	Including infiltration capacity
vii	Land use map	To identify potential pollution hot-spots, or sub-catchments
viii	Population density map	To identify areas of high public water demand
ix	Water Infrastructure map	To identify where schemes can be located to assimilate best with current water supply infrastructure (thus reducing cost)

By building up these layers of information through mapping and potentially ranking the importance of the parameters, zones and sites conducive to MAR schemes can be identified at a strategic level. As such, this becomes a critical decision making tool and acts as an Island wide feasibility study which can be applied across the Caribbean in selecting appropriate areas for MAR at all scales. This mapping technique will also assist, to an extent, decisions on the suitability of schemes, including the choice of technique and their construction and management, although understanding the site-specific physical processes governing recharge and water flow is essential, which necessitates on-site investigation. For smaller scale MAR adoption, such as soakaways, recharge trenches or even larger scale schemes integrated with land/catchment management, this level of detail may be enough to adopt or promote a technique in a particular area.

Universal strategies should also be applied to the choice of technique, for example by following Figure 1, the Decision Process Diagram. Also, before implementing large scale MAR schemes, realistic water quality requirements for injection and re-use should ideally be set, to provide a mechanism to protect the aquifers from infiltration of unsuitable waters or compounds.

Consideration should also be given to design and management specifications for the larger schemes such as the return periods specified for soakaway sizing, which may need to be regulated, given that their failure could result in common law nuisance to nearby neighbours and other third parties.

5.2 The Role of MAR in Water Sector Policies and Planning and Integrated Water Resources Management

The interconnected nature of hydrological resources, particularly in small island hydrological systems, dictates that water management should be integrated and must bring together stakeholders to determine how to meet society's long-term needs for water resources whilst maintaining economic and environmental sustainability. This is particularly pertinent in water scarce environments such as Antigua and Barbuda, where ecological services are also of particular importance as the economies of Caribbean states largely depend upon tourism. Integrated Water Resources Management (IWRM) is thus emerging as the accepted alternative to the sector-by-sector, ministerial-institutional mandate silo-implementation that has dominated in the past. IWRM helps to protect the environment, foster economic growth and sustainable agricultural development, promote democratic participation in governance and improve human health.

In Antigua and Barbuda and the Caribbean, surface and rainwater harvesting and MAR, where applicable, can be seen as an effective component in IWRM. MAR exploits the connectivity present within the hydrological system and can provide an environmentally sustainable and economically viable approach to water resource management, particularly in water scarce areas. Section 4 of this report has provided generic guidance for such schemes and highlighted a range of successful MAR schemes in similar environments, however unsuccessful schemes are often less well documented although probably prevalent. MAR schemes must therefore be integrated in to IWRM strategically and based on sound and holistic understanding and available science, if they are to be successful.

With increased regional advocacy for IWRM, as well as international support for IWRM, MAR can represent a tangible IWRM approach or tool to delivering IWRM at different scales and of interest to different stakeholder groups by:

- Linking surface water and ground water resources and their management;
- Reducing water losses and promoting water re-use;
- Linking terrestrial water management with marine ecosystem benefits;
- Requiring coordination of government and civil society stakeholders;
- Benefitting multiple water user groups – public health, agriculture, tourism; and
- Linking to climate adaptation methodologies and approaches.

Furthermore when considering existing Small Island Developing States strategies for sustainable water management, such as those advocated at the 3rd World Water Forum (ADB, 2002), MAR includes the three critical components of water resources management, water infrastructure and water governance.

Clearly MAR can help deliver improved water resources management and improved island resilience to climate variability, but it is not a panacea, and still needs to be implemented along side demand management and conservation approaches, watershed management strategies, institutional strengthening of utility providers and regulators, public education and awareness campaigns and a focus on financially affordable services.

6. Conclusions and Recommendations

The following summary conclusions and recommendations are drawn from this report and MAR guidelines.

SIDS Water Issues and the Role of MAR

Managed Aquifer Recharge (MAR), or enhanced recharge, previously known as 'artificial recharge' is the intentional diversion of surface water to the groundwater reservoir by modifying, through a variety of techniques, the natural movement of surface water.

The main purpose of Managed Aquifer Recharge is to augment groundwater resources by storing excess surface water for later use and restore groundwater levels and quality which may have been depleted due to over-abstraction, thus enhancing the sustainability of groundwater development.

The overall aim of this study was to produce a useful and practical guideline for the capture and management of surface water for aquifer recharge in the Caribbean Region, with a particular case study focus on drought prone Antigua and Barbuda.

The key issue in terms of water resources faced by Antigua and Barbuda, much of the Caribbean, and other SIDS, is the annual variability in rainfall (which is dictated by the climate), combined with a lack of natural hydrological cycle water storage. For Antigua and Barbuda, this issue is compounded by relatively recent land use changes which generate high runoff rates and loss of valuable fresh water to the sea.

More recently, desalination has been used to supply the majority of freshwater on Antigua, supporting a demand, which is beyond the existing carrying capacity of the island, unless additional resources can be secured.

Given an appropriate geological setting, the available techniques for MAR are relatively straightforward, cost-effective and generally sustainable in the long term. Many of these can be adopted by communities at a small scale with locally available materials and manpower. Techniques can also be applied at much larger scales. Generally the source for water is harvested rainfall and harnessed surface water runoff.

MAR, however, must not be seen as a single solution to water resources problems, and integrated management is crucial. MAR could potentially provide a false confidence in the security of groundwater resources, leading to increased abstraction rates, an unwanted outcome. Demand management is therefore an important part of any water resources strategy, particularly when MAR is involved.

Implementation of large scale MAR projects requires detailed investigations and monitoring systems which produce a variety of data to inform the choice of MAR technique, its specific design considerations, its operation and maintenance.

MAR Techniques

Infiltration techniques are used to infiltrate water into the vadose (unsaturated) zone, above the water table. From here water percolates to the water table through the soil and rock, which can provide a degree of natural treatment of pollution. These methods are generally simple and applicable but require appropriate ground and hydrogeological conditions.

Clogging, or silting of the infiltration surface and the shallow soil/rock matrix reduces infiltration capacity and depends on the quality, particularly the turbidity, of recharge water. Turbid water, with high suspended sediment loads, can be treated through settlement before entry into the system, or maintenance (de-silting) of schemes can be periodically provided, when required, to increase their longevity and effectiveness. Examples of infiltration techniques include soakaways, swales, trenches, ditches and furrows, infiltration galleries and basins.

Direct recharge techniques are used to recharge water directly into the phreatic (saturated) zone of the aquifer, below the water table. The advantages of direct recharge are that they generally require less land surface area, easing procurement and reducing cost; they may improve control over the ultimate location of water within the aquifer and thus improve the chance of subsequent abstraction recovery; they are useful in areas where either the aquifer is overlain by less permeable strata or soil infiltration rates may be low; they reduce the normal soil moisture losses (induced by percolation through the vadose zone) and evaporative losses associated with other recharge techniques; or in areas where structures for direct aquifer recharge are already in place (dug wells or boreholes) thus reducing capital cost. Direct techniques include open boreholes, recharge shafts and injection bores.

Channel modification techniques refer to ways of minimising excess surface water runoff, providing additional channel storage and increasing the wetted area generally through use of dams. Infiltration through the streambed either upstream or downstream of the dam structures is maximised. Channel modification schemes must be located upstream of a well field or in a position where the recharged groundwater and augmented water table can be developed. Channel modification techniques include check dams, recharge dams, and streambed modification.

Catchment management techniques have also been identified as contributing to managed groundwater recharge. These techniques include: contour bunding and trenching, gulley plugging, afforestation and controlled grazing.

Indirect recharge techniques promote aquifer recharge, whether intentionally or not, as a result of some other human activity. This includes induced river recharge, over-irrigation, leaking water supply and wastewater networks, and deliberate seepage disposal from septic tanks.

MAR Technique Selection Criteria

To develop, operate and maintain an economic and efficient recharge project, proper planning, including selection of the most appropriate method, is necessary. The existing conditions (namely the hydrological and hydrogeological setting) may limit the methods of MAR to be considered and will affect the design, operation and maintenance of the project. The nature, scale and distribution of benefits also depend on such site specific factors - it cannot be assumed that MAR will always lead to an improvement in groundwater availability. Therefore, the selection of an appropriate method for MAR requires detailed investigation of the appropriate site specific factors.

The basic requirements for MAR are:

iv. Identify a suitable aquifer for storing water or where water table recovery is desirable and procure land for recharge.

v. Identify available non-committed surplus wet season runoff, or water from another potential source.

vi. Identify the most cost effective recharge technique given the site specific conditions.

These requirements need to be met through geological, hydrological and hydrogeological investigation.

Implementation Scales and MAR Techniques

MAR techniques can be applied at a range of scales, varying from individual household roofs, to communal buildings, to multiple building complexes as well as at the sub-catchment and catchment scale.

The costs and design criteria to ensure successful MAR implementation increase proportionate to the scale of the structures being considered, from minimal costs affordable to a household, to engineering projects only affordable at the municipal or national scale.

The report identifies the appropriate range of techniques to consider for each scale of possible implementation, as well as the appropriate water sources (rainfall, overland run-off, spate flood, wastewater) most applicable to these scales of implementation.

Individual dwellings are best suited to targeting excess roof run-off capture and disposal using soakaways or similar structures. Larger buildings and associated areas of hardstanding may necessitate the use of trench soakaways and infiltration galleries.

Complexes of multiple buildings can use a combination of techniques, depending on the site layout, but may well require the additional storage offered by infiltration basins to attenuate storm run-off before releasing it to soakaway trenches, recharge shafts and injection bores.

All of the above can be targeted to recharge groundwater resources in close proximity to nearby household or communal wells.

The small size of the watersheds in Small Island States generally, and the plethora of upland mini-catchments due to radial drainage patterns, means 'sub-catchment' size schemes may be appropriate for many Caribbean countries, especially where there is an incentive to recharge the groundwater systems upstream of high level springs used for public water supply. Techniques appropriate to this scale of intervention include contour bunding and trenching, check dams, ditch and furrow systems, and infiltration basins – depending on whether surface waters are being targeted from dispersed overland flow or from ephemeral stream beds, and whether off-line or on-line approaches are possible.

Full catchment scale approaches may suit some Caribbean situations, where well fields are near to the coast, where saline intrusion is a problem, and where the catchments land use is not heavily utilized, which can bring with it increased pollution threats. Large recharge dams have been successfully operated in the Middle East and been demonstrated to have tangible improvements on groundwater resources.

<u>MAR Planning and Water Sector Policy Linkages</u>

MAR approaches whilst possible to implement in a piecemeal fashion, will clearly have the greatest impact when implemented in a more strategic manner. By considering the MAR Selection Criteria parameters at a national scale it should be possible to identify areas or zones of each island where geology, surface water run-off, catchment use and water supply infrastructure are progressively more favorable to MAR technologies and most likely to have benefits from these techniques.

It also has two other advantages: i) being a more multi-sector and multi-stakeholder approach to water resources management and hence can be closely linked to Integrated Water Resources Management approaches, which are presently being advocated strongly within the Caribbean and other SIDS regions; and ii) addressing climate variability and thus being considered to be a legitimate climate change adaptation strategy, which is also presently an area of international focus in the Region.

MAR is however a resource augmentation approach and does not represent a panacea in sustainable water resources management. Its introduction could support an increase in demand. MAR needs to be balanced by holistic and integrated water sector management including water demand management and conservation approaches, strong service providers and regulators, an educated and aware civil society, financially sustainable infrastructure systems, and appropriate watershed and land use management.

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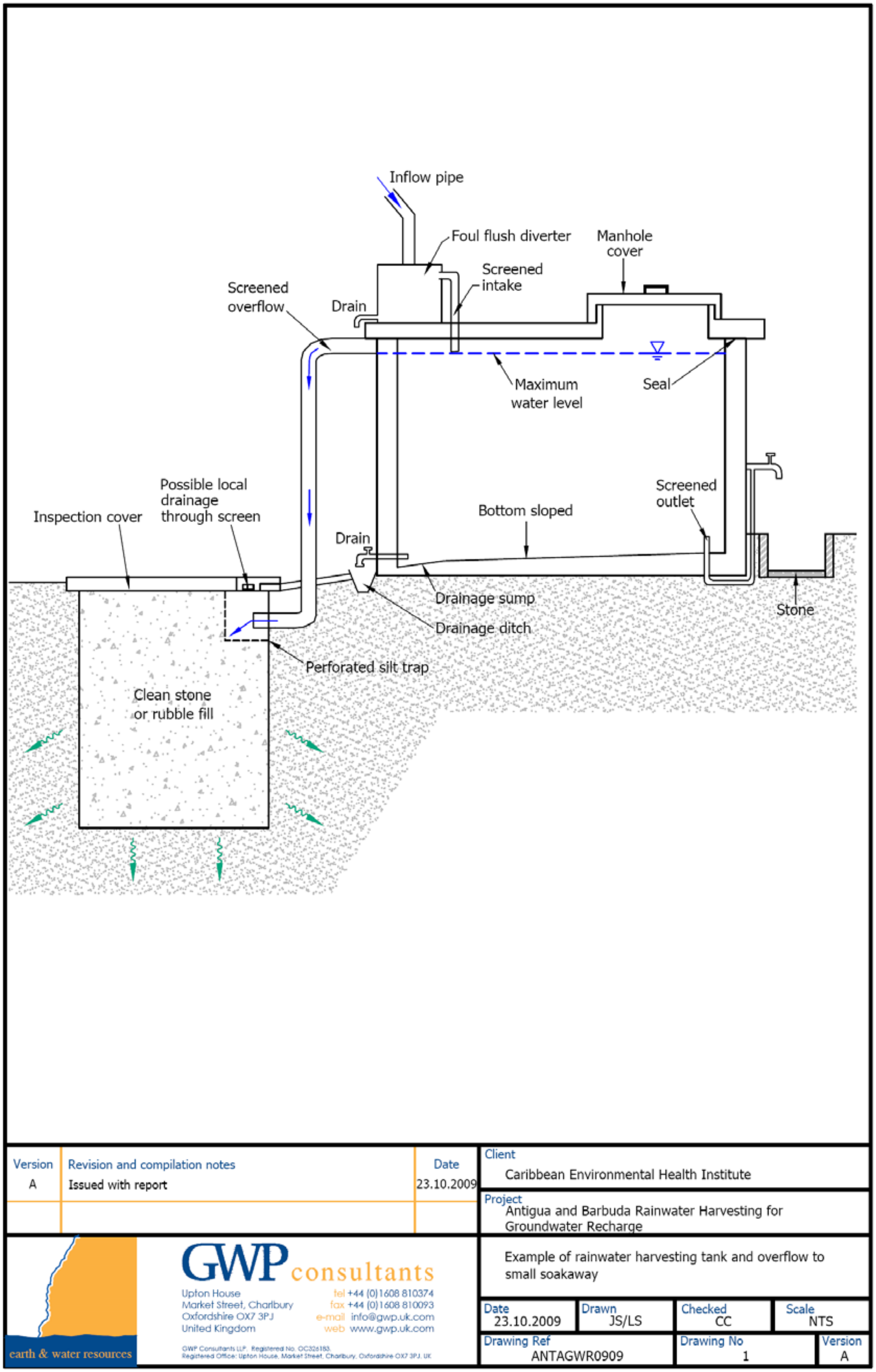
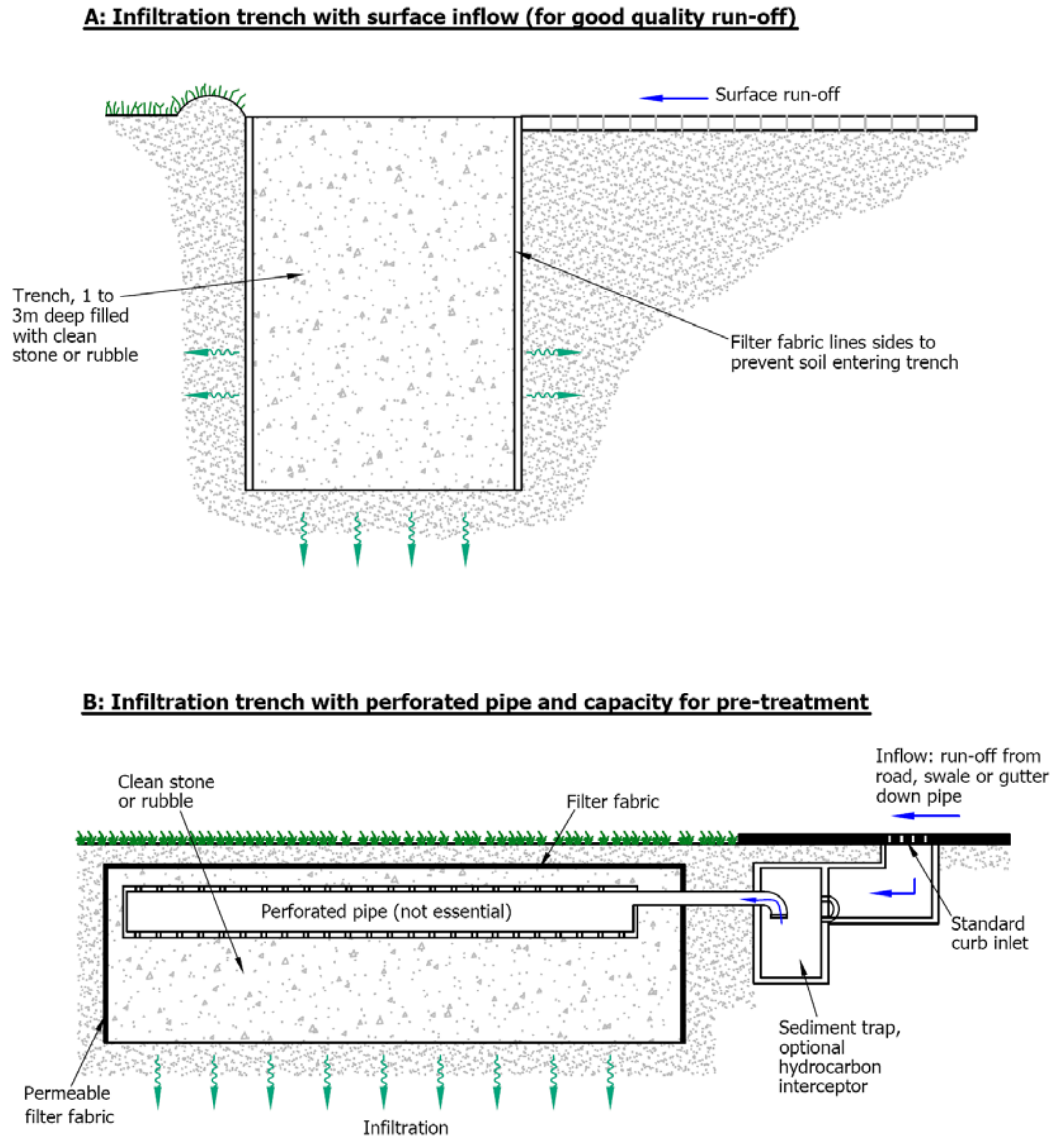
DRAWINGS

1. Example of rainwater harvesting tank and overflow to small soakaway
2. Examples of infiltration trenches
3. Example of an infiltration basin for storm run-off
4. Example of a grassed swale
5. Example of recharge wells/shafts
6. Example of infiltration gallery to recharge treated waste water
7. Example layout of contour trenching with bunds
8. Example of an earth check dam with a masonry core
9. Examples of simple stream offtake/diversion structures
10. Examples of offline infiltration systems

Drawing 1: Example of rainwater harvesting tank and overflow to small soakaway



Drawing 1: Examples of infiltration trenches



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Client: Caribbean Environmental Health Institute

Project: Antigua and Barbuda Rainwater Harvesting for Groundwater Recharge

Examples of infiltration trenches

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ANTAGWR0909	2	A

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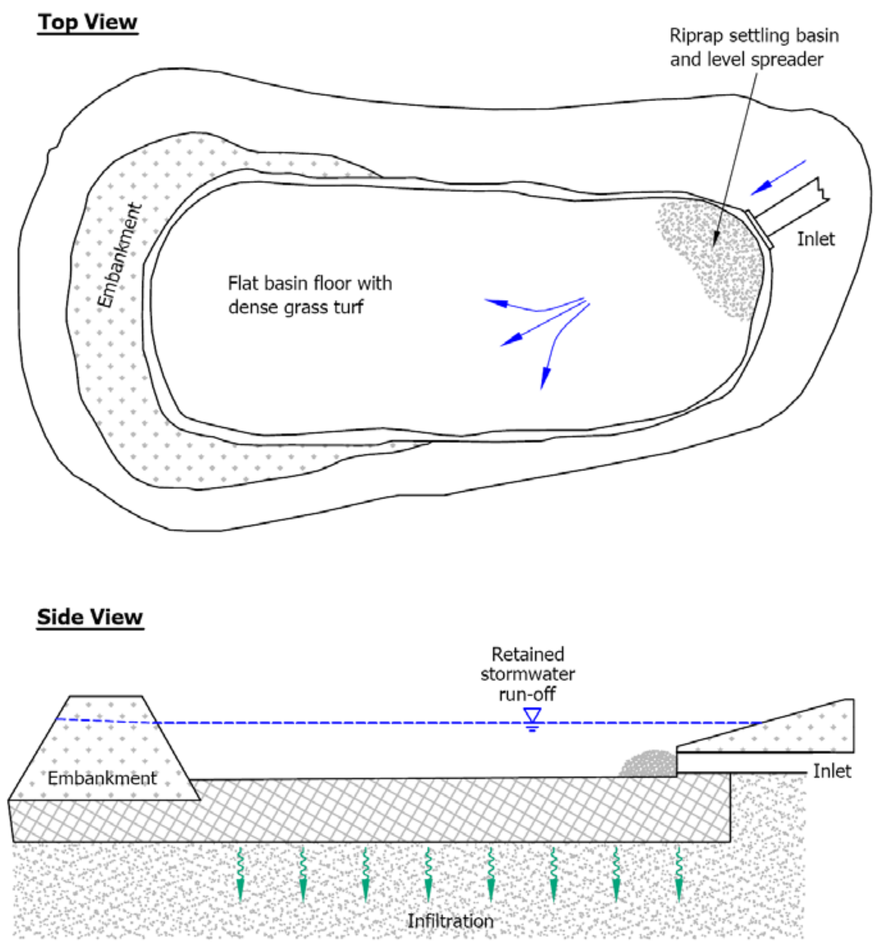
Drawing 3: Example of an infiltration basin for storm run-off



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Example of an infiltration basin for storm run-off

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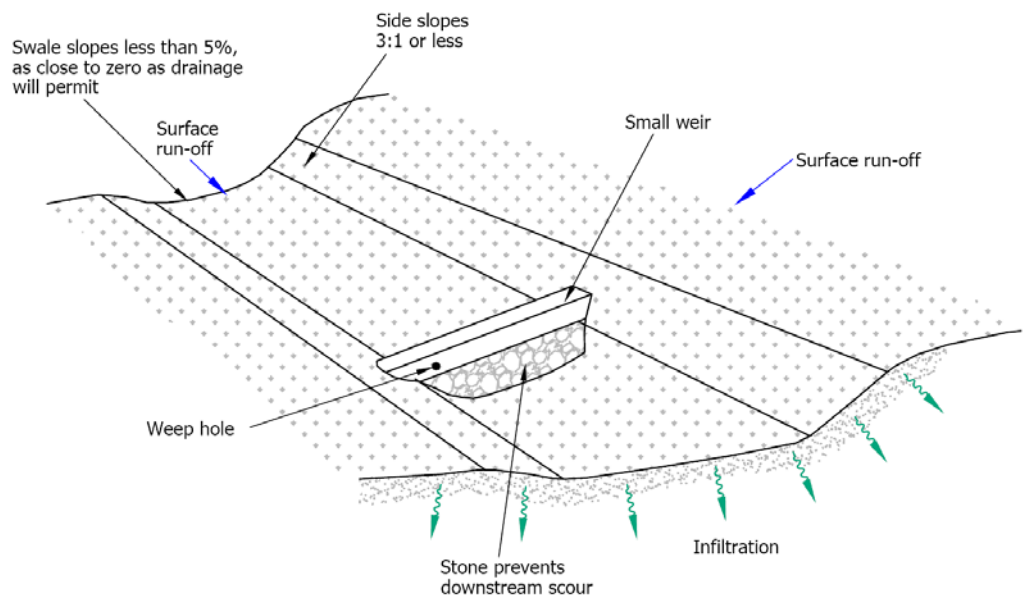
Drawing 4: Example of a grassed swale



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			Example of a grassed swale

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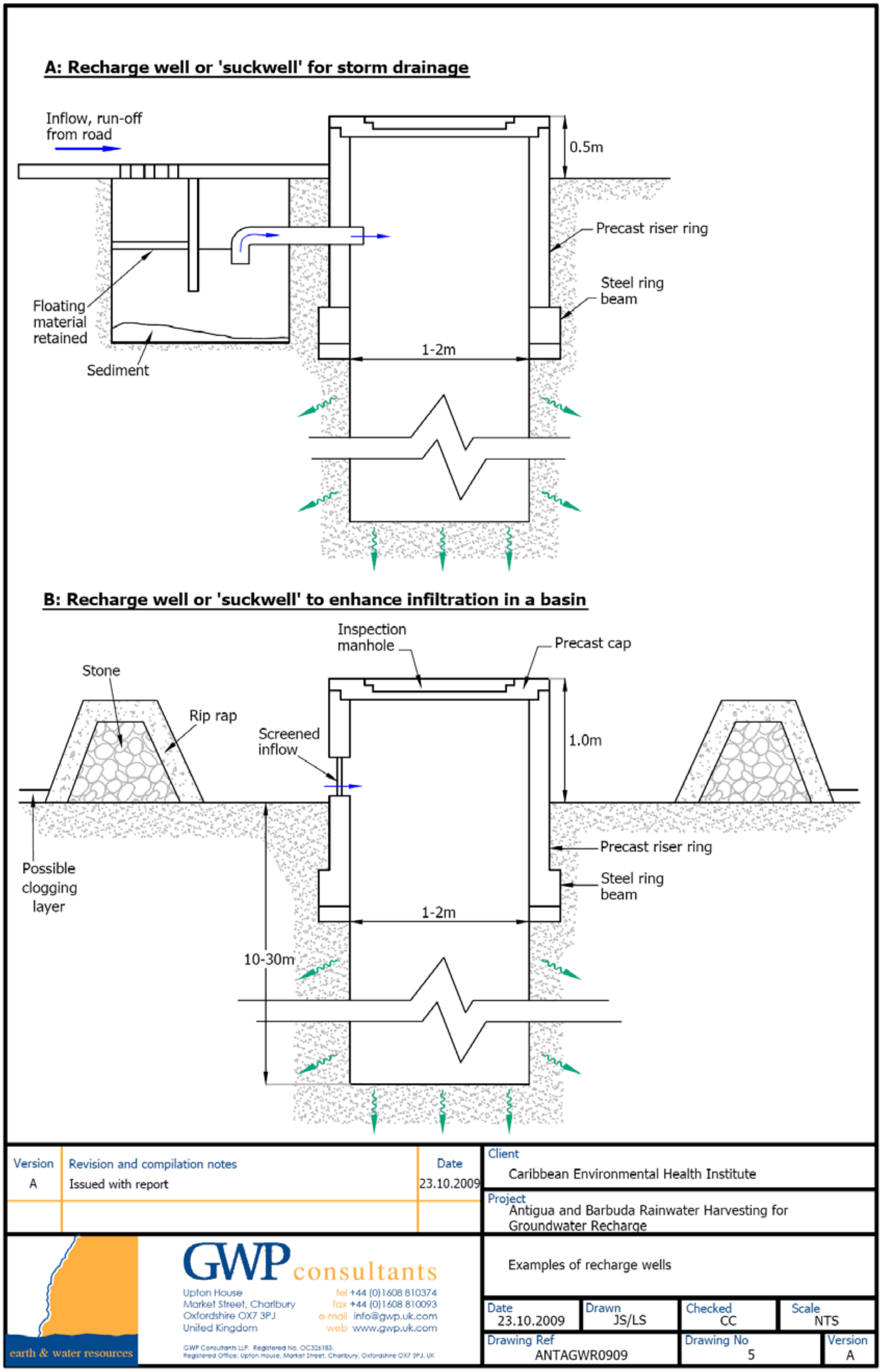
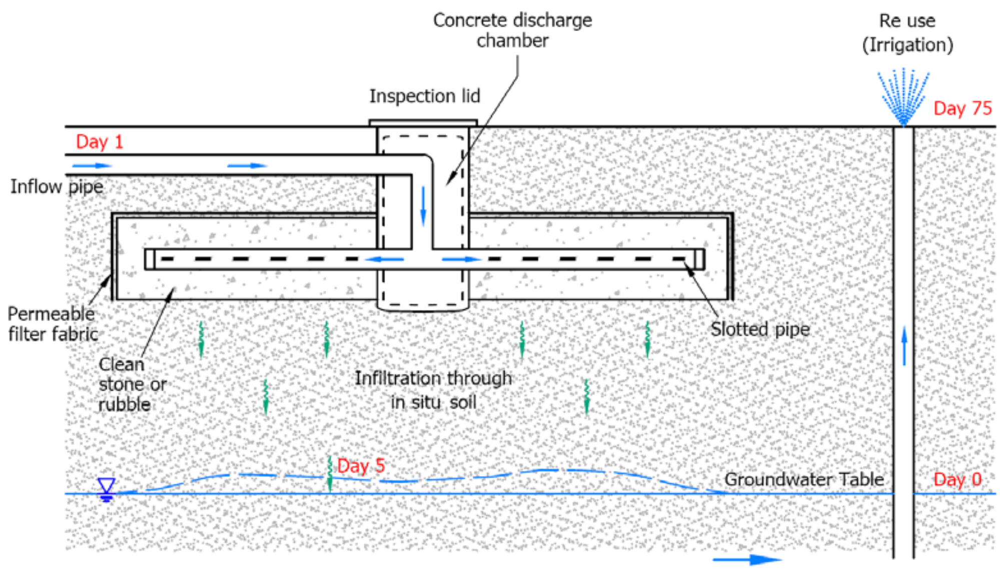
Drawing 5: Example of recharge wells/shafts



Drawing 6: Example of infiltration gallery to recharge treated waste water



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Example of infiltration gallery to recharge treated waste water

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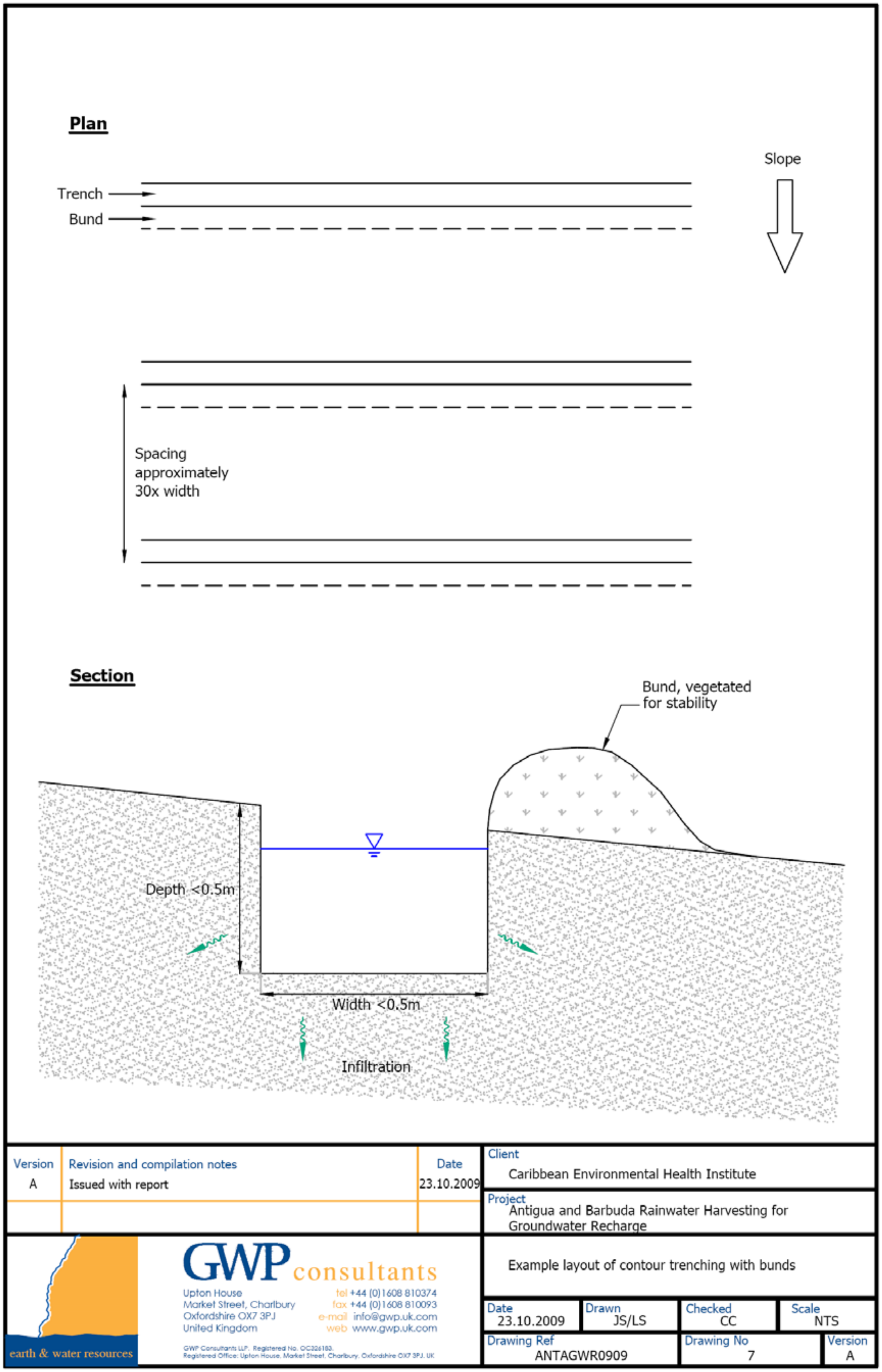
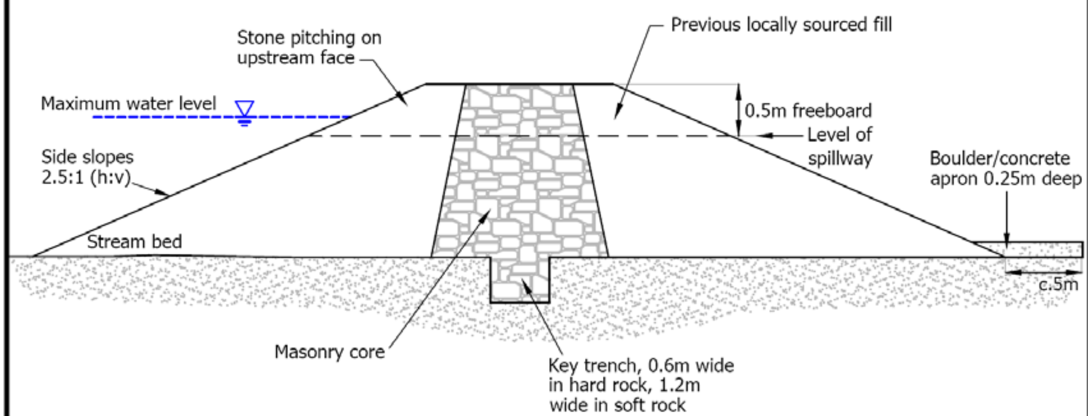
Drawing 7: Example layout of contour trenching with bunds



Drawing 8: Example of an earth check dam with a masonry core



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Example of an earth check dam with a masonry core

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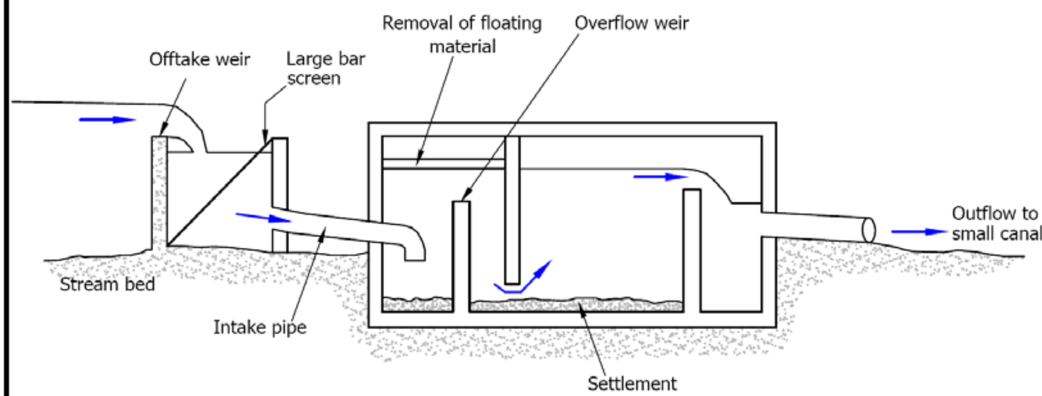
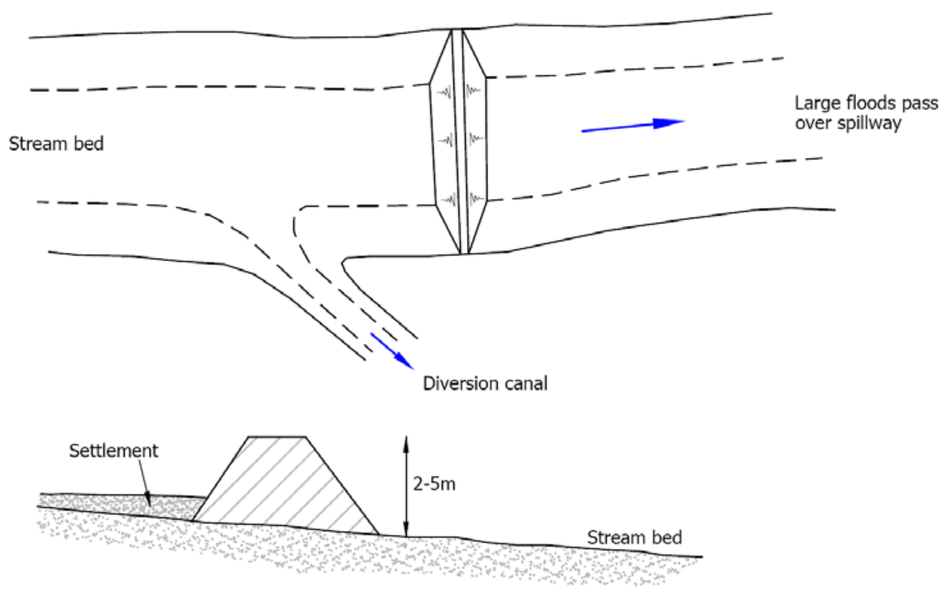
Drawing 9: Examples of simple stream offtake/diversion structures

A: For small stream of relatively low sediment load



B: Diversion with earth bund across stream bed



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Project	Antigua and Barbuda Rainwater Harvesting for Groundwater Recharge
	Examples of simple stream offtake/diversion structures

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Drawing 10: Examples of offline infiltration systems